
UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

IBM Corporation
Petitioner

vs.

Rigetti & Co., Inc.
Patent Owner

U.S. Patent No. 9,893,262

DECLARATION OF INGRID HSIEH-YEE, PHD, UNDER 37 C.F.R. § 1.68

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I, Ingrid Hsieh-Yee, Ph.D., do hereby declare as follows:

I. INTRODUCTION

1. I have been retained as an independent expert witness on behalf of International Business Machines Corporation ("IBM") for an *Inter Partes* Review ("IPR") of U.S. Patent No. 9,893,262 ("the '262 patent").

2. I am being compensated for my work in this matter at my accustomed hourly rate. I am also being reimbursed for reasonable and customary expenses associated with my work and testimony in this investigation. My compensation is not contingent on the results of my study, the substance of my opinions, or the outcome of this matter.

3. In the preparation of this declaration, I have reviewed the exhibits referenced below, each of these is a type of material that experts in my field would reasonably rely upon when forming their opinions:

(1) Hatridge, M. *et al.*, ("Hatridge"), "Quantum Back-Action of an Individual Variable-Strength Measurement," in *Science*, Vol. 339, Issue 6116 (January 2013), available at https://science.sciencemag.org/content/339/6116/178/tab-pdf, obtained from the website of *Science*, **Exhibit 1004**;

(2) Hatridge, M. *et al.*, ("Hatridge"), "Quantum Back-Action of an Individual Variable-Strength Measurement," in *Science*, Vol. 339, Issue 6116 (January 2013), obtained from the Library of Congress,

Appendix 1004-A;

(3) Hatridge, M. *et al.*, ("Hatridge"), "Quantum Back-Action of an Individual Variable-Strength Measurement," in *Science*, Vol. 339, Issue 6116 (January 2013), obtained from the University of Wisconsin-Madison Libraries, **Appendix 1004-B**;

(4) MARC Record Information for *Science*, which contains Hatridge, available at the online catalog of the University of Wisconsin-Madison Libraries at https://search.library.wisc.edu/serial/999482621202121 (select "Staff View" for the MARC record), **Appendix 1004-C**;

(5) Bibliographic Record Information for *Science*, which contains Hatridge, available at the online catalog of the University of Wisconsin-Madison Libraries at https://search.library.wisc.edu/serial/999482621202121, **Appendix 1004-D**;

(6) Abstract format of PubMed record for Hatridge, available at https://www.ncbi.nlm.nih.gov/pubmed/?term=Quantum+Back-Action+of+an+Individual+Variable-Strength+Measurement, **Appendix 1004-E**;

(7) MEDLINE Record for Hatridge, available at PubMed at Action+of+an+Individual+Variable-Strength+Measurement&report=medline&format=text, **Appendix 1004-F**;

(8) Hatridge, M. *et al.*, ("Hatridge"), "Quantum Back-Action of an Individual Variable-Strength Measurement," in *Science*, Vol. 339,

Issue 6116 (January 2013), obtained from the webpage for the Hatridge article on the *Science* website (http://science.sciencemag.org/content/339/6116/178?panels_ajax_tab_trigger=tab-pdf&panels_ajax_tab_tab=jnl_sci_tab_pdf&_=1545417642403&sso=1&sso_redirect_count=1&oauth-code=f4f7216a-2815-4734-9c3d-d091a8dbeb4f), document PDF available at http://science.sciencemag.org/content/sci/339/6116/178.full.pdf, **Appendix 1004-G;**

(9) Selected citations of Hatridge, **Appendix 1004-H**;

(10) Geerlings, K., Shankar, S., Edwards, E., Frunzio, L., Schoelkopf, R. J., & Devoret, M. H., ("Geerlings"), "Improving the Quality Factor of Microwave Compact Resonators by Optimizing Their Geometrical Parameters", *Applied Physics Letters*, vol. 100, no. 19 (2012), article 192601, available at https://aip.scitation.org/doi/pdf/10.1063/1.4710520?class=pdf, obtained from the website of *Applied Physics Letters*, **Exhibit 1005**;

(11) Geerlings, K., Shankar, S., Edwards, E., Frunzio, L., Schoelkopf, R. J., & Devoret, M. H., ("Geerlings"), "Improving the Quality Factor of Microwave Compact Resonators by Optimizing Their Geometrical Parameters", *Applied Physics Letters*, vol. 100, no. 19 (2012), article 192601, obtained from the British Library, **Appendix 1005-A**;

(12) Bibliographic record for *Applied Physics Letters*, whose vol. 100,

no. 19 (2012) contains Geerlings, available at the online catalog of British Library at http://explore.bl.uk/BLVU1:LSCOP-ALL:BLL01014532647, **Appendix 1005-B**;

(13) MARC record for *Applied Physics Letters*, whose vol. 100, no. 19 (2012) contains Geerlings, available at the online catalog of British Library at http://primocat.bl.uk/F/?func=direct&local_base=PRIMO&doc_number=014532647&format=001&con_lng=eng, **Appendix 1005-C**;

(14) Copyright registration record for *Applied Physics Letters*, vol. 100, no. 19 (2012) that contains Geerlings, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=254&ti=251,254&Search%5FArg=applied%20physics%20letters&Search%5FCode=TALL&CNT=25&PID=Vzxeihwz6ZLpSqJizG5xYZ87_9yM&SEQ=20190803160347&SID=1, **Appendix 1005-D**;

(15) Public availability date confirmation letter for Geerlings obtained from the British Library, **Appendix 1005-E**;

(16) Supporting pages for the Public availability date confirmation letter for Geerlings obtained from the British Library, **Appendix 1005-F**;

(17) Selected early citations to Geerlings, **Appendix 1005-G**;

(18) Pozar, D. M., ("Pozar"), MICROWAVE ENGINEERING, 4th edition, 2012, obtained from the Library of Congress, **Exhibit 1006**;

(19) Bibliographic record for Pozar, available at the online catalog of the Library of Congress at https://lccn.loc.gov/2011033196, **Appendix 1006-A**;

(20) MARC record for Pozar, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=3968&recPointer=0&recCount=25&searchType=2&bibId=16910802, **Appendix 1006-B**;

(21) Copyright registration record for Pozar, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=1&ti=1,1&Search%5FArg=Microwave%20engineering&Search%5FCode=TALL&CNT=25&PID=7Y1AWD7EkpwZqS9YFSycPuqWg7i3&SEQ=20190803161921&SID=1, **Appendix 1006-C**;

(22) Selected citations to Pozar, **Appendix 1006-D**;

(23) Stubbins, W. F., ("Stubbins"), ESSENTIAL ELECTRONICS, John Wiley & Sons, Inc., 1986, obtained from the Library of Congress, **Exhibit 1007**;

(24) Bibliographic record for Stubbins, available at the online catalog of the Library of Congress at https://lccn.loc.gov/85009447, **Appendix 1007-A**;

(25) MARC record for Stubbins, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=3949&recPoint

er=0&recCount=25&searchType=2&bibId=2859348, **Appendix 1007-B**;

(26) Copyright registration record for Stubbins, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=3&ti=1,3&Search%5FArg=Essential%20electronics&Search%5FCode=TALL&CNT=25&PID=_BG21W2TvZp0jWq4Shkg52ppI5YU&SEQ=20190803163034&SID=1, **Appendix 1007-C**;

(27) Simons, R., & Simons, R. N., ("Simons"), COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS, John Wiley, 2001, obtained from the Library of Congress, **Exhibit 1009**;

(28) Bibliographic record for Simons, available at the online catalog of the Library of Congress at https://lccn.loc.gov/00043812, **Appendix 1009-A**;

(29) MARC record for Simons, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=3944&recPointer=0&recCount=25&searchType=2&bibId=12139501, **Appendix 1009-B**;

(30) Copyright registration record for Simons, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?Search_Arg=COPLANAR+WAVEGUIDE+CIRCUITS%2C+COMPONENTS%2C+AND+SYSTEMS&Search_

Code=TALL&PID=Rf81-XgAx16ZiIBPNRS4v44G1Sdw&SEQ=20190803163616&CNT=25&HIST=1, **Appendix 1009-C**;

(31) Selected citations to Simons, **Appendix 1009-D**;

(32) Vissers, M. R., Weides, M. P., Kline, J. S., Sandberg, M., & Pappas, D. P., "Identifying Capacitive and Inductive Loss in Lumped Element Superconducting Hybrid Titanium Nitride/Aluminum Resonators," *Applied Physics Letters*, vol. 101, no. 2 (2012), article 022601, available at https://aip.scitation.org/doi/pdf/10.1063/1.4730389?class=pdf, obtained from the website of *Applied Physics Letters*, **Exhibit 1010**;

(33) Vissers, M. R., Weides, M. P., Kline, J. S., Sandberg, M., & Pappas, D. P., ("Vissers"), "Identifying Capacitive and Inductive Loss in Lumped Element Superconducting Hybrid Titanium Nitride/Aluminum Resonators," *Applied Physics Letters*, vol. 101, no. 2 (2012), article 022601, obtained from the British Library, **Appendix 1010-A**;

(34) Bibliographic record for *Applied Physics Letters*, whose vol. 101, no. 2 (2012) contains Vissers, available at the online catalog of British Library at http://explore.bl.uk/BLVU1:LSCOP-ALL:BLL01014532647, **Appendix 1010-B**;

(35) MARC record for *Applied Physics Letters*, whose vol. 101, no. 2 (2012) contains Vissers, available at the online catalog of British Library at

http://primocat.bl.uk/F/?func=direct&local_base=PRIMO&doc_number=014532647&format=001&con_lng=eng, **Appendix 1010-C**;

(36) Public availability date confirmation letter for Vissers obtained from the British Library, **Appendix 1010-D**;

(37) Supporting pages for the Public availability date confirmation letter for Vissers obtained from the British Library, **Appendix 1010-E**;

(38) Copyright registration record for *Applied Physics Letters*, vol. 101, no. 2 (2012), available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=261&ti=251,261&Search%5FArg=applied%20physics%20letters&Search%5FCode=TALL&CNT=25&PID=9V81tE_cvfCuE0qjc5QymCNNzn-e&SEQ=20190803164416&SID=1, **Appendix 1010-F**;

(39) Selected early citations to Vissers, **Appendix 1010-G**;

(40) Kim, Z., Suri, B., Zaretskey, V., Novikov, S., Osborn, K. D., Mizel, A., ... & Palmer, B. S., "Decoupling a Cooper-Pair Box to Enhance the Lifetime to 0.2 ms," in *Physical review letters*, vol. 106, no. 12 (2011), article 120501, available at https://journals.aps.org/link/73509d3a-0131-4558-882e-37abada8f2d6, obtained from the website of "Physical Review Journals" published by American Physical Society **Exhibit 1011**;

(41) Kim, Z., Suri, B., Zaretskey, V., Novikov, S., Osborn, K. D., Mizel, A., ... & Palmer, B. S., ("Kim"), "Decoupling a Cooper-Pair Box to Enhance the Lifetime to 0.2 ms," in *Physical review*

letters, vol. 106, no. 12 (2011), article 120501, obtained from the University of Michigan Libraries, **Appendix 1011-A**;

(42) Bibliographic record for *Physical review letters*, whose vol. 106, no. 12 (2011) contains Kim, available at the online catalog of the University of Michigan Libraries at https://search.lib.umich.edu/catalog/record/004528039, **Appendix 1011-B**;

(43) MARC record for *Physical review letters*, whose vol. 106, no. 12 (2011) contains Kim, available at the online catalog of the University of Michigan Libraries at https://search.lib.umich.edu/catalog/record/004528039, select "View MARC data", **Appendix 1011-C**;

(44) Copyright registration record for *Physical review letters*, whose vol. 106, no. 12 (2011) contains Kim, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=223&ti=201,223&Search%5FArg=Physical%20review%20letters&Search%5FCode=TALL&CNT=25&PID=btGhSWnXXVmcNlPgvDwA8F5mcnF&SEQ=20190803165744&SID=1, **Appendix 1011-D**;

(45) Selected citations to Kim, **Appendix 1011-E**;

(46) Bahl, I. J., ("Bahl"), Lumped Elements for RF and Microwave Circuits, Artech House, 2003, obtained from the Library of Congress, **Exhibit 1013**;

(47) Bibliographic record for Bahl, available at the online catalog of the

Library of Congress at https://lccn.loc.gov/2003048102, **Appendix 1013-A**;

(48) MARC record for Bahl, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=8125&recPointer=0&recCount=25&bibId=13134921, **Appendix 1013-B**;

(49) Copyright registration record for Bahl, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?Search_Arg=Lumped+Elements+for+RF+and+Microwave+Circuits&Search_Code=TALL&PID=E0eDYQwupE87nzox7Xa6Uxc-5a6&SEQ=20190803170347&CNT=25&HIST=1, **Appendix 1013-C**;

(50) Selected citations to Bahl, **Appendix 1013-D**;

(51) Blais, A., Huang, R. S., Wallraff, A., Girvin, S. M., & Schoelkopf, R. J., "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: An Architecture for Quantum Computation," *Physical Review A*, vol. 69, no. 6 (2004), article 062320 (14 pages), available at https://journals.aps.org/link/b44d1e15-f60e-40d1-b272-50a6b1a76e64, obtained from obtained from the website of "Physical Review Journals" published by American Physical Society **Exhibit 1015**;

(52) Blais, A., Huang, R. S., Wallraff, A., Girvin, S. M., & Schoelkopf,

R. J., ("Blais"), "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: An Architecture for Quantum Computation," *Physical Review A*, vol. 69, no. 6 (2004), article 062320 (14 pages), obtained from Library of Congress, **Appendix 1015-A**;

(53) Bibliographic record for *Physical Review A*, whose vol. 69, no. 6 (2004) contains Blais, available at the online catalog of the Library of Congress at https://lccn.loc.gov/90656533, **Appendix 1015-B**;

(54) MARC record for *Physical Review A*, whose vol. 69, no. 6 (2004) contains Blais, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=18128&recPointer=3&recCount=25&bibId=11376368, **Appendix 1015-C**;

(55) Copyright registration record for vol. 69, no. 6 (2004) of *Physical Review A* that contains Blais, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=45&ti=26,45&Search%5FArg=physical%20review%20A&Search%5FCode=TALL&CNT=25&PID=6ZOvLFl5zSmL1ahdY5GALk9PCFS0&SEQ=20190803230518&SID=1, **Appendix 1015-D**;

(56) Selected citations of Blais, **Appendix 1015-E**;

(57) Barends, R., Kelly, J., Megrant, A., Sank, D., Jeffrey, E., Chen, Y., ... & O'Malley, P., "Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits," *Physical Review Letters*, vol. 111, no. 8 (August 2013), article 080502, available at

https://journals.aps.org/link/f3f1de1e-3c72-4807-b81c-6268b041c1d4, obtained from the website of "Physical Review Journals" published by American Physical Society **Exhibit 1019**;

(58) Barends, R., Kelly, J., Megrant, A., Sank, D., Jeffrey, E., Chen, Y., ... & O'Malley, P., ("Barends"), "Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits," *Physical Review Letters*, vol. 111, no. 8 (August 2013), article 080502, obtained from the Library of Congress, **Appendix 1019-A**;

(59) Bibliographic record for *Physical Review Letters*, whose vol. 111, no. 8 (August 2013) contains Barends, available at the online catalog of the Library of Congress at https://lccn.loc.gov/59037543, **Appendix 1019-B**;

(60) MARC record for *Physical Review Letters*, whose vol. 111, no. 8 (August 2013) contains Barends, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=9273&recPointer=0&recCount=25&bibId=11152495, **Appendix 1019-C**;

(61) Copyright registration record for vol. 111, no. 8 (August 2013) of *Physical Review Letters* that contains Barends, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=351&ti=351,351&Search%5FArg=physical%20review%20letters&Search%5FCode=TALL&CNT=25&PID=H5vCo5QaTI8fZN7CBoGJNmSK3TER&SEQ=20190803225715&SID=2, **Appendix 1019-D**;

(62) Selected citations of Barends, **Appendix 1019-E**;

(63) Paik, H., Schuster, D. I., Bishop, L. S., Kirchmair, G., Catelani, G., Sears, A. P., ... & Girvin, S. M., "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture," *Physical Review Letters*, vol. 107, no. 24 (December 2011), article 240501, available at https://journals.aps.org/link/80786b6d-bff7-47b3-8505-318e04c6fbca, obtained from the website of "Physical Review Journals" published by American Physical Society **Exhibit 1020**;

(64) Paik, H., Schuster, D. I., Bishop, L. S., Kirchmair, G., Catelani, G., Sears, A. P., ... & Girvin, S. M., ("Paik"), "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture," *Physical Review Letters*, vol. 107, no. 24 (December 2011), article 240501, obtained from the Library of Congress, **Appendix 1020-A**;

(65) Bibliographic record for *Physical Review Letters*, whose vol. 107, no. 24 (December 2011) contains Paik, available at the online catalog of the Library of Congress at https://lccn.loc.gov/59037543, **Appendix 1020-B**;

(66) MARC record for *Physical Review Letters*, whose vol. 107, no. 24 (December 2011) contains Paik, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=9273&recPointer=0&recCount=25&bibId=11152495, **Appendix 1020-C**;

(67) Copyright registration record for vol. 107, no. 24 (December 2011)

of *Physical Review Letters* that contains Paik, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=259&ti=251,259&Search%5FArg=physical%20review%20letters&Search%5FCode=TALL&CNT=25&PID=h3g_ND3UTGNmtVSbLZlpuNCCedOz&SEQ=20190803225426&SID=2, **Appendix 1020-D**;

(68) Selected citations of Paik, **Appendix 1020-E**;

(69) Griffiths, David J., ("Griffiths"), INTRODUCTION TO ELECTRODYNAMICS, 4th edition, Pearson, 2013, obtained from the University of Wisconsin Libraries, **Exhibit 1021**;

(70) Bibliographic and MARC records for Griffiths, available at the online catalog of the University of Wisconsin Libraries at https://search.library.wisc.edu/catalog/9910134691602121, **Appendix 1021-A**;

(71) MARC record for Griffiths, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=9353&recPointer=3&recCount=25&bibId=17463252, **Appendix 1021-B**;

(72) Copyright registration record for Griffiths, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=1&ti=1,1&Search%5FArg=introduction%20to%20electrodynamics&Search%5FCode=TALL&CNT=25&PID=LAxDS2JGrUS4aXEOSpJQ-

VVTwoGI&SEQ=20190803225036&SID=1, **Appendix 1021-C**;

(73) Selected citations of Griffiths, **Appendix 1021-D;**

(74) Houck, A. A., Koch, J., Devoret, M. H., Girvin, S. M., & Schoelkopf, R. J., “Life after charge noise: Recent results with transmon qubits,” *Quantum Information Processing,* vol. 8, nos. 2/3 (June 2009), 105-115, available at https://link.springer.com/content/pdf/10.1007%2Fs11128-009-0100-6.pdf, obtained from the website of Springer Link, **Exhibit 1025**;

(75) Houck, A. A., Koch, J., Devoret, M. H., Girvin, S. M., & Schoelkopf, R. J., “Houck,” “Life after charge noise: Recent results with transmon qubits,” *Quantum Information Processing*, vol. 8, nos. 2/3 (June 2009), 105-115, obtained from the Library of Congress, **Appendix 1025-A**;

(76) Bibliographic record for *Quantum Information Processing* whose vol. 8, nos. 2/3 (June 2009) contains Houck, available at the online catalog of the Library of Congress at https://lccn.loc.gov/2004242011, **Appendix 1025-B**;

(77) MARC record for *Quantum Information Processing* whose vol. 8, nos. 2/3 (June 2009) contains Houck, available at the online catalog of the Library of Congress at https://catalog.loc.gov/vwebv/staffView?searchId=13367&recPointer=0&recCount=25&searchType=1&bibId=14234500, **Appendix 1025-C**;

(78) Copyright registration record for vol. 8, nos. 2/3 (June 2009) of

Quantum Information Processing that contains Houck, available at the public catalog of the United States Copyright Office at https://cocatalog.loc.gov/cgi-bin/Pwebrecon.cgi?v1=1&ti=1,1&Search%5FArg=quantum%20information%20processing&Search%5FCode=TALL&CNT=25&PID=D-VtwFU3Swk7nO3IAYQ6J0sUV&SEQ=20190903153906&SID=1, **Appendix 1025-D**;

(79) August 2009-June 2015 Citation of Houck, **Appendix 1025-E**;

(80) Gambetta, J. M., Ketchen, M. B., Rigetti, C. T., & Steffen, M., inventors; International Business Machines Corp, assignee. Array of Quantum Systems in a Cavity for Quantum Computing. United States Patent US 8,642,998. 2014 Feb. 4, **Appendix 1025-F**;

(81) Archived page of vol. 8, nos. 2/3 (June 2009) of *Quantum Information Processing*, which contains Houck, available from Internet Archive at https://web.archive.org/web/20150425042303/http://link.springer.com/journal/11128/8/2/page/1, **Appendix 1025-G.**

4. In forming the opinions expressed within this declaration, I have considered:

(1) The documents listed above;

(2) The reference materials cited herein; and

(3) My own academic background and professional experiences, as

described below.

II. BACKGROUND AND QUALIFICATIONS

5. My complete qualifications and professional experience are described in my curriculum vitae, a copy of which is provided as **Appendix A**. The following is a brief summary of my relevant qualifications and professional experience.

6. I am currently a Professor in the Department of Library and Information Science at the Catholic University of America. I have experience working in an academic library, a medical library, and a legislative library and have been a professor for more than 25 years. I hold a Ph.D. in Library and Information Studies from the University of Wisconsin-Madison and a Masters in Library and Information Studies from the University of Wisconsin-Madison.

7. I am an expert on library cataloging and classification and have published two books on this subject, *Organizing Audiovisual and Electronic Resources for Access*: *A Cataloging Guide* (2000, 2006). I teach a variety of courses, including Cataloging and Classification, Advanced Cataloging and Classification, Organization of Internet Resources, Organization of Information, Digital Content Creation and Management, Internet Searches and Web Design, Information Literacy Instruction, Advanced Information Retrieval and Analysis

Strategies, and The Information Professions in Society. My research interests cover cataloging and classification, information organization, metadata, information retrieval, information architecture, digital collections, scholarly communication, user interaction with information systems, and others.

III. LIBRARY RECORDS

A. MARC

8. I am fully familiar with a library cataloging encoding standard known as the "Machine-Readable Cataloging" standard, also known as "MARC," which became the national standard for sharing bibliographic data in the United States by 1971 and the international standard by 1973. MARC is the primary communications protocol for the transfer and storage of bibliographic metadata in libraries. Experts in my field would reasonably rely upon MARC records when forming their opinions.

9. A MARC record comprises several fields, each of which contains specific data about the work. Each field is identified by a standardized, unique, three-digit code corresponding to the type of data that follows. **Appendix B** is a true and correct copy of Parts 7 to 10 of "Understanding MARC Bibliographic: Machine-Readable Cataloging" (http://www.loc.gov/marc/umb/) from the Library of Congress that explains commonly used MARC fields. For example, the personal author of the work is recorded in Field 100, the title is recorded in Field 245, publisher information is recorded in Field 260, the physical volume and characteristics of a publication are recorded in Field 300, and topical subjects are recorded in the 650 fields.

B. OCLC

10. The Online Computer Library Center (OCLC) is the largest bibliographic network of the world, with more than 449 million records and thousands of libraries from more than 100 countries. According to the "Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Inc.," OCLC was created "to establish, maintain and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific, literary and educational knowledge and information." The Third Article, Amended Articles of Incorporation of OCLC Online Computer Library Center, Inc. was last revised on November 30, 2016 and is available at https://www.oclc.org/content/dam/oclc/membership/articles-of-incorporation.pdf (**Appendix C**)

11. OCLC members can contribute original cataloging records in MARC to the system or derive cataloging records from existing records, an activity referred to as "copy cataloging." When an OCLC participating institution acquires a work, it can create an original MARC record for the work in OCLC's Connexion system (a system for catalogers to create and share MARC records), and the system will automatically generate a code for the date of record creation in the *yymmdd* format, and the creating library's OCLC symbol is recorded in subfield "a" of the 040 field. Once the MARC record is in Connexion, it becomes available to other OCLC members for adoption to their local online catalogs (*i.e.*, copy cataloging).

12. After a MARC record is created in Connexion, it also becomes searchable and viewable on WorldCat, which is a web portal to more than 10,000 libraries worldwide. The record in WorldCat, however, is not presented in MARC fields. Instead, the data elements are labeled to help users interpret the record.

C. WorldCat

13. WorldCat (http://www.worldcat.org) is "the world's largest network of library content and services" and its features are summarized in "What is WorldCat" (http://www.worldcat.org/whatis/default.jsp). Through WorldCat, users can search for information in their local libraries and libraries around the world. WorldCat allows users to search for books, CDs, videos, and many new types of digital content, such as audiobooks, in many languages. Users can also retrieve research materials and article citations with links to their full text. After an item is retrieved, WorldCat helps users identify a library nearby that holds the item or all the libraries that hold the item. WorldCat is an efficient way to explore the content held by more than 10,000 libraries around the world.

14. Library online catalogs are based on MARC records that represent their collections in order to help the public understand what materials are publicly accessible in those libraries. Most libraries with online catalogs have made their catalogs freely available on the Web. These online catalogs offer user-friendly search interfaces. Strong user interest in keyword searches and the popularity of Google have led to the “googlization” of library search systems. As a result, many library catalogs now provide a single search box for users to conduct keyword searches, with additional support for searches by author, title, subject terms, and other data elements such as ISBN (International Standard Book Number). Library catalogs these days also offer features for users to narrow their search results by language, year, format, and other elements. Many libraries display MARC records on their online catalogs with labels for the data elements to help the public interpret MARC records. Many libraries also offer the option to display MARC records in MARC fields.

15. Libraries create MARC records for works they acquire, including books, serials, motion pictures, and publications in other formats. The cataloging of monographs is a fairly common activity, and most academic libraries make newly cataloged books available to users soon after the cataloging work is completed, usually within a week. The cataloging of serials and the serial check-in process are discussed here to show how libraries usually provide access to newly received serial issues. According to the glossary of the *RDA: Resource Description and Access* cataloging standard, a serial is "a mode of issuance of a manifestation issued in successive parts, usually bearing numbering, that has no predetermined conclusion. A serial includes a periodical, monographic series, newspaper, etc." Because the publisher of a serial makes new issues of the serial available successively, a customary cataloging practice is to create one bibliographic record for the serial, and the MARC serial record typically provides information on the beginning date and frequency of the serial, not the dates of individual issues. In other words, libraries typically do not create MARC records for individual issues of a serial. Instead, they rely on a serial check-in system to track the receipt of new issues. A common check-in practice is to date stamp a new issue when it arrives. This practice has become automated since the late 1990s, and libraries now vary in how they share the receipt date of a new serial issue with the public. Some libraries use a date stamp, some affix a label to indicate the receipt date, some pencil in the receipt date, and some do not provide the information to the public.

16. The serial check-in process usually takes less than an hour, and one of the steps involves placing a date stamp on the new issue to document the date the issue is checked in. After that, the holdings information of the serial is updated in the library's catalog so that users know which issues are available for request or access. After serial check-in is completed, the new issue is placed on the shelf with the previous issues of the serial. Libraries with a public periodical room typically place new issues in the periodical room for easy user access. Because information presented in serials often reflects latest discovery, a general practice of libraries is to make new issues of serials available for user access soon after they are checked in, usually within a week.

17. I am personally familiar with many online catalogs, databases, and search engines. In preparing for this declaration I used authoritative information systems, including WorldCat (https://www.worldcat.org), the online catalog of the Library of Congress (https://catalog.loc.gov), the online catalog of the University of Wisconsin-Madison (https://search.library.wisc.edu), the online catalog of the British Library (http://explore.bl.uk/primo_library/libweb/action/search.do?vid=BLVU1), the online catalog of the University of Michigan Libraries (https://search.lib.umich.edu/everything), and Google Scholar to search for records. These records are identified and discussed in this declaration. Experts in the field would reasonably rely on the data described herein to form their opinions.

IV. PRINTED PUBLICATIONS

A. Exhibit 1004 (Hatridge)

1. Authentication

18. **Exhibit 1004** is a true and correct copy of "Quantum Back-Action of an Individual Variable-Strength Measurement" by Hatridge et al. in *Science*, Vol. 339, Issue 6116 (January 2013) that I obtained from the website of *Science*. I also located a copy of the Hatridge article from the print journal at the Library of Congress (**Appendix 1004-A**), compared the electronic copy and the Library of Congress copy closely, and concluded that **Exhibit 1004** and **Appendix 1004-A** contain the same article. The differences are that **Exhibit 1004** includes a page of links to supplemental materials at the end of the file, while **Appendix 1004-A** includes the front matter of the journal issue that contains the Hatridge article.

19. **Appendix 1004-A** is a true and correct copy of "Quantum Back-Action of an Individual Variable-Strength Measurement" ("Hatridge") by Hatridge et al. in *Science*, Vol. 339, Issue 6116 (January 2013) that I made during my personal visit to the Library of Congress. When I was originally asked to prepare this declaration, I searched WorldCat for the title of Hatridge, "Quantum back-

action of an individual variable-strength measurement," and the search results identified the Library of Congress as one of the libraries that hold this periodical. I then searched the Library of Congress online catalog to confirm the holdings information. The search results informed me that the Library of Congress provides access to the issue of *Science* that contains Hatridge. I obtained **Appendix 1004-A** at the Library of Congress and personally scanned the front matter (the front cover and the table of contents) and select content pages, specifically, pages 178-181, of this periodical.

20. To locate a copy of Hatridge from a periodical issue that carries a date stamp, I sent a request to Wisconsin TechSearch (WTS), a document delivery service based in the University of Wisconsin-Madison, for them to "find the print version of this issue to scan the cover, the page with the date stamp, they copyright page, the table of contents pages, and the Hatridge article."

21. **Appendix 1004-B** is a true and correct copy of the pages WTS delivered to me, pursuant to my request. It consists of the cover, table of contents and the Hatridge article from Vol. 339, Issue 6116 of *Science*. The address label on the cover shows that this issue was mailed to the University of Wisconsin Memorial Library, and a stamp on the table of contents page shows it was "Received Jan 24 2013 University Library." I have compared **Appendix 1004-A**

(the Library of Congress copy) with **Appendix 1004-B** (the University of Wisconsin copy) closely. These two documents appear to be identical copies of select portions of Vol. 339, Issue 6116 that contains Hatridge.

22. **Appendix 1004-A** and **Appendix 1004-B** show that volume 339 of *Science* was published on "11 January 2013" and the end of the table of contents area shows the ISSN (International Standard Serial Number) of *Science* is "0036-8075" and that the periodical is published "weekly on Friday, except for the last week of December, by the American Association for the Advancement of Science."

2. University of Wisconsin-Madison Records

23. **Appendix 1004-C** contains two MARC records for the *Science* periodical. The first MARC record represents the print version of the periodical and includes some data on the online and microform versions of this periodical. The second MARC record represents the HTML version of the periodical and is not included in the discussion below.

24. The first MARC record in **Appendix 1004-C** is a true and correct copy of the MARC record for the *Science* periodical (**Appendix 1004-B**) that I retrieved from the online catalog of the University of Wisconsin-Madison libraries after conducting a periodical title search by "Science." I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

25. **Appendix 1004-D** is a true and correct copy of the bibliographic record for the *Science* periodical (**Appendix 1004-B**) that I retrieved from the online catalog of the University of Wisconsin-Madison libraries, which experts in my field would reasonably rely upon when forming their opinions. **Appendix 1004-D** shows that the library holds "new ser.:v.123=no.3184(1956:Jan. 6)- new ser.:v.358=no.6361(2017:Oct.21)," including volume 339, no. 6116, the issue that contains Hatridge. The first page of **Appendix 1004-B** is the work sheet of WTS and the "Library/Supplier" field shows "Mem AP S415 A102," which matches the call number for *Science* in the Memorial Library of the University of Wisconsin-Madison, noted as "AP S415 A102," in the bibliographic record (**Appendix 1004-D)**.

26. Field 130 of the MARC record (**Appendix 1004-C**) and the title at the top of the bibliographic record (**Appendix 1004-D**) identify the uniform title of the periodical as "Science (New York, N.Y.)," which is created according to the cataloging standard to distinguish this periodical from other periodicals with the same title. Field 245 of the MARC record and the title field of the bibliographic record show the title presented on individual issues of "Science". The first six digits of Field 008 of the MARC record show that the record for the periodical was first created and entered into the OCLC Connexion on "750921" (*i.e.*, September 21, 1975). Field 040 identifies MUL as the creator of the record and Field 049 shows GZM is the holding library. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), MUL is the OCLC symbol for MULS, a library network located in Minneapolis, Minnesota, and GZM is the OCLC symbol for the University of Wisconsin-Madison, General Library System. Field 022 of the MARC record and the International Standard Serial Number (ISSN) field of the bibliographic record inform me that the ISSN of the periodical is "0036-8075," which matches the information from the copy I obtained from the Library of Congress (**Appendix 1004-A**) and the scanned pages obtained from the University of Wisconsin-Madison Libraries (**Appendix 1004-B**). Field 260 of the MARC record and the publication field of the bibliographic record inform me that the periodical has been published in "New York, N.Y." since 1880 but the publisher is not identified. Field 310 of the MARC record indicates the current publication frequency is "Weekly (except last week in December)," which matches the data presented in the table of contents area of **Appendix 1004-A** and **Appendix 1004-B**. Field 362 of the MARC record and the publication history field of the bibliographic record inform me that the *Science* periodical began publication with "Vol. 1, no. 1" on July 3, 1880. The "contributors" field of the bibliographic record and Field 710 of the MARC record identify "American Association of the Advancement of Science" as a contributing organization.

27. Field 050 of the MARC record (**Appendix 1004-C**) informs me the *Science* periodical is assigned a Library of Congress Classification (LCC) number of "Q1," which represents the science periodicals category; and Field 082 informs me the periodical is also assigned a Dewey Decimal Classification (DDC) number of "505," which represents the science periodicals category. The first two 650 Fields show a Library of Congress subject heading and a National Library of Medicine subject heading that indicate the periodical is about "Science" and is published in the form of "periodicals" (represented by a form subdivision in subfield "v"). Users interested in topics in science would be able to use this subject heading string to locate this periodical. The MARC record (**Appendix 1004-C**) of the University of Wisconsin-Madison Libraries makes the *Science* periodical, including Vol. 339, Issue 6116 that contains Hatridge (**Appendix 1004-B**), searchable in the online catalog of the University of Wisconsin-Madison Libraries by the periodical title, the American Association for the Advancement of Science, the LCC number, the DDC number, and the subject headings assigned to it.

28. Based on the information above, it is my opinion that *Science* is a long running periodical that has been made discoverable at the online catalog of the

University of Wisconsin-Madison libraries catalog, meaning that anyone who was interested in the topic would be able to search for and access the *Science* periodical.

3. University of Wisconsin-Madison Date Stamp

29. The Table of Contents page of vol. 339, issue 6116 in **Appendix 1004-B** bears a stamp of "RECEIVED JAN 24 2013 UNIVERSITY LIBRARY." The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular periodical issue was received by the library. As I noted above, it is ordinary and regular practice for a library, as part of its regularly conducted activity, to maintain intake records, including date stamping periodical issues during the check-in process, and to make an issue of a periodical available to the public in the library shortly after the library receives and date stamps the issue for serial check-in, usually within a week. In this case, it is my understanding that the University of Wisconsin-Madison libraries, upon receiving the issue that contains Hatridge (**Appendix 1004-B**), date stamped it on January 24, 2013 (as shown in **Appendix 1004-B**), and, shortly thereafter, would have placed it with other recent issues of this periodical so as to make the issue findable and accessible to the public.

30. Based on the date stamp placed on the Table of Contents page in **Appendix 1004-B**, which has a date of January 24, 2013, and my understanding of the ordinary and customary check-in practices of libraries, it is my opinion that the issue that contains Hatridge (**Appendix 1004-B**) (and, therefore, Hatridge included therein) was accessible through the University of Wisconsin-Madison Libraries to the public shortly after being checked in on January 24, 2013, meaning vol. 339, issue 6116 would have been available for public access by January 31, 2013. If workload was unusually heavy it might take more than one week for the issue to become publicly available. My conservative estimate is that Hatridge would be available no later than February 24, 2013, at the latest, which would be one month after serial check-in of this issue was completed.

4. PUBMED Records

31. In addition to investigating the earliest public availability of vol. 339, issue 6116 of the *Science* periodical in libraries, I also searched for records that index Hatridge. Due to the nature of the Hatridge article, I chose to search PubMed for records. PubMed (https://www.ncbi.nlm.nih.gov/pubmed/) is developed and maintained by the National Center for Biotechnology Information (NCBI) at the U.S. National Library of Medicine. It is an authoritative free database of more than 28 million citations for biomedical literature from MEDLINE, life science journals, and online books. PubMed records often contain links to full-text articles on the publishers' websites and/or in PubMed Central, a free archive for full-text biomedical and life sciences journal articles. Experts in the field would reasonably rely on the data described herein to form their opinions.

32. I searched for "Quantum Back-Action of an Individual Variable-Strength Measurement" in PubMed to determine if this article was indexed. The search results indicate that the record was indexed soon after publication.

33. **Appendix 1004-E** is a true and correct copy of the PubMed record in the abstract format that I personally retrieved and obtained from PubMed, which experts in my field would reasonably rely upon when forming their opinion. It presents the title of the Hatridge article, the authors, the issue of *Science* in which the article was published, and an abstract. It also shows the article's PubMed ID number is "23307736" and indicates its digital object identifier (DOI) is "10.1126/science.1226897." **Appendix 1004-E** also includes a note indicating full text can be obtained for free. It provides a direct link to the *Science* website for users to access the full text of Hatridge at http://science.sciencemag.org/content/339/6116/178.full. Users will need to create an account on the website to view the article. I followed the link to obtain a PDF version of Hatridge from the *Science* website (**Appendix 1004-G**) and closely compared this PDF version with the Hatridge article I personally scanned from the Library of Congress (**Appendix 1004-A**) and the Hatridge article obtained from WTS (**Appendix 1004-B**). I have found these three documents to have the same content. The differences are that **Appendix 1004-B** is not colored and has a statement "This material may be protected by Copyright law (Title 17 U.S. Code) at the top of the page, and **Appendix 1004-G** has the download date stamp "Downloaded from http://science.sciencemag.org/ on December 21, 2018" on the side and a list of supplementary materials at the end. **Appendix 1004-G,** which I obtained via a link in the PubMed record, is the same as the Hatridge article I obtained from the website of Science (**Exhibit 1004**).

34. **Appendix 1004-F** is a true and correct copy of the PubMed record in the MEDLINE format that I personally retrieved from PubMed, which experts in my field would reasonably rely upon when forming their opinion. MEDLINE is the primary component of PubMed. According to the MEDLINE Fact Sheet (https://www.nlm.nih.gov/pubs/factsheets/medline.html), "MEDLINE is the U.S. National Library of Medicine® (NLM) premier bibliographic database that contains more than 24 million references to journal articles in life sciences with a concentration on biomedicine." The PubMed search result indicated Hatridge was indexed by MEDLINE.

35. **Appendix 1004-F** shows the Hatridge record in MEDLINE format, with "23307736" as the PubMed record id and "20130124" (*i.e.,* January 24, 2013) as DCOM, the date when the record was completed. "MEDLINE: PubMed Data

Element (Field) Descriptions" (https://www.nlm.nih.gov/bsd/mms/medlineelements.html) is used to identify the data elements. The IS field identifies "0036-8075" as the International Standard Serial Number, which matches the data in **Appendix 1004-A** and **Appendix 1004-B**. The VI field shows the volume containing Hatridge is "339," the IP field shows the issue containing Hatridge is "6116" and the DP field shows the date of publication is "2013 Jan 11." The TI field shows "Quantum back-action of an individual variable-strength measure" as the title of the article. The PG field shows the article runs from page 178 to page 81. The FAU field identifies "Hatridge, M" as the full author. The JT field shows "Science (New York, N.Y.)" as the journal title. The "SO" (source) field shows the full citation information and the doi (digital object identifier) of Hatridge is "Science. 2013 Jan 11;339(6116):178-81. doi: 10.1126/science.1226897."

36. This PubMed MEDLINE record (**Appendix 1004-F**) informs my opinion that the MEDLINE record was completed on January 24, 2013 to index Hatridge. This record makes Hatridge searchable in MEDLINE by authors, article title, journal title and terms in the abstract field. Because MEDLINE records are added to PubMed seven days a week, it is my opinion that this PubMed MEDLINE record would have been available for searching in PubMed as early as January 25,

2013. If workload was very heavy at the time and it took more than a week for the record to be uploaded to PubMed, my conservative estimate is that interested users would have been able to search for this article in PubMed and MEDLINE no later than February 24, 2013, one month after the MEDLINE index record was completed. This index record of Hatridge makes the article directly discoverable in PubMed. Interested users could locate the record in PubMed, then follow the link to the Science website to view the full text for free. Or, users could use the information presented in this record to locate a library that holds vol. 339, issue 6116 of the *Science* periodical to obtain a physical copy of Hatridge.

37. Because the MEDLINE record for Hatridge (**Appendix 1004-F**) is not assigned subject headings, I selected keywords from the abstract to simulate the search experience of users who were interested in this topic in 2013. My first keyword search used "quantum variable-strength measurement" and PubMed responded with the record for the Hatridge article (**Appendix 1004-E**). My second keyword search used "quantum back-action measurement" with the publication period limited to 2013, and PubMed responded with six records. My third keyword search used "quantum qubit measurement" with the publication period limited to 2013, and PubMed responded with 29 records. For the second and third keyword searches I limited the time period to 2013 because a user searching for publications with these keywords in 2013 would be very likely to want to focus on new articles published in 2013. The search results of these three keyword searches informed me that a user conducting keyword searches on this topic in PubMed in 2013 would have received search results that they could browse quickly to discover Hatridge.

5. Actual Usage Records

38. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar for Hatridge shows that it has been cited 207 times and 28 citations were published in 2013. **Appendix 1004-H** presents 15 citations published in 2013 to demonstrate early usage and show that the earliest citation of Hatridge was published in March 2013, further supporting my opinion that Hatridge was available in 2013.

6. Summary on Hatridge

39. Taken together, Hatridge (**Appendix 1004-A**), the MARC record (**Appendix 1004-C)**, the bibliographic record (**Appendix 1004-D)**, the date stamp for the *Science* periodical (**Appendix 1004-B)**, the PUBMED record (**Appendix 1004-E** and **F)**, and ten selected citations of Hatridge published in 2013 (**Appendix 1004-H)** support my opinion that Hatridge was publicly accessible soon after it was indexed by MEDLINE on January 24, 2013, and soon after vol. 339, issue 6116 of the *Science* periodical that contains Hatridge was date stamped by the University of Wisconsin-Madison Libraries on January 24, 2013. My estimate is that the MEDLINE index record would have been available for searching as early as January 25, 2013, and the physical copy of Hatridge would have been available to the public as early as January 31, 2013 at the University of Wisconsin-Madison Libraries. If heavy workload contributed to added time for processing, the physical copy would have been available for public access no later than February 24, 2013, one month after serial check in was completed. The citation history of Hatridge shows that the earliest citation was published in March 2013.

B. Exhibit 1005 (Geerlings)

1. Authentication

40. **Exhibit 1005** is a true and correct copy of "Improving the Quality Factor of Microwave Compact Resonators by Optimizing Their Geometrical Parameters" by Geerlings et al., in *Applied Physics Letters*, vol. 100, no. 19 (2012), article 192601 that I obtained from the website of *Applied Physics Letters*. I also obtained a copy of the Geerlings article from the British Library (**Appendix 1005-A**), compared these the electronic copy and the print copy closely, and concluded that **Exhibit 1005** and **Appendix 1005-A** contain the same article. The differences are that **Exhibit 1005** is colored and includes a cover page for the Geerlings article, while **Appendix 1005-A** is black and white and includes the front matter of the journal issue that contains the Geerlings article.

41. **Appendix 1005-A** is a true and correct copy of "Improving the

Quality Factor of Microwave Compact Resonators by Optimizing Their Geometrical Parameters" ("Geerlings") by Geerlings et al., in *Applied Physics Letters*, vol. 100, no. 19 (2012), article 192601. When I was originally asked to prepare this declaration, I searched WorldCat for records by the article title. The search results informed me that the British Library held *Applied Physics Letters* that published Geerlings. I then requested a copy of the article through Wisconsin TechSearch (WTS), a document delivery service based in the University of Wisconsin, and then received the scanned pages from the British Library. These pages include the front matter of vol. 100, no. 19 (2012) of *Applied Physics Letters* (the front cover, table of contents, copyright page) and Geerlings (three pages).

42. Page 1 of **Appendix 1005-A** is the front cover of an issue of *Applied Physics Letters* that shows this issue is "Volume 100, Number 19" that was published on "7 May 2012." The cover also shows a check-in label indicating "18/06/12 Boston Spa LS23 7BQ" (*i.e.*, checked in on June 18, 2012 at the Boston Spa site of the British Library) and "1576.400000 BLSDD Volume 100:Number 19(2012:May 07)" that has the appearance of a shelfmark and numerical and chronological designations of this issue. The table of contents shows that article 192601 has three pages, is published in the "Superconductivity and superconducting electronics" section of this issue, and has a title of "Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters" and six authors. At the end of the table of contents on Page 8 of **Appendix 1005-A** a note indicates this journal is "a publication of the American Institute of Physics" in Melville, New York. Page 9 of **Appendix 1005-A** is the copyright page that shows the journal's ISSN (International Standard Serial Number) is "0003-6951" and its CODEN (a six character alphanumeric bibliographic code that provides unique identification of periodicals and non-serial publications) is "APPLAB." It also indicates that content of the journal is "published online daily and collected into weekly online and printed issues (52 issues per year)." The copyright page shows a "2012" copyright date for this issue and "American Institute of Physics" as the copyright holder. The first page of article 192601 shows the authors and title information and the publication history of the article, indicating it was "received 27 March 2012; accepted 16 April 2012; published online 7 May 2012." At the end of the abstract, a note shows the abstract has a "2012" copyright date and "American Institute of Physics" is the copyright holder. The DOI (digital object identifier, a unique code to permanently identify documents on the Web) of the article is presented as a link http://dx.doi.org/10.1063/1.4710520. The bottom of the page shows a "2012" copyright date for this article and "American Institute of Physics" as the copyright holder. It also shows a note of "0003-6951/2012/100(19)/192601/3" that indicates article 192601 has three pages, is published in vol. 100, no. 19 in 2012 in the journal with an ISSN of 0003-6951, which is *Applied Physics Letters*.

2. British Library Records

43. **Appendix 1005-B** is a true and correct copy of the bibliographic record for the journal *Applied Physics Letters* whose vol. 100, no. 19 (May 7 2012) issue contains Geerlings. I retrieved the record from the online catalog of the British Library by searching for the journal's ISSN "0003-6951." I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, a customary library cataloging practice is to create one bibliographic record for a serial and create no records for individual issues of the serial. The bibliographic record (**Appendix 1005-B**) shows that "Applied Physics Letters" is the journal title, and the American Institute of Physics of New York has been publishing this journal since 1962. The identifier shows the ISSN of this journal is "0003-6951" and a note indicates the current publication frequency is "Fortnightly." The holdings notes show that the British Library keeps this journal in its Science Technology and Business section and holds issues since volume 1 in 1962. The shelfmark shows a Document Supply number of "1676.400000." The title, publisher, and ISSN match the information presented in **Appendix 1005-A.**

44. The bibliographic record has a link for "MARC Display," which brings up the MARC record for *Applied Physics Letters*. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

45. Field 245 of the MARC record (**Appendix 1005-C**) shows the journal title is “Applied physics letters,” Field 022 shows the ISSN of this journal is “0003-6951,” Field 040 shows “Uk” is the original creator of this serial record. According to the MARC codes for organizations in the UK and its dependencies (http://www.bl.uk/bibliographic/pdfs/marc-codes-directory.pdf), “UK” is the code for the British Library. The first six digits of Field 008 show the record was added to the system on “840320” (*i.e.*, March 20, 1984) and the “c19629999” code following these digits indicates that the journal began publication in 1962 and is an ongoing publication. Field 260 shows the American Institute of Physics is the publisher, and Field 310 shows the current publication frequency is “Fortnightly.” Field 852 shows information needed to locate this journal, with subfield “j” indicating the shelf control number is “1576.400000.” and subfield “j” since February 1976 has been “weekly.” Field 082 shows the subject of this journal is represented by a “621” Dewey Decimal Classification (DDC) number, which represents the “Applied physics” category. Field 710 shows the American Institute of Physics, the journal publisher, is another access point for this journal.

46. This MARC record (**Appendix 1005-C**) makes *Applied Physics Letters*, whose vol. 100, no. 19 (May 2012) contains Geerlings, searchable in the online catalog of the British Library. As a result, users interested in journals in the field of applied physics are able to search for and retrieve this journal by the DDC number. Users can also search for this journal by its title, ISSN, and the publisher.

3. British Library Date Stamp

47. The front cover of the journal in **Appendix 1005-A** bears a date stamp of "18/06/12 BOSTON SPA" with "1576.400000." The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. Based on my knowledge and understanding of library serial check-in practice and the effort to make new journal issues available to users as soon as possible, it is my opinion that vol. 100, no. 19 (May 2012) of *Applied Physics Letters* that contains Geerlings would have been publicly accessible soon after it was checked in at the British Library on June 18, 2012. Most libraries make newly checked-in journal issues available on the same day of check-in or within a week after check-in is completed. If the workload was very heavy at that time, it might take more than one week for the new issue to become available to users. My estimate is that this issue would have been available to users at the British Library as early as June 18, 2012, and no later than July 18, 2012, which would be one month after serial check-in was completed.

4. British Library Public Availability Date Confirmation Letter

48. **Appendix 1005-E** is a true and accurate copy of a confirmation letter regarding vol. 100, no. 19 (May 2012) of *Applied Physics Letter* that contains Geerlings (**Appendix 1005-A**). I received the letter from the British Library. This is the type of record experts in my field would reasonably rely upon when forming their opinions. **Appendix 1005-E** includes a confirmation letter stating that regarding Geerlings, "according to our records, this item was receipted by The British Library on **June 18, 2012**. It was then catalogued and would have been available for public use from that date." It further indicates that "copies of the date stamps indicating the dates of availability have been attached" (presented as **Appendix 1005-F**). The letter also states that "Please note that we can only provide the date that the British Library made this item available for public use; for the actual date of publication, please contact the publisher." These statements inform my opinion that vol. 100, no. 19 (May 2012) of *Applied Physics Letter* that contains Geerlings (**Appendix 1005-A**) was received by the British Library on June 18, 2012, and became accessible to the public soon after the receipt.

5. United States Copyright Registration Records

49. **Appendix 1005-D** is a true and accurate copy of the copyright registration record for the Vol. 100, no. 19 (May 7 2012) issue of *Applied Physics Letters* that I obtained from the public catalog of the United States Copyright

Office in the Library of Congress. I obtained **Appendix 1005-D** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the journal title to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

50. The copyright registration record (**Appendix 1005-D**) shows that the title of this serial is "Applied Physics Letters" whose ISSN is "0003-6951" and it is published "Weekly" by the American Institute of Physics. The record also shows that this "vol. 100, no. 19, 7 May 2012" issue was "created 2012; Pub. 2012-05-24. Reg. 2012-06-04" (*i.e.*, published on May 24, 2012 and registered with the copyright office on June 4, 2012). The journal title, ISSN, numerical and chronological designations, publisher and publication year match the information contained in **Appendix 1005-A**.

51. Taken together, the "18/06/2012" date stamp in **Appendix 1005-A**, the bibliographic record (**Appendix 1005-B**), the MARC record (**Appendix 1005-C**), the copyright registration record (**Appendix 1005-D**), the public availability date letter (**Appendix 1005-E**) and supporting documents from the British Library (**Appendix 1005-F**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that *Applied*

Physics Letters is a long-running journal that has been made available at the British Library, and that the vol. 100, no. 19 (May 2012) issue that contains Geerlings (**Appendix 1005-A**) would have been accessible to the public on June 18, 2012, and by July 18, 2012 at the latest.

6. Actual Usage Records

52. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Geerlings has been cited at least 77 times, and 15 citations were published in 2012 and 2013. **Appendix 1005-G** presents seven citations published in 2012 and 2013 to demonstrate early usage of Geerlings. The earliest citing document was published on October 9, 2012, further demonstrating public availability of Geerlings in 2012.

7. Summary on Geerlings

53. Taken together, the "18/06/2012" date stamp in **Appendix 1005-A**, the bibliographic record (**Appendix 1005-B**), the MARC record (**Appendix 1005-C**), the copyright registration record (**Appendix 1005-D**), the public availability date letter (**Appendix 1005-E**) and supporting documents from the British Library (**Appendix 1005-F**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Geerlings (**Appendix 1005-A**) would have been available for public access in June, 2012. In fact, the earliest citing article to Geerlings was published on October 9, 2012,

(**Appendix 1005-G**) further demonstrating public availability of Geerlings in 2012.

C. Exhibit 1006 (Pozar)

1. Authentication

54. **Exhibit 1006** is a true and correct copy of portions of the 4th edition of MICROWAVE ENGINEERING ("Pozar") that I made during my personal visit to the Library of Congress. When I was asked to prepare this declaration, I searched the Library of Congress online catalog for records because books published in the United States tend to be registered with the Copyright Office of the Library of Congress and cataloged by the Library of Congress. The search results informed me that the Library of Congress provided access to Pozar. The "Item Availability" area of the library records shows that the book's call number is "TK7876 .P69 2012" and that it is "stored offsite" and can be requested in the "Jefferson or Adams Building Reading Rooms." I requested access to this title and received the book at the Science and Technology Reading Rooms in the Library of Congress Adams Building.

55. **Exhibit 1006** is a true and correct copy of portions of Pozar that I made on while the book was in my possession at the Library of Congress. I obtained **Exhibit 1006** by personally scanning the front matter (the front cover, title page, copyright page, table of contents), pages 147 to 161, page 732 (the last numbered page of this volume), the back cover and spine of this volume.

56. The first page of **Exhibit 1006** shows "MICROWAVE ENGINEERING" as the title on the cover. It also shows "DAVID M. POZAR" as the author and identifies the book as the "FOURTH EDITION." The second page of **Exhibit 1006** is the title page that shows the same title, author and edition information as the cover and shows "John Wiley & Sons, Inc." as the publisher. Page 3 of **Exhibit 1006** is the copyright page that shows "2012" as the copyright date and "John Wiley & Sons, Inc." as the copyright holder. The copyright page also shows a record identified as the "Library of Congress Cataloging-in-Publication Data" that includes a number of "2011033196," which has the appearance of a Library of Congress Control Number. Page 29 of **Exhibit 1006** is the back cover that shows "978-0-470-63155-3" as the ISBN (International Standard Book Number) assigned to this book and a barcode label of "LC CIP 0 028 866 209 5."

2. Library of Congress Records

57. **Appendix 1006-A** a true and correct copy of the bibliographic record for the fourth edition of MICROWAVE ENGINEERING ("Pozar"). I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. **Appendix 1006-A** shows that the main title is "Microwave engineering," the author is "Pozar, David M.", the edition is “4th ed.” and Wiley of Hoboken, NJ is the publisher of this book with a “2012” copyright date. The ISBN field shows “9780470631553” is the number assigned to this title, and the LCCN (Library of Congress Control Number) field shows “2011033196” as the number assigned to this title. The author, title, edition number, publisher, publication year, ISBN and LCCN match the information contained in **Exhibit 1006**. The “Item Availability” area shows that the book’s call number is “TK7876 .P69 2012 CABIN BRANCH” and it is “stored offsite.” Users can request this title at the “Jefferson or Adams Building Reading Rooms.” The “status” field indicates the copy is “not charged,” meaning it is available.

58. **Appendix 1006-B** is a true and correct copy of the MARC record for the fourth edition of MICROWAVE ENGINEERING (“Pozar”). I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

59. The first six digits of Field 008 show the MARC record was created on “110809” (*i.e.*, August 9, 2011). Field 955, the local note field for cataloging activity dates, shows that “2012-03-13 1 copy rec'd., to CIP ver.” (i.e., one copy was received on March 13, 2012 and sent to the Cataloging in Publication Program for verification). Two other dates show the copy was CIP verified on March 15, 2012 ("2012-03-15 Z-CipVer") and sent to the Binding and Collections Care Division (BCCD) for processing on March 15, 2012 ("2012-03-15 to BCCD"). The last date in Field 955 shows "2012-04-11 copy 2 added," meaning copy 2 was added to the collection on April 11, 2012. The Cataloging in Publication Program (CIP) at the Library of Congress is responsible for cataloging books in advance of publication to alert the library community to forthcoming publications and to facilitate acquisition. The initial CIP record is created based on information submitted by the publisher. When the CIP record is ready, it is sent to the publisher for inclusion in the publication.

60. Field 040 subfield "a" shows that "DLC" is the library that created the original MARC record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. These data inform my opinion that the MARC record (**Appendix 1006-B**) was first created on August 9, 2011, as a Cataloging-in-Publication record based on the information presented by the publisher. After the CIP record was completed, it was sent to the publisher for inclusion in the physical volume. The Cataloging-in-Publication data printed on the copyright page of **Exhibit 1006** reflects this practice. After the physical volume was received by the Library of Congress, catalogers of the Cataloging-in-Publication Program used the volume to verify the CIP MARC record on March 15, 2012. After that, the physical volume was sent to the processing unit. On April 11, 2012, a second copy of this title was added to the Library of Congress collection.

61. Field 010 of the MARC record (**Appendix 1006-B**) shows the Library of Congress control number of this book is "2011033196," which matches the number on the copyright page of **Exhibit 1006**. Field 020 shows the ISBN assigned to this publication is "9780470631553," which matches the ISBN printed on the back cover of **Exhibit 1006**. Field 245 shows the title is "Microwave engineering" and the author is "David M. Pozar." Field 100 presents the author's name in the authorized form "Pozar, David M." and makes it an access point for this book. Field 250 shows the edition number as "4th ed." and Field 260 shows that Wiley of Hoboken, NJ published this book in 2012. Field 300 indicates that the book has 732 pages. The number "732" matches the last numbered page included in **Exhibit 1006**.

62. Field 050 of the MARC record (**Appendix 1006-B**) shows this book has a Library of Congress Classification (LCC) number of "TK7876," which is the class number for "Microwaves." Field 082 shows the book has a Dewey Decimal Classification (DDC) number of "621.381/3," which is the class number for "Microwave electronics." Users interested in the topic represented by the LCC number or the DDC number could search it as a keyword in the Library of Congress catalog to retrieve materials that have been assigned the same classification number. The subject of this book is also represented in three 650 fields by three Library of Congress subject headings, "Microwaves," "Microwave devices," and "Microwave circuits." This MARC record (**Appendix 1006-B**) shows that the fourth edition of MICROWAVE ENGINEERING by David M. Pozar is a book that has been made searchable at the online catalog of the Library of Congress, and users interested in the topics of the book can find it by the LCC and DDC numbers and by subject terms assigned to it. Users can also find this book by its title, author, and ISBN.

63. Based on the information above, it is my opinion that the fourth edition of MICROWAVE ENGINEERING by David M. Poza is a book that has been made available by the Library of Congress, meaning that members of the public with an interest in the topics covered by the book would be able to search for and access the fourth edition of MICROWAVE ENGINEERING.

64. Field 008 and the cataloging dates in Field 955 of the MARC record (**Appendix 1006-B**) inform my opinion that the MARC record was created by Library of Congress catalogers on "110809" (*i.e.*, August 9, 2011) as a CIP record, that the physical volume was received by Library of Congress on March 13, 2012, and that CIP catalogers used the physical volume to verify the record on "2012-03-15" (*i.e.*, March 15, 2012), then sent it to the processing unit the same day. In most academic libraries a newly cataloged book would become available for the public soon after the cataloging record is completed, usually within a week. Considering the volume of materials the Library of Congress needs to catalog and process, my conservative estimate is that Pozar would have become available for public access by June 15, 2012, three months after the cataloging record was verified and the physical volume was sent to the processing unit.

65. Based on the bibliographic record (**Appendix 1006-A**), the MARC record (**Appendix 1006-B**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that Pozar (**Exhibit 1006**) was cataloged and the record became searchable as early as August 9, 2011, and the physical item would have become accessible to the public by June 2012, three months after the cataloging record was verified in March 2012.

3. United States Copyright Registration Records

66. **Appendix 1006-C** is a true and accurate copy of the copyright registration record for the fourth edition of MICROWAVE ENGINEERING by David M. Poza obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1006-C** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright

Records," and performing a search by the title to retrieve the record for "microwave engineering." I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

67. The copyright registration record shows that the title of this book is "Microwave Engineering, 4th Edition (9780470631553)," "David M. Pozar" is the author, and "John Wiley & Sons, Inc." is the copyright claimant. The record shows the date of creation is "2011," the date of publication is "2011-11-04" (*i.e.*, November 4, 2011), and the copyright registration number and date are "TX0007478448 / 2012-01-27" (*i.e.*, January 27, 2012). The title, author, edition number, publisher, publication date, and the copyright holder match the information contained in **Exhibit 1006**. The copyright record also shows that Pozar has 732 pages, which matches the last numbered page of this book recorded in Field 300 of the MARC record (**Appendix 1006-B**) and the page number of the last page of Pozar (**Exhibit 1006**), which I personally scanned at the Library of Congress.

4. Actual Usage Records

68. Actual usage of a publication is reflected by the papers that make reference to it. My research on Google Scholar has found Pozar cited more than 200 times. **Appendix 1006-D** presents five citations selected to demonstrate early usage from 2013 to 2015. The earliest citing document was published in February

2013.

5. Summary on Pozar

69. Taken together, the bibliographic record (**Appendix 1006-A**), the MARC record (**Appendix 1006-B**), the copyright record (**Appendix 1006-C**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Pozar (**Exhibit 1006**) would have been cataloged and discoverable by the public at the online catalog of the Library of Congress by August 2011 when the CIP cataloging record was created, and the physical item would have been available for public access by June 15, 2012, three months after the CIP record was verified. Citation history (**Appendix 1006-D**) shows that the earliest citation was published in February 2013, further demonstrating the availability of Pozar in 2012.

D. Exhibit 1007 (Stubbins)

1. Authentication

70. **Exhibit 1007** is a true and correct copy of portions of ESSENTIAL ELECTRONICS ("Stubbins") that I made during my personal visit to the Library of Congress. When I was asked to prepare this declaration, I searched the Library of Congress online catalog for records because books published in the United States tend to be registered with the Copyright Office of the Library of Congress and cataloged by the Library of Congress. The search results informed me that the

Library of Congress provided access to Stubbins. The "Item Availability" area of the library records shows that the book's call number is "TK7816 .S74 1986" and Copy 1 is available for user request at the "Jefferson or Adams Building Reading Rooms" while Copy 2 is "stored offsite" at the Fort Meade facility. I requested access to this title and received the book at the Science and Technology Reading Rooms in the Library of Congress Adams Building.

71. **Exhibit 1007** is a true and correct copy of portions of Stubbins that I made while the book was in my possession at the Library of Congress. I obtained **Exhibit 1007** by personally scanning the front matter (the front cover, title page, copyright page, dedication page, and table of contents), pages 193, 195, 196 and 505 (the last numbered page of this volume), the back cover and spine of this volume.

72. The first page of **Exhibit 1007** shows "ESSENTIAL ELECTRONICS" as the title on the cover. It also shows "Warren Fenton Stubbins" as the author. Page 2 of **Exhibit 1007** is the title page that shows the same title and author information, and further indicates "John Wiley & Sons" of New York is the publisher. Page 3 of **Exhibit 1007** is the copyright page that shows "1986" as the copyright date and "John Wiley & Sons, Inc." as the copyright holder. The copyright page also shows a record identified as the "Library of Congress

Cataloging in Publication Data" that includes a number of "85-9447," which has the appearance of a Library of Congress Control Number. This page also shows a date stamp of "LIBRARY OF CONGRESS. JAN 24 1986 CIP" and a hand-written call number of "TK7816 .S74 1986." Page 4 **Exhibit 1007** is the dedication page that shows two hand-written notes--"CIP/bc73 4/18/85" and "br14 2/6/86"--that indicate activities related to the Cataloging in Publication Program. Page 16 of **Exhibit 1007** shows an ISBN ((International Standard Book Number) of "0-471-88604-1" on the back cover, and page 17 shows the spine with a label of "TK 7816 .S74 1986."

2. Library of Congress Records

73. **Appendix 1007-A** a true and correct copy of the bibliographic record for ESSENTIAL ELECTRONICS ("Stubbins"). I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. **Appendix 1007-A** shows that the main title is "Essential electronics," the author is "Stubbins, Warren Fenton," and Wiley of New York is the publisher of this book with a "1986" copyright date. The ISBN field shows "0471886041" is the number assigned to this title, and the LCCN (Library of Congress Control Number) field shows "85009447" as the number assigned to this title. The author, title, publisher, publication year, ISBN and

LCCN match the information contained in **Exhibit 1007**. The "Item Availability" area shows that the book's call number is "TK7816 .S74 1986" and the Library of Congress holds two copies, with Copy 1 stored on site and Copy 2 stored offsite at the Fort Meade facility. The "status" field indicates both copies are "not charged," meaning available for user requests.

74. **Appendix 1007-B** is a true and correct copy of the MARC record for ESSENTIAL ELECTRONICS ("Stubbins"). I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. The first six digits of Field 008 show the MARC record was created on "850426" (*i.e.*, April 26, 1985). Field 040 subfield "a" shows that "DLC" is the library that created the original MARC record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. Because ESSENTIAL ELECTRONICS was published by Wiley with a copyright date of 1986, the date information from Field 008 informs my opinion that the original record was completed on April 26, 1985 as a Cataloging-in-Publication record based on the information presented by the publisher. After the CIP record was completed, it was sent to the publisher for inclusion in the physical volume. The Cataloging-in-Publication data printed on the copyright page of **Exhibit 1007** reflects this practice.

75. Field 010 of the MARC record (**Appendix 1007-B**) shows the Library of Congress control number of this book is "85009447," which matches the number on the copyright page of **Exhibit 1007**. Field 020 shows the ISBN assigned to this publication is "0471886041," which matches the ISBN printed on the back cover of **Exhibit 1007**. Field 245 shows the title is "Essential electronics" and the author is "Warren Fenton Stubbins." Field 100 presents the author's name in the authorized form "Stubbins, Warren Fenton" and makes it an access point for this book. Field 260 shows that Wiley of New York published this book with a copyright date of 1986. Field 300 indicates that the book has 505 pages. The number "505" matches the last numbered page included in **Exhibit 1007**.

76. Field 050 of the MARC record (**Appendix 1007-B**) shows this book has a Library of Congress Classification (LCC) number of "TK7816," which is the class number for "Elementary textbooks on electronics." Field 082 shows the book has a Dewey Decimal Classification (DDC) number of "621.381," which is the class number for "Electronics." Users interested in the topic represented by the LCC number or the DDC number could search it as a keyword in the Library of Congress catalog to retrieve materials that have been assigned the same classification number. The subject of this book is also represented by a Library of

Congress subject heading, "Electronics." This MARC record (**Appendix 1007-B**) shows that ESSENTIAL ELECTRONICS by Warren Fenton Stubbins is a book that has been made searchable at the online catalog of the Library of Congress, and users interested in the topics of the book can find it by the LCC and DDC numbers and by the subject term assigned to it. Users can also find this book by its title, author, and ISBN.

77. Based on the information above, it is my opinion that ESSENTIAL ELECTRONICS by Warren Fenton Stubbins is a book that has been made available by the Library of Congress, meaning that members of the public with an interest in the topics covered by the book would be able to search for and access it.

3. Library of Congress Date Stamp Records

78. The copyright page of Stubbins in **Exhibit 1007** bears a stamp of "LIBRARY OF CONGRESS JAN 24 1986 CIP" that indicates the date when the Cataloging in Publication Program received the physical volume of Stubbins. The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. The date stamp and the dates on the dedication page of **Exhibit 1007** in inform my opinion that Library of Congress received the physical volume of Stubbins on January 24, 1986, the CIP record was created on April 26, 1985, and CIP catalogers verified the CIP record on February 6, 1986. In most academic libraries a newly cataloged book would become available for the public soon after the cataloging record is completed, usually within a week. Considering the volume of materials the Library of Congress needs to catalog and process, my conservative estimate is that Stubbins would have become available for public access by May 6, 1986, three months after CIP catalogers verified the cataloging record.

79. Based on the January 24, 1986 date stamp placed on the copyright page of Stubbins (**Exhibit 1007**), the CIP verification date of February 6, 1986 on the dedication page of Stubbins, the bibliographic record (**Appendix 1007-A**), the MARC record (**Appendix 1007-B**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that Stubbins (**Exhibit 1007**) was cataloged and became searchable as early as April 26, 1985, when the CIP record was completed, and the physical volume became accessible to the public by May 6, 1986 at the latest, which is three months after the CIP record was verified.

4. United States Copyright Registration Records

80. **Appendix 1007-C** is a true and accurate copy of the copyright registration record for ESSENTIAL ELECTRONICS by Warren Fenton Stubbins obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1007-C** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright

Records," and performing a search by the title to retrieve the record for "essential electronics." I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

81. The copyright registration record shows that the title of this book is "Essential electronics," "Warren Fenton Stubbins" is the author, and "J. Wiley" of New York published the book with a "1986" copyright date. The record shows the date of creation is "1985," the date of publication is "1986-02-10" (*i.e.*, February 10, 1986), and the copyright registration number and date are "TX0001793448 / 1986-04-01" (*i.e.*, April 1, 1986). The title, author, publisher, publication date, and the copyright holder information match the information contained in **Exhibit 1007**. The copyright registration record also shows that Stubbins has 505 pages, which matches the last numbered page of this book recorded in Field 300 of the MARC record (**Appendix 1007-B**) and the page number of the last page of Stubbins (**Exhibit 1007**), which I personally scanned at the Library of Congress.

5. Summary on Stubbins

82. Taken together, the date stamp and CIP dates in **Exhibit 1007**, the bibliographic record (**Appendix 1007-A**), the MARC record (**Appendix 1007-B**), the copyright registration record (**Appendix 1007-C**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Stubbins (**Exhibit 1007**) would have been cataloged and discoverable by the public at the online catalog of the Library of Congress by April 1985 when the CIP cataloging record was created, and the physical item would have been available for public access by May 1986, three months after the CIP record was verified.

E. Exhibit 1009 (Simons)

1. Authentication

83. **Exhibit 1009** is a true and correct copy of portions of COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS ("Simons") obtained from the Library of Congress. When I was asked to prepare this declaration, I searched the Library of Congress online catalog for records because books published in the United States tend to be registered with the Copyright Office of the Library of Congress and cataloged by the Library of Congress. The search results informed me that the Library of Congress provides access to Simons. The "Item Availability" area of the library records indicates that Copy 1 is on site and Copy 2 is "stored offsite" at the Fort Meade facility, and both can be requested at the "Jefferson or Adams Building Reading Rooms." I requested access to this title and received the book at the Science and Technology Reading Rooms in the Library of Congress Adams Building.

84. **Exhibit 1009** is a true and correct copy of portions of Simons that I made while the book was in my possession at the Library of Congress. I obtained

Exhibit 1009 by personally scanning the front matter (the front cover, the series title pages, the title page, the copyright page, and the table of contents page), pages 17 to 21, and page 439 (the last numbered page), the back cover, and the spine of this book.

85. Page 1 of **Exhibit 1009** is the cover that shows that "COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS" is the title, "RAINEE N. SIMONS" is the author, and the book is part of the "Wiley Series in Microwave and Optical Engineering." Pages 2 and 3 of **Exhibit 1009** are the series title pages that list "COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS" as a volume in the "Wiley series in microwave and optical engineering." Page 4 of **Exhibit 1009** is the title page that shows the same title and author information as the cover and also indicates "Wiley-Interscience" of New York as the publisher. Page 5 of **Exhibit 1009** is the copyright page that shows a date stamp of "LIBRARY OF CONGRESS APR-2 2001" and a "2001" copyright date with "John Wiley & Sons" as the copyright holder. The copyright page also shows a record identified as the "Library of Congress Cataloging-in-Publication Data" that includes a number of "00-043812," which has the appearance of a Library of Congress Control Number. Page 24 of **Exhibit 1009** is the back cover that shows "0-471-16121-7" as the ISBN (International Standard Book Number) assigned to this book and a barcode label. Page 25 shows the spine of the book has a label with the call number "TK 7876 .S572 2001 Copy 1."

2. Library of Congress Records

86. **Appendix 1009-B** is a true and correct copy of the MARC record for Simons and **Appendix 1009-A** is a true and correct copy of the bibliographic record for Simons. I personally identified, located, and obtained these records from the online catalog of the Library of Congress for this declaration. These are the types of records experts in my field would reasonably rely upon when forming their opinions.

87. Field 245 of the MARC record (**Appendix 1009-B**) and the title field of the bibliographic record (**Appendix 1009-A**) identify the title of the book as "Coplanar waveguide circuits, components, and system." Field 100 of the MARC record and the personal name field of the Bibliographic record identify the author as "Simons, Rainee, 1949- " Field 260 of the MARC record and the published/created field of the bibliographic record show that John Wiley of New York published this book in 2001. Field 300 shows the book has 439 pages and Field 440 of the MARC record shows the book is part of the "Wiley series in microwave and optical engineering." Field 020 of the MARC record and the ISBN field of the bibliographic record show "0471161217" is the International Standard Book Number assigned to Simons. The title, author, publisher, publication date and the ISBN in the MARC record and the Bibliographic record match the information contained in **Exhibit 1009**.

88. The first six digits of Field 008 of the MARC record (**Appendix 1009-B**) inform me that the record for this book was created on "000811" (*i.e.*, August 11, 2000). Field 955, the local note field for cataloging activity dates, includes two important dates: "CIP ver … 06/13/01" (*i.e.*, verified by CIP on June 13, 2001) and "to BCCD 06-14-01" (*i.e.*, sent to the Binding and Collections Care Division on June 14, 2001). Field 040 subfield "a" shows that "DLC" is the library that created the original MARC record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. These data inform me that the MARC record (**Appendix 1009-B**) was first created on August 11, 2000, as a Cataloging-in-Publication record based on the information presented by the publisher. After the CIP record was completed, it was sent to the publisher for inclusion in the physical volume. The Cataloging-in-Publication data printed on the copyright page of **Exhibit 1009** reflects this practice. After the physical volume was received by the Library of Congress, catalogers of the Cataloging-in-Publication Program used the volume to verify the CIP MARC record on June 13, 2001, and sent the volume to the processing unit on June 14, 2001.

89. Field 050 of the MARC record (**Appendix 1009-B**) shows this publication has been assigned a Library of Congress Classification (LCC) number, "TK7876," which is the class number for "general works" on microwaves. Field 082 shows the Dewey Decimal Classification (DDC) Number assigned to this publication is "621.381/331," which is the class number for "components and devices" of Microwave electronics. The subjects of this publication are also represented by three Library of Congress subject headings in Field 650: Microwave transmission lines, Wave guides, and Antennas (Electronics). This MARC record (**Appendix 1009-B**) shows that COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS by Rainee N. Simons is a book that has been made searchable at the online catalog of the Library of Congress, and users interested in the topics of the book can find it by the LCC and DDC numbers and by the subject terms assigned to it. Users can also find this book by its title, author, series, and ISBN.

90. Based on the information above, it is my opinion that COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS (**Exhibit 1009**) is a book that has been made available by the Library of Congress, meaning that members of the public with an interest in the topics covered by the book would be able to search for and access COPLANAR WAVEGUIDE CIRCUITS, COMPONENTS, AND SYSTEMS.

3. Library of Congress Date Stamp

91. The copyright page of Simons in **Exhibit 1009** bears a stamp of

"LIBRARY OF CONGRESS APR-2 2001 CIP" that indicates the date when the Cataloging in Publication Program of the Library of Congress received this physical volume. The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. The date stamp and the cataloging dates in Field 008 and Field 955 of the MARC record (**Appendix 1009-B**) inform my opinion that a CIP record was created for Simons on August 11, 2000, the CIP Program received the physical copy on April 2, 2001, and CIP catalogers used the physical copy to verify the record on "06/13/01" (*i.e.*, June 13, 2001) and then sent it to the processing unit on "06-14-01" (*i.e.*, June 14, 2001). In most academic libraries a newly cataloged book would become available for the public soon after the cataloging record is completed, usually within a week. Considering the volume of materials the Library of Congress needs to catalog and process, my conservative estimate is that copy 1 of Simons would have become available for public access by September 14, 2001 at the latest, which would be three months after the volume was sent to the processing unit.

92. Based on the April 2, 2001 date stamp placed on the copyright page of Simons (**Exhibit 1009**), the MARC record (**Appendix 1009-B**), the bibliographic record (**Appendix 1009-A**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that Simons

(**Exhibit 1009**) was cataloged and became searchable as early as August 2000, and the physical item would become accessible to the public by September 2001, three months after the cataloging record was verified and the volume was sent to the processing unit.

4. United States Copyright Registration Records

93. **Appendix 1009-C** is a true and accurate copy of the copyright registration record obtained from the public catalog of the Copyright Office of the Library of Congress. I obtained **Appendix 1009-C** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the title then I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

94. The copyright registration record shows that the title of this book is "Coplanar waveguide circuits, components, and systems," "Rainee N. Simons" is the author, and "Wiley-Interscience" of New York published this book with a "2001" copyright date. It also shows "John Wiley & Sons, Inc." as the copyright Claimant and indicates the book is part of the "Wiley series in microwave and optical engineering." The record shows that the date of creation is "2000," the date of publication is "2001-03-23" (*i.e.*, March 23, 2001) and the copyright registration date is "2001-05-22" (*i.e.*, May 22, 2001). The author, title, publisher, publication date and the copyright holder information on the copyright registration record match the information contained in **Exhibit 1009**. The copyright registration record also shows that Simons has 439 pages, which matches the last numbered page of this book recorded in Field 300 of the MARC record (**Appendix 1009-B**) and is consistent with the page number of the last page of Simons (**Exhibit 1009**), which I personally scanned at the Library of Congress.

5. Actual Usage Records

95. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Simons has been cited at least 1,391 times, and 29 citations were published in 2002 and 2003. **Appendix 1009-D** presents ten citations selected to demonstrate early usage of Simons. The earliest citing document was published in August 2002.

6. Summary on Simons Records

96. Taken together, the "APR-2 2001" date stamp on the copyright page of Simons (**Exhibit 1009**), the MARC record (**Appendix 1009-B**), the bibliographic record (**Appendix 1009-A**), the copyright registration record (**Appendix 1009-C**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Simons (**Exhibit 1009**) would have been cataloged and discoverable by the public at the online catalog of the Library of Congress by August 2000 when the CIP record was created, and the physical item would have been available for public access by September 2001, three months after the CIP record was verified. Actual usage of Simons took place as early as August 2002 (**Appendix 1009-D**) when the earliest citing document of Simons was published.

F. Exhibit 1010 (Vissers)

1. Authentication

97. **Exhibit 1010** is a true and correct copy of "Identifying capacitive and inductive loss in lumped element superconducting hybrid titanium nitride/aluminum resonators" by Vissers et al., article 022601 in *Applied Physics Letters*, vol. 101, no. 2 (2012) that I obtained from the website of *Applied Physics Letters*. I also obtained a copy of the Vissers article from the British Library (**Appendix 1010-A**), compared the two documents closely, and concluded that **Exhibit 1010** and **Appendix 1010-A** contain the same article. The differences are that **Exhibit 1010** is colored and includes a cover page for the article, while **Appendix 1010-A** is black and white and includes the front matter of the journal issue that contains the Vissers article.

98. **Appendix 1010-A** is a true and correct copy of "Identifying capacitive and inductive loss in lumped element superconducting hybrid titanium nitride/aluminum resonators" ("Vissers") by Vissers et al., article 022601 in *Applied Physics Letters*, vol. 101, no. 2 (2012). When I was originally asked to prepare this declaration, I searched WorldCat for records by the article title. The search results informed me that the British Library held *Applied Physics Letters* that published Vissers. I then requested a copy of the article through Wisconsin TechSearch (WTS), a document delivery service based in the University of Wisconsin, and received the scanned pages from the British Library. These pages include the front matter of vol. 101, no. 2 (2012) of *Applied Physics Letters* (the front cover, table of contents, copyright page) and Vissers (five pages).

99. Page 1 of **Appendix 1010-A** is the front cover of an issue of *Applied Physics Letters* that shows this issue is "Volume 101, Number 2" that was published on "9 July 2012." The cover also shows a check-in label indicating "03/08/12 Boston Spa LS23 7BQ" (*i.e.*, checked in on August 3, 2012 at the Boston Spa site of the British Library) and "1576.400000 BLSDD Volume 101:Number 2(2012:Jul. 09)," which has the appearance of a shelfmark and numerical and chronological designations of this issue. The table of contents shows that article 022601 has five pages, is published in the "Superconductivity and superconducting electronics" section of this issue, and has a title of "Identifying capacitive and inductive loss in lumped element superconducting hybrid titanium nitride/aluminum resonators" and five authors. Page 7 of **Appendix 1010-A** is the copyright page that shows the journal's ISSN (International Standard Serial Number) is "0003-6951" and its CODEN (a six character alphanumeric bibliographic code that provides unique identification of periodicals and non-serial publications) is "APPLAB." It also indicates that content of the journal is "published online daily and collected into weekly online and printed issues (52 issues per year)." The copyright page shows a "2012" copyright date for this issue and "American Institute of Physics" as the copyright holder. The first page of article 022601 shows the authors and title information and the publication history of the article, indicating it was "received 21 March 2012; accepted 7 June 2012; published online 9 July 2012." At the end of the abstract, the DOI (digital object identifier, a unique code to permanently identify documents on the Web) of the article is presented as a link http://dx.doi.org/10.1063/1.4730389. The bottom of the page shows a note of "0003-6951/2012/101(2)/022601/5" that indicates article 022601 has five pages, is published in vol. 101, no. 2 in 2012 in the journal with an ISSN of 0003-6951, which is *Applied Physics Letters*.

2. British Library Records

100. **Appendix 1010-B** is a true and correct copy of the bibliographic record for the journal *Applied Physics Letters* whose vol. 101, no. 2 (July 9 2011) issue contains Vissers. I retrieved the record from the online catalog of the British Library by searching for the journal's ISSN "0003-6951." I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, a customary library cataloging practice is to create one bibliographic record for a serial and create no records for individual issues of the serial. The bibliographic record (**Appendix 1010-B**) shows that "Applied Physics Letters" is the journal title, and the American Institute of Physics of New York has been publishing this journal since 1962. The identifier shows the ISSN of this journal is "0003-6951" and a note indicates the current publication frequency is "Fortnightly." The holdings notes show that the British Library keeps this journal in its Science Technology and Business section and holds issues since volume 1 in 1962. The shelfmark shows a Document Supply number of "1576.400000." The title, publisher, and ISSN match the information presented in **Appendix 1010-A.**

101. The bibliographic record has a link for "MARC Display," which brings up the MARC record for *Applied Physics Letters*. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

102. Field 245 of the MARC record (**Appendix 1010-C**) shows the journal title is "Applied physics letters," Field 022 shows the ISSN of this journal is "0003-6951," Field 040 shows "Uk" is the original creator of this serial record. According to the MARC codes for organizations in the UK and its dependencies (http://www.bl.uk/bibliographic/pdfs/marc-codes-directory.pdf), "UK" is the code for the British Library. The first six digits of Field 008 show the record was added to the system on "840320" (*i.e.*, March 20, 1984) and the "c19629999" code following these digits indicates that the journal began publication in 1962 and is an ongoing publication. Field 260 shows American Institute of Physics is the publisher, and Field 310 shows the current publication frequency is "Fortnightly." Field 852 shows information needed to locate this journal, with subfield "j" indicating the shelf control number is "1576.400000." and subfield "j" since February 1976 has been "weekly." Field 082 shows the subject of this journal is represented by a "621" Dewey Decimal Classification (DDC) number, which represents the "Applied physics" category. Field 710 shows the American Institute of Physics, the journal publisher, is another access point for this journal.

103. This MARC record (**Appendix 1010-C**) makes *Applied Physics Letters*, whose vol. 101, no. 2 (July 9 2012) issue contains Vissers, searchable in the online catalog of the British Library. As a result, users interested in journals in the field of applied physics are able to search for and retrieve this journal by the DDC number. Users can also search for this journal by its title, ISSN, and the publisher.

3. British Library Date Stamp

104. The front cover of the journal in **Appendix 1010-A** bears a date stamp of "03/08/12 BOSTON SPA" with "1576.400000." The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. Based on my knowledge and understanding of library serial check-in practice and the effort to make new journal issues available to users as soon as possible, it is my opinion that vol. 101, no. 2 (July 9 2012) of *Applied Physics Letters* that contains Vissers would have been publicly accessible soon after it was checked in at the British Library on August 3, 2012. Most libraries make newly checked-in journal issues available on the same day of check-in or within a week after check-in is completed. If the workload was very heavy at that time, it might take more than one week for the new issue to become available to users. My estimate is that this issue would have been available to users at the British Library as early as August 3, 2012, and no later than September 3, 2012, which would be one month after serial check-in was completed.

4. British Library Public Availability Date Confirmation Letter

105. Appendix 1010-D is a true and accurate copy of a confirmation letter regarding vol. 101, no. 2 (July 9, 2012) of *Applied Physics Letter* that contains Vissers (**Appendix 1010-A**). I received the letter from the British Library. This is the type of record experts in my field would reasonably rely upon when forming their opinions. **Appendix 1010-D** includes a confirmation letter stating that regarding Vissers, "according to our records, this item was receipted by The British Library on August 3, 2012. It was then catalogued and would have been available for public use from that date." It further indicates that "copies of the date stamps indicating the dates of availability have been attached" (presented as **Appendix 1010-E**). The letter also states that "Please note that we can only provide the date that the British Library made this item available for public use; for the actual date of publication, please contact the publisher." These statements inform my opinion that vol. 101, no. 2 (July 9 2012) of *Applied Physics Letter* that contains Vissers (**Appendix 1010-A**) was received by the British Library on August 3, 2012, and became accessible to the public from that day on.

5. United States Copyright Registration Records

106. **Appendix 1010-F** is a true and accurate copy of the copyright registration record for the vol. 101, no. 2 (July 9 2012) issue of *Applied Physics Letters* that I obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1010-F** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the journal title to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

107. The copyright registration record (**Appendix 1010-F**) shows that the title of this serial is "Applied Physics Letters" whose ISSN is "0003-6951" and it is published "Weekly" by the American Institute of Physics. The Issues Registered field of the record shows the "vol. 101, no. 2, 9 July 2012" issue was "created 2012; Pub. 2012-07-26. Reg. 2012-08-06" (*i.e.*, published on July 26, 2012 and registered with the copyright office on August 6, 2012). The journal title, ISSN, numerical and chronological designations, publisher and publication year match the information contained in **Appendix 1010-A**.

108. Taken together, the "03/08/2012" date stamp in **Appendix 1010-A**, the bibliographic record (**Appendix 1010-B**), the MARC record (**Appendix 1010-C**), the public availability date confirmation letter from the British Library (**Appendix 1010-D**) and supporting documents (**Appendix 1010-E**), the copyright registration record (**Appendix 1010-F**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that *Applied Physics Letters* is a long-running journal that has been made available at the British Library, and that the vol. 101, no. 2 (July 9 2011) issue that contains Vissers (**Appendix 1010-A**) would have been accessible to the public on August 3, 2012.

6. Actual Usage Records

109. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Vissers has been cited at least 16 times, and seven citations were published in 2012 and 2013. **Appendix 1010-G** presents five citations published in 2012 and 2013 to demonstrate early usage of Vissers. The earliest citing document was published in November 2012.

7. Summary on Vissers

110. Taken together, the "03/08/2012" date stamp in **Appendix 1010-A**, the bibliographic record (**Appendix 1010-B**), the MARC record (**Appendix 1010-C**), the public availability date letter (**Appendix 1010-D**) and supporting documents from the British Library (**Appendix 1010-E**), the copyright registration record (**Appendix 1010-F**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Vissers (**Appendix 1010-A**) would have been available for public access in August 3, 2012. In fact, as shown by actual usage (**Appendix 1010-G**), the earliest citing article to Vissers was published on November 2012, further demonstrating public availability of Vissers in 2012.

G. Exhibit 1011 (Kim)

1. Authentication

111. **Exhibit 1011** is a true and correct copy of "Decoupling a Cooper-Pair Box to Enhance the Lifetime to 0.2 ms" by Kim et al., published in *Physical Review Letters*, vol. 106, no 12 (2011), as article 120501 that I obtained from the website of "Physical Review Journals" published by the American Physical Society. I also obtained a copy of the Kim article from the University of Michigan

Libraries (**Appendix 1011-A**), compared these two documents closely, and concluded that **Exhibit 1011** and **Appendix 1011-A** contain the same article. The differences are that **Exhibit 1011** is colored while **Appendix 1011-A** has some colored graphs and includes the front matter of the journal issue that contains the Kim article.

112. **Appendix 1011-A** is a true and correct copy of "Decoupling a Cooper-Pair Box to Enhance the Lifetime to 0.2 ms" ("Kim") by Kim et al., published in *Physical Review Letters*, vol. 106, no 12 (2011), as article120501. When I was originally asked to prepare this declaration, I searched WorldCat for records by the article title. The search results informed me that the University of Michigan Libraries held the journal *Physical Review Letters* that published "Kim." I then requested a copy of the article through Wisconsin TechSearch (WTS), a document delivery service based in the University of Wisconsin, and received the scanned pages from the University of Michigan Libraries. These pages include the front matter (the front cover of vol. 106, no. 12 (March 25, 2011) of *Physical Review Letters*, the copyright page, the table of contents, the page with a date stamp) and the Kim article (four pages).

113. Page 1 of **Appendix 1011-A** is the front cover of an issue of *Physical Review Letters* that shows this issue is "Volume 106, Number 12" that contains "articles published week ending 25 March 2011" published by American Physical Society. It also carries a label of "SCIENCE QC1 .P5813 v. 106 no. 12" and a date stamp of "APR 11 2011." Page 2 of **Appendix 1011-A** is the copyright page that shows the journal "is published weekly by the American Physical Society" of Ridge, New York, and its ISSN (International Standard Serial Number) is 0031-9007. The copyright page shows this issue has a "2011" copyright date and American Physical Society holds the copyright. Page 3 of **Appendix 1011-A** shows a date stamp of "APR 11 2011" on the first page of the first article in this issue. Page 4 of **Appendix 1011-A** shows the table of contents of vol. 106, no. 12 (25 March 2011) that shows "Decoupling a Cooper-Pair Box to Enhance the lifetime to 0.2 ms" by Kim et al. is article "120501" in this journal. The first page of Kim shows the article was "received 21 September 2010; published 22 March 2011." It also shows "10.1103/PhysRevLett.106.120501" as the DOI (digital object identifier, a unique code to permanently identify documents on the Web) of this article, and "03.67.Lx, 42.50.Pq, 84.40.Dc, 85.25.Cp" as the PACS numbers. PACS is the Physics and Astronomy Classification Scheme developed by the American Institute of Physics to identify fields and sub-fields of physics. The copyright page of **Appendix 1011-A** instructs authors to "provide indexing codes according to the PAC scheme (available at http://publish.asp.org/PACS/)." The bottom of the page shows a "2011" copyright date with American Physical Society as the copyright holder, and a note of "0031-9007/11/106(12)/120501(4)" that indicates article 120501 has four pages, is published in vol. 106, no. 12 in 2011 in the journal with an ISSN of 0031-9007 (*i.e.*, *Physical Review Letters*).

2. University of Michigan Libraries Records

114. **Appendix 1011-B** is a true and correct copy of the bibliographic record for the journal *Physical Review Letters* whose vol. 106, no. 12 (March 2011) contains Kim. I retrieved the record from the online catalog of the University of Michigan Libraries by searching for "physical review letters." I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, a customary library cataloging practice is to create one bibliographic record for a serial and create no records for individual issues of the serial. The bibliographic record (**Appendix 1011-B**) shows that "Physical Review Letters" is the journal title, which is published by the American Physical Society, and the University of Michigan Libraries hold volumes from vol. 1 (1958) on, and v. 92-117 (2004-2016) are shelved by title and "on shelf" for user access. By selecting "View MARC data" I retrieved the MARC record (**Appendix 1011-C**) for this journal. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

115. Field 245 of the MARC record (**Appendix 1011-C**) shows the journal title is "Physical review letters," Field 022 shows the ISSN of this journal is "0031-9007," and Field 010 shows the Library of Congress Control Number for this journal is "59037543." Field 040 subfield "a" shows "DLC" is the original creator of the serial record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. This means the University of Michigan Libraries used the Library of Congress serial record to create their copy cataloging record for this journal. The first six digits of Field 008 show the copy cataloging record was added to the system on "940310" (*i.e.*, March 10, 1994) and the "c19589999" code following these digits indicates that the journal began publication in 1958 and is an ongoing publication. Field 260 shows American Physical Society is the publisher, Field 362 shows the journal began publication with "v. 1- " in "July 1958" and Field 310 shows the publication frequency since February 1976 has been "weekly." Field 510 shows this journal is indexed by Nuclear science abstracts. Field 710 shows the American Physical Society, the journal publisher, is another access point for this journal.

116. Field 050 of the MARC record (**Appendix 1011-C**) shows that this journal is assigned a Library of Congress Classification (LCC) number, "QC," which is the class number for "periodicals" in the field of physics. Field 082 shows the Dewey Decimal Classification number assigned to this journal is "530.5," which represents periodicals in the field of physics. The subject of this journal is also represented by one Library of Congress subject heading in Field 650, with "Physics" as the main heading and "Periodicals" encoded in subfield "x" to indicate the form of this publication. This MARC record (**Appendix 1011-C**) makes *Physical Review Letters*, whose vol. 106, no. 12 (March 2011) contains Kim, searchable in the online catalog of the University of Michigan Libraries. As a result, users interested in journals in the field of physics are able to search for and retrieve this journal by the LCC number, the DDC number and the subject term in Field 650. Users can also search for this journal by its title, ISSB, and the publisher.

3. University of Michigan Libraries Date Stamp

117. The front cover of the journal in **Appendix 1011-A** bears a date stamp of "APR 11 2011" and the first page of the first article in vol. 106, no. 12 of *Physical Review Letters* carries the same date stamp. The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. Based on my knowledge and understanding of library serial check-in practice and the effort to make new journal issues available to users as soon as possible, it is my opinion that vol. 106, no. 12 (March 2011) of *Physical Review Letters* that contains Kim would have been publicly accessible by April 18, 2011, a week after it was checked in at the University of Michigan Libraries. If the workload was very heavy at that time, it might take more than one week for the new issue to become available to users. My conservative estimate is that this issue would have been available to users no later than May 11, 2011, one month after serial check-in was completed.

4. United States Copyright Registration Records

118. Appendix 1011-D is a true and accurate copy of the copyright registration record for the Vol. 106, no. 12 (25 March 2011) issue of *Physical Review Letters* that I obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1011-D** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the journal title, to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

119. The copyright registration record shows that the title of this serial is "Physical Review Letters" whose ISSN is "0031-9007" and it is published "Weekly" by the American Physical Society or Ride, NY. The record also shows this particular issue was "created 2001; Pub. 2011-04-04. Reg. 2011-08-24" (*i.e.*, published on April 4, 2011 and registered with the copyright office on August 24, 2011). The journal title, ISSN, issue number and chronological designation, publisher and publication year match the information contained in **Appendix 1011-A**.

120. Taken together, the April 11, 2011 date stamp in **Appendix 1011-A**, the bibliographic record (**Appendix 1011-B**), the MARC record (**Appendix 1011-C**), the copyright registration record (**Appendix 1011-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that *Physical Review Letters* is a long-running journal that has been made available at the University of Michigan Libraries, and that vol. 106, no. 12 (March 2011) of this journal that contains Kim (**Appendix 1011-A**) would have been accessible to the public by May 11, 2011, at the latest.

5. Actual Usage Records

121. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Kim has been cited at least 78 times, and eight citations were published in 2011. **Appendix 1011-E** presents seven citations published in 2011 to demonstrate early usage of Kim. The earliest citing document was published in July 2011.

6. Summary on Kim

122. Taken together, the "April 11 2011" date stamp in **Appendix 1011-A**, the bibliographic record (**Appendix 1011-B**), the MARC record (**Appendix 1011-C**), the copyright registration record (**Appendix 1011-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Kim (**Appendix 1011-A**) would have been available for public access in April 2011 and no later than May 2011. In fact, as shown by actual usage (**Appendix 1011-E**), the earliest citing article to Kim was published in July 2011, further demonstrating public availability of Kim in 2011.

H. Exhibit 1013 (Bahl)

1. Authentication

123. **Exhibit 1013** is a true and correct copy of portions of LUMPED ELEMENTS FOR RF AND MICROWAVE CIRCUITS ("Bahl") that I made during my personal visit to the Library of Congress. When I was asked to prepare this declaration, I searched the Library of Congress online catalog for records because books published in the United States tend to be registered with the Copyright Office of the Library of Congress and cataloged by the Library of Congress. The search results informed me that the Library of Congress provided access to Bahl. The "Item Availability" area of the library records shows that the book's call number is "TK7874.54 .B34 2003" and Copy 1 is available for user request at the "Jefferson or Adams Building Reading Rooms" while Copy 2 is "stored offsite" at the Fort Meade facility. I requested access to this title and received the book at the Science and Technology Reading Rooms in the Library of Congress Adams Building.

124. **Exhibit 1013** is a true and correct copy of portions of Bahl that I made while the book was in my possession at the Library of Congress. I obtained **Exhibit 1013** by personally scanning the front matter (the front cover, title page, copyright page, and table of contents), pages 121 to 124, 229 to 235, and 488 (the last numbered page of this volume), the back cover and spine of this volume.

125. The first page of **Exhibit 1013** shows "Lumped Elements for RF and Microwave Circuits" as the title on the cover and "Inder Bahl" as the author. Page 2 of **Exhibit 1013** is the title page that shows the same title and author information, and further indicates that "Artech House" of Boston is the publisher. Page 3 of **Exhibit 1013** is the copyright page that shows "2003" as the copyright date and "ARTECH HOUSE, INC." as the copyright holder. The copyright page also shows "1-58053-309-4" as the International Standard Book Number of this book and "2003048102" as the Library of Congress Catalog Card Number for this book. The copyright page also shows a record identified as the "Library of Congress Cataloging-in-Publication Data" and another record identified as the "British Library Cataloguing in Publication Data." The copyright page also carries a date stamp of "LIBRARY OF CONGRESS JUN 18 2003 CIP." Page 26 of **Exhibit 1013** shows an ISBN (International Standard Book Number) of "1-58053-309-4" on the back cover, and page 17 shows the spine with a label of "TK 7874.54 .B34 2003 COPY 1."

2. Library of Congress Records

126. Appendix 1013-A a true and correct copy of the bibliographic record for LUMPED ELEMENTS FOR RF AND MICROWAVE CIRCUITS ("Bahl"). I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. **Appendix 1013-A** shows that the main title is "Lumped elements for RF and microwave circuits," the author is "Bahl, I. J.," and "Artech House" of Boston published this book with a "2003" copyright date. The ISBN field shows "1580533094" is the number assigned to this title, and the LCCN (Library of Congress Control Number) field shows "2003048102" as the number assigned to this title. The author, title, publisher, publication year, ISBN and LCCN match the information contained in **Exhibit 1013**. The "Item Availability" area shows that the book's call number is "TK7874.54 .B34 2003" and the Library of Congress holds two copies, with Copy 1 stored on site and Copy 2 stored offsite at the Fort Meade facility. The "status" field indicates both copies are "not charged," meaning available for user requests.

127. Appendix 1013-B is a true and correct copy of the MARC record for LUMPED ELEMENTS FOR RF AND MICROWAVE CIRCUITS ("Bahl"). I personally identified, located, and obtained this record from the online catalog of the Library of Congress for this declaration. This is the type of record experts in my field would reasonably rely upon when forming their opinion. The first six digits of Field 008 show the MARC record was created on "030324" (*i.e.*, March 24, 2003). Field 040 subfield "a" shows that "DLC" is the library that created the original MARC record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. Field 955, the local note field that record cataloging activity dates, shows that "2003-06-27 2 copies rec'd., to CIP ver." (meaning two copies were received by CIP for verification on June 27, 2003) and "2003-07-17 CIP ver to BCCD 2 copies" (meaning two copies verified by the CIP were sent to the Binding and Collections Care Division on July 17, 2003). These dates from Field 008 and Field 955 inform my opinion that the original record was completed on March 24, 2003 as a Cataloging-in-Publication record based on the information provided by the publisher. After the CIP record was completed, it was sent to the publisher for inclusion in the physical volume. The Cataloging-in-Publication data printed on the copyright page of **Exhibit 1013** reflects this practice.

128. Field 010 of the MARC record (**Appendix 1013-B**) shows the Library of Congress control number of this book is "2003048102," which matches the number on the copyright page of **Exhibit 1013**. Field 020 shows the ISBN assigned to this publication is "1580533094," which matches the ISBN printed on the copyright page and the back cover of **Exhibit 1013**. Field 245 shows the title is

"Lumped elements for RF and microwave circuits" and the author is "Inder Bahl." Field 100 presents the author's name in the authorized form "Bahl, I. J." and makes it an access point for this book. Field 260 shows that Artech House of Boston published this book with a copyright date of 2003. Field 300 indicates that the book has 488 pages. The number "488" matches the last numbered page included in **Exhibit 1013**. Field 440 shows the book is part of the "Artech House microwave library" series.

129. Field 050 of the MARC record (**Appendix 1013-B**) shows this book has a Library of Congress Classification (LCC) number of "TK7874.54," which is the class number for "Lumped elements." Field 082 shows the book has a Dewey Decimal Classification (DDC) number of "621.381/32," which is the class number for "Circuits of microwave electronics." Users interested in the topic represented by the LCC number or the DDC number could search it as a keyword in the Library of Congress catalog to retrieve materials that have been assigned the same classification number. The subjects of this book are also represented by four Library of Congress subject heading in Field 650s, "Lumped elements (Electronics)," "Microwave integrated circuits," "Radio frequency integrated circuits," and "Passive components." This MARC record (**Appendix 1013-B**) shows that LUMPED ELEMENTS FOR RF AND MICROWAVE CIRCUITS by Inder Bahl is a book that has been made searchable at the online catalog of the Library of

Congress, and users interested in the topics of the book can find it by the LCC and DDC numbers and by the subject terms assigned to it. Users can also find this book by its title, author, ISBN, and the Artech House microwave library series.

130. Based on the information above, it is my opinion that LUMPED ELEMENTS FOR RF AND MICROWAVE CIRCUITS by Inder Bahl is a book that has been made available by the Library of Congress, meaning that members of the public with an interest in the topics covered by the book would be able to search for and access it.

3. Library of Congress Date Stamp

131. The copyright page of Bahl in **Exhibit 1013** bears a stamp of "LIBRARY OF CONGRESS JUN 18 2003 CIP" that indicates the date when the Cataloging in Publication Program received the physical volume of Bahl. The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. This date stamp and the dates in Field 955 of the MARC record (**Appendix 1013-B**) inform my opinion that the Library of Congress received the physical volume of Bahl on June 18, 2003, that the CIP catalogers received the copies for verification on June 27, 2003, and that after CIP verification was completed, two copies were sent to the processing unit on July 17, 2013. In most academic libraries a newly cataloged book would become available for the public soon after the cataloging record is completed, usually within a week. Considering the volume of materials the Library of Congress needs to catalog and process, my conservative estimate is that Bahl would have become available for public access by October 17, 2013, three months after two copies were sent to the processing unit after the original CIP record was verified.

132. Based on the June 18, 2003 date stamp placed on the copyright page of Bahl (**Exhibit 1013**), the CIP verification date, the date two copies were sent to the processing unit, the bibliographic record (**Appendix 1013-A**), the MARC record (**Appendix 1013-B**), and my understanding of the ordinary and customary cataloging and processing practices of libraries, it is my opinion that Bahl (**Exhibit 1013**) was cataloged and became searchable as early as March 24, 2003, when the CIP record was completed, and the physical volume became accessible to the public by October 17, 2013 at the latest, which would be three months after the CIP record was verified and two copies were sent to the processing units.

4. United States Copyright Registration Records

133. **Appendix 1013-C** is a true and accurate copy of the copyright registration record for LUMPED ELEMENTS FOR RF AND MICROWAVE CIRCUITS by Inder Bahl obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1013-C** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright

Records," and performing a search by the first few words of the title, to retrieve the record for "lumped elements for RF and microwave circuits." I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

134. The copyright registration record shows that the title of this book is "Lumped elements for RF and microwave circuits," "Inder Bahl" is the author, and "Artech House" of Norwood, MA published the book with a "2003" copyright date and is the copyright claimant. The record shows the date of creation is "2003," the date of publication is "2003-05-30" (*i.e.*, May 30, 2003), and the copyright registration number and date are "TX0005754523 / 2003-06-20." The title, author, publisher, publication date, and the copyright holder information match the information contained in **Exhibit 1013**. The copyright registration record also shows that Bahl has 488 pages, which matches the last numbered page of this book recorded in Field 300 of the MARC record (**Appendix 1013-B**) and the page number of the last page of Bahl (**Exhibit 1013**), which I personally scanned at the Library of Congress.

5. Actual Usage Records

135. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows that Bahl has been cited more than 890 times and 33 citing papers were published between 2004 and

2005. **Appendix 1013-D** presents 10 citing documents selected from Google Scholar to demonstrate early usage of Bahl. The earliest citing document was published in January 2004.

6. Summary on Bahl

136. Taken together, the date stamp in **Exhibit 1013**, the bibliographic record (**Appendix 1013-A**), the MARC record (**Appendix 1013-B**), the copyright registration record (**Appendix 1013-C**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Bahl (**Exhibit 1013**) would have been cataloged and discoverable by the public at the online catalog of the Library of Congress by March 24, 2003 when the CIP cataloging record was created, and the physical item would have been available for public access by October 17, 2003, three months after the CIP record was verified and two copies were sent to the processing unit. The citation history of Bahl (**Appendix 1013-D**) shows that the earliest citing document was published in January 2004, further demonstrating public availability of Bahl in 2003.

I. Exhibit 1015 (Blais)

1. Authentication

137. **Exhibit 1015** is a true and correct copy of "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: An Architecture for Quantum Computation" by Blais et al. in *Physical Review A*, vol. 69, no. 6 (2004), as article 062320 (14 pages) that I obtained from the website of "Physical Review Journals" published by the American Physical Society. I also obtained a copy of the Blais article from the Library of Congress (**Appendix 1015-A**), compared these two documents closely, and concluded that **Exhibit 1015** and **Appendix 1015-A** contain the same article. The differences are that **Exhibit 1015** has some colored illustrations, while **Appendix 1015-A** contains the front matter of the journal issue that contains the Blais article and a page that carries a date stamp and a copyright registration mark.

138. **Appendix 1015-A** is a true and correct copy of "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: An Architecture for Quantum Computation" ("Blais") by Blais et al. in *Physical Review A*, vol. 69, no. 6 (2004), as article 062320 (14 pages), that I obtained from Library of Congress. As I prepared this declaration, I searched WorldCat for records by the article title. The search results informed me that the Library of Congress held *Physical Review A* that published Blais. I then requested access to vol. 69, no. 6 (2004) of *Physical Review A* and received the volume at the Library of Congress Business and Science Reading Room in the Adams Building. While the copy was in my possession I personally scanned the front matter (cover, copyright page, date stamped page, and table of contents) and "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: An Architecture for Quantum Computation" by Blais et al.

These pages are presented as **Appendix 1015-A** in this declaration.

139. Page 1 of **Appendix 1015-A** is the front cover of an issue of *Physical Review A* that shows this issue is "Volume 69, Third Series, Number 6," that contains "articles published in JUNE 2004" by "The American Physical Society", and the journal title has "Atomic, Molecular, and Optical Physics" as a subtitle. Page 2 of **Appendix 1015-A** is the copyright page that shows "1050-2947" as the journal's ISSN (International Standard Serial Number) and "PLRAAN" as its CODEN (a six-character alphanumeric code that permanently identifies a serial or non-serial publication). It also shows that the journal is published "monthly by The American Physical Society through the American Institute of Physics" and Vol. 69, no. 6 carries a "2004" copyright date, with The American Physical Society shown as the copyright holder. Page 3 of **Appendix 1015-A** is the page that carries a date stamp of "LIBRARY OF CONGRESS AUG 06 2004 COPYRIGHT OFFICE" and a stick of "TX 6-012-968" that has the appearance of a copyright registration number and barcode. Page 4 of **Appendix 1015-A** is the first page of "Cavity Quantum Electrodynamics for Superconducting Electrical Circuits: An Architecture for Quantum Computation" by Blais et al. It shows the article was "received 7 February 2004; published 29 June 2004." The page also shows that the article's DOI (digital object identifier) is "10.1103/PhysRevA.69.062320", the PACS (Physics and Astronomy Classification Scheme) numbers provided by authors to indicate the article's subject matters are "03.67.Lx, 73.23.Hk, 74.50.+r, 32.80.-t" and the article has a "2004" copyright date with the American Physical Society as the copyright holder. The bottom of this page shows "1050-2947/2004/69(6)/062320(14)" as an identifier that means article 062320 has 14 pages, and was published in vol. 69, number 6 in 2004, in the journal whose ISSN is "1050-2947" (*i.e.*, *Physical Review A*). *Physical Review A* places its table of contents on the back cover of the issue. Page 18 of **Appendix 1015-A** shows that it is the table of contents of "third series, volume 69, number 6" of Physical Review A whose ISSN is "1050-2947", and pages 19 and 20 show that article 062320 is placed in the "Quantum Information" section, authored by Blais et al. with a title "Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation" and is 14 pages long.

2. Library of Congress Records

140. **Appendix 1015-B** is a true and correct copy of the bibliographic record for the journal *Physical Review A* whose vol. 69, no. 7 (2004) contains Blais. I retrieved the record from the online catalog of the Library of Congress by searching for the journal's ISSN "1050-2947." I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, a customary library cataloging practice is to create one bibliographic record for a serial and create no records for individual issues of the serial. The bibliographic record (**Appendix 1015-B**) shows that "Physical review. A, Atomic, molecular, and optical physics" is the journal title, and the American Physical Society of New York has been publishing this journal since 1990. The ISSN field shows "1050-2947" as the ISSN of this journal, the CODEN field shows "PLRAAN" as the journal's CODEN identifier, and a current frequency note indicates the journal has been published "monthly" since 1993. The Item Availability area shows the journal's call number at the Library of Congress is "QC1 .P42" and the Library of Congress holds several sets, including Set 1 that can be requested in the "Jefferson or Adams Building Reading Rooms" and the holdings include older receipts beginning with "ser.3:v.44:no.3-ser.3:v.76 (1991:Aug.-2007)" (*i.e.*, series 3, vol. 44, no. 3 to series 3, vol. 76, from 1991 to August 2007). The title, publisher, ISSN, CODEN, and publication frequency match the information presented in **Appendix 1015-A**, and the holdings information shows that Library of Congress holds vol. 69, no. 6 (2004) that contains Blais.

141. The bibliographic record has a link for "MARC Tags" that brings up the MARC record for *Physical Review A.* This is the type of record experts in my field would reasonably rely upon when forming their opinion.

142. Field 245 of the MARC record (**Appendix 1015-C**) shows the journal title is "Physical review. A, Atomic, molecular, and optical physics," Field 022 shows the ISSN of this journal is "1050-2947," Field 030 shows the CODEN of this journal is "PLRAAN." Subfield a of Field 040 shows "NYG" is the original creator of this serial record and subfield d shows "DLC" used the original record to create a copy cataloging record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "NYG" is the OCLC symbol for the New York State Library, and "DLC" is the symbol for the Library of Congress. The first six digits of Field 008 show this serial MARC record was created on "900326" (*i.e.*, March 26, 1990) and the "d19902015" code following the record creation date indicates that the journal began publication in 1990 and ceased publication in 2015. Field 260 shows the journal has been "published by the American Physical Society through the American Institute of Physics" in New York since 1990. Field 310 shows the current publication frequency is "Monthly" since 1993, Field 362 shows this journal began with "Third ser., v. 41, no. 1 (1 Jan. 1990)" and a second Field 362 shows the publication "ceased with v. 92, no. 6 (Dec. 2015)."

143. Field 050 of the MARC record (**Appendix 1015-C**) shows the Library of Congress Classification (LCC) number assigned to this journal is "QC1," which represents the "periodicals on physics" category, and Field 082 shows the Dewey Decimal Classification (DDC) number assigned to this journal is "530/.05," which represents the "periodicals on physics" category. Subjects are also represented by four Library of Congress subject headings in four 650 fields, with "Nuclear physics," "Statistical physics," "Plasma (ionized gases)" and "Fluids" as the main topical headings, and "periodicals" added as a form subdivision (encoded in subfield "v") to indicate the main topics are published in a journal. Two 710 fields show the American Physical Society and the American Institute of Physics are related to this journal and users can use them to discover and access this journal.

144. This MARC record (**Appendix 1015-C**) makes *Physical Review A*, whose vol. 69, no. 6 (2004) contains Blais, searchable in the online catalog of the Library of Congress. As a result, users interested in the topics covered by this journal are able to search for and retrieve this journal by the LCC number, DDC number and subject terms assigned to it. Users can also search for this journal by its title, ISSN, two related organizations.

3. Library of Congress Date Stamp

145. Page 3 of **Appendix 1015-A** bears a date stamp of "LIBRARY OF CONGRESS AUG 06 2004 COPYRIGHT OFFICE". The stamp has the appearance and distinctive characteristics of a typical check-in date stamp utilized by libraries to indicate the date a particular publication was received by the library. Based on my knowledge and understanding of library serial check-in practice and the effort to make new journal issues available to users as soon as possible, it is my opinion that vol. 69, no. 6 (2004) of *Physical Review A* that contains Blais would have been publicly accessible by August 13, 2004, a week after it was checked in at the Library of Congress. If the workload was very heavy at that time, it might take more than one week for the new issue to become available to users. My conservative estimate is that this issue would have been available to users no later than September 6, 2004, one month after serial check-in was completed.

4. United States Copyright Registration Records

146. **Appendix 1015-D** is a true and correct copy of the copyright registration record for vol. 68, no. 6 (Dec03) to vol. 70, no. 5 (Nov04) of *Physical Review A* that I obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1015-D** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the journal title to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

147. The copyright registration record (**Appendix 1015-D**) shows that the record represents a serial, the serial title is "Physical Review. A : third series" and the title qualifier field shows "Atomic, molecular & optical physics AND Statistical physics, plasmas, fluids …" A note further clarifies that "numbers issued on the 1st of the month are called: Atomic, Molecular, and Optical physics." The copyright registration record shows that "1050-2947" is one of the ISSNs of this journal, that the journal began publication with "Vol. 41, no. 1, 1 Jan. 1990" and its publication frequency since 1993 has been "monthly." It also shows the "American Physical Society" as the copyright claimant. The "issues registered" field shows that "v. 69, no. 6, Jun04." was "created 2004; Pub. 2004-07-20; Reg. 2004-08-06; TX0006012968" meaning this particular issue was published on July 20, 2004 and registered with the Copyright Office on August 6, 2004, with "TX0006012968" as the registration number. The copyright registration date and number match the information on page 3 of **Appendix 1015-A** that carries a date stamp and a registration barcode. The journal title, ISSN, publication history, publication frequency, and copyright holder match the information presented in **Appendix 1015-A**.

148. Taken together, the date stamp page in **Appendix 1015-A**, the bibliographic record (**Appendix 1015-B**), the MARC record (**Appendix 1015-C**), the copyright registration record (**Appendix 1015-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that vol. 69, no. 6 (2004) of *Physical Review A* that contains Blais (**Appendix 1015-A**) was published on July 20, 2004, checked in by the Copyright Office on August 6, 2004, and registered with that Office on the same date. The physical issue would have been available in the Library of Congress periodical reading room by August 13, 2004, a week after serial check in was completed. If workload caused some delay, the issue would have been available for public access by September 6, 2004, at the latest.

5. Actual Usage Records

149. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Blais has been cited at least 2,400 times, and at least 13 citations were published in 2004. **Appendix 1015-E** presents five citations published in 2004 to demonstrate early usage of Blais. They include a preprint deposited in February 2004, two journal articles in October 2004, and two dissertations completed in 2004. These citations support my opinion that Blais was publicly available in 2004.

6. Summary on Blais

150. Taken together, the "AUG 06 2004" date stamp in Blais (**Appendix 1015-A**), the bibliographic record (**Appendix 1015-B**), the MARC record (**Appendix 1015-C**), the copyright registration record (**Appendix 1015-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Blais would have been available for public access by August 13, 2004, and no later than September 6, 2004. In fact, citations selected from 2004 (**Appendix 1015-E**) show that the earliest journal citation of Blais was published in October 2004, further demonstrating public availability of

Blais in 2004.

J. Exhibit 1019 (Barends)

1. Authentication

151. Exhibit 1019 is a true and correct copy of "Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits" by Barends et al., in *Physical Review Letters*, vol. 111, no. 8 (August 2013), as article 080502 that I obtained from the website of "Physical Review Journals" published by the American Physical Society. I also obtained a copy of the Barends article from the Library of Congress (**Appendix 1019-A**), compared these two documents closely, and concluded that **Exhibit 1019** and **Appendix 1019-A** contain the same article. The differences are that **Exhibit 1019** is colored, while **Appendix 1019-A** is black and white and includes the front matter of the journal issue that contains the Barends article.

152. Appendix 1019-A is a true and correct copy of "Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits" ("Barends") by Barends et al., in *Physical Review Letters*, vol. 111, no. 8 (August 2013), as article 080502, that I obtained from the Library of Congress. As I prepared this declaration, I searched WorldCat for records by the article title. The search results informed me that the Library of Congress held *Physical Review Letters* that published Barends. I then requested access to vol. 111, no. 8 (august 2013) of this journal and received the physical volume at the Library of Congress Business and Technology Reading Room in the Adams Building. While the volume was in my possession, I personally scanned the front matter (cover, copyright page, and table of contents) and article 080502. These pages are presented as **Appendix 1019-A** in this declaration.

153. Page 1 of **Appendix 1019-A** is the front cover of an issue of *Physical Review Letters* that shows this issue is "Volume 111, Number 8" that contains "articles published week ending 23 August 2013" and the American Physical Society is the publisher. The cover carries a check-in label showing the journal title, publisher, and issue number of this issue with "QC1 .P43" as the call number. Page 2 of **Appendix 1019-A** is the copyright page that shows a "2013" copyright date for this issue and the American Physical Society as the copyright holder. It also shows "0031-9007" as the journal's ISSN (International Standard Serial Number), and "PRLTAO" as its CODEN (the six character alphanumeric code that uniquely identifies a serial or non-serial publication), and shows the journal is published "weekly" by the American Physical Society of Ridge, New York. Page 3 of **Appendix 1019-A** is the first page of "Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits" by Barends et al. It shows the article was "received 5 April 2013; published 22 August 2013." The page also shows that the article's DOI (digital object identifier) is "10.1103/PhysRevLett.111.080502," and the PACS (Physics and Astronomy Classification Scheme) numbers provided by the authors to indicate the article's subject matters are "03.67.Lx, 03.65.Yz, 85.25.Cp." The article has a "2013" copyright date with the American Physical Society as the copyright holder. The bottom of this page shows "0031-9007/13/111(8)/080502(5)" as an identifier that means article 080502 has five pages, and was published in vol. 111, number 8 in 2013, in the journal whose ISSN is "0031-9007" (*i.e.*, *Physical Review Letters*). *Physical Review Letters* places its table of contents on the back cover of the issue. Page 8 of **Appendix 1019-A** shows that it is the table of contents of "volume 111, number 8" that contains "articles published 17 August – 23 August 2013" and the issue publication date is "23 August 2013." This table of contents page shows article 080502 is placed in the "General physics: Statistical and quantum mechanics, quantum information, etc." section, has 16 authors, is entitled "Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits" and is five pages long. Page 11 of **Appendix 1019-A** is the spine of the volume containing Barends, indicating the bound volume includes "111 AUG 16-30 2013 7-9" meaning vol. 111, numbers 7 to 9 published from August 16 to 30 of 2013, and the call number of this volume is QC 1 . P43 Set 1. Page 12 of **Appendix 1019-A** is the cover of the last issue in this bound volume, indicating it is vol. 111, no. 9 that contains "articles published week ending 30 AUGUST 2013." Page 13 of **Appendix 1019-A** is the back cover of the bound volume that shows a sticker with a binding date of "10/14/2014."

2. Library of Congress Records

154. Appendix 1019-B is a true and correct copy of the bibliographic record for the journal *Physical Review Letters* whose vol. 111, no. 8 (August 2013) contains Barends. I retrieved the record from the online catalog of the Library of Congress by searching for the journal's ISSN "0031-9007." I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, a customary library cataloging practice is to create one bibliographic record for a serial and create no records for individual issues of the serial. The bibliographic record (**Appendix 1019-B**) shows that "Physical review letters" is the journal title, and the American Physical Society of New York is the publisher. The ISSN field shows "0031-9007" as the ISSN of this journal, the CODEN field shows "PRLTAO" as the journal's CODEN, and a current frequency note indicates the journal has been published "weekly" since "Feb. 1976." The Item Availability area shows the journal's call number at Library of Congress is "QC1 .P43" and Set 1 can be requested at the "Jefferson or Adams Building Reading Rooms." Set 1 includes older receipts such as "v. 104:no.18-v.114:no.23 (2010:May-2015:June 12). Library of Congress also has two copies of the unbound issues of this journal and makes them available to users at the Newspaper & Current Periodical Reading

Room. The title, publisher, ISSN, CODEN, and publication frequency in the bibliographic record (**Appendix 1019-B**) match the information presented on the copyright page of **Appendix 1019-A**, and the holdings information shows that Library of Congress holds vol. 111, no. 8 (August 2013) that contains Barends.

155. The bibliographic record has a link for "MARC Tags" that brings up the MARC record for *Physical Review Letters.* This is the type of record experts in my field would reasonably rely upon when forming their opinion.

156. Field 245 of the MARC record (**Appendix 1019-C**) shows the journal title is "Physical review letters," Field 022 shows the ISSN of this journal is "0031-9007," Field 030 shows the CODEN of this journal is "PRLTAO." Subfield a of Field 040 shows "DLC" is the original creator of this serial record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. The first six digits of Field 008 show this serial MARC record was created on "751019" (*i.e.*, October 19, 1975) and the "c19589999" code following the record creation date indicates that the journal began publication in 1958 and is an ongoing serial. Field 260 shows the American Physical Society is the publisher. Field 310 shows the current publication frequency is "Weekly" since February 1973, Field 362 shows this journal began with "v. 1-July 1958."

157. Field 050 of the MARC record (**Appendix 1019-C**) shows the Library of Congress Classification (LCC) number assigned to this journal is "QC1," which represents the "periodicals on physics" category in LCC, and Field 082 shows the Dewey Decimal Classification (DDC) number assigned to this journal is "530.5," which represents the "periodicals on physics" category in DDC. Subject of this journal is represented by a Library of Congress subject heading in Field 650, with "Physics" as the main topical heading, and "periodicals" added as a form subdivision (encoded in subfield "v") to indicate this publication is a journal. Field 710 presents the American Physical Society as an access point to discover and access this journal.

158. This MARC record (**Appendix 1019-C**) makes *Physical Review Letters*, whose vol. 111, no. 8 (August 2013) contains <u>Barends</u>, searchable in the online catalog of the Library of Congress. As a result, users interested in the topics covered by this journal are able to search for and retrieve this journal by the LCC number, DDC number and the subject term assigned to it. Users can also search for this journal by its title, ISSN, and the publisher.

3. Library of Congress Binding Date

159. Page 13 of **Appendix 1019-A** is the back cover of the bound volume that contains vol. 111, no. 8 (August 2013) of *Physical Review Letters*. It carries a label with a binding date of "10/14/2014" that indicates the date the binding was completed for this bound volume. As discussed earlier, the customary library practice in processing journal issues is to check them into the library system, then make the newly received issues available to users, usually within one week after serial check in. Libraries with a periodical reading room usually place unbound issues in the room for user access, and bind the loose issues into a bound volume when several issues have been received. As the bibliographic record (**Appendix 1019-B**) shows, Library of Congress has two copies of unbound issues of *Physical Review Letters* in its Newspaper & Current Periodical Reading Room, meaning newly received loose issues are placed in this room for direct user access. After the issues are bound into one volume, the bound volume is then placed in the closed stacks and users can request them at the Jefferson or Adams Building Reading Rooms. When binding is completed, the bound volume is shelved in the closed stack areas. This process should not take much time. My conservative estimate is that the bound volume that contains vol. 111, no. 8 (August 2013) would have been available for user request by November 14, 2014, one month after binding was completed.

4. United States Copyright Registration Records

160. **Appendix 1019-D** is a true and correct copy of the copyright registration record for vol. 111, no. 8 (August 23 2013) of *Physical Review Letters* that I obtained from the public catalog of the United States Copyright Office in the

Library of Congress. I obtained **Appendix 1019-D** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the title to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

161. The copyright registration record (**Appendix 1019-D**) shows that the record represents a serial and the serial title is "Physical Review Letters." The copyright registration record shows that "0031-9007" is the ISSN of this journal, the publication frequency is "weekly," and the "American Physical Society" is the copyright claimant and the publisher. The "issues registered" field shows that "vol. 111, no. 8, 23 August 2013" was "created 2013; Pub. 2013-09-03; Reg. 2014-02-21; TX0007809526" meaning this particular issue was published on September 3, 2013, and registered with the Copyright Office on February 21, 2014, with "TX0007809526" as the registration number. The title, ISSN, publication frequency, publisher and copyright holder match the information presented in **Appendix 1019-A**.

162. Taken together, the binding date in **Appendix 1019-A**, the bibliographic record (**Appendix 1019-B**), the MARC record (**Appendix 1019-C**), the copyright registration record (**Appendix 1019-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that vol. 111, no. 8 (August 2013) of *Physical Review Letters* that contains Barends (**Appendix 1019-A**) was published on September 3, 2013 and registered with the Copyright Office on February 21, 2014. The issue was received by the Library of Congress and later bound with no. 7 and no. 9 of volume 111 into one physical volume, and the binding was completed on October 14, 2014. Based on my knowledge of library cataloging and processing practices, it is my opinion that the physical volume that contains vol. 111, no. 8 (August 2013) of *Physical Review Letters* would have been available to the public very soon after the binding was completed, meaning members of the public with an interest in this issue in the bound volume would have been able to access it by November 14, 2014, at the latest.

5. Actual Usage Records

163. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Barends has been cited 403 times, and 15 citations were published in 2013. **Appendix 1019-E** presents five citations published in 2013 to demonstrate early usage of Barends. The earliest citation was published in September 2013, demonstrating public availability of Barends in 2013.

6. Summary on Barends

164. Taken together, the "10/14/2014" binding date in Barends (**Appendix 1019-A**), the bibliographic record (**Appendix 1019-B**), the MARC record (**Appendix 1019-C**), the copyright registration record (**Appendix 1019-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that the physical copy of vol. 111, no. 8 (August 2013) of *Physical Review Letters* that contains Barends would have been available for public access by November 14, 2014, at the latest. Citations selected from 2013 (**Appendix 1019-E**) show that the earliest citation of Barends was published in September 2013, further demonstrating public availability of Barends in 2013.

K. Exhibit 1020 (Paik)

1. Authentication

165. Exhibit 1020 is a true and correct copy of "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture" by Paik et al. in *Physical Review Letters*, vol. 107, no. 24 (December 2011), as article 240501 that I obtained from the website of "Physical Review Journals" published by the American Physical Society. I obtained a copy of the Paik article from the Library of Congress (**Appendix 1020-A**), compared these two documents closely, and concluded that **Exhibit 1020** and **Appendix 1020-A** contain the same article. The differences are that **Exhibit 1020** is colored, while **Appendix 1020-A** is black and white and includes the front matter, spine, and back cover of the bound volume containing the journal issue that contains the Paik article.

166. **Appendix 1020-A** is a true and correct copy of "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture" ("Paik") by Paik et al. in *Physical Review Letters*, vol. 107, no. 24 (December 2011), as article 240501 that I obtained from the Library of Congress. As I prepared this declaration, I searched WorldCat for records by the article title. The search results informed me that the Library of Congress held *Physical Review Letters* that published Paik. I then requested access to vol. 107, no. 24 (December 2011) of this journal and received the physical volume at the Library of Congress Business and Technology Reading Room in the Adams Building. While the volume was in my possession, I personally scanned the front matter (cover, copyright page, and table of contents), spine, back cover, and article 240501. These pages are presented as **Appendix 1020-A** in this declaration.

167. Page 1 of **Appendix 1020-A** is the front cover of an issue of *Physical Review Letters* that shows this issue is "Volume 107, Number 24" containing "articles published week ending 9 December 2011" and the American Physical Society is the publisher. Page 2 of **Appendix 1020-A** is the copyright page that shows a "2011" copyright date for this issue and the American Physical Society as the copyright holder. It also shows "0031-9007 (print)" as the print journal's ISSN (International Standard Serial Number), and "PRLTAO" as its CODEN (the six character alphanumeric code that uniquely identifies a serial or non-serial publication), and shows the journal is published "weekly" by the American Physical Society of Ridge, New York. Page 3 of **Appendix 1020-A** is the first page of "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture" by Paik et al. It shows the article was "received 3 July 2011; revised manuscript received 15 September 2011; published 5 December 2011." The page also shows that the article's DOI (digital object identifier) is "10.1103/PhysRevLett.107.240501," and the PACS (Physics and Astronomy Classification Scheme) numbers provided by the authors to indicate the article's subject matters are "03.67.Lx, 42.50.Pq, 85-25.-j." The article has a "2011" copyright date with the American Physical Society as the copyright holder. The bottom of this page shows "0031-9007/11/107(24)/240501(5)" as an identifier that means article 240501 has five pages, and was published in vol. 107, number 24 in 2011, in the journal whose ISSN is "0031-9007" (*i.e.*, *Physical Review Letters*). *Physical Review Letters* places its table of contents on the back cover of the issue. Page 8 of **Appendix 1020-A** shows that it is the table of contents of "volume 107, number 24" that contains "articles published 3 December

– 9 December 2011" and the issue publication date is "3 December 2011." This table of contents page shows article 240501 is placed in the "General physics: Statistical and quantum mechanics, quantum information, etc." section, has 13 authors, is entitled "Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture." Page 11 of **Appendix 1020-A** is the spine of the volume containing Paik, indicating the bound volume includes "107 DEC 2-9 2011 23-24" meaning vol. 107, numbers 23 to 24, published from December 2 to 9, 2011, and the call number of this volume is "QC 1 .P43 Set 1." Page 12 of **Appendix 1020-A** is the back cover of the bound volume that shows a sticker with a binding date of "6/19/2012."

2. Library of Congress Records

168. The bibliographic record for *Physical Review Letters* (**Appendix 1020-B**) shows that "Physical review letters" is the journal title, and the American Physical Society of New York is the publisher. It also shows the journal's ISSN "0031-9007," its CODEN is "PRLTAO," and the current publication frequency has been "weekly" since "Feb. 1976." The Item Availability area shows the journal's call number at the Library of Congress is "QC1 .P43" and Set 1 can be requested at the "Jefferson or Adams Building Reading Rooms." Set 1 includes older receipts such as "v. 104:no.18-v.114:no.23 (2010:May-2015:June 12). The Library of Congress also has two copies of the unbound issues of this journal and makes them available to users at the Newspaper & Current Periodical Reading Room. The title, publisher, ISSN, CODEN, and publication frequency in the bibliographic record for *Physical Review Letters* (**Appendix 1020-B**) match the information presented on the copyright page of vol. 107, no. 24 (December 2011) that contains Paik (**Appendix 1020-A)**, and the holdings information shows that the Library of Congress holds vol. 107, no. 24 (December 2011) that contains Paik.

169. The bibliographic record has a link for "MARC Tags" that brings up the MARC record for *Physical Review Letters.* This is the type of record experts in my field would reasonably rely upon when forming their opinion.

170. Field 245 of the MARC record for *Physical Review Letters* (**Appendix 1020-C**) shows the journal title is "Physical review letters," Field 022 shows the ISSN of this journal is "0031-9007," Field 030 shows the CODEN of this journal is "PRLTAO." Subfield a of Field 040 shows "DLC" is the original creator of this serial record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "DLC" is the OCLC symbol for the Library of Congress. The first six digits of Field 008 show this serial MARC record was created on "751019" (*i.e.*, October 19, 1975) and the "c19589999" code following the record creation date indicates that the journal began publication in 1958 and is an ongoing serial. Field 260 shows the American Physical Society is the publisher. Field 310 shows the current publication frequency is "Weekly" since February 1973, Field 362 shows this journal began with "v. 1-July 1958."

171. Field 050 of the MARC record for *Physical Review Letters* (**Appendix 1020-C**) shows the Library of Congress Classification (LCC) number assigned to this journal is "QC1," which represents the "periodicals on physics" category in LCC, and Field 082 shows the Dewey Decimal Classification (DDC) number assigned to this journal is "530.5," which represents the "periodicals on physics" category in DDC. Subject of this journal is represented by a Library of Congress subject heading in Field 650, with "Physics" as the main topical heading, and "periodicals" added as a form subdivision (encoded in subfield "v") to indicate this publication is a journal. Field 710 presents the American Physical Society as an access point to discover and access this journal.

172. This MARC record for *Physical Review Letters* (**Appendix 1020-C**) makes *Physical Review Letters*, whose vol. 107, no. 24 (December 2011) contains Paik, searchable in the online catalog of the Library of Congress. As a result, users interested in the topics covered by this journal are able to search for and retrieve this journal by the LCC number, DDC number and the subject term assigned to it. Users can also search for this journal by its title, ISSN, and the publisher.

3. Library of Congress Binding Date

173. Page 12 of **Appendix 1020-A** is the back cover of the bound volume that contains vol. 107, no. 24 (December 2011) of *Physical Review Letters*. It carries a label with a binding date of "6/19/2012" that indicates the date the binding was completed for this bound volume. As discussed earlier, the customary library practice in processing journal issues is to check them into the library system, then make the newly received issues available to users, usually within one week after serial check in. Libraries with a periodical reading room usually place unbound issues in the room for user access, and bind the loose issues into a bound volume when appropriate. As the bibliographic record for *Physical Review Letters* (**Appendix 1020-B**) shows, the Library of Congress has two copies of unbound issues of *Physical Review Letters* in its Newspaper & Current Periodical Reading Room, meaning newly received loose issues are placed in this room for direct user access. After the issues are bound into one volume, the bound volume is then placed in the closed stacks and users can request them at the Jefferson or Adams Building Reading Rooms. When binding is completed, the bound volume is shelved in the closed stack areas. This process should not take much time. My conservative estimate is that the bound volume that contains vol. 107, no. 24 (December 2011) would have been available for user request by July 19, 2012, at the latest, which would be one month after binding was completed.

4. United States Copyright Registration Records

174. **Appendix 1020-D** is a true and correct copy of the copyright registration record for vol. 107, no. 24 (December 2011) of *Physical Review Letters* that I obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1020-D** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the title to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

175. The copyright registration record (**Appendix 1020-D**) shows that the record represents a serial and the serial title is "Physical Review Letters." The copyright registration record shows that "0031-9007" is the ISSN of this journal, the publication frequency is "weekly," and the "American Physical Society" is the copyright claimant and the publisher. The "issues registered" field shows that "vol. 107, no. 24, 9 DECEMBER 2011" was "created 2011; Pub. 2011-12-19; Reg. 2012-01-17; TX0007492725" meaning this particular issue was published on December 19, 2011, and registered with the Copyright Office on January 17, 2012, with "TX0007492725" as the registration number. The title, ISSN, publication frequency, publisher and copyright holder match the information presented in Paik (**Appendix 1020-A**).

176. As discussed earlier, the customary library cataloging of serials is to create a library record for an entire serial and use the serial check-in process to keep track of the receipt of individual issues of the journal. After serial check-in is completed, a newly received issue is promptly placed in a public periodical reading room for easy user access if a library has such a reading room. After the library has received enough issues, the unbound issues are bound, and the bound volumes are usually shelved in the stacks.

177. Taken together, the binding date in **Appendix 1020-A**, the bibliographic record for *Physical Review Letters* (**Appendix 1020-B**), the MARC record for *Physical Review Letters* (**Appendix 1020-C**), the copyright registration record for vol. 107, no. 24 (December 2011) of *Physical Review Letters* (**Appendix 1020-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that vol. 107, no. 24 (December 2011) of *Physical Review Letters* that contains Paik (**Appendix 1020-A**) was published on December 19, 2011, and registered with the Copyright Office on January 17, 2012. The issue was received by the Library of Congress and later bound with no. 23 of volume 107 into one physical volume, and the binding was completed on June 19, 2012. Based on my knowledge of library cataloging and processing practices, it is my opinion that the bound volume that contains vol. 107, no. 24 (December 2011) of *Physical Review Letters*, which contains Paik, would have been available to the public very soon after the binding was completed, meaning members of the public with an interest in this issue would have been able to access it by July 19, 2012, at the latest, at Library of Congress.

5. Actual Usage Records

178. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Paik has been cited 856 times, and at least 91 citations were published in 2011 and 2012. **Appendix 1020-E** presents 10 citations published in 2012 to demonstrate early usage of Paik. The earliest journal article citing Paik was published in February 2012, further demonstrating public availability of Paik in 2012.

6. Summary on Paik Records

179. Taken together, the "6/19/2012" binding date in Paik (**Appendix 1020-A**), the bibliographic record for *Physical Review Letters* (**Appendix 1020-B**), the MARC record for *Physical Review Letters* (**Appendix 1020-C**), the copyright registration record for vol. 107, no. 24 (December 2011) of *Physical Review Letters* (**Appendix 1020-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that the bound volume that contains vol. 107, no. 24 (December 2011) of *Physical Review Letters*, which contains Paik, would have been available for public access by July 19, 2012, at the latest, at Library of Congress. In fact, citations selected from 2011 and 2012

(**Appendix 1020-E**) show that the earliest citation of Paik was published in February 2012, further demonstrating public availability of Paik by 2012.

L. Exhibit 1021 (Griffith)

1. Authentication

180. **Exhibit 1021** is a true and correct copy of portions of INTRODUCTION TO ELECTRODYNAMICS ("Griffiths") that I obtained from the University of Wisconsin Libraries with the assistance of Wisconsin TechSearch (WTS), a document delivery service based at the University of Wisconsin. When I was asked to prepare this declaration, I searched WorldCat by the title of this book for records and the search results informed me that the Library of Congress and the University of Wisconsin Libraries held this book. I accessed the copy held by the Library of Congress but the copy did not have date stamp or check out data, so I asked WTS to obtain a copy from the University of Wisconsin Libraries. **Exhibit 1021** includes the cover, title page, checkout slip, copyright page, table of contents and pages 151-166 of INTRODUCTION TO ELECTRODYNAMICS.

181. Page 2 of **Exhibit 1021** shows on the title page that "Introduction to Electrodynamics" is the title, "David J. Griffiths" of Reed College is the author, Pearson of Boston is the publisher, and the copy is the "Fourth Edition." Page 3 is the checkout slip that shows the first due date for this book was "DEC 30 2014" (*i.e.*, December 30, 2014). Page 4 is the copyright page that shows a copyright date of "2013" and "Pearson Education, Inc." as the copyright holder. It also shows that "Library of Congress Cataloging-in-Publication Data" is available upon request and the ISBNs (International Standard Book Numbers) assigned to this book are "0-321-85656-2" and "978-0-321-85656-2." In addition, the copyright page carries two stamps that indicate ownership of this publication: "General Library System, University of Wisconsin – Madison, 728 State Street, Madison, WI 53706-1494, U.SA." and "Steenbock Memorial Library, University of Wisconsin-Madison, 550 Babcock Drive, Madison, WI 53706-1293." Page 5 is the table of contents that shows a hand-written call number "QC 680 G74 2013 c.2" with "STEE" above the number, and another number "9258383."

2. University of Wisconsin Libraries Records

182. **Appendix 1021-A** is a true and correct copy of the bibliographic and MARC record for Griffiths. I retrieved this record from the online catalog of the University of Wisconsin-Madison Libraries after searching for "introduction to electrodynamics" for records. The top portion of **Appendix 1021-A** is the bibliographic record, followed by a "Staff View" link that leads users to the MARC record for this book. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

183. Page 1 of **Appendix 1021-A** is the bibliographic record that shows that "introduction to electrodynamics" is the title, "David J. Griffiths, Reed

College" is the creator, and Pearson of Boston published this "Fourth edition" in 2013. The bibliographic record also shows four ISBNs assigned to this book (the first two are for the print version), and an OCLC number of "794711764" associated with this record. The "Physical Availability" area shows the book is held by the "Steenbock Library" with "QC680 G74 2013" as the call number. It also indicates the book was "unavailable for checkout … in transit" when I saved the record. The record also shows the content type of this book is "Textbooks."

184. Page 2 of **Appendix 1021-A** is the MARC record for the fourth edition of INTRODUCTION TO ELECTRODYNAMICS by David J. Griffiths. The first six digits of Field 008 show the record was added to the system on "130220" (*i.e.*, February 20, 2013) and the code "t20132013" following the record creation date indicates that the book has a publication date of 2013 and a copyright date of 2013. Subfield "a" of Field 040 shows that "DLC" (the OCLC symbol for the Library of Congress, according to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html)), created the original record, and Field 049 shows "GZMA," the OCLC symbol for the University of Wisconsin Libraries holds this title. These data inform me that the University of Wisconsin MARC record is based on the original record created by the Library of Congress. I then searched for the original record in the online catalog of the Library of Congress at https://catalog.loc.gov.

185. Appendix 1021-B is a true and correct copy of the Library of Congress MARC record for Griffiths that I personally identified, located, and obtained from their online catalog. The first six digits of Field 008 show the record was created on "120914" (*i.e.*, September 14, 2012) and subfield "a" of Field 040 shows "DLC" (*i.e.*, the Library of Congress) created the 2012 record. The fact that a MARC record was created in September 2012 for a book with a "2013" publication date informs me that the original Library of Congress MARC record is a Cataloging-in-Publication (CIP) record. The Cataloging in Publication Program at the Library of Congress is responsible for cataloging books in advance of publication to alert the library community to forthcoming publications and to facilitate acquisition. The initial CIP record is created based on information submitted by the publisher. When the CIP record is ready, it is sent to the publisher for inclusion in the publication. The "Library of Congress Cataloging-in-Publication Data" mentioned as "available upon request" on the copyright page of **Exhibit 1021** reflects this practice and confirms my understanding of the nature of the original MARC record by the Library of Congress. The author name in Field 100, the title in Field 245, the edition statement in Field 250, the ISBNs in Fields 020 and the publisher information in Field 300 match the information contained in **Exhibit 1021**, confirming this MARC record is a representation of the fourth edition of INTRODUCTION TO ELECTRODYNAMICS by David J. Griffiths.

186. The record dates in field 008 of the University of Wisconsin Libraries MARC record (**Appendix 1021-A**) and the Library of Congress MARC record (**Appendix 1021-B**) inform my opinion that the Library of Congress created a CIP record for INTRODUCTION TO ELECTRODYNAMICS on September 14, 2012, and the University of Wisconsin Libraries used that record to create a copy cataloging record on February 20, 2013. Field 245 of the University of Wisconsin MARC record (**Appendix 1021-A**) shows "Introduction to electrodynamics" as the title and "David J. Griffiths, Reed College" as the author. Field 250 identifies this version as the "Fourth edition" and two 264 fields show the publication date and the copyright date are "2013." The first Field 264 identifies Pearson of Boston as the publisher. Four 020 fields show the book has two regular ISBNs and two ISBNs for the "Pearson international" edition. The author, title, edition statement, publisher, and the first two ISBNs match the information presented in <u>Griffiths</u> (**Exhibit 1021**). Field 035 shows the MARC record has an OCLC number of "794711764," which makes the record searchable in WorldCat, a free portal to more than 10,000 library collections on the Internet.

187. Field 050 of the University of Wisconsin MARC record (**Appendix 1021-A**) shows <u>Griffiths</u> has been assigned a Library of Congress Classification (LCC) number, "QC 680," which is the class number for "General works, treatises, and textbooks" on Quantum electrodynamics. Field 082 shows the Dewey Decimal

Classification (DDC) Number assigned to Griffiths is "537.6," which is the class number for "Electric currents (Electrodynamics) and thermoelectricity." The subject of Griffiths is also represented in Field 650 by a Library of Congress subject heading, "Electrodynamics" with "Textbooks" added as a form subdivision to indicate the level of this publication. This MARC record (**Appendix 1021-A**) makes Griffiths (**Exhibit 1021**) searchable in the online catalog of the University of Wisconsin Libraries. As a result, users interested in electrodynamics would be able to search for and retrieve this book by the subject term in Field 650 and by the subject areas represented by the LCC number and the DDC number. Users would also be able to find this book by its title, author, and ISBNs.

188. Based on the information above, it is my opinion that INTRODUCTION TO ELECTRODYNAMICS (**Exhibit 1021**) is a book that has been made available by the University of Wisconsin Libraries and Library of Congress, meaning that anyone interested in the topics covered by the book would be able to search for and access INTRODUCTION TO ELECTRODYNAMICS.

3. University of Wisconsin Libraries Checkout Slip

189. Page 3 of **Exhibit 1021** is the checkout slip for the fourth edition of INTRODUCTION TO ELECTRODYNAMICS that shows "DEC 30 2014" as the first due date when the book was due at the library. This checkout slip and the dates on it inform my opinion that Griffiths was available for public access prior to December

30, 2014.

190. Based on the checkout slip for the University of Wisconsin copy of INTRODUCTION TO ELECTRODYNAMICS (**Exhibit 1021**), the bibliographic and MARC records (**Appendix 1021-A**), the Library of Congress Cataloging in Publication record (**Appendix 1021-B**), and my knowledge and understanding of library cataloging and processing practices, it is my opinion that Griffiths (**Exhibit 1021**) was first cataloged by the Library of Congress in September 2012 as a Cataloging in Publication record, and the University of Wisconsin Libraries used the Library of Congress MARC record to create their copy cataloging record in February 2013. The MARC record made the book searchable in the online catalog of the University of Wisconsin Libraries at that time, and the physical copy of INTRODUCTION TO ELECTRODYNAMICS became available for user access by December 2014.

4. United States Copyright Registration Records

191. **Appendix 1021-C** is a true and accurate copy of the copyright registration record obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1021-C** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by "introduction to electrodynamics" to retrieve the record. I personally identified and located this record, which experts in my field would reasonably rely upon when forming their opinions.

192. The copyright record (**Appendix 1021-C**) shows that "Introduction to Electrodynamics, 4/E" is authored by "Griffiths, David J.," the ISBN is "0-321-85656-2," and "Pearson Education, Inc." of Upper Saddle River, NJ is the copyright claimant of this edition. The date of creation was "2012," the date of publication was "2012-09-26" (*i.e.*, September 26, 2012) and the Registration Number and Date are "TX0007714182" and "2013-05-07" meaning the book was registered with the Copyright Office on May 7, 2013. The title, author, edition information, ISBN, copyright date and copyright holder information on the copyright registration record match the information contained in **Exhibit 1021**.

5. Actual Usage Records

193. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar for INTRODUCTION TO ELECTRODYNAMICS by David J. Griffith shows that this title has been cited more than 6,800 times. **Appendix 1021-D** presents ten early citations of the fourth edition of INTRODUCTION TO ELECTRODYNAMICS showing the earliest citation was published in December 2013, followed by citations in January and February 2014. These citations further demonstrating the availability of Griffiths in 2013.

6. Summary on Griffiths

194. Taken together, the "DEC 30 2014" due date on the checkout slip of the University of Wisconsin copy of Griffiths (**Exhibit 1021**), the bibliographic and MARC records (**Appendix 1021-A**), the Library of Congress MARC record (**Appendix 1021-B**), the copyright record (**Appendix 1021-C**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Griffiths was first cataloged and made discoverable by the public at the online catalog of the Library of Congress in September 2012 when the Cataloging in Publication record was created; the book was published in late September of 2012; and the University of Wisconsin Libraries used the Library of Congress record to create their copy cataloging record in February 2013, making the book discoverable and accessible in their libraries. The checkout slip of their copy shows that the physical copy of Griffiths would have been available for public access by December 30, 2014, at the latest. The citation history (**Appendix 1021-D**) in fact shows that the earliest citation of Griffiths was published in December 2013, demonstrating that users were able to access INTRODUCTION TO ELECTRODYNAMICS in 2013.

M. Exhibit 1025 (Houck)

1. Authentication

195. **Exhibit 1025** is a true and correct copy of “Life After Charge Noise: Recent Results with Transmon Qubits” by Houck et al. in *Quantum Information Processing*, vol. 8, (11 February 2009), pages 105-115, that I obtained from the website of Springer Link. I also obtained a copy of the Houck article from the Library of Congress (**Appendix 1025-A**), compared these two documents closely, and concluded that **Exhibit 1025** and **Appendix 1025-A** contain the same article. The differences are that **Exhibit 1025** includes colored illustrations, while **Appendix 1025-A** is black and white and includes the front matter of the journal issue that contains the Houck article.

196. Appendix 1025-A is a true and correct copy of "Life After Charge Noise: Recent Results with Transmon Qubits" ("Houck") by Houck et al. in *Quantum Information Processing,* vol. 8, nos. 2/3 (June 2009), pages 105-115, that I obtained from the Library of Congress with the assistance of Wisconsin TechSearch (WTS), a document delivery service based at the University of Wisconsin-Madison. As I prepared this declaration, I searched WorldCat for records by the article title. The search results informed me that the Library of Congress held *Quantum Information Processing* that published Houck. I searched the online catalog of the Library of Congress for this journal and the records confirmed the holdings information. I then asked WTS to obtain from the Library of Congress a scan copy of Houck and the front matter of vol. 8, nos. 2/3 (June 2009) of *Quantum Information Processing* that contains Houck. I received the scan copy from WTS. The copy includes the cover, editorial page, table of contents, copyright page, and Houck. These pages are presented as **Appendix 1025-A** in this declaration.

197. Page 1 of **Appendix 1025-A** shows *Quantum Information Processing* as the journal title on the cover. It identifies the issue as “Volume 8, Numbers 2/3 June 2009” that contains pages “51-282” and shows the journal ISSN (International Standard Serial Number” as “1570-0755.” It also shows Springer as the publisher and indicates the journal is “available online” at www.springerlink.com. The cover carries a check-in label that shows the title, the numerical and chronological designations of this issue (“v. 8, no. 2/3 (2009 June)”), the call number of this journal (“QA76.889 .Q855”), and a number of “2004-242011” that has the appearance of a Library of Congress control number. Page 3 of **Appendix 1025-A** is the table of contents that shows that this issue is a special issue on “Quantum Computing with Superconducting Qubits” and that “Life after charge noise: recent results with transmon qubits” by Houck et al. begins on page 105. The end of the table of contents (page 4 of **Appendix 1025-A**) shows this journal is abstracted/indexed in nine indexes, including “Chemical Abstracts Service, Compendex, Current Contents/Physical, Chemical and Earth Sciences, Inspect, Journal Citation Reports-Science, Mathematial Reviews, Science Citation Index Expanded, Zentralblatt Math,” which enable users to search for articles published in this journal directly. Page 5 of **Appendix 1025-A** is the copyright page that shows the journal is published “bimonthly by Spring

Science+Business Media, LLC (Springer)," vol. 8 , nos. 2/3 has a "2009" copyright date and the publisher holds the copyright. Page 1 of Houck identifies the authors, article title, and journal publisher, and shows the article has a "2009" copyright date. It also shows the article was "published online: 11 February 2009" and its DOI (digital object identifier) is "10.1007/s11128-009-0100-6." The page also shows the article's PACS (Physics and Astronomy Classification Scheme) numbers are "03.67.Lx. 85.25.-j. 42.50.-p." that indicate the article's subject matters.

2. Library of Congress Records

198. Appendix 1025-B is a true and correct copy of the bibliographic record for the journal *Quantum Information Processing* whose vol. 8, nos. 2/3 (June 2009) contains Houck. I retrieved the record from the online catalog of the Library of Congress by searching for the journal's title. I personally located, identified and obtained this bibliographic record, which experts in my field would reasonably rely upon when forming their opinion. As indicated earlier, a customary library serial cataloging practice is to create one bibliographic record for the entire serial and create no records for individual issues of the serial. The bibliographic record (**Appendix 1025-B**) shows that "Quantum information processing" is the journal title, and Springer of New York has been the publisher since 2013. The ISSN field shows "1570-0755" as the ISSN of this print journal, and a current frequency note indicates the journal has been published "bimonthly." The Item Availability area shows the journal's call number at the Library of Congress is "QA76.889 .Q855" and the Library of Congress holds one set of bound volumes, which can be requested at the "Jefferson or Adams Building Reading Rooms," and unbound issues are available at the "Newspaper & Current Periodical Reading Room" at LM133 of the Madison Building. The bound volumes include older receipts, including "v.7-v.8 (2008-2009)." The journal title, publisher, ISSN, and publication frequency match the information presented in **Appendix 1025-A**, and the holdings information shows that the Library of Congress holds vol. 8, nos. 2/3 (June 2009) that contains Houck.

199. The bibliographic record has a link for "MARC Tags" that brings up the MARC record for *Quantum Information Processing*. This is the type of record experts in my field would reasonably rely upon when forming their opinion.

200. Field 245 of the MARC record (**Appendix 1025-C**) shows the journal title is "Quantum information processing," Field 022 shows the ISSN of this journal is "1570-0755," Subfield "a" of Field 040 shows "MYG" is the original creator of this serial record and subfield "d" shows "DLC" used the original record to create a copy cataloging record. According to the Directory of OCLC Members (https://www.oclc.org/en/contacts/libraries.html), "MYG" is the OCLC symbol for the Massachusetts Institute of Technology, and "DLC" is the symbol for the Library of Congress. The first six digits of Field 008 show this serial MARC record was created at Library of Congress on "060118" (*i.e.*, January 18, 2006) and the code of "c20029999" following the record creation date indicates that the journal began publication in 2002 and is ongoing. Field 955 keeps track of cataloging activities related to this journal and shows that the record was created on "2006-01-18" (*i.e.*, January 18, 2006) and completed on "2006-02-13" (*i.e.*, February 13, 2006), meaning this journal has been made accessible at the Library of Congress since 2006. Field 010 shows "2004242011" is the Library of Congress control number, which matches the number on the label of Houck (**Appendix 1025-A)**. Field 260 shows the journal has been published by Springer of New York since 2013. Field 310 shows the current publication frequency is "bimonthly," Field 362 shows this journal began with "Vol. 1, issue ½ (Apr. 2002)."

201. Field 050 of the MARC record (**Appendix 1025-C**) shows the Library of Congress Classification (LCC) number assigned to this journal is "QA76.889," which represents the "quantum computers" class, and subjects are also represented by two Library of Congress subject headings in two 650 fields, with "Quantum computers" and "Information theory" as the main headings, and "periodicals" added as a form subdivision (encoded in subfield "v") to indicate the main topics are treated in a journal.

202. This MARC record (**Appendix 1025-C**) shows that *Quantum Information Processing* is a long-running journal. The record makes *Quantum Information Processing,* whose vol. 8, nos. 2/3 (June 2009) contains Houck, searchable in the online catalog of the Library of Congress. As a result, users interested in the topics covered by this journal are able to search for and retrieve this journal by the LCC number and subject terms assigned to it. Users can also search for this journal by its title and ISSN.

3. United States Copyright Registration Records

203. **Appendix 1025-D** is a true and correct copy of the copyright registration record for vol. 8, nos. 2/3 (June 2009) of *Quantum Information Processing* that I obtained from the public catalog of the United States Copyright Office in the Library of Congress. I obtained **Appendix 1025-D** by first accessing the http://www.copyright.gov/ website, selecting the hyperlink "Search Copyright Records," and performing a search by the journal title to retrieve the record. I personally located and identified this record, which experts in my field would reasonably rely upon when forming their opinions.

204. The copyright registration record (**Appendix 1025-D**) shows that the record represents a serial, the serial title is "Quantum information processing," the journal's ISSN is "1570-0755" and it is published "Bimonthly." The record also shows that "Springer Science+Business Media, LLC" as the copyright claimant and that "v. 8, no. 2-3, Jun09" was "Created 2009; Pub. 2009-03-24; Reg. 2009-03-30; TX0006922040," meaning this issue was created in 2009, published on March 24, 2009, and registered with the Copyright Office on March 30, 2009 with "TX0006922040" as the registration number. The journal title, ISSN, publication frequency, and copyright holder match the information presented in **Appendix 1025-A**.

205. Taken together, the bibliographic record (**Appendix 1025-B**), the MARC record (**Appendix 1025-C**), the copyright registration record (**Appendix 1025-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that the print version of vol. 8, nos. 2/3 (June 2009) of *Quantum Information Processing* that contains Houck (**Appendix 1025-A**) was published on March 24, 2009, and registered with that Office on March 30, 2009. Because the customary cataloging practice is not to create cataloging records for serial issues, vol. 8, nos. 2/3 (June 2009) would have been made available in the Library of Congress Newspapers and Current Periodical Reading Room as an unbound issue soon after it was registered with the Copyright Office on March 30, 2009 and was checked in at the Library of Congress. My conservative estimate is that vol. 8, nos. 2/3 (June 2009) would have been available for public access by December 2009, at the latest.

4. Actual Usage Records

206. Actual usage of a publication is reflected by the papers that make reference to it. The citation history on Google Scholar shows Houck has been cited at least 122 times. **Appendix 1025-E** presents 58 citations published from August 2009 to June 2015 to demonstrate usage of Houck. The earliest citing documents include an article deposited in ArXiv (an authoritative depository for preprints in physics, mathematics and other fields) in August 2009 and a doctoral dissertation completed at the University of Colorado at Boulder in 2009.

207. Additionally, **Appendix 1025-F** shows that Houck has been cited by the examiner on January 7, 2013, during prosecution of IBM's US Pat. No. 8,642,998 and appears on the face of the patent, which was issued on February 4, 2014.

208. These citations support my opinion that vol. 8, nos. 2/3 (June 2009) of *Quantum Information Processing*, which contains Houck, was accessible to the public in 2009.

5. Archived Webpage

209. **Appendix 1025-G** is a true and correct copy of the publisher’s webpage for volume 8, nos. 2/3 (June 2009) of *Quantum Information Processing* that was archived by the Internet Archive. I personally located, identified and obtained this webpage, which experts in my field would reasonably rely upon when forming their opinions.

210. Page 1 of **Appendix 1025-G** shows this webpage is for "Volume 8, Issue 2-3, June 2009" of *Quantum Information Processing*, which has 12 articles, including "Life after charge noise: recent results with transmon qubits" by "A. A. Houck, Jens Koch, M. H. Devoret, S. M. Girvin" and others that runs from pages 105 to 115. The webpage shows the ISSN of the print version is "1570-0755" and the ISSN of the online version is "1573-1332." It also shows the URL of the original webpage is http://link.springer.com/journal/11128/8/2/page/1 and that the webpage was captured by the Internet Archive once on "25 Apr 2015." The URL at the bottom of page 1 of **Appendix 1025-G** shows the URL of the archived webpage is https://web.archive.org/web/20150425042303/http://link.springer.com/journal/11128/8/2/page/1. According to the URL convention of the Internet Archive, the URL of an archived webpage or website begins with the Internet Archive's URL (https://web.archive.org/web), followed by the date a webpage or website was archived, and the URL of the original webpage. The archived webpage's URL means the webpage was archived on "20150425042303" (*i.e.*, April 25, 2015, 4 a.m., 23 minutes, and 3 seconds). This date informs my opinion that the webpage for vol. 8, nos. 2/3 (June 2009) of *Quantum Information Processing* that contains Houck was available on the Internet at least by April 25, 2015, meaning users interested in this issue would have been able to find it by April 25, 2015, on the Internet, at the latest.

6. Summary on Houck

211. Taken together, Houck (**Exhibit 1025**), the bibliographic record (**Appendix 1025-B**), the MARC record (**Appendix 1025-C**), the copyright registration record (**Appendix 1025-D**), and my understanding of the ordinary and customary cataloging and processing practices of libraries inform my opinion that Houck **1025** would have been available for public access by February 2009 when Houck was published online, and no later than January 7, 2013 when Houck was of record with the United States Patent and Trademark Office. (**Appendix 1025-F**). Citations selected from August 2009 to June 2015 (**Appendix 1025-E**) show that the earliest citations of Houck appeared in 2009, further demonstrating public availability of Houck in 2009. Furthermore, the Internet Archive of Houck (**Appendix 1025-G**) demonstrates public availability as of April 25, 2015.

V. CONCLUSION

212. In signing this declaration, I recognize that the declaration will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I also recognize that I may be subject to cross-examination in the case. If cross-examination is required of me, I will appear at a reasonable time and place to be agreed upon.

213. I hereby declare that all statements made herein on my own knowledge are true and that all statements made on information and belief are believed to be true, and further, that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Date: 1-17-2020 Executed: ______________________
Ingrid Hsieh-Yee, Ph.D.

APPENDIX A

Ingrid Hsieh-Yee

Professor
Dept. of Library and Information Science
Catholic University of America
Washington, D.C. 20064
E-mail: hsiehyee@cua.edu
Phone: (202) 319-5085
Fax: (202) 319-5574

Education

Ph.D. Library and Information Studies, University of Wisconsin-Madison
Minors: Sociology and Psychology

M.A. Library and Information Studies, University of Wisconsin-Madison.

M.A. Comparative Literature, University of Wisconsin-Madison.

B.A. Foreign Languages and Literature, National Taiwan University.

Work Experience

Professor, School/Dept. of Library and Information Science, Catholic University of America, 2004- (Assistant Professor, 1990-1996; Associate Professor, 1997-2004)

Co-Chair, Dept. of Library and Information Science, Catholic University of America, June 2015-August 2016.

Acting Dean, School of Library and Information Science, Catholic University of America, January 2010-June 2012.

Cataloger, Dept. of Legislative Reference Library, Annapolis, Maryland, 1989-1990.

Lecturer, School of Library and Information Studies, University of Wisconsin-Madison, 1988.

Teaching Assistant, School of Library and Information Studies, University of Wisconsin-Madison, 1986-1988.

Cataloger, Health Sciences Library, University of Wisconsin-Madison, 1984-1986.

Areas of Teaching and Research Interests

Information Organization and Access; Metadata; Cataloging & Classification; Information Architecture; Information Retrieval; Digital Collections; Scholarly Communication; Information

Behavior; Health Informatics; Human Computer Interaction; Usability Studies

Grants & Honors

Cultural Heritage Information Management Project. IMLS grant. Amount: $498,741. Period: Aug. 2012 to July 2015. Co-PI with Dr. Youngok Choi.

D.C. Health Information Technology (HIT4): Building Capacity & Providing Access in Our Nation's Capital. Dept. of Labor H2B Training Grant. Grant amount: $4,175,500. Grant period: Nov. 2011 to Dec. 2015. Partner with the Metropolitan School of Professional Studies of the Catholic University of America, Children's National Medical Center, D.C. Department of Employment Services, Holy Cross Hospital, Howard University, Center for Urban Progress, Providence Hospital, and Sibley Memorial Hospital.

Capital Health Careers Project. Department of Labor Healthcare Sector and Other High Growth and Emerging Industries Grant. Grant amount: $4,953,999. Grant period: March 2010 – February 2013. Awarded to a group of healthcare organizations and educational institutions in Washington, D.C. Providence Health Foundation of Providence Hospital (Lead institution). Part of the grant supported the development of a Master's degree program in Information Technology with a concentration in Health Information Technology offered by the School of Library and Information Science.

The Washington D.C. School Librarians Project. IMLS grant. Grant amount: $412,660. Grant period: Aug. 2007 – June 2011. The School partnered with the District of Columbia Public Schools (DCPS) and the District of Columbia Library Association to educate and mentor school media specialists for the DCPS system. PI, Jan. 2010 to June 2011.

SIG Member of the Year, American Society for Information Science and Technology (2009).

Most Outstanding Paper of *OCLC Systems & Services* (2001).

ALISE Research Grant (2001).

Most Outstanding Paper of *OCLC Systems & Services* (2000).

Research Grant from ERIC (1999-2000).

Best Research Paper Award; Association for Library and Information Science Education (1998).

Research Grants, Catholic University of America. 1991, 1992, 1993, 1996, 1998, 1999, 2004, 2005, 2006, 2007, 2013-14.

Cooperative Faculty Research Grant, Consortium of Universities in the Washington Metropolitan Area (1993-1994).

Cooperative Research Grant, Council on Library Resources (1993-1994).

Journal of the American Society for Information Science Best Paper Award (1993).

ASIS/ISI Information Science Doctoral Dissertation Scholarship (1989).

HEA Title IIB Fellowship (Dept. of Education) (1989)

Chinese-American Librarians Association Scholarship (1987).

Beta Phi Mu (1985).

Vilas Fellowship, University of Wisconsin-Madison. 1984

Publications

Choi, Y., and Hsieh-Yee, I. (2010). Finding Images in an OPAC: Analysis of User Queries, Subject Headings, and Description Notes. *Canadian Journal of Information and Library Science,* 34(3): 271 – 295.

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Choi, Y., Hsieh-Yee, I., and Kules, B. (2007). Retrieval Effectiveness of TOC and LCSH. *Proceedings of the Joint Conference on Digital Libraries*, pp. 233-234.

Vellucci, S., and Hsieh-Yee, I. (2007). They Didn't Teach Me That in Library School! Building a Digital Teaching Commons to Enhance Metadata Teaching, Learning and Research. *Proceedings of the National Conference of the Association of College and Research Libraries, Baltimore, MD*, pp. 26-31.

Mitchell, Vanessa, and Ingrid Hsieh-Yee. (2007). Converting Ulrich's Subject Headings to FAST Headings: A Feasibility Study. *Cataloging & Classification Quarterly,* 45(1): 59-85.

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Hsieh-Yee, I. (2006). *Organizing Audiovisual and Electronic Resources for Access: A Cataloging Guide*. 2nd ed. Westport, Conn.: Libraries Unlimited.

NISO A Framework of Guidance for Building Good Digital Collections. 2nd ed. Bethesda, MD: National Information Standards Organization, 2004. Framework Advisory Group: Grace Agnew, Liz Bishoff, Priscilla Caplan (Chair), Rebecca Gunther and Ingrid Hsieh-Yee.

Hsieh-Yee, I. (2004). Cataloging and Metadata Education in North American LIS Programs. *Library Resources & Technical Services,* 48(1): 59-68.

Hsieh-Yee, I. (2004). Cataloging and Metadata Education. In Gary E. Gorman (Ed.), *International Yearbook of Library and Information Management 2003: Metadata Applications and Management*, (pp.204-234). London: Facet Publishing.

Yee, P. L., Hsieh-Yee, I., Pierce, G.R., Grome, R., and Schantz, L. (2004). Self-Evaluative Intrusive Thoughts Impede Successful Searching on the Internet. *Computers in Human Behavior,* 20(1): 85-101.

Hsieh-Yee, I. (2003). Cataloging and Metadata Education: A Proposal for Preparing Cataloging Professionals of the 21st Century. A report submitted to the ALCTS-Education Task Force in response to Action Item 5.1 of the *Bibliographic control of Web Resources: A Library of Congress Action Plan*. Approved by the Association for Library Collections and Technical Services. Web version available since April 2003 at http://lcweb.loc.gov/catdir/bibcontrol/CatalogingandMetadataEducation.pdf.

Hsieh-Yee, I. (2002). Cataloging and Metadata Education: Asserting a Central Role in Information Organization. *Cataloging & Classification Quarterly* 34(½): 203-222.

Hsieh-Yee, I., and Smith, M. (2001). The CORC Experience: Survey of Founding Libraries, Part I. *OCLC Systems & Services,* 17: 133-140. (Received "The Most Outstanding Paper of OCLC Systems & Services in 2001" award.)

Hsieh-Yee, I., and Smith, M. (2001). The CORC Experience: Survey of Founding Libraries, Part II, Automated Tools and Usage. *OCLC Systems & Services,* 17: 166-177. (Received "The Most Outstanding Paper of OCLC Systems & Services in 2001" award.)

Hsieh-Yee, I. (2001). ERIC User Services: Changes and Evaluation for the Future. *Government Information Quarterly,* 18: 31-42.

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Logan, E., and Hsieh-Yee, I. (2001). Library and Information Science Education in the Nineties. *Annual Review of Information Science and Technology,* 35: 425-477.

Hsieh-Yee, I. (Ed.) (2001). *Library and Information Science Research*, 23 (2). A special issue in honor of the retirement of Douglas L. Zweizig.

Hsieh-Yee, I. (2000). *ERIC User Services: Evaluation in a Decentralized Environment*. Washington, D.C.: Dept. of Education.

Hsieh-Yee, Ingrid. (2000). *Organizing Audiovisual and Electronic Resources for Access: A Cataloging Guide*. Littleton, CO: Libraries Unlimited.

Hsieh-Yee, I. (2000). Organizing Internet Resources: Teaching Cataloging Standards and Beyond. *OCLC Systems & Services,* 16: 130-143. (Received "The Most Outstanding Paper of OCLC Systems & Services in 2000" award.)

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Hsieh-Yee, I. (1998). Search Tactics of Web Users in Searching for Texts, Graphics, Known Items and Subjects: A Search Simulation Study. *Reference Librarian,* 60: 61-85. (Received the 1997 Best ALISE Research Paper Award.)

Hsieh-Yee, I. (1997). Access to OCLC and Internet Resources: LIS Educators' Views and Teaching Practices. *RQ,* 36: 569-86.

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Hsieh-Yee, I. (1995). Ten entries in James S. C. Hu (Ed.), *Encyclopedia of Library & Information Science*, 913, 1028-29, 1036, 1037, 1145-46, 1514, 1575, 1763-64, 2216-27, 2378-79. Taipei, Taiwan: Sino-American Publishing. (Topics include "Advanced Technology/Libraries," "Information Ethics," "Instruction on Cataloging and Classification," "Instruction on Reference Services.")

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Presentations

Hsieh-Yee, I. and Fragan-Fly, J. (May 2018) Trends, Design & Strategies for Digital Scholarship Services. Presented at the 2018 Maryland/Delaware Library Association Conference, Cambridge, MD.

Hsieh-Yee, I. (February, 2018) Research Data Management: What It Takes to Succeed. Presented at the 10th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I. (February, 2017) *Research Data Management: New Competencies and Opportunities for Information Professionals*. Presented at the 9th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I. and Lawton, P. (February, 2017) *Enhancing Catholic Portal Searches with User Terms and LCSH*. Presented at the 9th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I. (2016, October) *Visualizing Data for Information*. Presented at the 2016 Virginia Library Association Conference, Hot Springs, VA.

Hsieh-Yee, I. (2016, August) *Religious Materials Toolbox for Archivists: Solutions to Problems Facing the Profession*. Presented at Archives * Records 2016, Atlanta, GA.

Hsieh-Yee, I. and Lawton, P. (2016, March) *Enhancing Retrieval of Catholic Materials with LCSH Knowledge Structure*. Presented at the 2016 Catholic Library Association Conference, San Diego, CA.

Fagan-Fry, J. and Hsieh-Yee, I. (2016, February) *Approaches to Digital Scholarship at Top Universities around the World: Scholarly Publishing in the Digital Age.* Presented at the 8th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee and Fagan-Fry, J. (2016, January) *Innovative Services for Digital Scholarship at Top 100 Research Libraries of the World*. Poster presented at the 2016 Annual Conference of the Association for Library and Information Science Education, Boston, Mass.

Hsieh-Yee, I. and Lawton, P. (2015, June). *Crowdsourcing terms for CRRA portal themes.* Poster presented at the third CRRA symposium and annual meeting, Bringing the created toward the Creator: Liturgical art and design since Vatican II. Catholic Theological Union, Chicago, Illinois.

Hsieh-Yee, I. and Lawton, P. (2015, February). *Crowdsourcing terms for thematic exploration in the Catholic Portal.* Poster presented at the 7th Annual Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I., James, R., and Fagan-Fry, J. (2015, February). *Support for digital scholarship at top university libraries of the world.* Poster presented at the 7th Annual Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I., Zhang, S., Lin, K., and Cherry, S. (2015, February). *Thus said the end users: Summon experience and support for research workflows*. Poster presented at the 7th Annual Bridging the Spectrum Symposium, Washington, D.C.

Yontz, E., Hsieh-Yee, I., & Houston, S. (2015, February). *Healthy Heroes Summer Reading Club: Developing healthy youth at public libraries.* 11th Annual Jean Mills Health Symposium, Greenville, North Carolina.

Yontz, E., Hsieh-Yee, I., and Houston, S. (2015, January). *Healthy youth and libraries: A pilot study.* Association for Library & Information Science Education (ALISE) Annual Conference, Chicago, Illinois.

Hsieh-Yee, I. (2014, May). *Linking CRRA resources to portal themes via authority files*. Presented at the Catholic Research Resources Alliance 2014 Membership Meeting, Marquette, WI.

Hsieh-Yee, I. (2014, April). *Enhancing subject access to CRRA resources*. Presented at the 2014 Catholic Library Association Conference, Pittsburgh, PA.

Hsieh-Yee, I. (2014, January). *Health Information Technology Program: Educational entrepreneurship in action*. Presented at the 2014 annual Conference of the Association for Library and Information Science Education, Philadelphia, PA

Hsieh-Yee, I., Zhang, S., Lin, K., and Cherry, S. (2014, January). *Discovering information through Summon: An analysis of user search strategies and search success*. Paper presented at the 6th Bridging the Spectrum Symposium, Washington, D.C.

Hsieh-Yee, I. (2012, December). *National Digital Stewardship Alliance and SLIS at CUA: An Educational Partnership*. Paper presented at Best Practices Exchange: Acquiring, Preserving, and Providing Access to Government Information in the Digital Era, Annapolis, MD

Choi, Y. and Hsieh-Yee, I. (2010, January). *Finding Images in an OPAC: Analysis of User Queries, Subject Headings, and Description Notes*. Paper presented at 2nd Annual Bridging the Spectrum Symposium, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. and Coogan, J. (2010, January). *Google Scholar vs. Academic Search Premier: What Libraries and Searchers Need to Know*. Paper presented at 2nd Annual Bridging the Spectrum Symposium, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (2009, November). *Information Science Education: An LIS School's Perspective*. Paper presented at Annual Meeting of the American Society for Information Science and Technology, Vancouver, British Columbia, Canada.

Hsieh-Yee, I., Menard, E., Ya-Ning Chen, A., Shu-Jiun Chen, S., Kalfatovic, M. R., Wisser. K. M. (2009, November). *Information Organization in Libraries, Archives and Museums: Converging Practices and Collaboration Opportunities*. Presented at Annual Meeting of the American Society for Information Science and Technology, Vancouver, British Columbia, Canada. (Organizer and moderator of this panel.)

Hsieh-Yee, I. and Coogan, J. (2009, July). *Catching up to Google Scholar: The Retrieval Power of Academic Search Premier and Google Scholar*. Poster presented at American Library Association Conference, Chicago, Illinois.

Hsieh-Yee, I., with the CUA Scholarly Communications Project Team. (2009, January). *Digital Scholarship@CUA: Developing an Institutional Repository for CUA*. Poster presented at 1st Annual Bridging the Spectrum Symposium, Catholic University of America, Washington, D.C.

Wise, M., Cylke, K., and Hsieh-Yee, I. (2009, January). *Digital Talking Books: Meeting the Needs of the Blind and the Handicapped*. Paper presented at the Bridging the Spectrum Symposium, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (2009, January). *User Expectations of MERIC*. Presented at the Information Organization Competencies for the 21st Century Discussion Session of the 2009 Conference of the Association for Library and Information Science Education, Denver, Colorado.

Choi, Y., and Hsieh-Yee, I. (2008,November). *Subject Access for Images in an OPAC.* Annual Meeting of the American Society for Information Science and Technology, Columbus, Ohio. (Also co-organized a panel on Retrieving and Using Visual Resources: Challenges and Opportunities for Research and Education.)

Hsieh-Yee, I. (2008, June). *Educating Cataloging Professionals in a Changing Information Environment*. National Taiwan University, Taipei, Taiwan.

Vellucci, S. L., Moen, W.E., Hsieh-Yee, I., Marson, B., and Wisser, K. (2008, January) *Building a Metadata Education and Research Community through MERIC (Metadata Education and Research Information Commons): Demo and Stakeholder Input*. A panel presented at the 2008 Conference of the Association for Library and Information Science Education, Philadelphia, Pennsylvania.

Hsieh-Yee, I., Choi,Y. and Kules, B. (2007, October). *Searching for Books and Images in OPAC: Effects of LCSH, TOC and Subject Domains.* A poster presented at the American Society for Information Science and Technology Annual Meeting, Milwaukee, Wisconsin.

Hsieh-Yee, I. and Coogan, J. (2007, August) *Google Scholar vs. Academic Search Premier: A Comparative Analysis.* Presented to the Faculty and Staff of the University of the District of Columbia.

Hsieh-Yee, I. and Coogan, J. (2007, June). *Google Scholar vs. Academic Search Premier: A Comparative Analysis*. Presented to the Washington Research Library Consortium Community, Catholic University of America, Washington, D.C.

Hsieh-Yee, I., Choi, Y., and Kules, B.. (2007, June). *What Users Need for Subject Access: Table of Contents or Subject Headings?* A poster presented at the 2007 American Library Association Annual Conference, Washington, D.C., June 2007.

Choi, Y., Hsieh-Yee, I., and Kules, B. (2007, June). *Retrieval Effectiveness of TOC and LCSH.* A paper presented at the Joint Conference on Digital Libraries 2007, Vancouver, Canada.

Vellucci, S. L., Hsieh-Yee, I., and Moen, W.E. (2007, May). *If We Build It, Will They Come? Building a Community of Practice for Metadata Stakeholders.* A poster presented at the Rutgers University Research Day, Bridgeton, New Jersey.

Hsieh-Yee, I. (2007, May). *Federated Searching: User Experience & Perceptions.* International Conference on Information Organization & Retrieval, National Taiwan University, Taipei, Taiwan.

Hsieh-Yee, I. (2007, May). *Search Performance of Google Scholar and Academic Search Premier.* International Conference on Information Organization & Retrieval, National Taiwan University, Taipei, Taiwan.

Hsieh-Yee, I. (2007, May) *MERIC: Building a Digital Commons for Metadata Education & Research.* International Conference on Information Organization & Retrieval, National Taiwan University, Taipei, Taiwan.

Hsieh-Yee, I., and Coogan, J. (2007, March/April). *A Comparative Analysis of Google Scholar and Academic Search Premier.* Poster presented at the Association of College & Research Libraries 13th National Conference, Baltimore, Maryland.

Vellucci, S. L. and Hsieh-Yee, I. (2007, March/April) *They Didn't Teach Me That in Library School! Building a Digital Teaching Commons to Enhance Metadata Teaching, Learning and Research*. On-site presentation and Webcast by Elluminate. A contributed paper presented at the Association of College & Research Libraries 13th National Conference, Baltimore, Maryland. The acceptance rate for contributed paper was 20%. This paper was one of 10 conference papers chosen for live webcast during the conference.

Moen, W., Hsieh-Yee, I. and Vellucci, S.L. (2007, January) *A DSpace Foundation for a Teaching & Research Commons: The Metadata Education and Research Information Commons.* A poster session presented at the Open Repositories Conference 2007, San Antonio, Texas.

Tang, R., Hsieh-Yee, I., and Zhang, S. (2006, November) *User Perception of MetaLib Combined Search*. Paper presented at the Annual Meeting of the American Society for Information Science and Technology, Austin, Texas, Nov. 2006.

Hsieh-Yee, I. (2006, November). *Federated Searching: User Perceptions, System Design, and Library Instructions.* Paper presented at the Annual Meeting of the American Society for Information Science and Technology, Austin, Texas. (Panel organizer, moderator, presenter).

Hsieh-Yee, I. (2006, November). *Building a Digital Teaching Commons to Enhance Teaching and Learning: The MERIC Experience and Challenges.* Paper presented at the Annual Meeting of the American Society for Information Science and Technology, Austin, Texas. (Panel organizer, moderator, presenter)

Hsieh-Yee, I. (2006, September). *Search Performance of Google Scholar and Academic Search Premier.* Paper presented at the ERIC Publishers Meeting, Washington, D.C.

Hsieh-Yee, I., Zhang, S., and Rong Tang, R. (2006, June). *User Perceptions of a Federated Search System*. Poster presented at Joint Conference on Digital Libraries, Chapel Hill, North Carolina.

Hsieh-Yee, I. and Zhang, S. (2006, June). *Preparing Users for Federated Search: Implications of a MetaLib User Perceptions Study.* Paper presented at the 2006 Ex Libris User Groups of North America Conference, Knoxville, Tennessee.

Hsieh-Yee, I. (2006, January). *MERIC Organizations and Navigation*. Paper presented at the 2006 ALISE Annual Conference, San Antonio, Texas.

Hsieh-Yee, I. (2006, January). *Metadata and Cataloging Education: Recommended Competencies.* Paper presented at the 2006 ALISE Annual Conference, San Antonio, Texas.

Hsieh-Yee, I. (2005, November). *Digital Library Evaluation: Progress & Next Steps.* Presentation at the Annual Meeting of the American Society for Information Science & Technology, Charlotte, North Carolina.

Hsieh-Yee, I. (2005, August). *Providing Access to Digital Content: Issues for DL Managers.* Presentation at MDK12 Digital Library Steering Committee Meeting, Columbia, Maryland.

Hsieh-Yee, I. (2005, April). *Enhancing Teaching and Learning: The Role of School Library Media Specialists.* Presentation at Meeting of the Baltimore County Public School System School Media Specialists, Baltimore, Maryland.

Hsieh-Yee, I. (2005, January). *Subject Access and Users: Insights & Inspirations from Marcia J. Bates.* Paper presented at the Historical Perspectives SIG, 2005 Conference of the Association for Library and Information Science Education, Boston, Massachusetts.

Hsieh-Yee, I. (2005, January). *Electronic Resource Management: Practice, Employer Expectations, & CE Interests.* Paper presented at Technical Services Education SIG, 2005 Conference of the Association for Library and Information Science Education, Boston, Massachusetts.

Hsieh-Yee, I. (2004, October). *Library Professionals for the Digital Age: Competencies & Preparation.* Paper presented at Bibliographic Access Management Team meeting, Library of Congress, Washington, D.C.

Hsieh-Yee, I. (2004, January). *Cataloging and metadata expertise for the digital era.* Presented at Preparing 21st Century Cataloging and Metadata Professionals: A Workshop for Educators and Trainers, San Diego and sponsored by ALCTS, ALISE, LC, and OCLC.

Hsieh-Yee, I. (2004, January). *Educating catalogers for the digital era.* Paper presented at the Technical Services SIG, 2004 Conference of the Association for Library and Information Science Education, San Diego.

Hsieh-Yee, I. (2003, July). *Cataloging Education for the 21st Century.* A presentation at the Library of Congress, Washington, D.C.

Hsieh-Yee, I. (2002, January) *Metadata Education and Research Priorities: A Delphi Study of*

Metadata Experts. Presentation at the 2002 Conference of the Association for Library and Information Science Education, New Orleans.

Hsieh-Yee, I. (2001, November). *A Delphi Study of Metadata: Preliminary Findings.* Poster session at the 2001 Annual Meeting of the American Society for Information Science & Technology, Washington, D.C.

Hsieh-Yee, I. (2001, June). *Resources on Asian American Children: Analysis of Retrieval by Search Engines and WorldCat.* Presentation at the National Conference on Asian Pacific American Librarians, San Francisco.

Hsieh-Yee, I. (2001, January). *Delphi Study on Metadata: Project Design.* Presentation at Research Awards Session, Association for Library & Information Science Education, Washington, D.C.

Hsieh-Yee, I. (2000, May). *Web Search Behavior Research: Progress and Implications.* Presentation at the Symposium on Evaluating Library and Information Science Research, University of Wisconsin-Madison, Madison, Wisconsin.

Hsieh-Yee, I. (2000, March). *ERIC User Services: Evaluation in a Decentralized Environment.* Presentation at the National ERIC Joint Directors/Technical Meeting, Arlington, Virginia.

Hsieh-Yee, I. (2000, January). *Enhancing Learning with Web Technology.* Presentation at Faculty Conversations, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (2000, January). *From Surrogates to Objects: CUA's Approaches to Organizing Electronic Resources.* Paper presentation at the Annual Conference of the Association for Library and Information Science Education, San Antonio, Texas.

Yee, P., and Hsieh-Yee, I. (1997, November). *Individual Differences in Search Behavior on the WWW.* A poster session presented at the 38th Annual Meeting of the Psychonomic Society, Philadelphia, Pennsylvania.

Hsieh-Yee, I. (1997, April). *Research + Marketing + Preparation = Job!* Presented at the "Workshop on Resume and Interview Techniques," Special Libraries Association, Student Chapter, Catholic University of America, Washington, D.C.

Hsieh-Yee, I. (1997, February). *Creating CyberCatalogers: Education and Training.* Presentation at ALA's Midwinter Meeting, Washington, D.C.

Hsieh-Yee, I. (1997, February). *Search Tactics of Web Users in Searching for Texts, Graphics, Known Items and Subjects: A Search Simulation Study.* Presented at the Conference of the Association for Library and Information Science Education, Washington, D.C.

Hsieh-Yee, Ingrid. "Beginning Your Special Library/Information Center Career." Presented at SLA's "Career Day," Jan. 11, 1997, Catholic University of America.

Hsieh-Yee, I. (1996, September). *The Roles of Library and Information Scientists in Managing Electronic Information.* Presentation at Hamilton College, Clinton, New York.

Hsieh-Yee, I. (1996, May). *The Future of Cataloging as a Profession.* Presented at "The Cataloging Forum, Library of Congress, Washington, D.C.

Hsieh-Yee, I. (1994, October). *The Impact of the Internet on OPACs.* Presented at the Third Workshop on User Interfaces for OPACs, Library of Congress, Washington, D.C.

Reports

Hsieh-Yee, I., with Knowledge Management Competencies and Performance Action Group of the Federal Knowledge Management Initiative. “From Knowledge Management Competencies to Improved Organizational Performance.” April 9, 2009.

Hsieh-Yee, I., with Knowledge Practices Action Group of the Federal Knowledge Management Initiative. “KM Practice in Government Agencies: Findings and Recommendations.” April 9, 2009.

Hsieh-Yee, I. “Delphi Study on Metadata.” 2001. Three quarterly reports submitted to the Association for Library and Information Science Education.

Hsieh-Yee, I. “College Students' Information Channels: Patterns of Use and Possible Factors in Channel Selection.” 1995. Submitted to the Catholic University of America.

Hsieh-Yee, I. “The Information-Seeking Patterns of Scholars and Their Use of an Online Information System.” 1994. Submitted to the Council on Library Resources.

Book Reviews

Review of *The Measurement and Evaluation of Library Services*, by Sharon L. Baker and F. Wilfrid Lancaster. *Information Processing and Management* 30 (1994): 450-52.

Review of *Subject Access to Films and Videos, by Sheila S. Intner and William E. Studwell; and Cataloging Unpublished Nonprint Materials*, by Verna Urbanski with Bao Chu Chang and Bernard L. Karon. *Information Processing and Management* 30 (1994): 449-50.

Review of *Automated Information Retrieval in Libraries: A Management Handbook*, by Vicki Anders. *Journal of Library and Information Science* 19 (1993): 98-100.

Review of *Full Text Databases*, by Carol Tenopir and Jung Soon Ro. *Information Processing and Management* 28 (1992): 667-68.
Review of *Descriptive Cataloging for the AACR2R And USMARC: A How-to-Do It Workbook*, by Larry Millsap and Terry Ellen Ferl. *Information Processing and Management* 28 (1992): 809-11.

Review of *MARC Manual: Understanding and Using MARC Records*, by Deborah J. Byrne. *Information Processing and Management* 28 (1992): 537-38.

Service

Professional Associations and Societies

- Library of Congress. RDA Training Program for the Profession. Co-authored with Tim Carlton. 2013-2014.
- 2014 Digital Preservation Outreach & Education Survey. Contributed to the design of the survey, 2014.
- National Digital Stewardship Alliance. Outreach Committee. 2011-2014.
- National Digital Stewardship Residency Program. Advisory Group, 2012-2013.
- FEDLINK Health Information Technology Advisory Council, 2011-2015.
- 2012 Joint Conference on Digital Libraries. Program Planning Committee, Pre-Conference Proposals Review Committee, 2012
- Catholic Research Resources Alliance. Five-Year Strategic Plan Task Force, 2011-2012
- Institute of Museum and Library Services. Grant reviewer. 2004, 2005, 2010.

- Association for Library and Information Science Education.
  * ALISE Bodan Wynar Research Paper Award Committee, 2015, 2016, 2017
  * ALISE Eugene Garfield Dissertation Award Competition, Jury, 2013, 2014
  * ALISE Research Grant Competition Committee. Chair, 2012
  * Pratt-Severn Faculty Innovation Award. Chair, 2009, 2010
  * ALISE Doctoral Poster Jury, 2012
  * "Information Organization Competencies for the 21st Century" Discussion session leader. 2009 Conference of the Association for Library and Information Science Education.
  * Assisted Technical Services SIG Convener in organizing a program, ""Building a Metadata Education and Research Community through MERIC (Metadata Education and Research Information Commons): Demo and Stakeholder Input" for the 2008 ALISE conference.
  * Association for Library Collections and Technical Services/Association for Library and Information Science Education (ALCTS/ALISE) Metadata Education and Research Information Center (MERIC) Advisory Board, Co-Chair (with Sherry Vellucci), 2005-2007. Chair, 2008-2009 (leading the effort to build MERIC, a repository and collaborative space for metadata educators, practitioners, and researchers)

* Technical Services SIG, Convener, 2004-2005. Organized a program on “Electronic Resources Management: Current Practices, Employer Expectations, and Teaching Strategies” for the 2005 conference in Boston, Massachusetts.
* Technical Services SIG, Convener, 2003-2004. Organized a program on “Organizing Information with Metadata: Desired Competencies and Teaching Innovations” for the 2004 conference.
* Technical Services SIG, Convener, 1999-2000. Organized a program on "Teaching the Organization of Electronic Resources" for the 2000 conference.
* Curriculum SIG, Co-convener (with Sibyl Moses), 1996-97. Organized a program on “Government Information Policy” for the 1997 conference.

- American Society for Information Science & Technology.
  * Reviewer, Conference program panel submissions and poster submissions, 2005, 2006, 2007, 2009, 2011, 2012, 2013, 2014, 2015, 2016, 2017
  * Nomination Committee, 2009-2011
  * Information Science Education Special Interest Group. American Society for Information Science and Technology. Chair-Elect, 2007-2008. Chair 2008-2009.
  * Committee on Information Science Education. 1999-2006.
  * Committee on Information Science Education. Organizing Committee for an orientation program for students at ASIS annual meetings, 1999-2001
  * Committee on Information Science Education. Sub-committee on Student Welfare (focusing on issues related to master's education), 1998-2001
  * SIG ED. Organizing Committee for the "Seminar on Research and Career Development" for junior researchers. 1995-96 (chair), 1997-2001
  * ISI Doctoral Dissertation Proposal Scholarship Jury, 1997; 2001, 2002
  * Pratt-Severn Best Student Research Paper Award Jury. Chair. 1997
  * 1998 Midyear Meeting (referee of contributed papers), 1997
  * Organizer and moderator of the ASIS Doctoral Forum and the Doctoral Research Seminar 1994-1995
  * SIG Human Computer Interaction. Chair-Elect, Chair, 1993-1995
  * Doctoral Forum Award Jury, 1995
  * Best Student Paper Award Jury, 1995

- American Library Association.
  * Committee on Accreditation, External Review Panelist, 2009- (site visiting team 2013-2014; site visiting team 2016-2017)
  * Association for Library Collections and Technical Services Task Force on Competencies and Education for a Career in Cataloging, member, 2008-2009
  * Facilitator for “What They Don't Teach in Library School: Competencies, Education and Employer Expectations for a Career in Cataloging,” an Association for Library Collections and Technical Services Preconference, June 22, 2007 in Washington, D.C. Also a local liaison for bringing this program to the Catholic University of America.
  * Facilitator for a discussion on "Effect of Electronic Resources on Technical Services" at ALA's Midwinter Meeting held in Feb. 1997 in Washington, D.C.

* International Relations Committee, Subcommittee Task Force for IFLA and China, 1994-1997

- Virginia Association of School Librarians. Scholarships and Awards Committee. 2010-2012

- Federal Knowledge Management Initiative, Knowledge Management Practices Action Group. Member. 2009 (leading the effort to build a knowledge management repository)
- Federal Knowledge Management Initiative, Knowledge Management Competencies & Learning Action Group. Member. 2009 (developing an action plan for helping government knowledge workers and government agencies to develop knowledge management competencies)
- National Center for Education Statistics. Technical Review Panel. 2008.
- External evaluator for a case of promotion to full professorship. University of Tennessee. 2008.
- National Information Standards Organization (NISO). Advisory Board, Revision of "IMLS Framework of Guidance for Building Good Digital Collections," 2004, 2007.
- Library of Congress, Bibliographic Control of Web Resources: A Library of Congress Action Plan. Principal Investigator of Action Item 5.1, focusing on cataloging and metadata education for students and new librarians, 2002-2003. (worked with the Association for Library Collections and Technical Services, Education Task Force)

- Chinese American Librarians Association
  * Chinese American Librarians Association Outstanding Library Leadership Award in Memory of Dr. Margaret Chang Fung, Award Committee, 2016-2017
  * Achievement Award Jury, 2000-2001
  * CALA Goal 2000 Task Force, 1997
  * Scholarship Committee, 1995, 1996-1997 (chair)
  * Board of Directors, 1994-1997
  * Publication Committee, 1993-1995
  * International Relations Committee, 1993-1996

- Sailor^{SM} Assessment Advisory Group (An impact study of Sailor, Maryland's Public Information Network), 1995

- Editorial boards
  - Journal of Library and Information Science. Editorial Board, 2012-
  - Chinese American Librarians Association, *Occasional Papers Series*. Editorial Board, 2009-2016.
  - *Library Quarterly.* Editorial Board, 2003-2008
  - *Bulletin of the Medical Library Association*, 1994-97
  - Newsletter editor for the Chinese American Librarians Association, 1989-92

- Referee for the following journals
  - *Information Processing and Management*

Journal of Digital Information
Journal of Education for Library and Information Science
Journal of Information Science
Journal of Library & Information Science
Journal of Library Metadata
Journal of the American Society for Information Science & Technology
Library and Information Science Research
Library Quarterly

- Expert reviewer, "Digital Library" course, Evaluation module, University of North Carolina, Chapel Hill, 2007-2008.
- Expert reviewer, "Information Organization" course, University of Michigan, Ann Arbor. 2007.

Catholic University of America

- School of Arts & Sciences, Academic Senate representative, 2017-2020
- School of Arts & Sciences, Committee on Appointments and Promotions, 2015-2019
- School of Arts & Sciences, Academic Council, 2015-2016.
- School of Arts & Sciences, Ordinary Professor Group, 2013-
- Doctoral Dissertation Defense Committee, Chair, Dept. of Psychology, 2016, 2017, 2018
- Doctoral Dissertation Defense Committee, Chair, Dept. of Education, 2014, 2015, 2017
- President's Administrative Council, 2010-2012
- Deans' Council, 2010-2012
- Academic Leadership Group, 2010-2012
- Academic Senate, 2003-2012
- Academic Senate, Committee on Committees and Rules, 2009-2012
- Academic Senate, Committee on Appointments and Promotions, 2005-2008
- Graduate Board, 2010-2012
- CUA Scholarly Communication Project Team, Member (2007), Chair, 2008-2009
- Academic Senate Library Committee, Interim Chair (2007), Member, 2008-2012
- Doctoral Dissertation Defense Committee, Chair, School of Nursing, 2006, 2008
- Dean Search Committee, 1992-1994, 1998-1999, 2002-2003, 2006-2007
- Fulbright Review Panel, 2006
- Academic Senate Committee on Computing, 1995-2003
- CUA Service Learning Advisory Board, 2001-2002
- CUA Faculty Conversations on Enhancing Teaching and Learning through Technology, Planning Group, 1999-2001
- CUA Initiative on Technology and Teaching, 1998-2001

Dept. of Library and Information Science

- Symposium and Colloquium Committee, fall 2016-May 2018, Chair, May 2018-

- Admissions Committee, 2007-2009, Chair 2010-2012, Member 2013-2015, Member 2018-
- Accreditation presentation, Chair, June 2015-August 2016
- Interim Co-Chair, June 2015-August 2016.
- Appointments and Promotions Committee, 1991-
- Blended/OWL Learning Committee, spring 2016-2018
- Scholarship and Awards Committee, fall 2016-
- Technology Committee, fall 2016-2017
- Comprehensive examination editor, 2016-2017, reader (every year since 1990)
- LIS Advisory Board, 2015-2016 (chair); fall 2016- May 2018 (member)
- Committee on Planning and Assessment, 2015-2016 (chair)
- Senior Faculty Committee, 2014-2016.
- Accreditation Steering Committee, 2014-2016 (Chair, 2015-2016)
- Accreditation Students Standard Committee, co-chair, 2014-2016
- Accreditation Mission, Goals, and Objectives Standard Committee, co-chair, 2014-2016
- Accreditation Curriculum Standard, member 2014-2-16
- Accreditation Administration and Finance Standard, member 2014-2016
- Cultural Heritage Information Management Project (IMLS-funded), Co-PI, 2012-2015
- Cultural Heritage Information Management Forum (scheduled for June 2015), Co-Organizer, 2013-2015
- Health Information Technology Interim Review Committee, 2015 (chair)
- Health Sciences Librarianship Advisory Group, 2015- (chair)
- Comprehensive examination editors, 2013-2014, 2016-2017
- National Digital Stewardship Alliance liaison, 2011-2014
- Advisory Board, Chair 2010-2012
- Academic Honesty Committee, Chair, 2008-2012
- Blended Learning Committee, 2010-2012
- Colloquium Committee, 2010-2012
- Comprehensive Examination Administration, 2010-2012
- Cultural Heritage Information Management Advisory Committee, 2010-2012 (chair), 2013-
- Curriculum Committee, 1991-2003, 2007-2009, Chair 2010-2012, member 2013-
- Curriculum Subcommittee on Comprehensive Examination, Chair 2009-2012
- Health Information Technology Advisory Board, Chair 2010-2012. Member 2013-
- Health Sciences Advisory Committee, 2009, Chair 2010-2012. Member 2013-
- HIT Expert Forum, Chair 2012. Member 2013-
- Health Information Technology Student Group Advisor, 2011-2012
- State Council for Higher Education of Virginia, SLIS Representative, 2010-2012
- Symposium Planning Committee, 2010-2012
- Website Management Team, Chair, 2010-2012
- Urban School Librarianship Project (IMLS-Funded), PI, 2007-2011 (chair, 2010-11)
- Failing Grades Committee, 1995-1997 (chair), 2000-2001 (chair), 2004-2005 (chair), 2007 (chair)-2011

- Faculty Search Committee, 1994-1998, 2002-2004, 2006 (chair), Fall 2007-2009, Chair fall 2009-2012
- Recruitment Committee, Chair 2010-2012
- Strategic Planning Committee, Chair 2010-2012
- Technology Committee, 2010-2012
- Accreditation Advisory Committee, 2007-2009
- Accreditation Coordinating Committee, 2007-2009
- Accreditation Steering Committee, 2007-2009
- SLIS Advisory Group, 2007-2009
- Accreditation Curriculum Standard Committee, Co-chair, 2007-2009
- Accreditation Faculty Standard Committee, Co-chair, 2007-2009
- LSC 551 Information Organization Review Team, Co-chair, 2008-2009, 2015-2016.
- Curriculum Subcommittee on Portfolios, 2009
- LSC 555 Information Systems in Libraries and Information Centers Review Team, contributor, 2008-2009
- Redesign of LSC 730 Use and Users of Libraries and Information. 2009-
- Development of a metadata institute that was taught as LSC 715 Organization of Internet Resources in 2008. The institute is being revised and will be offered in 2010 under a new course title.
- Development of lesson plans, assignments, and evaluation rubrics for LSC 606, Cataloging and Classification, for the School's NCATE accreditation. 2008
- Howard and Mathilde Rovelstad Scholarship Committee, Chair, 2004-2007
- Assistant Dean Search Committee, Chair, Fall 2007
- Liaison to the Association for Library Collections and Technical Services to bring its preconference program, Cataloging Education and Employer Expectations, to CUA during the 2007 American Library Association Annual Meeting in Washington, D.C.
- Organizer of the colloquium presentation and reception for Tamar Sadeh of Ex Libris on PRIMO June 2007
- Practicum review and design (work with potential supervisors, such as the American Indian Museum internship description revision) 2006-
- Comprehensive examinations (edits, proctoring, and grading), 1990-
- SLIS Web site redesign: Comments and suggestions. Fall 2007
- Conducted surveys of current students and alumni in preparation for the 2005 re-accreditation, 2004-2005
- Student advisement, 1990-
- Technology Committee, 1992-1999 (chair, 1996-1998), 2002-2003 (member)
- Colloquia Committee 1997-1999, 2002-2003.
- Advisor of the CUA Student Chapter of the American Society for Information Science and Technology, 2002-2003
- Visiting Professor Search Committee, 1999, 2000, 2001
- Leader, Participation in the CORC experiment, 1999-2000
- Advisor of the Special Libraries Association Student Chapter, 1993-1999; the group was recognized for outstanding leadership by SLA in 1999.

- COA planning Committee, Task Force on Electronic Presentation of SLIS Reports (team leader) 1997-1998
- COA Planning Committee, Subcommittee on Technology 1996-1998
- NLM practicum coordinator, 1997-1998
- Computer Literacy Workshops: Assisted with the development and evaluation of the workshops, 1996-1998
- Leader, Participation in the InterCat project, 1995-1997

APPENDIX B

Library of Congress >> MARC >> Understanding MARC

MARC 21 Reference Materials

Part VII: A Summary of Commonly Used MARC 21 Fields
Part VIII: A List of Other Fields Often Seen in MARC Records
Part IX: The Leader
Part X: Field 008 for Books

Part VII:

A Summary of Commonly Used MARC 21 Fields

This is a summary of the MARC 21 tags used most frequently by libraries in entering their own bibliographic records. For full listings of all MARC 21 tags, indicators, and subfield codes, see *MARC 21 Format for Bibliographic Data*.

In the explanations on these pages:

Tags -- The tags (3-digit numbers) are followed by the names of the fields they represent. In this summary, and in the *MARC 21 Format for Bibliographic Data*, if a tag can appear more than once in one bibliographic record, it is labeled repeatable (R). If it can only be used once, it is labeled non-repeatable (NR). For example, a catalog record can have several subjects, so the tags for subject added entries (6XX) are labeled repeatable (R).

Indicators -- The use of indicators is explained in fields where they are used. Indicators are one-digit numbers. Beginning with the 010 field, in every field -- following the tag -- are two character positions, one for Indicator 1 and one for Indicator 2. The indicators are not actually defined in all fields, however. And it is possible that a 2nd indicator will be used, while the 1st indicator remains undefined (or vice versa). When an indicator is undefined, the character position will be represented by the character # (for blank space).

Subfield codes -- All the data in each field (beginning with the 010 field) is divided into subfields, each of which is preceded by a delimiter-subfield code combination. The most common subfield codes used with each tag are shown. Each subfield code is preceded by the character $, signifying a delimiter. The name of the subfield follows the code.

In general, every field MUST have a subfield 'a' (**$a**). One exception that is often seen is in Field 020 (ISBN), when the ISBN information (subfield **$a**) is unavailable but the price (subfield **$c**) is known. Some subfields are repeatable. In this summary, repeatability is noted for only the more common repeatable subfields.

Examples: Examples follow the explanation for each field. For clarity, one space has been placed between the tag and the first indicator, one space has been placed between the second indicator and the first delimiter- subfield code, and one space has been inserted between the delimiter-subfield code and the subfield data.

010 Library of Congress Control Number -- (LCCN)

(NR, or Not Repeatable

Indicators undefined.

Subfield used most often:

$a -- Library of Congress control number

```
Example:    010 ##  $a ###86000988#
```

020 International Standard Book Number -- (ISBN)

(R, or Repeatable)

Indicators undefined.

Subfields used most often:

$a -- International Standard Book Number
$c -- Terms of availability (often a price)
$z -- Cancelled/invalid ISBN (R)

```
Example:    020 ##  $a 0877547637
```

040 Cataloging source -- (NR)

Indicators undefined.

Subfields used most often:

$a -- Original cataloging agency
$c -- Transcribing agency
$d -- Modifying agency (R)

```
Example:    040 ## $a DLC
                   $c DLC
                   $d gwhs
```

100 Main entry -- Personal name -- (primary author)

(NR; there can be only one main entry)

Indicator 1: Type of personal name entry element

0 -- Forename
1 -- Surname (this is the most common form)
3 -- Family name

Indicator 2 undefined.

Indicator 2 became obsolete in 1990. Older records may display 0 or 1

Subfields used most often:

$a -- Personal name
$b -- Numeration
$c -- Titles and other words associated with a name (R)
$q -- Fuller form of name
$d -- Dates associated with a name (generally, year of birth)

```
Example:    100 1# $a Gregory, Ruth W.
                   $q (Ruth Wilhelme),
                   $d 1910-
```

130 Main entry -- Uniform title -- (NR)

Indicator 1: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

Indicator 2 undefined.

Indicator 2 became obsolete in 1990. (See 100 above.)

Subfields used most often:

$a -- Uniform title
$p -- Name of part/section of a work (R)
$l -- Language of a work
$s -- Version
$f -- Date of a work

```
Example:    130 0# $a Bible.
                   $p O.T.
                   $p Psalms.
```

240 Uniform title (NR)

Indicator 1: Uniform title printed or displayed

0 -- Not printed or displayed
1 -- Printed or displayed (most common)

Indicator 2: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

Subfields used most often:

$a -- Uniform title
$l -- Language of a work
$f -- Date of a work

```
Example:    240 10 $a Ile mystérieuse.
                   $l English.
                   $f 1978
```

245 Title Statement (NR)

Indicator 1: Title added entry

(Should the title be indexed as a title added entry?)

0 -- No title added entry

(indicates a title main entry; i.e. no author is given)

1 -- Title added entry

(the proper indicator when an author given in 1XX; the most common situation)

Indicator 2: Nonfiling characters

0-9 -- Number of nonfiling characters present, including spaces; usually set at zero, except when the title begins with an article; e.g., for *The robe*, the second indicator would be set to 4. The letters *T*, *h*, *e*, and the space following them are then ignored in alphabetizing titles. The record will be automatically filed under "*r*" -- for *Robe*.

Subfields used most often:

$a --	Title proper
$h --	Medium (often used for non-book media)
$p --	Name of part/section of a work (R)
$b --	Reminder of title (subtitles, etc.)
$c --	Remainder of title page transcription/Statement of responsibility

```
Example:    245 14 $a The DNA story :
                   $b a documentary history of gene
                      cloning /
                   $c James D. Watson, John Tooze.
```

246 Varying form of title (R)

Indicator 1: Note/title added entry controller

1 -- Note, title added entry

3 -- No note, title added entry

Indicator 2: Type of title

-- No information provided

0 -- Portion of title

1 -- Parallel title

4 -- Cover title

8 -- Spine title

Subfield used most often:

$a -- Title proper

```
Example:    246 3# $a Four corners power review
```

250 Edition statement (NR)

Indicators undefined.

Subfield used most often:

$a -- Edition statement

```
Example:    250 ## $a 6th ed.
```

260 Publication, distribution, etc. (Imprint) (R)

Indicator 1: Sequence of publishing statements

-- No information provided

Indicator 2: Undefined

Subfields used most often:

$a -- Place of publication, distribution, etc. (R)
$b -- Name of publisher, distributor, etc. (R)
$c -- Date of publication, distribution, etc. (R)

```
Example:    260 ## $a New York :
                   $b Chelsea House,
                   $c 1986.
```

300 Physical description (R)

Indicators undefined.

Subfields used most often:

$a -- Extent (number of pages) (R)
$b -- Other physical details (usually illustration information)
$c -- Dimensions (cm.) (R)
$e -- Accompanying material (for example, "teacher's guide" or "manual")

```
Example:    300 ## $a 139 p. :
                   $b ill. ;
                   $c 24 cm.
```

440 Series statement / Added entry--Title

This field was made obsolete in 2008 to simplify the series statement. See 490 and 830.

490 Series statement (No added entry is traced from field) (R)

Indicator 1: Specifies whether series is traced (whether an 8XX tag is also present)
- 0 -- Series not traced
- 1 -- Series traced (8XX is in record)

Indicator 2 undefined.

Subfield used most often:
- **$a** -- Series statement (R)
- **$v** -- Volume number (R)

```
Example:    490 1# $a Colonial American craftsmen
```

500 General note (R)

Indicators undefined.

Subfield used most often:
- **$a** -- General note (Used when no specialized note field has been defined for the information. Examples: Notes regarding the index; the source of the title; variations in title; descriptions of the nature, form, or scope of the item.)

```
Example:    500 ##  $a Includes index.
```

504 Bibliography, etc. note (R)

Indicators undefined.

Subfield used most often:
- **$a** -- Bibliography, etc. note

```
Example:    504 ## $a Includes bibliographical
                      references.
```

505 Formatted contents note (R)

Indicator 1: Type of contents note
- 0 -- Complete contents
- 1 -- Incomplete contents (used with multivolume set when some volumes are not yet published)
- 2 -- Partial contents

Indicator 2: Level of content designation
- # -- Basic

Subfield used most often:
- **$a** -- Formatted contents note

```
Example:    505 0# $a Pride and prejudice -- Emma
                   -- Northanger Abbey.
```

520 Summary, etc. note (R)

Indicator 1: Display constant controller
- # -- Summary
- 1 -- Review
- 2 -- Scope and content
- 3 -- Abstract

Indicator 2 undefined

Subfields used most often
- **$a** -- Summary, abstract, or annotation
- **$b** -- Expansion of summary note

```
Example:    520 ## $a This basic guide to parliamentary
                   procedure tells how to conduct
                   and participate in a meeting
                   properly.
```

600 Subject added entry -- Personal name (R)

Indicator 1: Type of personal name entry element
- 0 -- Forename
- 1 -- Surname (this is the most common form)
- 3 -- Family name

Indicator 2: Subject heading system/thesaurus (identifies the specific list or file which was used)
- 0 -- Library of Congress Subject Headings
- 1 -- LC subject headings for children's literature
- 2 -- Medical Subject Headings
- 3 -- National Agricultural Library subject authority file
- 4 -- Source not specified
- 5 -- Canadian Subject Headings
- 6 -- Répertoire de vedettes-matière
- 7 -- Source specified in subfield $2

(Note regarding Sears subject headings: The MARC 21 format does not provide an assigned indicator for Sears subject headings. Therefore, an indicator of 7 is used, and the MARC defined code "sears" is placed in subfield $2.)

Subfields used most often:

$a -- Personal name (surname and forename)
$b -- Numeration
$c -- Titles and other words associated with a name (R)
$q -- Fuller form of name
$d -- Dates associated with a name (generally, year of birth)
$t -- Title of a work
$v -- Form subdivision (R)
$x -- General subdivision (R)
$y -- Chronological subdivision (R)
$z -- Geographic subdivision (R)
$2 -- Source of heading or term (used with 2nd indicator of 7)

```
Example:    600 10 $a Shakespeare, William,
                   $d 1564-1616
                   $x Comedies
                   $x Stage history.
```

```
Example:    600 10 $a Shakespeare, William,
                   $d 1564-1616
                   $x Knowledge
                   $z Rome
                   $v Congresses.
```

Notice that subfields $v, $x, and $z in the 600 field are repeatable. Subfields $v, $x, $y, and $z do not have to be in alphabetical order. They will be in the order prescribed by the instructions given by the subject heading system.

610 Subject added entry -- Corporate name (R)

*Indicator 1:*Type of corporate name entry element
0 -- Inverted name (not used with AACR2)
1 -- Jurisdiction name
2 -- Name in direct order
Indicator 2: Subject heading system/thesaurus.
See indicator 2 under 600
Subfields used most often:
$a -- Corporate name or jurisdiction name as entry element
$b -- Subordinate unit (R)
$v -- Form subdivision (R)
$x -- General subdivision (R)
$y -- Chronological subdivision (R)
$z -- Geographic subdivision (R)
$2 -- Source of heading or term (used with 2nd indicator of 7)

```
Example:    610 10 $a United States.
                   $b Army Air Forces
                   $v Biography.
```

650 Subject added entry -- Topical term (Most subject headings fit here.) (R)

- *Indicator 1:* Level of subject
  - # -- No information provided
- *Indicator 2:* Subject heading system/thesaurus
  (identifies the specific list or file which was used)
  - 0 -- Library of Congress Subject Headings
  - 1 -- LC subject headings for children's literature
  - 2 -- Medical Subject Headings
  - 3 -- National Agricultural Library subject authority file
  - 4 -- Source not specified
  - 5 -- Canadian Subject Headings
  - 6 -- Répertoire de vedettes-matière
  - 7 -- Source specified in subfield $2

Note regarding Sears subject headings: The MARC 21 format does not provide an assigned indicator for Sears subject headings. Therefore, an indicator of 7 is used, and the MARC defined code "sears" is placed in subfield $2.)

- *Subfields used most often:*
  - **$a** -- Topical term
  - **$v** -- Form subdivision (R)
  - **$x** -- General subdivision (R)
  - **$y** -- Chronological subdivision (R)
  - **$z** -- Geographic subdivision (R)
  - **$2** -- Source of heading or term used with 2nd indicator of 7)

```
Example:    650 #0 $a Theater
                   $z United States
                   $v Biography
                   $v Dictionaries.
```

Notice that subfields $v, $x, and $z in the 650 field are repeatable. Subfields $v, $x, $y, and $z do not have to be in alphabetical order. They will be in the order prescribed by the instructions given by the subject heading system.

651 Subject added entry -- Geographic name (R)

- *Indicator 1:* undefined.
- *Indicator 2:* Subject heading system/thesaurus.

  - See indicator 2 under 600

- *Subfields used most often:*
  - **$a** -- Geographic name
  - **$v** -- Form subdivision (R)
  - **$x** -- General subdivision (R)
  - **$y** -- Chronological subdivision (R)
  - **$z** -- Geographic subdivision (R)
  - **$2** -- Source of heading or term (used with 2nd indicator of 7)

```
Example:    651 #0 $a United States
                   $x History
                   $v Chronology.
```

Notice that subfields $v, $x, and $z in the 651 field are repeatable. Subfields $v, $x, $y, and $z do not have to be in alphabetical order. They will be in the order prescribed by the instructions given by the subject heading system.

700 Added entry -- Personal name (R)

- *Indicator 1:* Type of personal name entry element
  - 0 -- Forename
  - 1 -- Surname (this is the most common form)
  - 3 -- Family name
- *Indicator 2:* Type of added entry
  - # -- No information provided (most common; co-authors, editors, etc.)
  - 2 -- Analytical entry (The values for Indicator 2 changed in 1994 with Format Integration, and older records may display additional values. An analytical entry involves an author/title of an item contained in a work.)
- *Subfields used most often:*
  - **$a** -- Personal name
  - **$b** -- Numeration
  - **$c** -- Titles and other words associated with a name (R)
  - **$q** -- Fuller form of name
  - **$d** -- Dates associated with a name (generally, year of birth)
  - **$e** -- Relator term (such as ill.) (R)
  - **$4** -- Relator code (R)

```
Example:    700 1# $a Baldridge, Letitia.
```

710 Added entry -- Corporate name (R)

- *Indicator 1:* Type of corporate name entry element
  - 0 -- Inverted name (not used with AACR2)
  - 1 -- Jurisdiction name

2 -- Name in direct order

Indicator 2: Type of added entry.

See Indicator 2 under 700

-- No information provided

2 -- Analytical entry

Subfields used most often:

$a -- Corporate name or jurisdiction name as entry element

$b -- Subordinate unit (R)

```
Example:    710 2# $a Sunburst Communications (Firm)
```

740 Added entry -- Uncontrolled related/analytical title (R)

Indicator 1: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

*Indicator 2:*Type of added entry. See Indicator 2 under 700

-- No information provided

2 -- Analytical entry

(This field was redefined in 1994 with Format Integration. Prior to 1994, the field was also used for variant titles, such as a different wording on a spine title. In records created since Format Integration, those variant tiles appear in a 246 field.)

Subfield used most often:

$a -- Title

```
Example:    740 02 $a Uncle Vanya.
```

800 Series added entry -- Personal name (R)

Indicator 1: Type of personal name entry element

0 -- Forename

1 -- Surname

3 -- Family name

Indicator 2 undefined.

Subfields used most often:

$a -- Personal name

$b -- Numeration

$c -- Titles and other words associated with a name (R)

$q -- Fuller form of name

$d -- Dates associated with a name (generally, year of birth)

$t -- Title of a work (the series)

$v -- Volume number

```
Example:    800 1# $a Fisher, Leonard Everett.
                   $t Colonial American craftsmen.
```

830 Series added entry -- Uniform title (R)

Indicator 1 undefined.

Indicator 2: Nonfiling characters

0-9 -- Number of nonfiling characters present (for initial articles, including spaces)

Subfield used most often:

$a -- Uniform title

$v -- Volume number

```
Example:    830 #0 $a Railroads of America (Macmillan)
```

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Part VIII:

A List of Other Fields Often Seen in MARC Records

001	Control number
003	Control number identifier
005	Date and time of latest transaction
006	Fixed-length data elements -- additional material characteristics
007	Physical description fixed field
008	Fixed length data elements (See Part X)
022	International Standard Serial Number (ISSN)
037	Source of acquisition
041	Language code
043	Geographic area code
050	Library of Congress call number
060	National Library of Medicine call number
082	Dewey Decimal classification number (the one recommended by the Library of Congress; locally-assigned call numbers may appear elsewhere)
110	Main entry -- Corporate name (less frequent under AACR2 rules)
256	Computer file characteristics

263	Projected publication date (indicates a CIP -- Cataloging in Publication -- record)
306	Playing time
508	Creation/production credits note
510	Citation/references note (review sources)
511	Participant or performer note
521	Target audience note (first indicator: 0 = reading grade level, 1 = interest age level, 2 = interest grade level, 3 = special audience characteristics, 4 = motivation interest level)
530	Additional physical form available note
538	System details note
586	Awards note
656	Index term -- Occupation
730	Added entry -- Uniform title
852	Location
856	Electronic location and access
9XX	Reserved for local use. (They are used by vendors, systems, or individual libraries to exchange additional data)

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Part IX:

The Leader

There are 24 positions in the Leader, numbered from 00 to 23. For fuller explanation, see the *MARC 21 Format for Bibliographic Data*.

00-04 Record length (calculated by the computer for each record)
05 Record status
  a = increase in encoding level
  c = corrected or revised
  d = deleted
  n = new
  p = increase in encoding from prepublication (previous CIP)
06 Type of record
  a = language material
  c = printed music
  d = manuscript music
  e = cartographic material
  f = manuscript cartographic material
  g = projected medium
  i = nonmusical sound recording
  j = musical sound recording
  k = 2-dimensional nonprojectable graphic
  m = computer file

- o = kit
- p = mixed materials
- r = 3-dimensional artifact or naturally occurring object
- t = manuscript language material

07 Bibliographic level
- a = monographic component part
- b = serial component part
- c = collection
- d = subunit
- i = integrating resource
- m = monograph/item
- s = serial

08 Type of control
- # = no specified type
- a = archival

09 Character coding scheme
- # = MARC-8
- a = UCS/Unicode

10 Indicator count (always "2")
11 Subfield code count (always "2")
12-16 Base address of data (calculated by the computer for each record)
17 Encoding level
- # = full level
- 1 = full level, material not examined
- 2 = less-than-full level, material not examined
- 3 = abbreviated level
- 4 = core level
- 5 = partial (preliminary) level
- 7 = minimal level
- 8 = prepublication level (CIP)
- u = unknown
- z = not applicable

18 Descriptive cataloging form
- # = non-ISBD
- a = AACR2
- i = ISBD
- u = unknown

19 Multipart resource record level
- # = Not specified or not applicable
- a = Set
- b = Part with independent title
- c = Part with dependent title

20 Length of the length-of-field portion (always "4")
21 Length of the starting-character-position portion (always "5")
22 Length of the implementation-defined portion (always "0")
23 Undefined (always "0")

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Part X:

Field 008 for Books

Field 008 is used for Fixed Length Data Elements ("Fixed Field Codes"). There are 40 character positions in field 008, numbered from 00-39. Undefined positions must contain either a blank (#) or a fill character (|). Positions 00-17 and 35-39 are defined the same way for all media.

The information shown here for positions 18-34 applies only to books. For explanation of all the positions below and for positions 18-34 for other media, see the *MARC 21 Format for Bibliographic Data*.

Note that field 008 has no indicators or subfield codes.

00-05 Date entered on file (YYMMDD),
where Y=year, M=month, and D=day
06 Type of date/publication status:
b = no dates given; B.C. date involved
e = detailed date
s = single known date/probable date
m = multiple dates
r = reprint/reissue date (Date 1) and original date (Date 2)
n = dates unknown
q = questionable date
t = publication date and copyright date
| = no attempt to code
07-10 Date 1/beginning date of publication
11-14 Date 2/ending date of publication

Date fields contain the year(s) of publication. The type of date(s) in these elements are specified in fixed field element 06: Type of date/publication status. (For further details, see the field 008 description in the *MARC 21 Format for Bibliographic Data*.)

15-17 Place of publication, production, or execution
For example:
pk# = Pakistan
cau = California (US)

(For a full list of codes used in these positions, see the *MARC Code List for Countries*.)

18-21 Illustrations (up to 4 codes):
# = no illustrations
a = illustrations
b = maps
c = portraits

d = charts
e = plans
f = plates
g = music
h = facsimiles
i = coats of arms
j = genealogical tables
k = forms
l = samples
m = phonodisc, phonowire, etc.
o = photographs
p = illuminations
| = no attempt to code

22 Target audience:
# = unknown or not specified
a = preschool
b = primary
c = pre-adolescent
d = adolescent
e = adult
f = specialized
g = general
j = juvenile
| = no attempt to code

23 Form of item:
# = none of the following
a = microfilm
b = microfiche
c = microopaque
d = large print
f = braille
r = regular print reproduction
s = electronic
| = no attempt to code

24-27 Nature of contents (up to 4):
# = no specified nature of contents
a = abstracts/summaries
b = bibliographies (is one or contains one)
c = catalogs
d = dictionaries
e = encyclopedias
f = handbooks
g = legal articles
i = indexes
j = patent document
k = discographies
l = legislation

m = theses
n = surveys of literature
o = reviews
p = programmed texts
q = filmographies
r = directories
s = statistics
t = technical reports
u = standards/specifications
v = legal cases and notes
w = law reports and digests
z = treaties
| = no attempt to code

28 Government publication:
# = not a government publication
i = international intergovernmental
f = federal/national
a = autonomous or semi-autonomous component
s = state, provincial, territorial, dependent, etc.
m = multistate
c = multilocal
l = local
z = other type of government publication
o = government publication -- level undetermined
u = unknown if item is government publication
| = no attempt to code

29 Conference publication:
0 = not a conference publication
1 = conference publication
| = no attempt to code

30 Festschrift:
0 = not a festschrift
1 = festschrift
| = no attempt to code

31 Index:
0 = no index
1 = index present
| = no attempt to code

32 Undefined (since 1990) (Earlier records may contain the values 0 or 1)
= Undefined
| = no attempt to code

33 Literary form:
0 = not fiction (not further specified)
1 = fiction (not further specified)
c = comic strips
d = dramas
e = essays

f = novels
h = humor, satires, etc.
i = letters
j = short stories
m = mixed forms
p = poetry
s = speeches
u = unknown
| = no attempt to code

34 Biography:
# = no biographical material
a = autobiography
b = individual biography
c = collective biography
d = contains biographical information
| = no attempt to code

35-37 Language:
A three-letter code. For example: eng fre ger spa rus ita

(For a full list of codes used in these positions, see the *MARC Code List for Languages*.)

38 Modified record:
# = not modified
x = missing characters (because of characters unavailable in MARC character set)
s = shortened
d = "dashed-on" information omitted
r = completely romanized/printed cards in script
o = completely romanized/printed cards romanized
| = no attempt to code

39 Cataloging source:
# = national bibliographic agency
c = cooperative cataloging program
d = other sources
u = unknown
| = no attempt to code

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Library of Congress
Library of Congress Help Desk *(10/27/2009)*

APPENDIX C

Revised November 30, 2016

AMENDED ARTICLES OF INCORPORATION

OF

OCLC Online Computer Library Center, Inc.

FIRST The name of the corporation shall be OCLC Online Computer Library Center, Inc. (the "Corporation").

SECOND The place in this State where the principal office of the Corporation is to be located is in the City of Dublin, Franklin County, Ohio.

THIRD The purpose or purposes for which the Corporation is formed are to establish, maintain, and operate a computerized library network and to promote the evolution of library use, of libraries themselves, and of librarianship, and to provide processes and products for the benefit of library users and libraries, including such objectives as increasing availability of library resources to individual library patrons and reducing the rate of rise of library per-unit costs, all for the fundamental public purpose of furthering ease of access to and use of the ever-expanding body of worldwide scientific, literary, and educational knowledge and information.

FOURTH The affairs of the Corporation shall be managed by the Board of Trustees. The qualifications of the Trustees, together with their terms of office, manner of election, removal, change of number, filling of vacancies and of newly-created trusteeships, powers, duties and liabilities, shall, except as otherwise provided in these Articles, or by the laws of the State of Ohio, be as prescribed by the Code of Regulations.

FIFTH There shall be two classes of members of the Corporation and they shall be OCLC Members, and Trustee Members. The voting powers of each class of members shall be only as defined in the Code of Regulations or as stated in these Articles.

SIXTH There shall be a Global Council composed of Member Delegates as prescribed in the Code of Regulations.

SEVENTH These Articles may be amended at any business meeting of the Trustee Members called for that purpose provided that notice of the proposed amendment(s) has been sent to the Trustee Members at least ten (10) days prior to said meeting. A two-thirds (2/3) vote of all of the authorized Trustee Members of the Corporation is required for approval.

EIGHTH The duration of the Corporation shall be perpetual.

NINTH No part of the earnings, dues, or receipts of the Corporation shall inure to the benefit of or be distributed to its members, trustees, officers, or other private persons, except only that the Corporation shall be authorized and empowered to pay reasonable compensation for services rendered and expenses incurred and to make payments or distributions in furtherance of the purposes set forth in Article Third hereof. No substantial part of the activities of the Corporation shall be the carrying on of propaganda, or otherwise attempting to influence legislation, and the Corporation shall not participate in, or intervene in (including the publishing or distribution of statements) any political campaign on behalf of, or in opposition to**,** any candidate for public office. Notwithstanding any other provision of these Articles, the Corporation shall not carry on any other activities not permitted to be carried on (a) by a corporation exempt from Federal income tax under Section 501(c)(3) of the Internal Revenue Code of 1986, as amended (or the corresponding provision of any future United States internal revenue law) (the “Code”) or (b) by a corporation, contributions to which are deductible under Section 170(c)(2) of the Code.

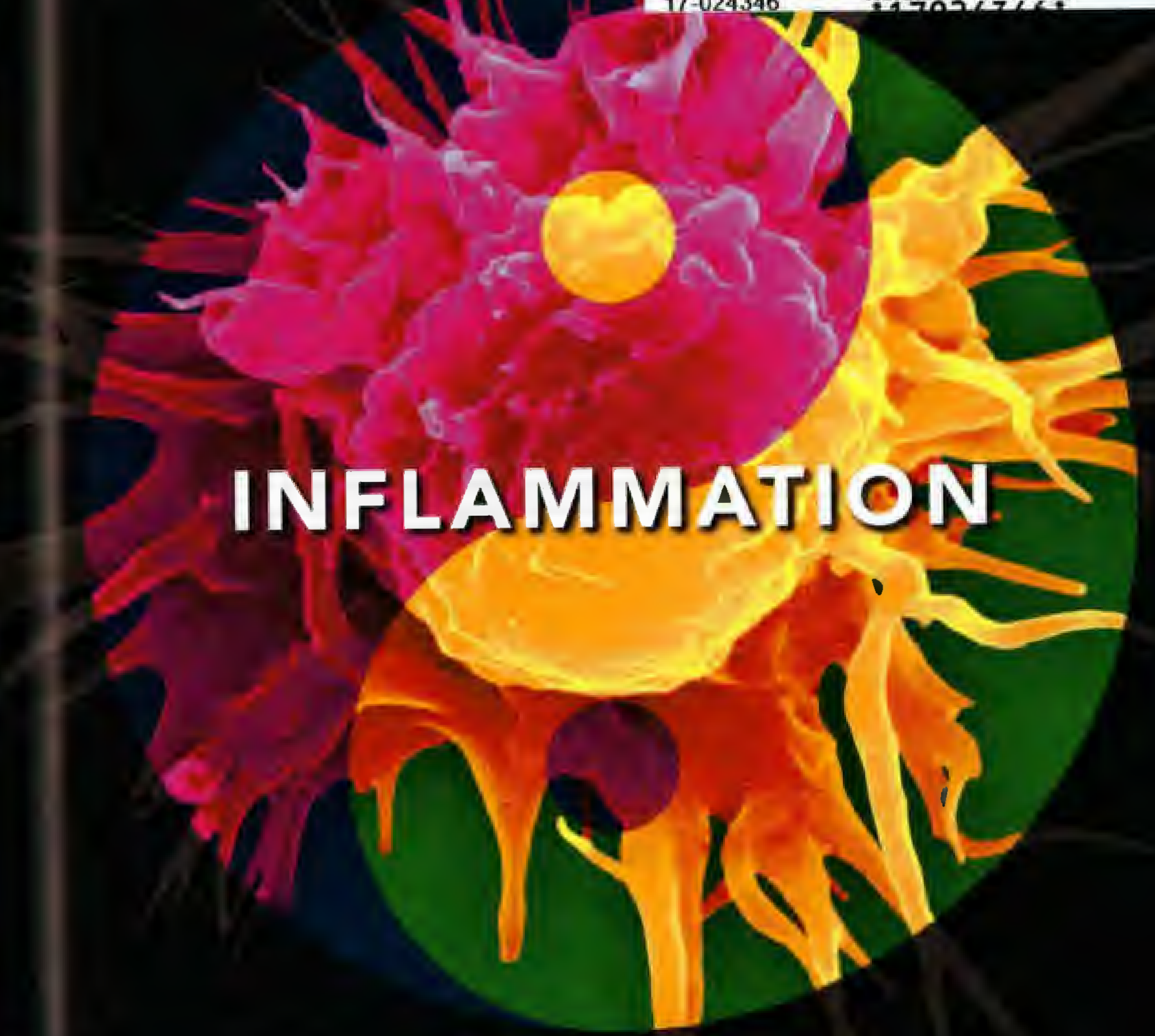
TENTH Upon the dissolution of the Corporation, the Board of Trustees shall, after paying or making provision for the payment of all of the liabilities of the Corporation, dispose of all of the assets of the Corporation exclusively for the purposes of the Corporation in such manner, or to such organization or organizations as are described in Section 170(c)(1) or (2) of the Code, as the Board of Trustees shall determine. Any of such assets not so disposed of shall be disposed of by the Court of Common Pleas of the county in which the principal office of the Corporation is then located, exclusively for such purposes or to such organization or organizations, as said Court shall determine, which are organized and operated exclusively for such purposes.

ELEVENTH These Articles supersede all prior Articles or Amended Articles.

APPENDIX 1004-A

11 January 2013 | $10

Science



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A yin-yang symbol superimposed on a scanning electron micrograph of a mouse tissue alveolar macrophage (diameter: ~18 micrometers). Macrophages are immune cells that mediate inflammation, but they often play protective roles as well. Several age-related chronic diseases—such as metabolic syndrome, cardiovascular disease, and neurodegenerative disease—have an inflammatory component. See the special section beginning on page 155.

Scanning electron microscope image: © Dennis Kunkel Microscopy, Inc.

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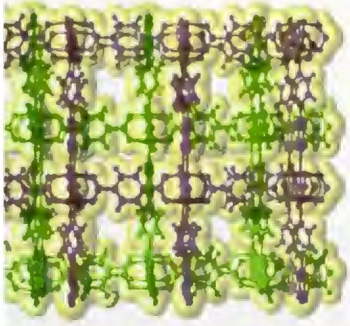

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CREDIT: (BOTTOM) CHRIS MARTIN

Quantum Back-Action of an Individual Variable-Strength Measurement

M. Hatridge,[1*†] S. Shankar,[1*] M. Mirrahimi,[1,2] F. Schackert,[1] K. Geerlings,[1] T. Brecht,[1] K. M. Sliwa,[1] B. Abdo,[1] L. Frunzio,[1] S. M. Girvin,[1] R. J. Schoelkopf,[1] M. H. Devoret[1]

Measuring a quantum system can randomly perturb its state. The strength and nature of this back-action depend on the quantity that is measured. In a partial measurement performed by an ideal apparatus, quantum physics predicts that the system remains in a pure state whose evolution can be tracked perfectly from the measurement record. We demonstrated this property using a superconducting qubit dispersively coupled to a cavity traversed by a microwave signal. The back-action on the qubit state of a single measurement of both signal quadratures was observed and shown to produce a stochastic operation whose action is determined by the measurement result. This accurate monitoring of a qubit state is an essential prerequisite for measurement-based feedback control of quantum systems.

Although the evolution ("state collapse") of a quantum system subject to an infinitely strong (i.e., projective) quantum nondemolition (QND) measurement is textbook physics, the subtlety and utility of finite strength (i.e., partial) measurement phenomena are neither widely appreciated nor commonly verified experimentally. Standard quantum measurement theory puts forward the principle that observing a system induces a decoherent evolution proportional to the measurement strength (*1*–*5*). Thus, partial measurement is often associated with partial decoherence of the state of a quantum system. However, this measurement-induced degradation occurs only if the measurement is inefficient informationally—that is, if only a portion of the measurement's information content is available to the observer for use in reconstructing the new state of the system.

If, instead, the measurement apparatus is entirely efficient, the new state of the quantum system can be perfectly reconstructed. This outcome-dependent revision of the system's imposed initial conditions constitutes a fundamental quantum effect called measurement back-action (*2*, *6*–*8*). Although the system's evolution under measurement is erratic (hence, the measurement outcome cannot be predicted in advance), the measurement record faithfully reports the perturbation of the system after the fact.

We use the powerful, combined qubit-cavity architecture, circuit quantum electrodynamics (cQED) (*9*, *10*), which allows for rapid, repeated quantum nondemolition (QND) (*11*, *12*) superconducting qubit measurement (*13*–*18*). The cavity output is monitored in real time by using a phase-preserving amplifier working near the quantum limit, where the noise is only caused by the fundamental quantum fluctuations of the electrodynamic vacuum (*19*). The decision to read out our qubit by using coherent states of the resonator has two important consequences. First, the outcomes of a partial measurement form a quasi-continuum, unlike the set of discrete answers obtained from a projective measurement. Second, measuring both quadratures of the signal leads to two-dimensional (2D) diffusion of the direction of the qubit effective spin. We show that the choice of measurement apparatus and of measurement strength both affect the evolution of a quantum system, but neither results in degradation of the system's state if the measurement is informationally efficient. Such precise knowledge of the measurement back-action is a necessary prerequisite for general feedback control of quantum systems.

Our superconducting qubit is a transmon (*20*), consisting of two Josephson junctions in a closed loop, shunted by a capacitor to form an anharmonic oscillator. The two lowest energy states, ($|g\rangle$ and $|e\rangle$), are the logical states of the qubit. The qubit is dispersively coupled to a compact resonator, which is further asymmetrically coupled to input and output transmission lines (Fig. 1, B and C), determining the resonator bandwidth ($\kappa/2\pi = 5.8$ MHz). To measure a qubit prepared in initial state $|\psi\rangle = c_g|g\rangle + c_e|e\rangle$, a microwave pulse of duration $T_m >> 1/\kappa$ is applied to the resonator. The state-dependent shift of the resonator frequency ($\chi/2\pi = 5.4$ MHz) results in an entangled state of the qubit and pulse $|\Psi\rangle = c_g|g\rangle \otimes |\alpha_g\rangle + c_e|e\rangle \otimes |\alpha_e\rangle$, where $|\alpha_{g,e}\rangle$ refers to the coherent state after traversing the resonator.

Amplification is required to convert the pointer state $|\Psi\rangle$ into a macroscopic signal that can be processed and recorded with standard instrumentation. In our case, the pulse, having traversed the resonator, is amplified by using a linear, phase-preserving amplifier with gain G, which can be seen as multiplying the average photon number in $|\alpha_{g,e}\rangle$ (Fig. 1B). For dynamical range considerations, our amplifier, called the Josephson parametric converter (JPC) (*21*–*24*) is operated in this experiment with a gain $G = 12.5$ dB and bandwidth of 6 MHz, adding close to the minimum amount of noise allowed by quantum mechanics. The added quantum fluctuations are due to a second, "idler," input (*19*). A measurement of both quadratures of the output mode results in an outcome, denoted (I_m, Q_m), which is then used to determine the new state of the qubit after measurement (Fig. 1A). As has been shown in (*8*), and detailed in the supplementary materials, this outcome contains all information necessary to perfectly reconstruct the new state of the qubit. Remarkably, the additional quantum fluctuations introduced during amplification enter in the measurement back-action on the qubit without impairing our knowledge of it.

We first demonstrate projective qubit readout by strongly measuring the qubit using an 8-μs pulse with the drive power set so that the average number of photons in the resonator during the pulse was $\bar{n} = 5$ (Fig. 2). Selected individual measurement records for the qubit are shown in Fig. 2B. The data are digitized with a sampling time of 20 ns and smoothed with a binomial filter with $T_m = 240$ ns width, which corresponds to eight cavity lifetimes, and scaled by the experimentally determined standard deviation (σ). The highlighted trace shows clear quantum jumps in the qubit state, which are identified by vertical black dotted lines indicating 4σ deviations from the current qubit state. The 8% equilibrium qubit excited-state population is consistent with other measurements of superconducting qubits (*25*). By counting the number of up and down transitions in 25,000 traces with no qubit excitation pulse, we calculate $T_1 \leq 3.1$ μs. Although we fail to resolve pairs of transitions separated by much less than our filter time constant, this method for estimating T_1 yields a value in good agreement with the value $T_1 = 2.8$ μs calculated from fitting an exponential to the averaged trajectory of all traces. Further, the average qubit polarization did not vary over 8 μs of continuous measurement, nor did T_1 diminish with larger readout amplitude up to $n \cong 15$, which demonstrates the QND nature of our readout.

Histograms of the scaled I_m component of the outcome for the first 240 ns of measurement after a qubit rotation by $\theta = 0, \pi/2, \pi$ are shown in Fig. 2C. The ground and excited distributions are separated by 4.8 σ, which corresponds to a measurement fidelity of 98% when $I_m = 0$ is used as the discrimination threshold. We emphasize that the discreteness of the *z* measurement of the transmon circuit, illustrated by the bimodality of the histogram, is here due only to the quantum nature of the circuit and not to any nonlinearity of the readout. Thus, this measurement of a continuous, unbounded pointer state is exactly equivalent to the Stern-Gerlach experi-

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[1] Department of Applied Physics and Physics, Yale University, New Haven, CT 06520, USA. [2] Institut National de Recherche en Informatique et en Automatique Paris-Rocquencourt, Domaine de Voluceau, B.P. 105, 78153 Le Chesnay Cedex, France.

*These authors contributed equally to this work.

†To whom correspondence should be addressed. E-mail: michael.hatridge@yale.edu

ment. These strong, high-fidelity measurements allow us to perform precise tomography and to prepare the qubit in a known state by measurement. We next use these tools to quantify measurement back-action of partial measurement on the qubit state.

The qubit evolution due to partial measurement can be precisely calculated from the complete measurement record using the quantum trajectory approach (*6*, *7*), but this is computationally intensive. Instead, we calculate the back-action from the average output over the time T_m, as in (*8*). Provided that the measurement time is short compared with the qubit coherence times T_1 and T_2, and long compared with the cavity lifetime and amplifier response time, this approach allows the qubit to be tracked without degradation. In this experiment, T_m = 240 ns, which is shorter than T_1 = 2.8 µs and T_{2R} = 0.7 to 2.0 µs, and much longer than the cavity lifetime and JPC response time of 30 ns.

Assuming the qubit is initially polarized along the +*y* axis, we calculate the final qubit Bloch vector (x_f, y_f, z_f) as a function of measurement outcome (I_m, Q_m) (see detailed derivation in the supplementary materials) to be

$$x_f^{\eta}(I_m,Q_m) = \operatorname{sech}\left(\frac{I_m\,\bar{I}_m}{\sigma^2}\right) \times \sin\left[\frac{Q_m\,\bar{I}_m}{\sigma^2} + \frac{\bar{Q}_m\,\bar{I}_m}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)\right] \times e^{\frac{\bar{I}_m^2}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)},$$

$$y_f^{\eta}(I_m,Q_m) = \operatorname{sech}\left(\frac{I_m\,\bar{I}_m}{\sigma^2}\right) \times \cos\left[\frac{Q_m\,\bar{I}_m}{\sigma^2} + \frac{\bar{Q}_m\,\bar{I}_m}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)\right] \times e^{\frac{\bar{I}_m^2}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)},$$

$$z_f^{\eta}(I_m) = \tanh\left(\frac{I_m\,\bar{I}_m}{\sigma^2}\right) \qquad (1)$$

where $\bar{I}_m$ and $\bar{Q}_m$ and σ define the center and standard deviation of the outcome distributions, and η is the quantum efficiency of the amplification chain (Fig. 1A). In this theory, we neglect the effect of qubit decoherence and losses before amplification. In the limit of a perfectly efficient amplification (η = 1), we see that the length of the Bloch vector is unity, irrespective of outcome. The parameter $\bar{I}_m/\sigma$ can be identified as the apparent measurement strength because the measurement becomes more strongly projective as $\bar{I}_m/\sigma$ increases. It is given in terms of experimental parameters as $\bar{I}_m/\sigma = \sqrt{2\bar{n}\eta\kappa T_m}\sin(\vartheta/2)$, where $\vartheta = 2\arctan\chi/\kappa$.

The pulse sequence for determining measurement back-action is shown in Fig. 3A. We first strongly read out the qubit with a 240 ns, $n = 5$ pulse and record the outcome, which will be used to prepare the qubit in the ground state by post-selection. Then, the qubit is rotated to the +*y* axis and measured with a variable measurement strength (T_m = 240 ns), and the outcome (I_m, Q_m) is recorded. The final, tomography, phase measures the *x*, *y*, or *z* component of the qubit Bloch vector with a strong ($\bar{n} = 5$, T_m = 240 ns) measurement pulse. To compensate for the finite

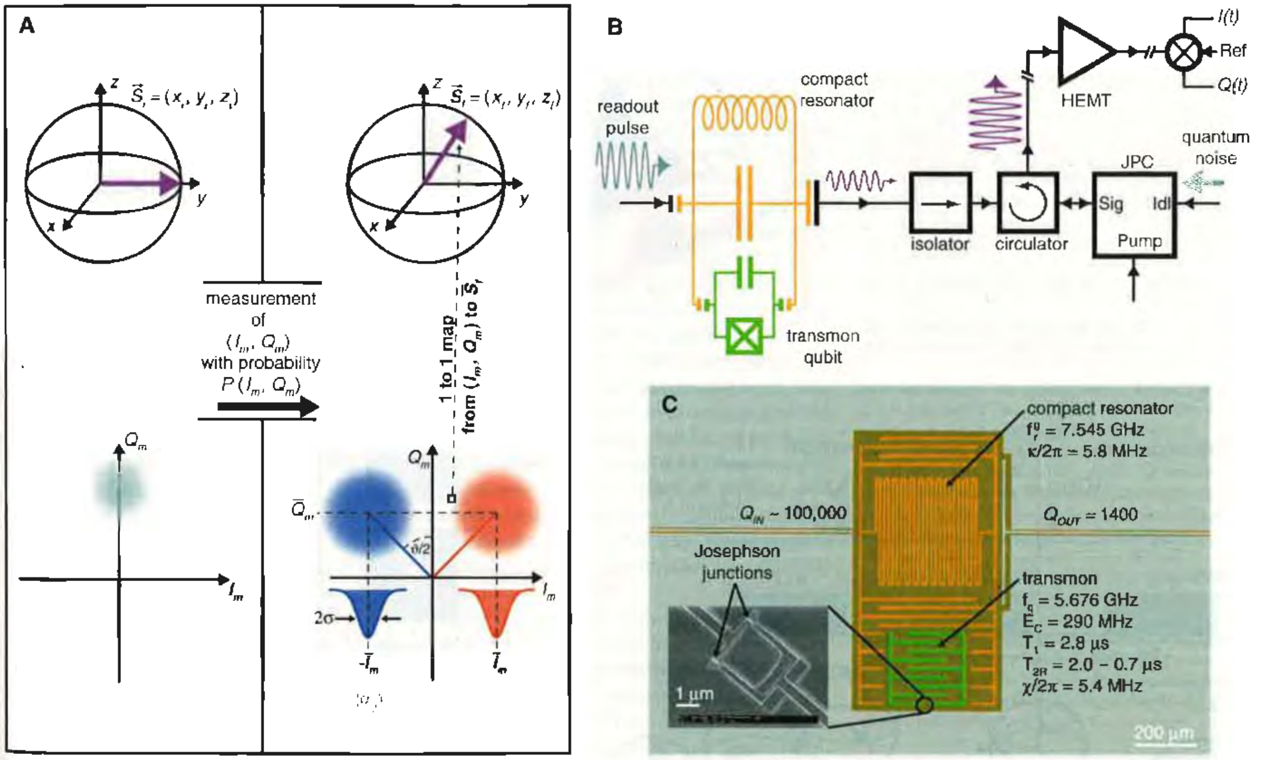

Fig. 1. **(A)** Bloch sphere representation of the effect on the qubit state of a phase-preserving measurement in a cQED architecture. After a measurement with outcome (I_m, Q_m), the qubit will be found in a final state $\vec{S}_f = (x_f, y_f, z_f)$, with I_m encoding information on the projection of the qubit state along *z* and corresponding back-action and Q_m encoding the other component of the back-action, which is parallel to $\hat{z} \times \vec{S}_i$. The measurement outcomes are Gaussian distributed, with $\bar{I}_m^2 + \bar{Q}_m^2 = \bar{n}\kappa T_m$. **(B)** Schematic of experiment mounted to the base plate of a dilution refrigerator. Readout pulses are transmitted through the strongly coupled port of the resonator, via an isolator and circulator, to the signal port (Sig) of a JPC. The idler port (Idl) is terminated in a 50 Ω load. The amplified signal output is routed via the circulator and further isolators (not shown) to a high electron mobility transistor (HEMT) amplifier operated at 4 K, and subsequently demodulated and digitized at room temperature. **(C)** False-color photograph of the transmon qubit in compact resonator with qubit and resonator parameters. Inset is a scanning electron micrograph of the center of the transmon showing a loop of two Al/AlOx/Al junctions that form an effective junction tunable by an external magnetic field.

readout strength and qubit temperature, trials with outcomes $|I_m/\sigma| < 1.5$ (corresponding to state purity < 99%) for the first and third measurements are discarded, as well as outcomes for the first measurement with the qubit in $|e\rangle$. To quantify the measurement back-action for a given measurement outcome (I_m, Q_m), the average final qubit Bloch vector, conditioned by the measurement outcome (I_m, Q_m), $(\langle X\rangle_c, \langle Y\rangle_c, \langle Z\rangle_c)$, is calculated versus outcome using the results of the tomography phase. These conditional maps of $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ were constructed using 201 by 201 bins in the plane of scaled measurement outcomes $(I_m/\sigma, Q_m/\sigma)$.

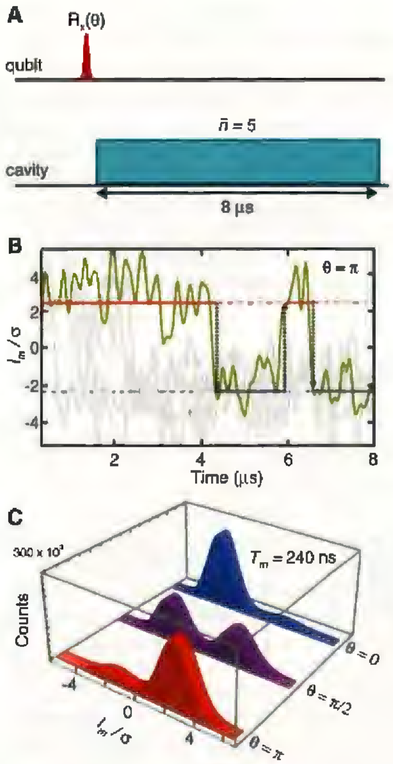

Fig. 2. **(A)** Pulse sequence for strong measurement. An initial qubit rotation $R_x(\theta)$ of θ radians about the x axis is followed by an 8-µs readout pulse with drive power such that $\bar{n} = 5$. **(B)** Individual measurement records. The data are smoothed with a binomial filter with a $T_m = 240$ ns time constant and scaled by the experimentally determined standard deviation (σ). Black dotted lines indicate 4σ deviation events. The qubit is initially measured to be in the excited state, and quantum jumps between excited and ground states are clearly resolved. The center of the ground- and excited-state distributions are represented as horizontal dotted lines. **(C)** Histograms of the initial 240-ns record of the readout pulse along I_m axis, for $\theta = 0, \pi/2, \pi$. Finite qubit temperature and T_1 decay during readout are visible as population in the undesired qubit state.

Results for four measurement strengths increasing by decades from $\bar{n} = 5 \times 10^{-3}$ to 5 are shown in Fig. 3B (see movie S1 of histograms and tomograms for all measurement strengths). The left column shows a 2D histogram of all scaled measurement outcomes recorded during the variable-strength readout pulse. At weak measurement strength, the ground- (left) and excited- (right) state distributions overlap almost completely. Their separation grows with increasing strength until they are well separated at $\bar{n} = 5$, which corresponds to the strong projective measurement shown in Fig. 1A. The rightmost columns show $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus the associated $(I_m/\sigma, Q_m/\sigma)$ bin. At weak measurement strength ($\bar{n} << 1$), the qubit state is only slightly perturbed, with all measurement outcomes corresponding to Bloch vectors pointing nearly along the $+y$ (initial) axis. However, gradients in $\langle X\rangle_c$ along the Q_m axis and $\langle Z\rangle_c$ along the I_m axis are visible, demonstrating the outcome-dependent back-action of the measurement on the qubit state. As the measurement strength increases, so does the back-action, as seen in the increase of the gradients in the $\langle X\rangle_c$ and $\langle Z\rangle_c$ maps (see fig. S2). When the measurement becomes strong, the qubit is projected to $+z$ for positive I_m ($-z$ for negative I_m), whereas $\langle X\rangle$ and $\langle Y\rangle$ go unconditionally to zero, as expected.

One of the key predictions of finite-strength measurement theory is that the statistics of the measurement process, in particular the apparent measurement strength in the I-quadrature (which can be determined experimentally from the statistics of the measurement outcomes), are sufficient to infer z_f for any apparent measurement strength or outcome (see Eq. 1). For weak measurement, where the back-action is symmetric along both x and z, the apparent measurement strength deter-

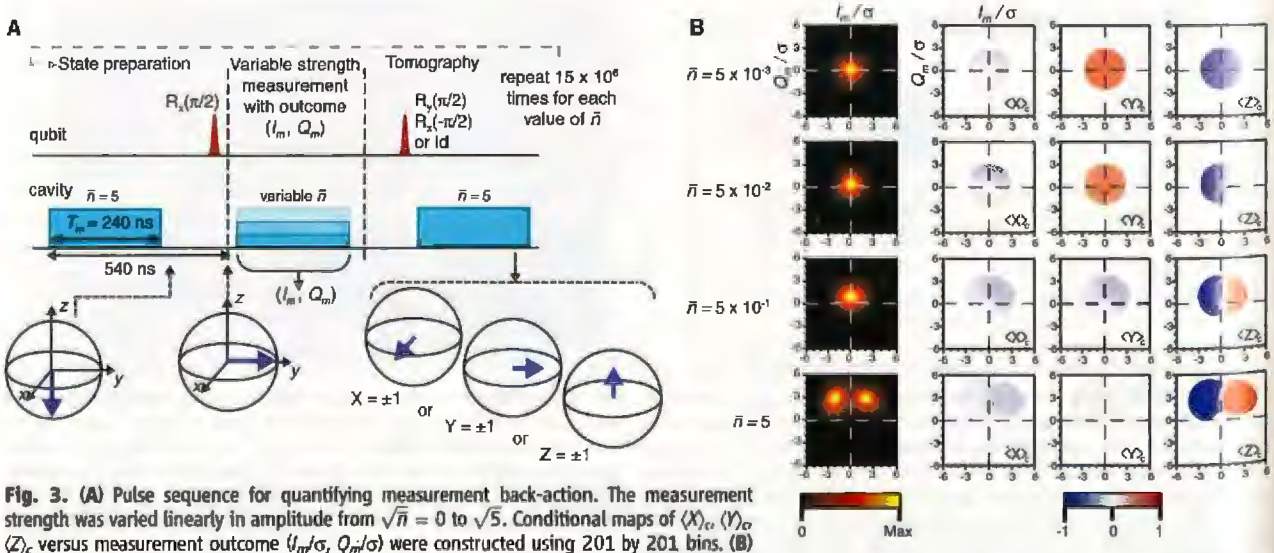

Fig. 3. **(A)** Pulse sequence for quantifying measurement back-action. The measurement strength was varied linearly in amplitude from $\sqrt{\bar{n}} = 0$ to $\sqrt{5}$. Conditional maps of $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus measurement outcome $(I_m/\sigma, Q_m/\sigma)$ were constructed using 201 by 201 bins. **(B)** Results are shown increasing by decades from $\bar{n} = 5\times10^{-3}$ to 5. The left column shows a 2D histogram of all scaled measurement outcomes recorded during the variable-strength readout pulse. The three rightmost columns are tomograms showing $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus the associated $(I_m/\sigma, Q_m/\sigma)$ bin.

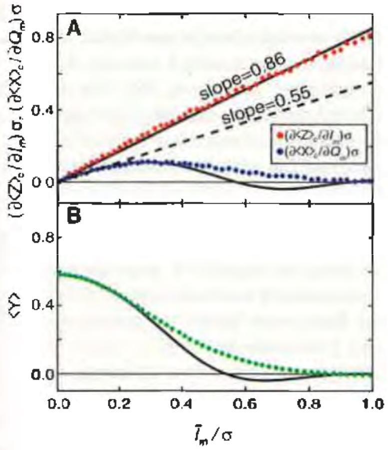

Fig. 4. Correlation between back-action and measurement outcome. **(A)** Experimental data for correlated back-action signal along z, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$, and along x, $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, evaluated at $(I_m, Q_m) = 0$, are plotted versus $\bar{I}_m/\sigma$. For weak measurement strength, the slopes at the origin (represented by solid and dashed line, for z and x, respectively) agree with theoretical predictions, including first-order corrections for T_1 and T_2. The solid curve is the full theoretical expression for the x back-action plotted with $\eta = 0.2$, $\bar{Q}_m = 1.28\ \bar{I}_m$, and $\exp(-\tau/T_2) = 0.58$. **(B)** Experimental data for unconditioned $\langle Y\rangle$ versus $\bar{I}_m/\sigma$. The data show the expected measurement-induced dephasing when the measurement outcome is not used to condition the perturbed qubit state. The dephasing rate is proportional to $(\bar{I}_m/\sigma)^2$, resulting in the apparent Gaussian dependence of $\langle Y\rangle$ versus $\bar{I}_m/\sigma$. The theoretical expression for $\langle Y\rangle$ versus $\bar{I}_m/\sigma$ with parameters listed above is shown as a solid curve.

mines the amplitude of the x back-action as well (see eq. 14 in the supplementary materials). In Fig. 4A, we quantitatively compare this prediction with our experimental result. The scaling coefficients relating measurement outcome to back-action along z, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$, and along x, $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, extracted from the tomograms at $I_m = Q_m = 0$, are plotted versus the apparent measurement strength extracted from the histograms, $\bar{I}_m/\sigma$ (see section 1.4 in the supplementary materials).

Both coefficients, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$ and $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, are predicted at $I_m = Q_m = 0$ to be equal to $\bar{I}_m/\sigma$; therefore, the data in Fig. 4A should have unity slope. However, finite T_1 and T_2 acting for a time τ reduce the state purity and the apparent back-action. To first order, the coefficients are modified to $(\partial\langle Z\rangle_c/\partial I_m)\sigma = (\bar{I}_m/\sigma)e^{-\tau/T_1}$ and $(\partial\langle X\rangle_c/\partial Q_m)\sigma \cong (\bar{I}_m/\sigma)e^{-\tau/T_2}$ for the z and x back-action, respectively. In our pulse sequence, $\tau \cong 380$ ns, predicting slopes of 0.87 ± 0.09 and 0.58 ± 0.06 for z and x, in excellent agreement with the experimentally determined slopes of 0.86 ± 0.01 and 0.55 ± 0.01. All further theoretical predictions are modified to reflect the effects of T_1 and T_2, following the description in eq. 2 in the supplementary materials. The black curve is the full theoretical dependence of $(\partial\langle X\rangle_c/\partial Q_m)\sigma = \bar{I}_m/\sigma \cos\{\bar{Q}_m\bar{I}_m/\sigma^2[(1-\eta)/\eta]\}e^{-\bar{I}_m^2(1-\eta)/\eta\sigma^2}e^{-\tau/T_2}$ using $\eta = 0.2$, the lowest value of η we extract from other measurements (see section 1.3 in the supplementary materials). We attribute the discrepancy between theory and data at high measurement strength to environmental dephasing effects due to finite T_2 and losses before the JPC. Additionally, we process the tomography results unconditioned by measurement outcome in Fig. 4B. Theory predicts $\langle Y\rangle = e^{-\bar{I}_m^2/\eta\sigma^2}\cos(\bar{I}_m\bar{Q}_m/\eta\sigma^2)e^{-\tau/T_2}$. This expression evaluated with $\eta = 0.2$ is shown as a black curve with the deviation for stronger measurements attributed to dephasing effects due to losses before amplification.

Similar experiments have studied measurement of the state of a microwave cavity by Rydberg atoms (*26*) and partial nonlinear measurement of phase qubits (*27*). Also, phase-sensitive parametric amplification has been used to implement weak measurement-based feedback (*18*). In our experiment, the ability to perform both weak and strong high-efficiency, QND, linear measurements within a qubit lifetime, coupled with our high-throughput and minimally noisy readout electronics, allows us to acquire 13.5 billion qubit measurements in ~28 hours, data that can be compared with complete theoretical predictions of the conditional evolution of quantum states under measurement. They provide strong evidence that the purity of the state would not decrease in the limit of a perfect measurement, even when the signal is processed by a phase-preserving amplifier.

Our experiment illustrates an alternate approach to the description of a quantum measurement. In the case of a qubit, a finite-strength QND measurement can be thought of as a stochastic operation whose action is unpredictable but known to the experimenters after the fact if they have a quantum-noise–limited amplification chain. Any final state is possible, and the type of quantity measured, combined with the measurement strength, determines the probability distribution for different outcomes. This partial (i.e., finite strength) measurement paradigm is not inconsistent with the usual view of projective (i.e., infinite strength) measurement. Rather, projective measurement is the limiting case of the broader class of finite strength measurements.

The finite-strength measurement predictions that we have verified have immediate applicability to proposed schemes for feedback stabilization and error correction of superconducting qubit states. Whereas classical feedback is predicated on the idea that measuring a system does not disturb it, quantum feedback has to make additional corrections to the state of the system to counteract the unavoidable measurement back-action. The measurement back-action that is the subject of this paper thus crucially determines the transformation of the measurement outcome into the optimal correction signal for feedback. Our ability to experimentally quantify the back-action of an arbitrary-strength measurement thus provides a dress rehearsal for full feedback control of a general quantum system.

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Supplementary Materials

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Supplementary Text
Figs. S1 to S3
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Movie S1

3 July 2012; accepted 20 November 2012
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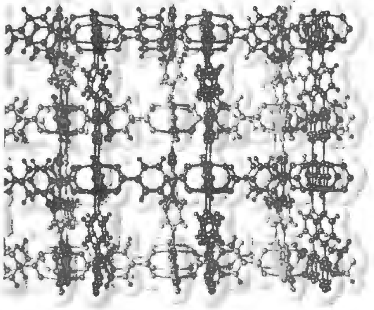
A yin-yang symbol superimposed on a scanning electron micrograph of a mouse tissue alveolar macrophage (diameter: ~18 micrometers). Macrophages are immune cells that mediate inflammation, but they often play protective roles as well. Several age-related chronic diseases—such as metabolic syndrome, cardiovascular disease, and neurodegenerative disease—have an inflammatory component. See the special section beginning on page 155.

Scanning electron microscope image: © Dennis Kunkel Microscopy, Inc.

DEPARTMENTS



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Quantum Back-Action of an Individual Variable-Strength Measurement

**M. Hatridge,[1]*† S. Shankar,[1]* M. Mirrahimi,[1,2] F. Schackert,[1] K. Geerlings,[1]
T. Brecht,[1] K. M. Sliwa,[1] B. Abdo,[1] L. Frunzio,[1] S. M. Girvin,[1] R. J. Schoelkopf,[1] M. H. Devoret[1]**

Measuring a quantum system can randomly perturb its state. The strength and nature of this back-action depend on the quantity that is measured. In a partial measurement performed by an ideal apparatus, quantum physics predicts that the system remains in a pure state whose evolution can be tracked perfectly from the measurement record. We demonstrated this property using a superconducting qubit dispersively coupled to a cavity traversed by a microwave signal. The back-action on the qubit state of a single measurement of both signal quadratures was observed and shown to produce a stochastic operation whose action is determined by the measurement result. This accurate monitoring of a qubit state is an essential prerequisite for measurement-based feedback control of quantum systems.

Although the evolution ("state collapse") of a quantum system subject to an infinitely strong (i.e., projective) quantum nondemolition (QND) measurement is textbook physics, the subtlety and utility of finite strength (i.e., partial) measurement phenomena are neither widely appreciated nor commonly verified experimentally. Standard quantum measurement theory puts forward the principle that observing a system induces a decoherent evolution proportional to the measurement strength (*1–5*). Thus, partial measurement is often associated with partial decoherence of the state of a quantum system. However, this measurement-induced degradation occurs only if the measurement is inefficient informationally—that is, if only a portion of the measurement's information content is available to the observer for use in reconstructing the new state of the system.

If, instead, the measurement apparatus is entirely efficient, the new state of the quantum system can be perfectly reconstructed. This outcome-dependent revision of the system's imposed initial conditions constitutes a fundamental quantum effect called measurement back-action (*2*, *6–8*). Although the system's evolution under measurement is erratic (hence, the measurement outcome cannot be predicted in advance), the measurement record faithfully reports the perturbation of the system after the fact.

We use the powerful, combined qubit-cavity architecture, circuit quantum electrodynamics (cQED) (*9*, *10*), which allows for rapid, repeated quantum nondemolition (QND) (*11*, *12*) superconducting qubit measurement (*13–18*). The cavity output is monitored in real time by using a phase-preserving amplifier working near the quantum limit, where the noise is only caused by the fundamental quantum fluctuations of the electrodynamic vacuum (*19*). The decision to read out our qubit by using coherent states of the resonator has two important consequences. First, the outcomes of a partial measurement form a quasi-continuum, unlike the set of discrete answers obtained from a projective measurement. Second, measuring both quadratures of the signal leads to two-dimensional (2D) diffusion of the direction of the qubit effective spin. We show that the choice of measurement apparatus and of measurement strength both affect the evolution of a quantum system, but neither results in degradation of the system's state if the measurement is informationally efficient. Such precise knowledge of the measurement back-action is a necessary prerequisite for general feedback control of quantum systems.

Our superconducting qubit is a transmon (*20*), consisting of two Josephson junctions in a closed loop, shunted by a capacitor to form an anharmonic oscillator. The two lowest energy states, ($|g\rangle$ and $|e\rangle$), are the logical states of the qubit. The qubit is dispersively coupled to a compact resonator, which is further asymmetrically coupled to input and output transmission lines (Fig. 1, B and C), determining the resonator bandwidth ($\kappa/2\pi = 5.8$ MHz). To measure a qubit prepared in initial state $|\psi\rangle = c_g|g\rangle + c_e|e\rangle$, a microwave pulse of duration $T_m >> 1/\kappa$ is applied to the resonator. The state-dependent shift of the resonator frequency ($\chi/2\pi = 5.4$ MHz) results in an entangled state of the qubit and pulse $|\Psi\rangle = c_g|g\rangle \otimes |\alpha_g\rangle + c_e|e\rangle \otimes |\alpha_e\rangle$, where $|\alpha_{g,e}\rangle$ refers to the coherent state after traversing the resonator.

Amplification is required to convert the pointer state $|\Psi\rangle$ into a macroscopic signal that can be processed and recorded with standard instrumentation. In our case, the pulse, having traversed the resonator, is amplified by using a linear, phase-preserving amplifier with gain G, which can be seen as multiplying the average photon number in $|\alpha_{g,e}\rangle$ (Fig. 1B). For dynamical range considerations, our amplifier, called the Josephson parametric converter (JPC) (*21–24*) is operated in this experiment with a gain $G = 12.5$ dB and bandwidth of 6 MHz, adding close to the minimum amount of noise allowed by quantum mechanics. The added quantum fluctuations are due to a second, "idler," input (*19*). A measurement of both quadratures of the output mode results in an outcome, denoted (I_m, Q_m), which is then used to determine the new state of the qubit after measurement (Fig. 1A). As has been shown in (*8*), and detailed in the supplementary materials, this outcome contains all information necessary to perfectly reconstruct the new state of the qubit. Remarkably, the additional quantum fluctuations introduced during amplification enter in the measurement back-action on the qubit without impairing our knowledge of it.

We first demonstrate projective qubit readout by strongly measuring the qubit using an 8-μs pulse with the drive power set so that the average number of photons in the resonator during the pulse was $\bar{n} = 5$ (Fig. 2). Selected individual measurement records for the qubit are shown in Fig. 2B. The data are digitized with a sampling time of 20 ns and smoothed with a binomial filter with $T_m = 240$ ns width, which corresponds to eight cavity lifetimes, and scaled by the experimentally determined standard deviation (σ). The highlighted trace shows clear quantum jumps in the qubit state, which are identified by vertical black dotted lines indicating 4σ deviations from the current qubit state. The 8% equilibrium qubit excited-state population is consistent with other measurements of superconducting qubits (*25*). By counting the number of up and down transitions in 25,000 traces with no qubit excitation pulse, we calculate $T_1 \leq 3.1$ μs. Although we fail to resolve pairs of transitions separated by much less than our filter time constant, this method for estimating T_1 yields a value in good agreement with the value $T_1 = 2.8$ μs calculated from fitting an exponential to the averaged trajectory of all traces. Further, the average qubit polarization did not vary over 8 μs of continuous measurement, nor did T_1 diminish with larger readout amplitude up to $\bar{n} \cong 15$, which demonstrates the QND nature of our readout.

Histograms of the scaled I_m component of the outcome for the first 240 ns of measurement after a qubit rotation by $\theta = 0, \pi/2, \pi$ are shown in Fig. 2C. The ground and excited distributions are separated by 4.8 σ, which corresponds to a measurement fidelity of 98% when $I_m = 0$ is used as the discrimination threshold. We emphasize that the discreteness of the z measurement of the transmon circuit, illustrated by the bimodality of the histogram, is here due only to the quantum nature of the circuit and not to any nonlinearity of the readout. Thus, this measurement of a continuous, unbounded pointer state is exactly equivalent to the Stern-Gerlach experi-

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[1]Department of Applied Physics and Physics, Yale University, New Haven, CT 06520, USA. [2]Institut National de Recherche en Informatique et en Automatique Paris-Rocquencourt, Domaine de Voluceau, B.P. 105, 78153 Le Chesnay Cedex, France.

*These authors contributed equally to this work.

†To whom correspondence should be addressed. E-mail: michael.hatridge@yale.edu

ment. These strong, high-fidelity measurements allow us to perform precise tomography and to prepare the qubit in a known state by measurement. We next use these tools to quantify measurement back-action of partial measurement on the qubit state.

The qubit evolution due to partial measurement can be precisely calculated from the complete measurement record using the quantum trajectory approach (*6*, *7*), but this is computationally intensive. Instead, we calculate the back-action from the average output over the time T_m, as in (*8*). Provided that the measurement time is short compared with the qubit coherence times T_1 and T_2, and long compared with the cavity lifetime and amplifier response time, this approach allows the qubit to be tracked without degradation. In this experiment, $T_m = 240$ ns, which is shorter than $T_1 = 2.8$ μs and $T_{2R} = 0.7$ to 2.0 μs, and much longer than the cavity lifetime and JPC response time of 30 ns.

Assuming the qubit is initially polarized along the $+y$ axis, we calculate the final qubit Bloch vector (x_f, y_f, z_f) as a function of measurement outcome (I_m, Q_m) (see detailed derivation in the supplementary materials) to be

$$x_f^\eta(I_m,Q_m) = \mathrm{sech}\left(\frac{I_m \overline{I}_m}{\sigma^2}\right) \times \sin\left[\frac{Q_m \overline{I}_m}{\sigma^2} + \frac{\overline{Q}_m \overline{I}_m}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)\right] \times e^{-\frac{\overline{I}_m^2}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)},$$

$$y_f^\eta(I_m,Q_m) = \mathrm{sech}\left(\frac{I_m \overline{I}_m}{\sigma^2}\right) \times \cos\left[\frac{Q_m \overline{I}_m}{\sigma^2} + \frac{\overline{Q}_m \overline{I}_m}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)\right] \times e^{-\frac{\overline{I}_m^2}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)},$$

$$z_f^\eta(I_m) = \tanh\left(\frac{I_m \overline{I}_m}{\sigma^2}\right) \qquad (1)$$

where $\overline{I}_m$ and $\overline{Q}_m$ and σ define the center and standard deviation of the outcome distributions, and η is the quantum efficiency of the amplification chain (Fig. 1A). In this theory, we neglect the effect of qubit decoherence and losses before amplification. In the limit of a perfectly efficient amplification ($\eta = 1$), we see that the length of the Bloch vector is unity, irrespective of outcome. The parameter $\overline{I}_m/\sigma$ can be identified as the apparent measurement strength because the measurement becomes more strongly projective as $\overline{I}_m/\sigma$ increases. It is given in terms of experimental parameters as $\overline{I}_m/\sigma = \sqrt{2\bar{n}\eta\kappa T_m}\sin(\vartheta/2)$, where $\vartheta = 2\arctan\chi/\kappa$.

The pulse sequence for determining measurement back-action is shown in Fig. 3A. We first strongly read out the qubit with a 240 ns, $\bar{n} = 5$ pulse and record the outcome, which will be used to prepare the qubit in the ground state by post-selection. Then, the qubit is rotated to the $+y$ axis and measured with a variable measurement strength (T_m = 240 ns), and the outcome (I_m, Q_m) is recorded. The final, tomography, phase measures the x, y, or z component of the qubit Bloch vector with a strong ($\bar{n} = 5$, T_m = 240 ns) measurement pulse. To compensate for the finite

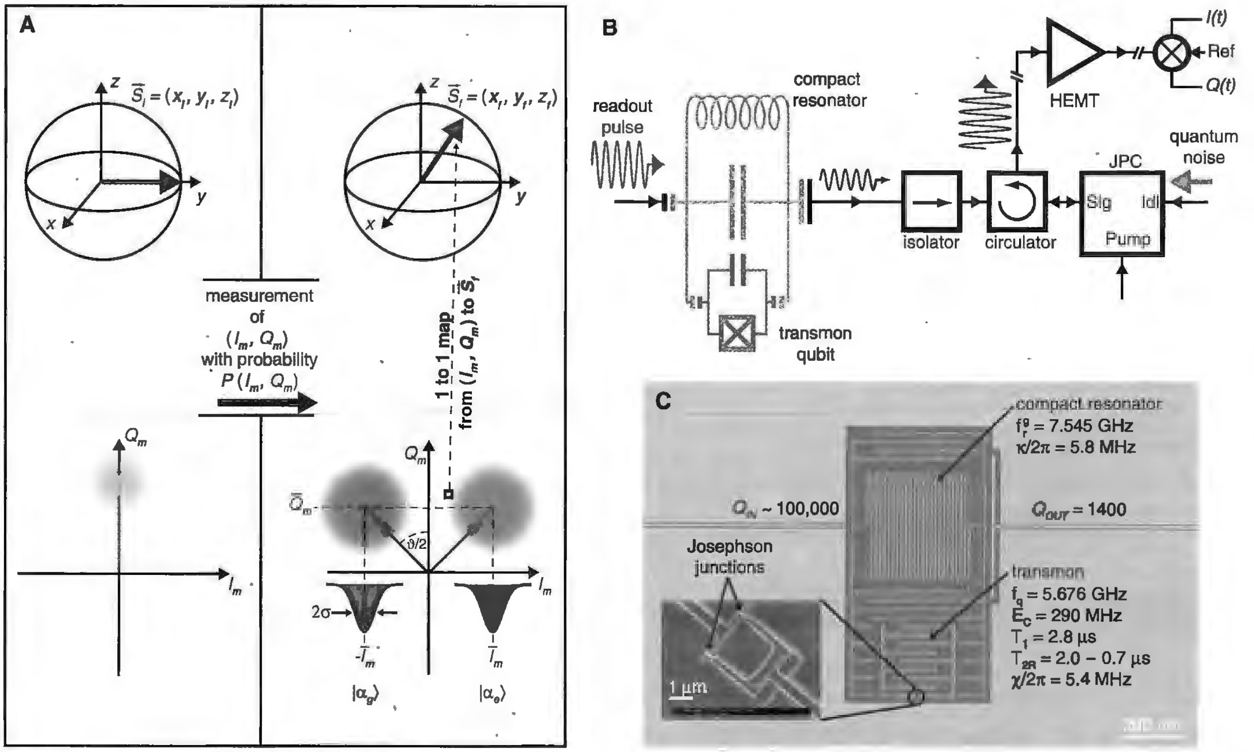

Fig. 1. (**A**) Bloch sphere representation of the effect on the qubit state of a phase-preserving measurement in a cQED architecture. After a measurement with outcome (I_m, Q_m), the qubit will be found in a final state $\vec{S}_f = (x_f, y_f, z_f)$, with I_m encoding information on the projection of the qubit state along z and corresponding back-action and Q_m encoding the other component of the back-action, which is parallel to $\hat{z} \times \vec{S}_i$. The measurement outcomes are Gaussian distributed, with $\overline{I}_m^2 + \overline{Q}_m^2 = \bar{n}\kappa T_m$. (**B**) Schematic of experiment mounted to the base plate of a dilution refrigerator. Readout pulses are transmitted through the strongly coupled port of the resonator, via an isolator and circulator, to the signal port (Sig) of a JPC. The idler port (Idl) is terminated in a 50 Ω load. The amplified signal output is routed via the circulator and further isolators (not shown) to a high electron mobility transistor (HEMT) amplifier operated at 4 K, and subsequently demodulated and digitized at room temperature. (**C**) False-color photograph of the transmon qubit in compact resonator with qubit and resonator parameters. Inset is a scanning electron micrograph of the center of the transmon showing a loop of two Al/AlOx/Al junctions that form an effective junction tunable by an external magnetic field.

readout strength and qubit temperature, trials with outcomes $|I_m/\sigma| < 1.5$ (corresponding to state purity < 99%) for the first and third measurements are discarded, as well as outcomes for the first measurement with the qubit in $|e\rangle$. To quantify the measurement back-action for a given measurement outcome (I_m, Q_m), the average final qubit Bloch vector, conditioned by the measurement outcome (I_m, Q_m), $(\langle X\rangle_c, \langle Y\rangle_c, \langle Z\rangle_c)$, is calculated versus outcome using the results of the tomography phase. These conditional maps of $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ were constructed using 201 by 201 bins in the plane of scaled measurement outcomes $(I_m/\sigma, Q_m/\sigma)$.

Results for four measurement strengths increasing by decades from $\bar{n} = 5 \times 10^{-3}$ to 5 are shown in Fig. 3B (see movie S1 of histograms and tomograms for all measurement strengths). The left column shows a 2D histogram of all scaled measurement outcomes recorded during the variable-strength readout pulse. At weak measurement strength, the ground- (left) and excited- (right) state distributions overlap almost completely. Their separation grows with increasing strength until they are well separated at $\bar{n} = 5$, which corresponds to the strong projective measurement shown in Fig. 1A. The rightmost columns show $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus the associated $(I_m/\sigma, Q_m/\sigma)$ bin. At weak measurement strength ($\bar{n} << 1$), the qubit state is only slightly perturbed, with all measurement outcomes corresponding to Bloch vectors pointing nearly along the $+y$ (initial) axis. However, gradients in $\langle X\rangle_c$ along the Q_m axis and $\langle Z\rangle_c$ along the I_m axis are visible, demonstrating the outcome-dependent back-action of the measurement on the qubit state. As the measurement strength increases, so does the back-action, as seen in the increase of the gradients in the $\langle X\rangle_c$ and $\langle Z\rangle_c$ maps (see fig. S2). When the measurement becomes strong, the qubit is projected to $+z$ for positive I_m ($-z$ for negative I_m), whereas $\langle X\rangle$ and $\langle Y\rangle$ go unconditionally to zero, as expected.

One of the key predictions of finite-strength measurement theory is that the statistics of the measurement process, in particular the apparent measurement strength in the I-quadrature (which can be determined experimentally from the statistics of the measurement outcomes), are sufficient to infer z_f for any apparent measurement strength or outcome (see Eq. 1). For weak measurement, where the back-action is symmetric along both x and z, the apparent measurement strength deter-

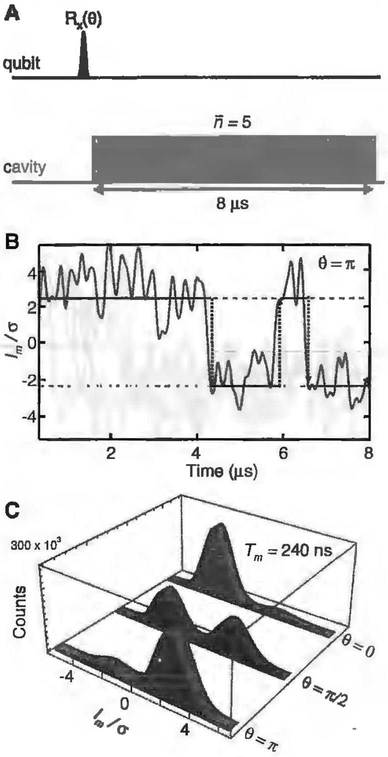

Fig. 2. (**A**) Pulse sequence for strong measurement. An initial qubit rotation $R_x(\theta)$ of θ radians about the x axis is followed by an 8-μs readout pulse with drive power such that $\bar{n} = 5$. (**B**) Individual measurement records. The data are smoothed with a binomial filter with a $T_m = 240$ ns time constant and scaled by the experimentally determined standard deviation (σ). Black dotted lines indicate 4σ deviation events. The qubit is initially measured to be in the excited state, and quantum jumps between excited and ground states are clearly resolved. The center of the ground- and excited-state distributions are represented as horizontal dotted lines. (**C**) Histograms of the initial 240-ns record of the readout pulse along I_m axis, for θ = 0, π/2, π. Finite qubit temperature and T_1 decay during readout are visible as population in the undesired qubit state.

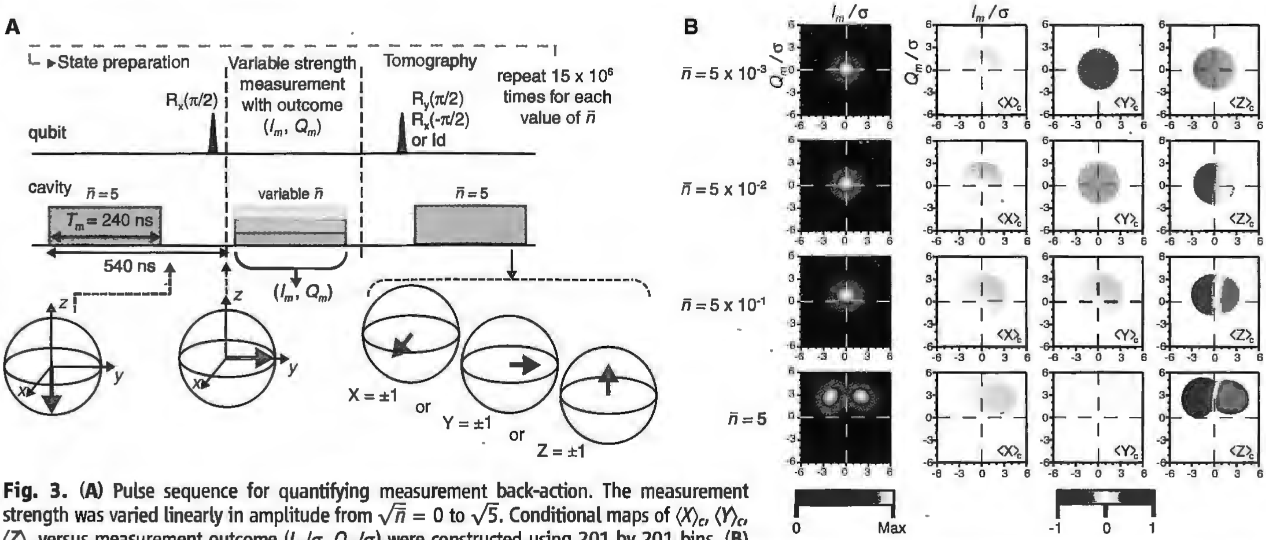

Fig. 3. (**A**) Pulse sequence for quantifying measurement back-action. The measurement strength was varied linearly in amplitude from $\sqrt{\bar{n}} = 0$ to $\sqrt{5}$. Conditional maps of $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus measurement outcome $(I_m/\sigma, Q_m/\sigma)$ were constructed using 201 by 201 bins. (**B**) Results are shown increasing by decades from $\bar{n} = 5\times10^{-3}$ to 5. The left column shows a 2D histogram of all scaled measurement outcomes recorded during the variable-strength readout pulse. The three rightmost columns are tomograms showing $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus the associated $(I_m/\sigma, Q_m/\sigma)$ bin.

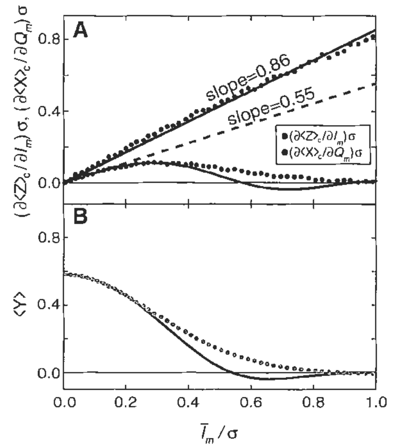

Fig. 4. Correlation between back-action and measurement outcome. **(A)** Experimental data for correlated back-action signal along z, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$, and along x, $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, evaluated at $(I_m, Q_m) = 0$, are plotted versus $\bar{I}_m/\sigma$. For weak measurement strength, the slopes at the origin (represented by solid and dashed line, for z and x, respectively) agree with theoretical predictions, including first-order corrections for T_1 and T_2. The solid curve is the full theoretical expression for the x back-action plotted with $\eta = 0.2$, $\bar{Q}_m = 1.28\ \bar{I}_m$, and $\exp(-\tau/T_2) = 0.58$. **(B)** Experimental data for unconditioned $\langle Y\rangle$ versus $\bar{I}_m/\sigma$. The data show the expected measurement-induced dephasing when the measurement outcome is not used to condition the perturbed qubit state. The dephasing rate is proportional to $(\bar{I}_m/\sigma)^2$, resulting in the apparent Gaussian dependence of $\langle Y\rangle$ versus $\bar{I}_m/\sigma$. The theoretical expression for $\langle Y\rangle$ versus $\bar{I}_m/\sigma$ with parameters listed above is shown as a solid curve.

mines the amplitude of the x back-action as well (see eq. 14 in the supplementary materials). In Fig. 4A, we quantitatively compare this prediction with our experimental result. The scaling coefficients relating measurement outcome to back-action along z, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$, and along x, $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, extracted from the tomograms at $I_m = Q_m = 0$, are plotted versus the apparent measurement strength extracted from the histograms, $\bar{I}_m/\sigma$ (see section 1.4 in the supplementary materials).

Both coefficients, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$ and $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, are predicted at $I_m = Q_m = 0$ to be equal to $\bar{I}_m/\sigma$; therefore, the data in Fig. 4A should have unity slope. However, finite T_1 and T_2 acting for a time τ reduce the state purity and the apparent back-action. To first order, the coefficients are modified to $(\partial\langle Z\rangle_c/\partial I_m)\sigma = (\bar{I}_m/\sigma)e^{-\tau/T_1}$ and $(\partial\langle X\rangle_c/\partial Q_m)\sigma \cong (\bar{I}_m/\sigma)e^{-\tau/T_2}$ for the z and x back-action, respectively. In our pulse sequence, $\tau \cong 380$ ns, predicting slopes of 0.87 ± 0.09 and 0.58 ± 0.06 for z and x, in excellent agreement with the experimentally determined slopes of 0.86 ± 0.01 and 0.55 ± 0.01. All further theoretical predictions are modified to reflect the effects of T_1 and T_2, following the description in eq. 2 in the supplementary materials. The black curve is the full theoretical dependence of $(\partial\langle X\rangle_c/\partial Q_m)\sigma = \bar{I}_m/\sigma\cos\{\bar{Q}_m\bar{I}_m/\sigma^2[(1-\eta)/\eta]\}e^{-\bar{I}_m^2/\sigma^2[(1-\eta)\eta]}e^{-\tau/T_2}$ using $\eta = 0.2$, the lowest value of η we extract from other measurements (see section 1.3 in the supplementary materials). We attribute the discrepancy between theory and data at high measurement strength to environmental dephasing effects due to finite T_2 and losses before the JPC. Additionally, we process the tomography results unconditioned by measurement outcome in Fig. 4B. Theory predicts $\langle Y\rangle = e^{-\bar{I}_m^2/\eta\sigma^2}\cos(\bar{I}_m\bar{Q}_m/\eta\sigma^2)e^{-\tau/T_2}$. This expression evaluated with $\eta = 0.2$ is shown as a black curve with the deviation for stronger measurements attributed to dephasing effects due to losses before amplification.

Similar experiments have studied measurement of the state of a microwave cavity by Rydberg atoms (*26*) and partial nonlinear measurement of phase qubits (*27*). Also, phase-sensitive parametric amplification has been used to implement weak measurement-based feedback (*18*). In our experiment, the ability to perform both weak and strong high-efficiency, QND, linear measurements within a qubit lifetime, coupled with our high-throughput and minimally noisy readout electronics, allows us to acquire 13.5 billion qubit measurements in ~28 hours, data that can be compared with complete theoretical predictions of the conditional evolution of quantum states under measurement. They provide strong evidence that the purity of the state would not decrease in the limit of a perfect measurement, even when the signal is processed by a phase-preserving amplifier.

Our experiment illustrates an alternate approach to the description of a quantum measurement. In the case of a qubit, a finite-strength QND measurement can be thought of as a stochastic operation whose action is unpredictable but known to the experimenters after the fact if they have a quantum-noise–limited amplification chain. Any final state is possible, and the type of quantity measured, combined with the measurement strength, determines the probability distribution for different outcomes. This partial (i.e., finite strength) measurement paradigm is not inconsistent with the usual view of projective (i.e., infinite strength) measurement. Rather, projective measurement is the limiting case of the broader class of finite strength measurements.

The finite-strength measurement predictions that we have verified have immediate applicability to proposed schemes for feedback stabilization and error correction of superconducting qubit states. Whereas classical feedback is predicated on the idea that measuring a system does not disturb it, quantum feedback has to make additional corrections to the state of the system to counteract the unavoidable measurement back-action. The measurement back-action that is the subject of this paper thus crucially determines the transformation of the measurement outcome into the optimal correction signal for feedback. Our ability to experimentally quantify the back-action of an arbitrary-strength measurement thus provides a dress rehearsal for full feedback control of a general quantum system.

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Supplementary Materials

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Supplementary Text
Figs. S1 to S3
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Movie S1

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APPENDIX 1004-C

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500		$aEdited by J. Michels.
500		$aPublished: Cambridge, Mass. : Science Company, Moses
500		$aSince Jan. 1901 the official proceedings and most of
500		$aSome issues accompanied by CD-ROM.
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710	2_	**$a**American Association for the Advancement of Science.
770	0_	**$t**AAAS observer**$x**1043-6936**$w**(DLC)sn 88019924**$w**(OCoLC)1
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891	20	**$8**1**$a**v.**$b**no.**$u**51**$v**c**$i**(year)**$j**(month)**$k**(day)**$w**w**$y**ow1204
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APPENDIX 1004-D

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Science

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Online Access

Highwire Press American Association for the Advancement of Science
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JSTOR
Available from 1880 volume: 1 issue: 1. Most recent 6 year(s) not available.

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Michels, John, 1875- editor

American Association for the Advancement of Science

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New York, N.Y. : [publisher not identified], 1880-

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Index in last issue of v., -1996; index only available in online version, 1997-

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"A weekly record of scientific progress."

Edited by J. Michels.

Published: Cambridge, Mass. : Science Company, Moses King, 1883- ; Lancaster, Pa. : Science Press, -1944; Lancaster, Pa. : American Association for the Advancement of Science, 1945- ; Washington, DC : American Association for the Advancement of Science, <Oct. 4, 1991->

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APPENDIX 1004-E

PubMed Quantum Back-Action of an Individual Variable-Strength Measuremen

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Quantum back-action of an individual variable-strength measurement.

Hatridge M[1], Shankar S, Mirrahimi M, Schackert F, Geerlings K, Brecht T, Sliwa KM, Abdo B, Frunzio L, Girvin SM, Schoelkopf RJ, Devoret MH.

Author information

Abstract

Measuring a **quantum** system can randomly perturb its state. The strength and nature of this **back-action** depend on the quantity that is measured. In a partial **measurement** performed by an ideal apparatus, **quantum** physics predicts that the system remains in a pure state whose evolution can be tracked perfectly from the **measurement** record. We demonstrated this property using a superconducting qubit dispersively coupled to a cavity traversed by a microwave signal. The **back-action** on the qubit state of a single **measurement** of both signal quadratures was observed and shown to produce a stochastic operation whose action is determined by the **measurement** result. This accurate monitoring of a qubit state is an essential prerequisite for **measurement**-based feedback control of **quantum** systems.

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DCOM- 20130124
LR  - 20130111
IS  - 1095-9203 (Electronic)
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      system remains in a pure state whose evolution can be tracked perfectly from the
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      on the qubit state of a single measurement of both signal quadratures was
      observed and shown to produce a stochastic operation whose action is determined
      by the measurement result. This accurate monitoring of a qubit state is an
      essential prerequisite for measurement-based feedback control of quantum systems.
FAU - Hatridge, M
AU  - Hatridge M
AD  - Department of Applied Physics and Physics, Yale University, New Haven, CT 06520,
      USA. michael.hatridge@yale.edu
FAU - Shankar, S
AU  - Shankar S
FAU - Mirrahimi, M
AU  - Mirrahimi M
FAU - Schackert, F
AU  - Schackert F
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AID - 339/6116/178 [pii]
AID - 10.1126/science.1226897 [doi]
PST - ppublish
SO  - Science. 2013 Jan 11;339(6116):178-81. doi: 10.1126/science.1226897.
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APPENDIX 1004-G

Quantum Back-Action of an Individual Variable-Strength Measurement

M. Hatridge,[1]*† S. Shankar,[1]* M. Mirrahimi,[1,2] F. Schackert,[1] K. Geerlings,[1] T. Brecht,[1] K. M. Sliwa,[1] B. Abdo,[1] L. Frunzio,[1] S. M. Girvin,[1] R. J. Schoelkopf,[1] M. H. Devoret[1]

Measuring a quantum system can randomly perturb its state. The strength and nature of this back-action depend on the quantity that is measured. In a partial measurement performed by an ideal apparatus, quantum physics predicts that the system remains in a pure state whose evolution can be tracked perfectly from the measurement record. We demonstrated this property using a superconducting qubit dispersively coupled to a cavity traversed by a microwave signal. The back-action on the qubit state of a single measurement of both signal quadratures was observed and shown to produce a stochastic operation whose action is determined by the measurement result. This accurate monitoring of a qubit state is an essential prerequisite for measurement-based feedback control of quantum systems.

Although the evolution ("state collapse") of a quantum system subject to an infinitely strong (i.e., projective) quantum nondemolition (QND) measurement is textbook physics, the subtlety and utility of finite strength (i.e., partial) measurement phenomena are neither widely appreciated nor commonly verified experimentally. Standard quantum measurement theory puts forward the principle that observing a system induces a decoherent evolution proportional to the measurement strength (*1*–*5*). Thus, partial measurement is often associated with partial decoherence of the state of a quantum system. However, this measurement-induced degradation occurs only if the measurement is inefficient informationally—that is, if only a portion of the measurement's information content is available to the observer for use in reconstructing the new state of the system.

If, instead, the measurement apparatus is entirely efficient, the new state of the quantum system can be perfectly reconstructed. This outcome-dependent revision of the system's imposed initial conditions constitutes a fundamental quantum effect called measurement back-action (*2*, *6*–*8*). Although the system's evolution under measurement is erratic (hence, the measurement outcome cannot be predicted in advance), the measurement record faithfully reports the perturbation of the system after the fact.

We use the powerful, combined qubit-cavity architecture, circuit quantum electrodynamics (cQED) (*9*, *10*), which allows for rapid, repeated quantum nondemolition (QND) (*11*, *12*) superconducting qubit measurement (*13*–*18*). The cavity output is monitored in real time by using a phase-preserving amplifier working near the quantum limit, where the noise is only caused by the fundamental quantum fluctuations of the electrodynamic vacuum (*19*). The decision to read out our qubit by using coherent states of the resonator has two important consequences. First, the outcomes of a partial measurement form a quasi-continuum, unlike the set of discrete answers obtained from a projective measurement. Second, measuring both quadratures of the signal leads to two-dimensional (2D) diffusion of the direction of the qubit effective spin. We show that the choice of measurement apparatus and of measurement strength both affect the evolution of a quantum system, but neither results in degradation of the system's state if the measurement is informationally efficient. Such precise knowledge of the measurement back-action is a necessary prerequisite for general feedback control of quantum systems.

Our superconducting qubit is a transmon (*20*), consisting of two Josephson junctions in a closed loop, shunted by a capacitor to form an anharmonic oscillator. The two lowest energy states, ($|g\rangle$ and $|e\rangle$), are the logical states of the qubit. The qubit is dispersively coupled to a compact resonator, which is further asymmetrically coupled to input and output transmission lines (Fig. 1, B and C), determining the resonator bandwidth ($\kappa/2\pi = 5.8$ MHz). To measure a qubit prepared in initial state $|\psi\rangle = c_g|g\rangle + c_e|e\rangle$, a microwave pulse of duration $T_m >> 1/\kappa$ is applied to the resonator. The state-dependent shift of the resonator frequency ($\chi/2\pi = 5.4$ MHz) results in an entangled state of the qubit and pulse $|\Psi\rangle = c_g|g\rangle \otimes |\alpha_g\rangle + c_e|e\rangle \otimes |\alpha_e\rangle$, where $|\alpha_{g,\,e}\rangle$ refers to the coherent state after traversing the resonator.

Amplification is required to convert the pointer state $|\Psi\rangle$ into a macroscopic signal that can be processed and recorded with standard instrumentation. In our case, the pulse, having traversed the resonator, is amplified by using a linear, phase-preserving amplifier with gain G, which can be seen as multiplying the average photon number in $|\alpha_{g,\,e}\rangle$ (Fig. 1B). For dynamical range considerations, our amplifier, called the Josephson parametric converter (JPC) (*21*–*24*) is operated in this experiment with a gain $G = 12.5$ dB and bandwidth of 6 MHz, adding close to the minimum amount of noise allowed by quantum mechanics. The added quantum fluctuations are due to a second, "idler," input (*19*). A measurement of both quadratures of the output mode results in an outcome, denoted (I_m, Q_m), which is then used to determine the new state of the qubit after measurement (Fig. 1A). As has been shown in (*8*), and detailed in the supplementary materials, this outcome contains all information necessary to perfectly reconstruct the new state of the qubit. Remarkably, the additional quantum fluctuations introduced during amplification enter in the measurement back-action on the qubit without impairing our knowledge of it.

We first demonstrate projective qubit readout by strongly measuring the qubit using an 8-μs pulse with the drive power set so that the average number of photons in the resonator during the pulse was $\overline{n} = 5$ (Fig. 2). Selected individual measurement records for the qubit are shown in Fig. 2B. The data are digitized with a sampling time of 20 ns and smoothed with a binomial filter with $T_m = 240$ ns width, which corresponds to eight cavity lifetimes, and scaled by the experimentally determined standard deviation (σ). The highlighted trace shows clear quantum jumps in the qubit state, which are identified by vertical black dotted lines indicating 4σ deviations from the current qubit state. The 8% equilibrium qubit excited-state population is consistent with other measurements of superconducting qubits (*25*). By counting the number of up and down transitions in 25,000 traces with no qubit excitation pulse, we calculate $T_1 \leq 3.1$ μs. Although we fail to resolve pairs of transitions separated by much less than our filter time constant, this method for estimating T_1 yields a value in good agreement with the value $T_1 = 2.8$ μs calculated from fitting an exponential to the averaged trajectory of all traces. Further, the average qubit polarization did not vary over 8 μs of continuous measurement, nor did T_1 diminish with larger readout amplitude up to $\overline{n} \cong 15$, which demonstrates the QND nature of our readout.

Histograms of the scaled I_m component of the outcome for the first 240 ns of measurement after a qubit rotation by $\theta = 0, \pi/2, \pi$ are shown in Fig. 2C. The ground and excited distributions are separated by 4.8 σ, which corresponds to a measurement fidelity of 98% when $I_m = 0$ is used as the discrimination threshold. We emphasize that the discreteness of the z measurement of the transmon circuit, illustrated by the bimodality of the histogram, is here due only to the quantum nature of the circuit and not to any nonlinearity of the readout. Thus, this measurement of a continuous, unbounded pointer state is exactly equivalent to the Stern-Gerlach experi-

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[1] Department of Applied Physics and Physics, Yale University, New Haven, CT 06520, USA. [2] Institut National de Recherche en Informatique et en Automatique Paris-Rocquencourt, Domaine de Voluceau, B.P. 105, 78153 Le Chesnay Cedex, France.

*These authors contributed equally to this work.

†To whom correspondence should be addressed. E-mail: michael.hatridge@yale.edu

ment. These strong, high-fidelity measurements allow us to perform precise tomography and to prepare the qubit in a known state by measurement. We next use these tools to quantify measurement back-action of partial measurement on the qubit state.

The qubit evolution due to partial measurement can be precisely calculated from the complete measurement record using the quantum trajectory approach (*6*, *7*), but this is computationally intensive. Instead, we calculate the back-action from the average output over the time T_m, as in (*8*). Provided that the measurement time is short compared with the qubit coherence times T_1 and T_2, and long compared with the cavity lifetime and amplifier response time, this approach allows the qubit to be tracked without degradation. In this experiment, $T_m = 240$ ns, which is shorter than $T_1 = 2.8$ μs and $T_{2R} = 0.7$ to 2.0 μs, and much longer than the cavity lifetime and JPC response time of 30 ns.

Assuming the qubit is initially polarized along the +*y* axis, we calculate the final qubit Bloch vector (x_f, y_f, z_f) as a function of measurement outcome (I_m, Q_m) (see detailed derivation in the supplementary materials) to be

$$x_f^{\eta}(I_m,Q_m) = \mathrm{sech}\left(\frac{I_m \overline{I}_m}{\sigma^2}\right) \times \sin\left[\frac{Q_m \overline{I}_m}{\sigma^2} + \frac{\overline{Q}_m \overline{I}_m}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)\right] \times e^{-\frac{\overline{I}_m^2}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)},$$

$$y_f^{\eta}(I_m,Q_m) = \mathrm{sech}\left(\frac{I_m \overline{I}_m}{\sigma^2}\right) \times \cos\left[\frac{Q_m \overline{I}_m}{\sigma^2} + \frac{\overline{Q}_m \overline{I}_m}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)\right] \times e^{-\frac{\overline{I}_m^2}{\sigma^2}\left(\frac{1-\eta}{\eta}\right)},$$

$$z_f^{\eta}(I_m) = \tanh\left(\frac{I_m \overline{I}_m}{\sigma^2}\right) \qquad (1)$$

where $\overline{I}_m$ and $\overline{Q}_m$ and σ define the center and standard deviation of the outcome distributions, and η is the quantum efficiency of the amplification chain (Fig. 1A). In this theory, we neglect the effect of qubit decoherence and losses before amplification. In the limit of a perfectly efficient amplification (η = 1), we see that the length of the Bloch vector is unity, irrespective of outcome. The parameter $\overline{I}_m/\sigma$ can be identified as the apparent measurement strength because the measurement becomes more strongly projective as $\overline{I}_m/\sigma$ increases. It is given in terms of experimental parameters as $\overline{I}_m/\sigma = \sqrt{2\bar{n}\eta\kappa T_m}\sin(\vartheta/2)$, where $\vartheta = 2\arctan\chi/\kappa$.

The pulse sequence for determining measurement back-action is shown in Fig. 3A. We first strongly read out the qubit with a 240 ns, $\bar{n} = 5$ pulse and record the outcome, which will be used to prepare the qubit in the ground state by post-selection. Then, the qubit is rotated to the +*y* axis and measured with a variable measurement strength (T_m = 240 ns), and the outcome (I_m, Q_m) is recorded. The final, tomography, phase measures the *x*, *y*, or *z* component of the qubit Bloch vector with a strong ($\bar{n} = 5$, T_m = 240 ns) measurement pulse. To compensate for the finite

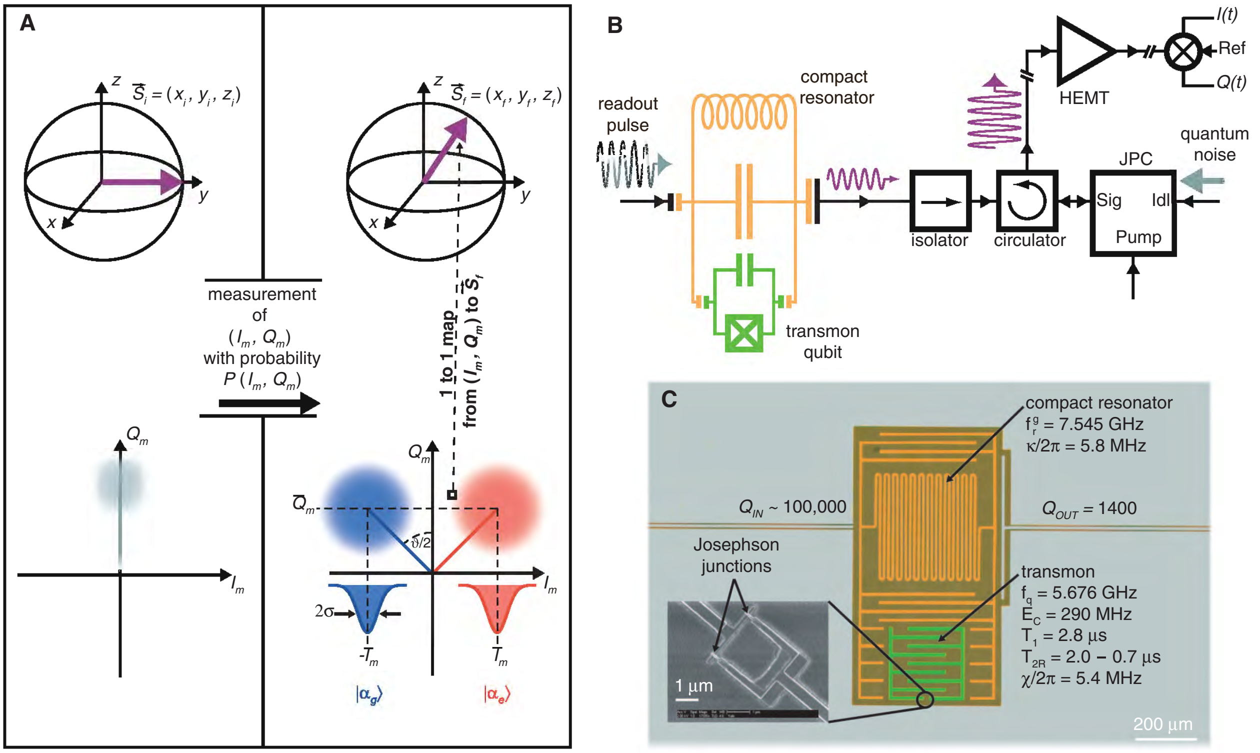

Fig. 1. (**A**) Bloch sphere representation of the effect on the qubit state of a phase-preserving measurement in a cQED architecture. After a measurement with outcome (I_m, Q_m), the qubit will be found in a final state $\vec{S}_f = (x_f, y_f, z_f)$, with I_m encoding information on the projection of the qubit state along *z* and corresponding back-action and Q_m encoding the other component of the back-action, which is parallel to $\hat{z} \times \vec{S}_i$. The measurement outcomes are Gaussian distributed, with $\overline{I}_m^2 + \overline{Q}_m^2 = \bar{n}\kappa T_m$. (**B**) Schematic of experiment mounted to the base plate of a dilution refrigerator. Readout pulses are transmitted through the strongly coupled port of the resonator, via an isolator and circulator, to the signal port (Sig) of a JPC. The idler port (Idl) is terminated in a 50 Ω load. The amplified signal output is routed via the circulator and further isolators (not shown) to a high electron mobility transistor (HEMT) amplifier operated at 4 K, and subsequently demodulated and digitized at room temperature. (**C**) False-color photograph of the transmon qubit in compact resonator with qubit and resonator parameters. Inset is a scanning electron micrograph of the center of the transmon showing a loop of two Al/AlOx/Al junctions that form an effective junction tunable by an external magnetic field.

readout strength and qubit temperature, trials with outcomes $|I_m/\sigma| < 1.5$ (corresponding to state purity < 99%) for the first and third measurements are discarded, as well as outcomes for the first measurement with the qubit in $|e\rangle$. To quantify the measurement back-action for a given measurement outcome (I_m, Q_m), the average final qubit Bloch vector, conditioned by the measurement outcome (I_m, Q_m), $(\langle X\rangle_c, \langle Y\rangle_c, \langle Z\rangle_c)$, is calculated versus outcome using the results of the tomography phase. These conditional maps of $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ were constructed using 201 by 201 bins in the plane of scaled measurement outcomes $(I_m/\sigma, Q_m/\sigma)$.

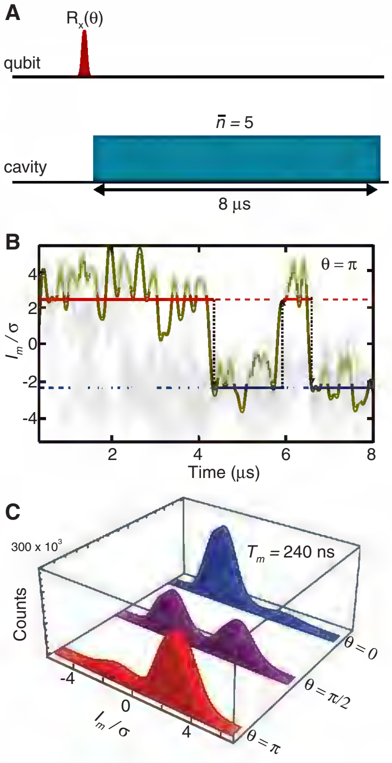

Fig. 2. (**A**) Pulse sequence for strong measurement. An initial qubit rotation $R_x(\theta)$ of θ radians about the x axis is followed by an 8-μs readout pulse with drive power such that $\bar{n} = 5$. (**B**) Individual measurement records. The data are smoothed with a binomial filter with a $T_m = 240$ ns time constant and scaled by the experimentally determined standard deviation (σ). Black dotted lines indicate 4σ deviation events. The qubit is initially measured to be in the excited state, and quantum jumps between excited and ground states are clearly resolved. The center of the ground- and excited-state distributions are represented as horizontal dotted lines. (**C**) Histograms of the initial 240-ns record of the readout pulse along I_m axis, for $\theta = 0$, $\pi/2$, π. Finite qubit temperature and T_1 decay during readout are visible as population in the undesired qubit state.

Results for four measurement strengths increasing by decades from $\bar{n} = 5 \times 10^{-3}$ to 5 are shown in Fig. 3B (see movie S1 of histograms and tomograms for all measurement strengths). The left column shows a 2D histogram of all scaled measurement outcomes recorded during the variable-strength readout pulse. At weak measurement strength, the ground- (left) and excited- (right) state distributions overlap almost completely. Their separation grows with increasing strength until they are well separated at $\bar{n} = 5$, which corresponds to the strong projective measurement shown in Fig. 1A. The rightmost columns show $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus the associated $(I_m/\sigma, Q_m/\sigma)$ bin. At weak measurement strength ($\bar{n} << 1$), the qubit state is only slightly perturbed, with all measurement outcomes corresponding to Bloch vectors pointing nearly along the $+y$ (initial) axis. However, gradients in $\langle X\rangle_c$ along the Q_m axis and $\langle Z\rangle_c$ along the I_m axis are visible, demonstrating the outcome-dependent back-action of the measurement on the qubit state. As the measurement strength increases, so does the back-action, as seen in the increase of the gradients in the $\langle X\rangle_c$ and $\langle Z\rangle_c$ maps (see fig. S2). When the measurement becomes strong, the qubit is projected to $+z$ for positive I_m ($-z$ for negative I_m), whereas $\langle X\rangle$ and $\langle Y\rangle$ go unconditionally to zero, as expected.

One of the key predictions of finite-strength measurement theory is that the statistics of the measurement process, in particular the apparent measurement strength in the I-quadrature (which can be determined experimentally from the statistics of the measurement outcomes), are sufficient to infer z_f for any apparent measurement strength or outcome (see Eq. 1). For weak measurement, where the back-action is symmetric along both x and z, the apparent measurement strength deter-

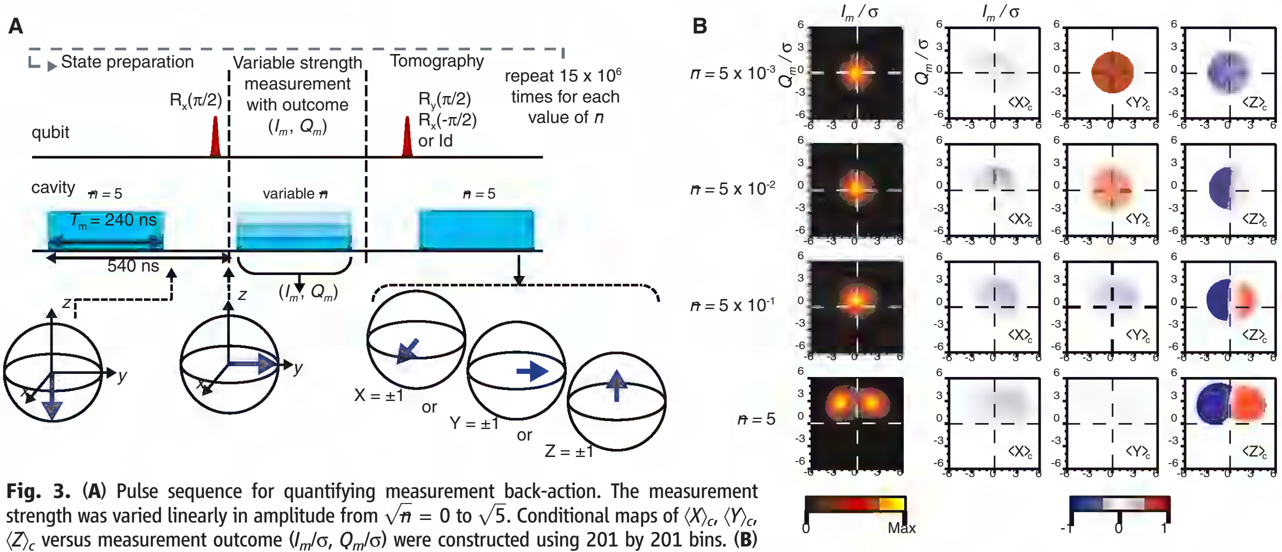

Fig. 3. (**A**) Pulse sequence for quantifying measurement back-action. The measurement strength was varied linearly in amplitude from $\sqrt{\bar{n}} = 0$ to $\sqrt{5}$. Conditional maps of $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus measurement outcome $(I_m/\sigma, Q_m/\sigma)$ were constructed using 201 by 201 bins. (**B**) Results are shown increasing by decades from $\bar{n} = 5 \times 10^{-3}$ to 5. The left column shows a 2D histogram of all scaled measurement outcomes recorded during the variable-strength readout pulse. The three rightmost columns are tomograms showing $\langle X\rangle_c$, $\langle Y\rangle_c$, $\langle Z\rangle_c$ versus the associated $(I_m/\sigma, Q_m/\sigma)$ bin.

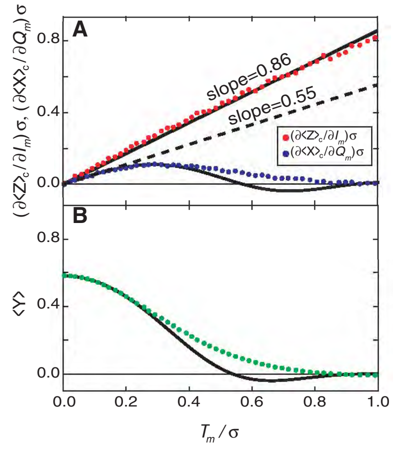

Fig. 4. Correlation between back-action and measurement outcome. (**A**) Experimental data for correlated back-action signal along z, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$, and along x, $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, evaluated at $(I_m, Q_m) = 0$, are plotted versus $\overline{I}_m/\sigma$. For weak measurement strength, the slopes at the origin (represented by solid and dashed line, for z and x, respectively) agree with theoretical predictions, including first-order corrections for T_1 and T_2. The solid curve is the full theoretical expression for the x back-action plotted with $\eta = 0.2$, $\overline{Q}_m = 1.28\ \overline{I}_m$, and $\exp(-\tau/T_2) = 0.58$. (**B**) Experimental data for unconditioned $\langle Y\rangle$ versus $\overline{I}_m/\sigma$. The data show the expected measurement-induced dephasing when the measurement outcome is not used to condition the perturbed qubit state. The dephasing rate is proportional to $(\overline{I}_m/\sigma)^2$, resulting in the apparent Gaussian dependence of $\langle Y\rangle$ versus $\overline{I}_m/\sigma$. The theoretical expression for $\langle Y\rangle$ versus $\overline{I}_m/\sigma$ with parameters listed above is shown as a solid curve.

mines the amplitude of the x back-action as well (see eq. 14 in the supplementary materials). In Fig. 4A, we quantitatively compare this prediction with our experimental result. The scaling coefficients relating measurement outcome to back-action along z, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$, and along x, $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, extracted from the tomograms at $I_m = Q_m = 0$, are plotted versus the apparent measurement strength extracted from the histograms, $\overline{I}_m/\sigma$ (see section 1.4 in the supplementary materials).

Both coefficients, $(\partial\langle Z\rangle_c/\partial I_m)\sigma$ and $(\partial\langle X\rangle_c/\partial Q_m)\sigma$, are predicted at $I_m = Q_m = 0$ to be equal to $\overline{I}_m/\sigma$; therefore, the data in Fig. 4A should have unity slope. However, finite T_1 and T_2 acting for a time τ reduce the state purity and the apparent back-action. To first order, the coefficients are modified to $(\partial\langle Z\rangle_c/\partial I_m)\sigma = (\overline{I}_m/\sigma)e^{-\tau/T_1}$ and $(\partial\langle X\rangle_c/\partial Q_m)\sigma \cong (\overline{I}_m/\sigma)e^{-\tau/T_2}$ for the z and x back-action, respectively. In our pulse sequence, $\tau \cong 380$ ns, predicting slopes of 0.87 ± 0.09 and 0.58 ± 0.06 for z and x, in excellent agreement with the experimentally determined slopes of 0.86 ± 0.01 and 0.55 ± 0.01. All further theoretical predictions are modified to reflect the effects of T_1 and T_2, following the description in eq. 2 in the supplementary materials. The black curve is the full theoretical dependence of $(\partial\langle X\rangle_c/\partial Q_m)\sigma = \overline{I}_m/\sigma \cos\{\overline{Q}_m\overline{I}_m/\sigma^2[(1-\eta)/\eta]\}e^{-\overline{I}_m^2/\sigma^2[(1-\eta)\eta]}e^{-\tau/T_2}$ using $\eta = 0.2$, the lowest value of η we extract from other measurements (see section 1.3 in the supplementary materials). We attribute the discrepancy between theory and data at high measurement strength to environmental dephasing effects due to finite T_2 and losses before the JPC. Additionally, we process the tomography results unconditioned by measurement outcome in Fig. 4B. Theory predicts $\langle Y\rangle = e^{-\overline{I}_m^2/\eta\sigma^2}\cos(\overline{I}_m\overline{Q}_m/\eta\sigma^2)e^{-\tau/T_2}$. This expression evaluated with $\eta = 0.2$ is shown as a black curve with the deviation for stronger measurements attributed to dephasing effects due to losses before amplification.

Similar experiments have studied measurement of the state of a microwave cavity by Rydberg atoms (*26*) and partial nonlinear measurement of phase qubits (*27*). Also, phase-sensitive parametric amplification has been used to implement weak measurement-based feedback (*18*). In our experiment, the ability to perform both weak and strong high-efficiency, QND, linear measurements within a qubit lifetime, coupled with our high-throughput and minimally noisy readout electronics, allows us to acquire 13.5 billion qubit measurements in ~28 hours, data that can be compared with complete theoretical predictions of the conditional evolution of quantum states under measurement. They provide strong evidence that the purity of the state would not decrease in the limit of a perfect measurement, even when the signal is processed by a phase-preserving amplifier.

Our experiment illustrates an alternate approach to the description of a quantum measurement. In the case of a qubit, a finite-strength QND measurement can be thought of as a stochastic operation whose action is unpredictable but known to the experimenters after the fact if they have a quantum-noise–limited amplification chain. Any final state is possible, and the type of quantity measured, combined with the measurement strength, determines the probability distribution for different outcomes. This partial (i.e., finite strength) measurement paradigm is not inconsistent with the usual view of projective (i.e., infinite strength) measurement. Rather, projective measurement is the limiting case of the broader class of finite strength measurements.

The finite-strength measurement predictions that we have verified have immediate applicability to proposed schemes for feedback stabilization and error correction of superconducting qubit states. Whereas classical feedback is predicated on the idea that measuring a system does not disturb it, quantum feedback has to make additional corrections to the state of the system to counteract the unavoidable measurement back-action. The measurement back-action that is the subject of this paper thus crucially determines the transformation of the measurement outcome into the optimal correction signal for feedback. Our ability to experimentally quantify the back-action of an arbitrary-strength measurement thus provides a dress rehearsal for full feedback control of a general quantum system.

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Supplementary Materials

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Materials and Methods
Supplementary Text
Figs. S1 to S3
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Movie S1

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Quantum Back-Action of an Individual Variable-Strength Measurement

M. Hatridge, S. Shankar, M. Mirrahimi, F. Schackert, K. Geerlings, T. Brecht, K. M. Sliwa, B. Abdo, L. Frunzio, S. M. Girvin, R. J. Schoelkopf and M. H. Devoret

Science **339** (6116), 178-181.
DOI: 10.1126/science.1226897

Tracking Quantum Evolution

The actual process of measuring a quantum system has an effect on the result making the outcome unpredictable. Using a superconducting qubit placed in a microwave cavity, **Hatridge *et al.*** (p. 178) found that a series of partial measurements on a quantum system left the system in a pure state. Looking at the record of the actual measurements allowed the final state of a superconducting-based quantum system to be determined accurately. Such control is crucial for achieving full feedback control of a general quantum system.

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APPENDIX 1004-H

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2013 Citations of Hatridge

Source Document
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APPENDIX 1005-A

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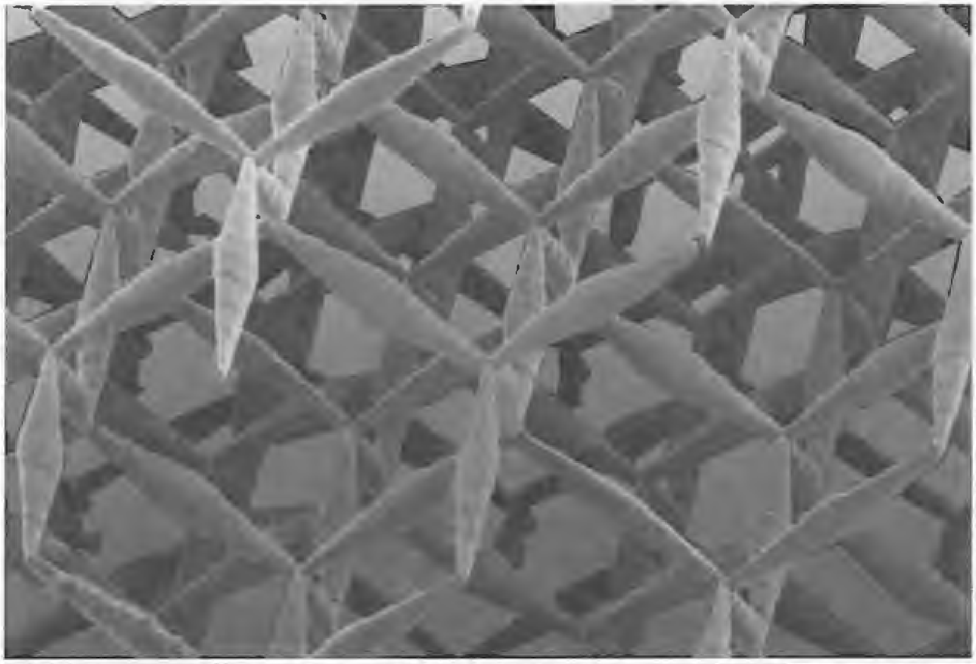

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Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters

K. Geerlings, S. Shankar, E. Edwards, L. Frunzio, R. J. Schoelkopf, and M. H. Devoret
Department of Applied Physics, Yale University, New Haven, Connecticut 06520-8284, USA

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Applications in quantum information processing and photon detectors are stimulating a race to produce the highest possible quality factor on-chip superconducting microwave resonators. We have tested the surface-dominated loss hypothesis by systematically studying the role of geometrical parameters on the internal quality factors of compact resonators patterned in Nb on sapphire. Their single-photon internal quality factors were found to increase with the distance between capacitor fingers, the width of the capacitor fingers, and the resonator impedance. Quality factors were improved from 210 000 to 500 000 at T = 200 mK. All of these results are consistent with our starting hypothesis. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4710520]

Improving the internal quality factor of on-chip microwave superconducting resonators is a key development for quantum information processing and photon detectors.[1,2] The internal quality factor at single-photon powers, Q_i, of particular interest for quantum information applications, is observed to be 10–100 times lower than high-power quality factors.[3–7] Ideas for increasing resonator Q_i include switching from conventional metals like Nb or Al to alloys such as TiN or NbTiN,[4,5,8,9] using interface layers of SiN,[4] etching the substrate between traces,[5] depositing metal under special conditions,[10] or using low loss substrates.[7] Results from these experiments have generated the hypothesis that resonator Q_i is limited by a surface two level system (TLS) distribution.[5,6,8,11]

Motivated by a previous study that showed that the Q_i of coplanar waveguide (CPW) resonators increases with increasing gap,[11] we extended the idea of geometrical optimization to compact resonators.[3,6,9] Compact resonators, as shown in Figure 1, consist of a meander inductor in parallel to an interdigitated capacitor. Their small size makes them an ideal element for multi-qubit processors. While compact resonators have been shown to have similar Q_i as the more widely used CPW resonators,[6] they permit more design choices. Here, we show that by changing parameters linked to the surface participation ratio, we have optimized these resonators to achieve an improvement by a factor of 2.4 ± 0.2. We have thus been able to reach a Q_i of 500 000 at a resonator temperature of 200 mK, our point of reference. In this paper, we prefer to quote Q_i at this temperature because we believe that even when the sample box is anchored to a colder plate, resonator temperatures substantially below 200 mK may not be reached reliably. We return to this point later in the paper.

We measure the quality factor of our compact resonators by performing a microwave transmission experiment. Coupling to the resonators is achieved by placing the resonator in a cutout in the ground plane of a CPW feedline, relying on the mutual inductance between the feedline and the resonator inductor. This coupling introduces a second quality factor, the coupling quality factor Q_c. Typical values of Q_c that we designed ranged from 20 000 to 150 000. As a control experiment, we have designed and measured resonators with Q_c as high as 1.6×10^6 with no change in Q_i. As shown in Refs. 10 and 12, the measurement of microwave transmission S_{21} through the feedline as a function of frequency ω provides access to Q_i. Although simple resonator models predict a symmetric S_{21} response, the measured response is typically asymmetric due to reflections in the feedline circuit, as shown in Figure 2. Nevertheless, the theory of the arbitrary linear circuit model with one pole and perfect transmission at zero frequency shows that the asymmetric response can still be fit to separately extract Q_c and Q_i by introducing an extra parameter $\delta\omega$ characterizing the asymmetry. We thus analyze our data with Eq. (1), where the total quality factor, Q_0, is defined as $1/Q_0 = 1/Q_i + 1/Q_c$.

$$S_{21} = 1 - \frac{\frac{Q_0}{Q_c} - 2iQ_0\frac{\delta\omega}{\omega_0}}{1 + 2iQ_0\frac{\omega-\omega_0}{\omega_0}}. \qquad (1)$$

This expression is exactly equivalent to Eq. (13) in Ref. 12 and to Eq. (3) in Ref. 10 with a different parametrization.

In our measurement setup, we cool 4 chips at once in a dilution refrigerator with a base temperature of 80 mK (sample temperature of approximately 200 mK). Since each of our chips contained one feedline coupled to 6 independent resonators at frequencies between 5 and 8 GHz, 24 resonators were tested in each cooldown. The chips were wirebonded to a printed circuit board with Arlon dielectric and placed inside a copper sample box. The box was mounted inside a magnetic shield (Amuneal A4K) and attenuators were installed totaling 50 dB on the input microwave line. All four chips were excited simultaneously using a passive 4-way microwave splitter. The output line consisted of two Pamtech 4–8 GHz isolators on the mixing chamber, a 12 GHz low-pass filter on the 700 mK stage, and a Caltech HEMT amplifier at the 4 K stage. The measurement line was switched between the 4 chips using a microwave switch (Radiall R573423600) mounted on the mixing chamber.

Our resonators were fabricated using etched Nb on c-plane sapphire. Before metal deposition, the sapphire surface was prepared by a 60 s ion-milling using a 3 cm

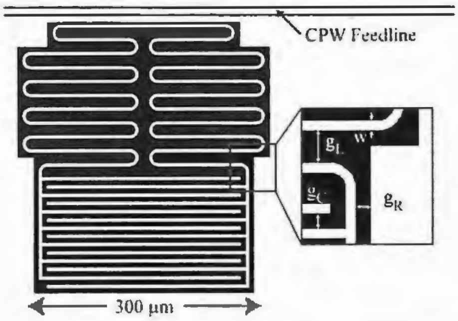


FIG. 1. Schematic of compact resonator and inset showing resonator parameters. The compact resonator is coupled inductively to the CPW feedline. The parameters indicated in the inset directly affect the participation of the insulator and metal surfaces to the reactive elements of the resonator.

Kaufmann source that shoots 500 eV argon ions at our wafer. Our source operates at a flow rate of 4.25 sccm and a pressure of about 10 μTorr, generating a current density of 0.67 mA/cm^2. A 200 nm layer of Nb was then dc magnetron sputtered on the wafer. Photolithography was performed by patterning directly onto S1808 resist using a 365 nm laser. After development, the Nb was etched using a 1:2 mixture of Ar: SF$_6$ at 10 mTorr for 3 min. The wafer was then diced into individual chips for measurement.

In the systematic variation of compact resonator parameters, we chose to optimize the following parameters shown pictorially in Figure 1: the gap g_C between two adjacent capacitor fingers, the distance g_L between two adjacent inductor meanders, the distance g_R between the resonator and the surrounding ground plane, and the width w of the resonator traces. In addition, we also varied the characteristic impedance Z$_0$ of the resonator. This set of parameters is relevant for surface losses.

We formed a benchmark set of resonators with parameter values: $g_C = 10\,\mu$m, $g_L = 20\,\mu$m, $g_R = 10\,\mu$m, $w = 5\,\mu$m, and Z$_0$ = 100Ω. Resonators with this set of parameters will now be called "design A" resonators. We measured 25 design A resonators with an average Q_i of 160 000 (±20 000) and a maximum of 210 000 at single-photon power. Additionally, one chip with 6 resonators inexplicably had quality factors ranging from 40 000 to 70 000, much lower than the rest; we did not include this chip in the benchmark. Q_i typically increased to around 1×10^6 at a "high" power corresponding to an average of 10^8 photons in the resonator. The resonant frequency typically decreased as the temperature passed below 1.3 K, consistent with TLS loss.[11] These results are consistent with the hypothesis that our benchmark Q_i is controlled by surface losses.

We measured 24 geometrical variants of design A, with each "mutant" resonator having only one parameter value that is changed. For example, the mutant values of g_C were: 3, 5, 20, 30, and 40 μm. The results of the mutant resonators are shown in Figure 3; percent changes in Q_i are given with respect to the design A resonator benchmark.

For g_C, small values lead to lower Q_i, and larger values lead to higher Q_i. The effect of changing g_L on Q_i is at least a factor of three smaller than for g_C. Thus, the gaps where electric fields are present (the capacitor and not the inductor), partially control Q_i, consistent with a surface loss mechanism coupled to the electric field. Similarly, Q_i increases for larger w, again consistent with surface loss, since wider traces lead to decreasing electric field strength at surfaces. Next, we find that Q_i drops by roughly 25% if $g_R \geq 50\,\mu$m, suggesting that the ground plane prevents electric fields from reaching lossy materials such as the copper box or printed circuit board (PCB) dielectric. Lastly, the trend indicating that larger values of Z$_0$ are beneficial to Q_i appears to contradict the usual hypothesis that dissipative mechanisms have a constant tanδ. The results for g_C, g_L, and w are all consistent with a loss dominated by surface electric field participation.

We chose two new sets of parameters from these results with the goal of improving the Q_i. Resonators with these parameters are called designs B and C resonators. Design B values were chosen to be relatively modest changes from design A, while design C values were chosen to maximize Q_i. Design B

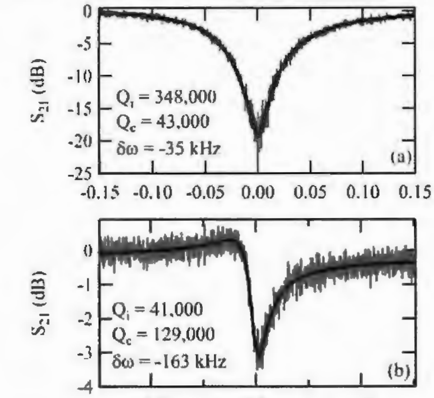
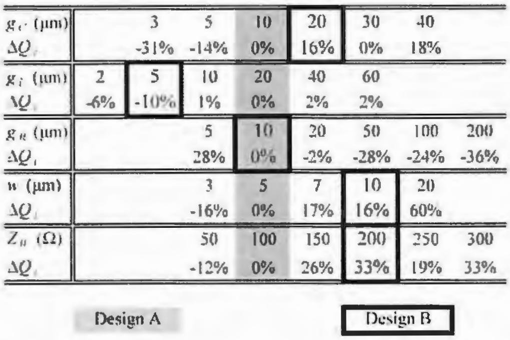


FIG. 2. Two extreme examples of resonator response curves fit with Eq. (1). Responses typically fall in between (a) symmetric and (b) strongly asymmetric about the resonant frequency.



g_C (μm)		3	5	10	20	30	40	
ΔQ_i		-31%	-14%	0%	16%	0%	18%	
g_L (μm)	2	5	10	20	40	60		
ΔQ_i	-6%	-10%	1%	0%	2%	2%		
g_R (μm)			5	10	20	50	100	200
ΔQ_i			28%	0%	-2%	-28%	-24%	-36%
w (μm)			3	5	7	10	20	
ΔQ_i			-16%	0%	17%	16%	60%	
Z_0 (Ω)			50	100	150	200	250	300
ΔQ_i			-12%	0%	26%	33%	19%	33%

Design A
Design B

FIG. 3. Dependence of Q_i on parameter values. The changes in Q_i for a given mutant value are reported in reference to the average Q_i (160 000) of design A with positive values representing improvements. The shaded column indicates the design A value of that parameter; ΔQ_i in this column is zero by definition. The square in each row with a bold border shows the value chosen for design B. Parameters for design C cannot easily be shown on this figure as explained in the main text.

chosen values were: $g_C = 20\,\mu\text{m}$, $g_L = 5\,\mu\text{m}$, $g_R = 10\,\mu\text{m}$, $w = 10\,\mu\text{m}$, and $Z_0 = 200\Omega$. Resonator size increases rapidly with g_L since the larger Z_0 requires twice the inductance. Therefore, to limit the overall size to roughly $700\,\mu\text{m} \times 500\,\mu\text{m}$, we reduced g_L to $5\,\mu\text{m}$, despite the fact that this may lower Q_i by 10%. Design C chosen values were: $g_C = 80\,\mu\text{m}$, $g_L = 10\,\mu\text{m}$, $g_R = 10\,\mu\text{m}$, and $Z_0 = 300\Omega$. Note that g_C was chosen beyond the range of tested mutant design A resonators. Also in design C, the trace width w was different for the capacitor ($40\,\mu\text{m}$) and inductor ($10\,\mu\text{m}$) halves in order to benefit from the larger capacitor width while keeping the resonator from being larger than $1000\,\mu\text{m} \times 1000\,\mu\text{m}$.

The results of all 49 design A, 73 design B, and 28 design C resonators are shown in Figure 4. Designs B and C each show significantly higher Q_i than design A, with design C on average better than design B. While there exists a spread in Q_i for each design, we observed an overall increase in the range of measured Q_i. The maximum/median Q_i rose from 210 000/160 000 for design A to 370 000/280 000 for design B and 500 000/380 000 for design C.

When ion-milling was not performed, the maximum/median Q_i was reduced to 50 000/30 000 for design A and 190 000/80 000 for design B (design C was not measured without ion-milling). For both designs A and B, the median quality factor was reduced by roughly a factor of four when ion-milling was left out during fabrication. Since this type of cleaning affects only the substrate-air interface and substrate-metal interface, we infer that these two surfaces participate strongly. The dominating participation of these surfaces has also been predicted by simulation.[13] This Q_i dependence on ion-milling also suggests that while the geometry controls the resonator sensitivity to the surface loss mechanism, the surface preparation determines the strength of the loss.

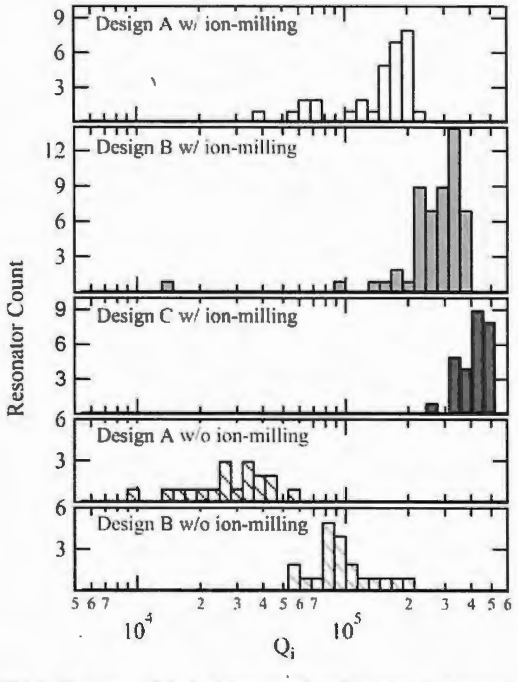


FIG. 4. Histograms of single-photon internal quality factors for designs A, B, and C resonators with ion-milling and designs A and B without ion-milling. Qi improves steadily from design A to B to C. For both designs A and B resonators, when ion-milling is not performed, Q_i is roughly a factor of four lower.

When re-measured in a dilution refrigerator with a lower base temperature (15 mK), we found that resonator Q_i drops by roughly a factor of 2, which is consistent with TLS loss.[11] We have measured similar resonators coupled to a qubit and found that their temperatures would not reach below 50 mK, as also reported by other groups.[14] However, directly measuring the linear resonator temperature without a qubit to add nonlinearity is outside the scope of this study. Reassuringly, the increase of Q_i from design A to B to C resonators remains even at lower temperatures; indicating that the geometric variation affects only the sensitivity to loss, not the absolute strength.

In conclusion, we have shown that the Q_i of compact resonators depends strongly on geometrical factors controlling where electric fields are stored. In addition, substrate surface preparation prior to metal deposition is crucial. Using our results indicating that surface loss is dominant, we have been able to increase, at our point of reference temperature of 200 mK, the maximum internal quality factor of our resonators from 210 000 to 500 000.

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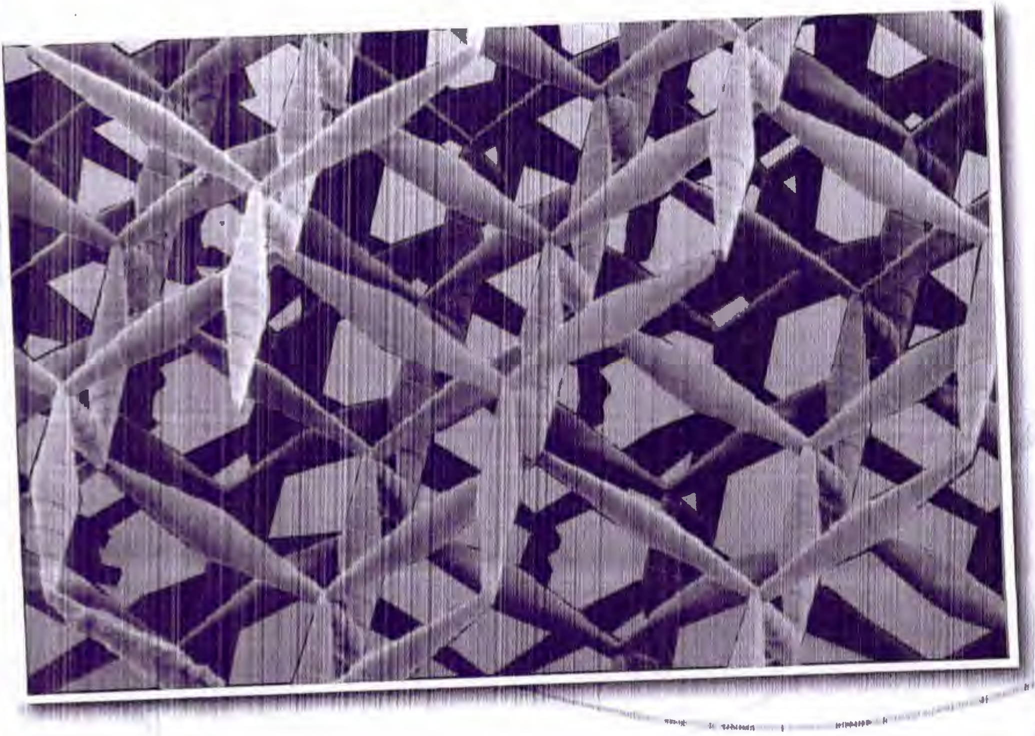

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Early Citations to Geerlings

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Geerlings, K., Shankar, S., Edwards, E., Frunzio, L., Schoelkopf, R. J., & Devoret, M. H. (2012). Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters. *Applied Physics Letters*, *100*(19), 192601.

Selected Citing Documents 2012 – 2013 (in chronological order)

D. H. Slichter, R. Vijay, S. J. Weber, S. Boutin, M. Boissonneault, J. M. Gambetta, A. Blais, I. Siddiqi. (2012) Measurement-Induced Qubit State Mixing in Circuit QED from Up-Converted Dephasing Noise. Physical Review Letters 109:15. Online publication date: 9-Oct-2012.

Nikos Daniilidis, Hartmut Häffner. (2013) Quantum Interfaces Between Atomic and Solid-State Systems. Annual Review of Condensed Matter Physics 4:1, 83-112. Online publication date: 1-Apr-2013.

J. M. Hornibrook, E. E. Mitchell, D. J. Reilly. (2013) Suppressing Dissipative Paths in Superconducting Coplanar Waveguide Resonators. IEEE Transactions on Applied Superconductivity 23:3, 1501604-1501604. Online publication date: 1-Jun-2013.

A.F. Qasrawi. (2013) Fabrication of Al/MgO/C and C/MgO/InSe/C tunneling barriers for tunable negative resistance and negative capacitance applications. Materials Science and Engineering: B 178:12, 851-856. Online publication date: 1-Jul-2013.

Josephine B. Chang, Michael R. Vissers, Antonio D. Córcoles, Martin Sandberg, Jiansong Gao, David W. Abraham, Jerry M. Chow, Jay M. Gambetta, Mary Beth Rothwell, George A. Keefe, Matthias Steffen, David P. Pappas. (2013) Improved superconducting qubit coherence using titanium nitride. Applied Physics Letters103:1, 012602. Online publication date: 3-Jul-2013.

Daniilidis, N., Gorman, D. J., Tian, L., & Haffner, H. (2013). *Quantum information processing with trapped electrons and superconducting electronics (Open Access, Publisher's Version)*. University of California Berkeley Berkeley United States. Published July 5, 2013.

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Pozar, David M. (2012). Microwave Engineering. 4th ed. Wiley.

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Doldán, R., Ginés, A. J., & Rueda, A. (February 2013). Inductor characterization in RF LC-VCOs. In *2013 IEEE 4th Latin American Symposium on Circuits and Systems (LASCAS)*(pp. 1-4). IEEE.

Ayed, A., Dubois, T., Levant, J. L., & Duchamp, G. (July 2014). Méthode RFIP: vers une meilleure caractérisation de l'immunité des circuits intégrés. In *CEM 2014, 17ème Colloque international et exposition sur la Compatibilité Electromagnétique*.

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Mesegar Dorta, D. (July 2015). Diseño, simulación y medida de un amplificador basado en estructura balanceada en la banda de 2000 MHz.

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Title:	Coplanar waveguide circuits, components, and systems / Rainee N. Simons.
Imprint:	New York : Wiley-Interscience, c2001.
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Series:	Wiley series in microwave and optical engineering
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Simons, R. N. (2004). *Coplanar Waveguide Circuits, Components, And Systems*. John Wiley & Sons.

Selected Citations, August 2002 – September 2003 (in chronological order)

Lee, J. C. (August 2002). *Magnetic flux measurement of superconducting qubits with Josephson inductors* (Doctoral dissertation, Massachusetts Institute of Technology).

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substrates. In *2003 IEEE International Symposium on Electromagnetic Compatibility, 2003. EMC'03.*(Vol. 1, pp. 296-299). IEEE.

Polyakov, A., Mendes, P. M., Sinaga, S. M., Bartek, M., Rejaei, B., Correia, J. H., & Burghartz, J. N. (May 2003). Processability and electrical characteristics of glass substrates for RF wafer-level chip-scale packages.

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Zheng, G., Kishk, A. A., Glisson, A. W., & Yakovlev, A. B. (September 2003). Slot antenna fed by a CPW line with tapered transition. *Microwave and Optical Technology Letters*, *38*(6), 465-467.

Allen, C. M., Eldek, A. A., Elsherbeni, A. Z., & Smith, C. E. (October 2003). A wideband coplanar-waveguide-fed multi-slot antenna for radar applications. *Microwave and Optical Technology Letters*, *39*(1), 24-27.

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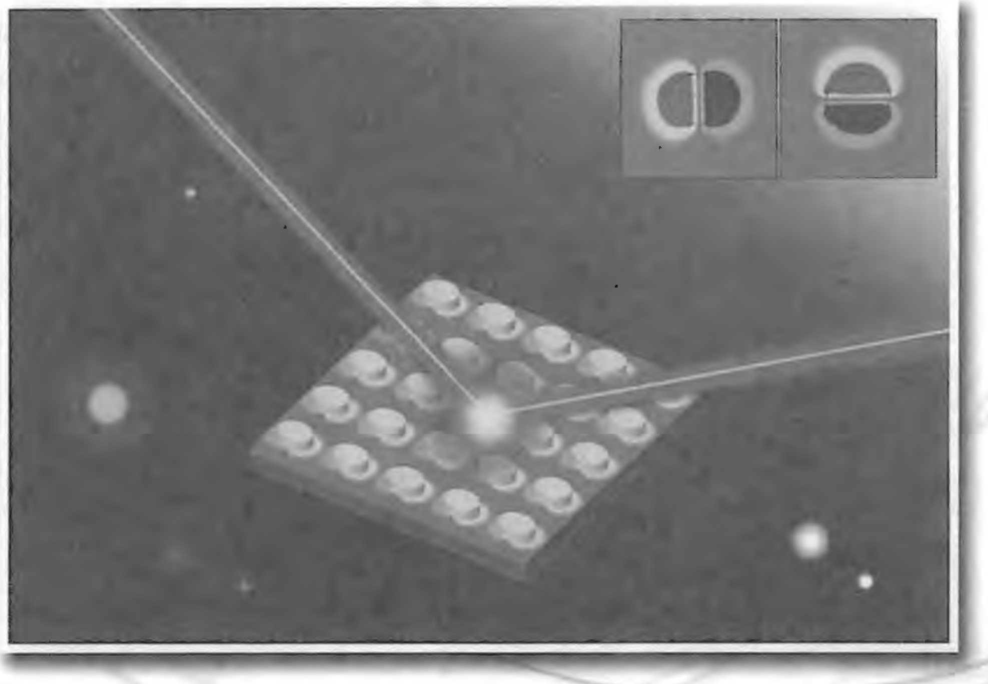

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Identifying capacitive and inductive loss in lumped element superconducting hybrid titanium nitride/aluminum resonators

Michael R. Vissers,[a] Martin P. Weides,[b] Jeffrey S. Kline, Martin Sandberg, and David P. Pappas[c]
National Institute of Standards and Technology, Boulder, Colorado 80305, USA

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We present a method to systematically locate and extract capacitive and inductive losses in superconducting resonators at microwave frequencies by use of mixed-material, lumped element devices. In these devices, ultra-low loss titanium nitride was progressively replaced with aluminum in the inter-digitated capacitor and meandered inductor elements. By measuring the power dependent loss at 50 mK as the Al/TiN fraction in each element is increased, we find that at low electric field, i.e., in the single photon limit, the loss is two level system in nature and is correlated with the amount of Al capacitance rather than the Al inductance. In the high electric field limit, the remaining loss is linearly related to the product of the Al area times its inductance and is likely due to quasiparticles generated by stray IR radiation. At elevated temperature, additional loss is correlated with the amount of Al in the inductance, with a power independent TiN-Al interface loss term that exponentially decreases as the temperature is reduced. The TiN-Al interface loss is vanishingly small at the 50 mK base temperature. [http://dx.doi.org/10.1063/1.4730389]

Superconducting resonators with low loss are of great interest for photon detection[1] and quantum computation.[2] Hybrid devices, using different materials in specific parts of the resonant circuit, allow the alteration of intrinsic materials properties such as the superconducting gap, radiation cross-section, and capacitive and inductive loss within the resonators to optimize the entire circuit. Locating whether the residual loss sources are inductive or capacitive in nature is of considerable relevance. So far, most resonator studies have been done on single films in either coplanar waveguide resonators (CPWs) or lumped element circuits.[3–9] The distributed capacitive and inductive elements in CPWs complicate the analysis, including the interpretation and location of the measured resonator loss. More specifically, the loss contributions of the capacitive δ_C and inductive δ_L parts are inherently linked and cannot be investigated separately in distributed element devices like CPWs. Further, even in lumped element devices typically both the capacitor and the inductor are usually formed by the same material, with limited research done on mixed-material devices with interfaces. In this work, we address these issues by studying lumped element resonators with components of mixed materials. However, we note that the lumped element approach is an approximation, depending on the exact current and voltage distributions in the resonant circuit. Therefore we distinguish between and investigate the actual capacitive and inductive losses in the specific elements as each element has contributions from both.

In a resonator the energy stored is E_{total}, where on average the capacitive energy equals the inductive energy. The measured resonator loss, $\delta_{\text{meas.}}$, is the measurement of the relative energy loss $\Delta E/E_{\text{total}}$ per cycle time and defined as

$$\delta_{\text{meas.}} = \frac{\Delta E}{2\pi E_{\text{total}}} = \frac{\Delta E_C + \Delta E_L}{2\pi E_{\text{total}}} = \delta_C + \delta_L . \qquad (1)$$

The conventional resonator characterization is done by measuring the resonator loss and frequency under power and temperature sweeps respectively. The capacitive loss, δ_C, is believed to be due to the presence of two-level systems (TLSs)[10] and is inferred from both the power dependent loss and resonance frequency temperature dependence, as reviewed in Ref. 11. The decreased loss at higher powers is naturally explained by TLS loss, which scales with the electric field, E, as

$$\delta_{\text{meas.}} \propto \frac{1}{\sqrt{1+\left(\frac{E}{E_s}\right)^2}} + \delta_{\text{P.I.}} . \qquad (2)$$

where E_s is a saturation electric field for TLS loss.[10] In addition to TLS loss, there is also a power-independent background loss, $\delta_{\text{P.I.}}$, typically attributed to the inductive loss, δ_L, caused, for example, by quasiparticles or radiative loss. The power independent loss typically limits the total resonator loss, causing the measured loss' electric field dependence to deviate from $1/E$ at high electric fields.[11]

In this paper, we present a complementary characterization method to determine the capacitive and inductive losses in resonators by use of lumped elements made up of different materials. Devices fabricated from different materials allow us to vary the T_c and the different microwave loss factors of the constituent components highlighting their contributions to the loss of the different circuit elements. We tested this approach using titanium nitride and aluminum on Si. In addition to having a $T_c = 4.5 - 5$ K, optimally grown TiN on Si

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[a] Electronic mail: michael.vissers@NIST.gov.
[b] Current address: Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany.
[c] Electronic mail: david.pappas@NIST.gov.

is one of the lowest loss resonator materials with 3 : 2 μm CPWs having a low electric field, low temperature, loss factor $\sim 1 \times 10^{-6}$, and high field loss $< 1 \times 10^{-7}$.[8] Evaporated Al, used in qubits, e.g., Refs. 12 and 13, has a $T_c = 1.2$ K. However when grown on Si, the oxide surface and intermixing at the substrate interface give rise to relatively high loss $\delta_{\mathrm{int}} > 10^{-5}$,[14] providing a contrast to the lower loss TiN. The lower superconducting gap in Al facilitates quasiparticle creation from elevated temperatures or infrared radiation.[15,16] In addition to determining the capacitive and inductive loss contributions, we also probe the Al-TiN material interface, which has not been investigated in previous single layer studies. This interface appears to have a small, but non-zero contribution to the loss at elevated temperature, but is negligible at the base temperature. This work highlights the feasibility of engineered lumped element resonators made from two or more materials whose specific capacitive or inductive properties are optimally tuned to take advantage of the constituent elements.

For our devices, 100 nm thick TiN was first grown at 500 °C on an intrinsic silicon wafer[8] and patterned using optical lithography and a Cl based reactive ion etch. While fluorine etched and deeply trenched TiN resonators have one of the lowest loss factors,[17] the chlorine etch chosen in this work gave a better defined silicon interface without trenches complicating the subsequent Al liftoff. However, the Cl based etch does cause slightly increased internal resonator loss of $\delta_{\mathrm{int.}} \approx 5 \times 10^{-6}$.[18] The exposed silicon surface was then radio frequency (RF) plasma cleaned before the aluminum evaporation. The RF treatment might increase the loss in the exposed silicon and TiN regions. Finally we deposited a 100 nm thick aluminum layer with e-beam evaporation which was patterned with a lift-off process. The Al film overlapped the TiN film forming 2 μm × 2 μm contacts which were also RF cleaned to give a clean interface. The films were patterned into frequency multiplexed lumped element resonators with varying degrees of TiN and Al participation. The internal wiring and microwave measurement lines were made from TiN for all devices. The resonators were capacitively coupled to a microwave coplanar waveguide feedline, permitting the loss extraction from transmission measurements of the S_{21} parameters, and the internal loss of a specific resonator, $\delta_{\mathrm{int.}}$, is given by

$$\delta_{\mathrm{int}} = \delta_{\mathrm{meas.}} - \delta_{\mathrm{coup.}}, \tag{3}$$

where $\delta_{\mathrm{coup.}}$ is the loss due to the capacitive coupling to the feedline.

The resonators are formed by an inductor (meandered 2 μm wide wire with 2 μm gap) being symmetrically shunted by two inter-digitated capacitors (IDCs) (2 μm wide fingers and gaps), see Fig. 1. The footprint per resonator is 400 μm × 450 μm. The superconductors' width and gap were chosen to be similar to the features in conventional coplanar waveguide resonators. One resonator electrode is galvanically connected to the ground plane formed by TiN. Around the resonator are flux holes in the ground plane to inhibit trapped vortices.[19] This resonator design yields intrinsic loss factors similar to those measured on otherwise identical coplanar waveguide resonators. On the first design, the hybrid capacitor device, the TiN capacitor was progressively replaced with Al while the inductor was formed by TiN. On the second design, the hybrid inductor device, the inductor had varied Al/TiN fractions, while the capacitor was always formed by TiN. Comparing simulations with our measurements of the resonant frequency for the different TiN fractions, we determined a kinetic inductance of 0.4 pH/square for the TiN film.

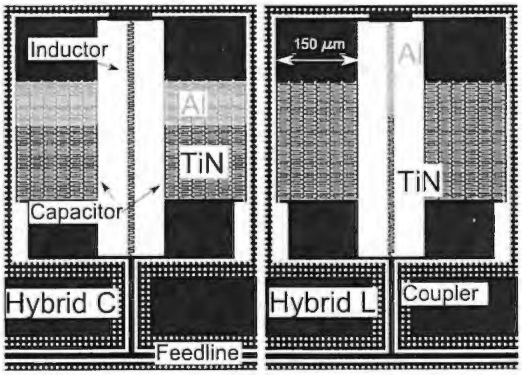

FIG. 1. Drawn resonator designs *hybrid capacitor* (left) and *hybrid inductor* (right) with 3 : 2 TiN : Al fraction. The TiN (black) inter-digitated capacitors and meandered inductors are progressively replaced with Al (green). The frequency multiplexed resonators are capacitively coupled to the feedline.

Illustrations of the resonator designs are shown in Fig. 1. Each design was integrated as frequency multiplexed resonators coupled to a common feedline. In total, for each design, we measured one all-TiN, one fully Al hybrid, and four mixed resonant elements with various Al/TiN fractions. The IDC capacitance was designed to be 600 fF, and the geometric meandered inductance was nominally 0.74 nH for the hybrid inductor devices. Frequency multiplexing of the resonators was a natural consequence of the kinetic inductance of the different TiN fraction. For the hybrid capacitor devices, the geometric inductances were varied (0.64–0.86 nH). The self-capacitance of the inductor and inductance of the capacitor plays an important role in the loss of the entire structure. Using calculations from an electromagnetic field solver we estimate the self-capacitance of the meandered inductor as 18% of the total capacitance and the self-inductance of the IDC as about 3% of the total inductance. These calculations agree well with the measured resonance frequencies, f_r, of 5.5 and 6.9 GHz, though we obtain better fits if we assume the capacitor has 4% of the inductance. The resonator impedance is around 30–35 Ω.

The devices were measured in an adiabatic demagnetization refrigerator with a base temperature of 50 mK. The aluminum sample box holding the resonator chip was magnetically shielded with outer paramagnetic and inner niobium superconducting shields. The openings for the two microwave connectors were minimized to reduce incoming stray light. Measurements were performed with a vector network analyzer. The measurement chain was comprised of a combination of attenuators (room temperature and cold) and a low pass filter on the input line to achieve the appropriate power level and eliminate radiation at the device input port (total attenuation −100 dB). On the output side of the sample box there was a microwave isolator and high- and low-pass filters before a high electron mobility transistor amplifier at the 4 K 2nd stage, with an additional room temperature amplifier. The power stored in the resonators was calculated in terms of both electric field and microwave photon numbers in the standard manner from the attenuation and measured resonance parameters.[20] Transmitted power measurements were taken as a function of frequency, power and temperature for all resonators. All traces were taken at low enough field such that the measured resonances remained symmetric. We measured over almost 4 decades of electric field (thus 7 decades in photon numbers) and at low temperature, i.e., with a base temperature T of 50 mK, and a resonance frequency of 6 GHz, $T < \hbar\omega_r/2k_B$ and the TLSs are not thermally saturated.

The electric field dependence of $\delta_{\rm int.}$ at 50 mK is shown in Fig. 2. The intrinsic loss, $\delta_{\rm int.}$, is constant for low electric fields, before starting to drop off above the critical field. The loss is highest below the critical field, i.e., in the single photon regime, referred to here as δ(SP), shown at about 1 V/m, due to the presence of unsaturated TLSs. The highest loss was observed for the hybrid device with the all-Al capacitor, with $\delta_c^{\rm Al}(SP) = 55 \pm 5 \times 10^{-6}$, while the lowest loss was observed for the all-TiN devices, with $\delta^{\rm TiN}(SP) = 5 \pm 1 \times 10^{-6}$. As expected, the loss curves of the hybrid Al-TiN devices fall between these two bounds.

An alternative method of determining loss due to TLSs is done with a temperature sweep. In this method, $\delta^{\rm TiN}(TLS)$ is extracted at high power from the resonant frequency shift with temperature. This occurs because the off-resonant TLSs become thermally saturated. However, this technique can only be used when there are no other temperature dependent sources of loss, e.g., quasiparticles. In particular, for Al, a superconductor with a relatively low T_c, the underlying condition, $T \ll T_c$ with resonator temperature T, does not hold. Hence, we can only use this technique for the all-TiN resonator. From this measurement, we obtained $\delta_C^{\rm TiN} \approx 5 \pm 1 \times 10^{-6}$, in agreement with the power-dependent loss shown in Fig. 2.

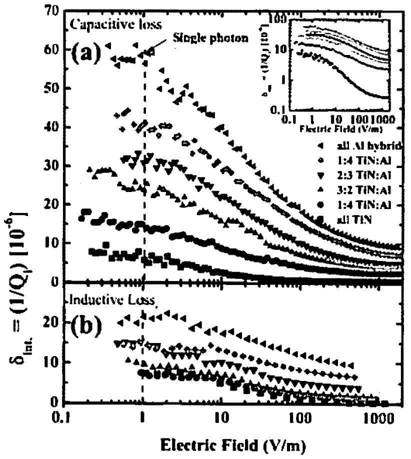

FIG. 2. Loss for (a) hybrid capacitor and (b) hybrid inductor resonators as a function of the electric field in the capacitor. The inset in (a) is the hybrid C loss plotted on a log scale to illustrate its characteristics at high power. The single photon levels are indicated. When Al is added to the capacitor, there is a greater increase in loss than if Al is added to the inductor. At higher fields the resonator loss reaches a minimum at an internal resonator power[1,20] ≈ −40 dBm.

In quantum information applications, the very low electric field, i.e., single photon regime, loss is important. However, this measured loss is composed of both power dependent loss terms, e.g., TLSs, as well as any power independent loss arising from quasiparticles, etc. In order to separate these loss terms, we fit to the loss at the highest powers and subtract a constant loss such that the electric field dependence of loss matches Eq. (2), i.e., proportional to $1/E$.[11] We now have two loss terms, $\delta_{\rm TLS}$ and $\delta_{\rm P.I.}$, which we then can independently investigate the source of their loss.

If the TLS loss was solely in the inductor or capacitor, we would expect to only measure a change when Al is substituted in that element. However, the circuit is not composed of completely lumped elements and there is finite capacitance in the meandered inductor amounting to 18% of the total capacitance of the circuit. When the loss is plotted vs. Al capacitive fraction in Fig. 3(a), i.e., the 100% Al fraction hybrid C device has 82% Al capacitive fraction while the 100% Al fraction hybrid L device has 18% Al capacitive fraction, the extracted TLS losses for all devices show good agreement with a linear fit to the hybrid C data. The hybrid L devices do exhibit slightly less loss than expected from the fit; but while the meandered inductor has the same 2 μm spacing as the IDC, the exact electric field distribution and corresponding filling factor will be different for the meandered inductor versus the IDC and we should not expect perfect agreement. The fitted line from the hybrid Al devices closely intersects with the measured all-TiN devices indicating that any additional loss due to the TiN-Al interface is small, beneath the ~1 × 10^{-6} uncertainty in our measurement.

We also observe increased loss at high electric fields in devices that contain more Al. This loss is not related to just the percentage of Al capacitance or inductance in isolation. It fits better to the product of the Al inductance and area than to any single circuit parameter. The small amount of inductance in the IDCs, ~4% of the total, is compensated by their 17× larger area than the meander. The relationship between the power independent loss at the lowest temperatures

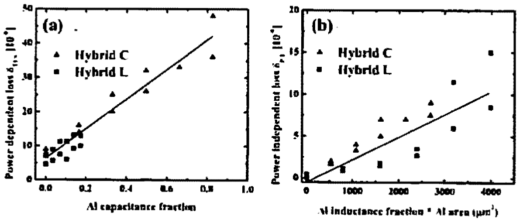

FIG. 3. (a) The power dependent loss $\delta_{\rm TLS}$ at 50 mK bath temperature versus Al capacitive fraction. As the TiN is replaced by the Al in the hybrid L (square) or hybrid C (triangle) devices, additional power dependent loss is measured and agrees with a linear fit. (b) The power independent loss, $\delta_{\rm P.I.}$, versus the product of the Al inductance fraction × area.

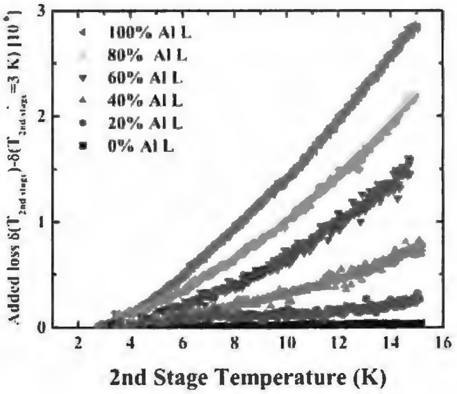

FIG. 4. The added loss measured in the hybrid L resonators as the 2nd stage temperature of the ADR is increased. The cold stage remains below 100 mK, which as shown in Fig. 5 does not add more loss. Greater loss is measured in devices which have larger Al percentages.

suggests that its source is likely due to quasiparticles generated by stray IR light emanating from the 4 K stage.[15,16] This is further supported by our measurements with better absorptive materials inside the box that reduced the power-independent loss term by up to 50% for the all Al devices.

Furthermore, we made measurements similar to those first done by Baselmans[21] to study the effect of IR radiation on the devices. The ADR pulse tube was turned off, and the 2nd stage was allowed to rise in temperature to 15 K over several minutes. During this time the FAA cold stage temperature remained below 100 mK implying that any additional thermal quasiparticle generation in the Al would be minimal. As is shown in Fig. 4, increasing the 2nd stage temperature increased the measured loss in all devices containing Al, with greater loss correlated with greater Al percentage. The all-TiN device was practically unchanged, with the loss increasing by $<1 \times 10^{-7}$. While we cannot rule out the effect of microscopic roughness and morphology or fabrication damage, based on the similarity in the Al RF properties to other lightly shielded Al on Si measurements[4,14] and the discussion above we believe that stray IR light is the dominant loss term contributing to the greater power independent loss in the Al hybrid devices.

The loss in the hybrid devices can also be studied as a function of temperature. In order to separate the temperature dependent loss from any potential TLS loss, the devices were measured at very high power where the TLS loss is saturated. The measured temperature dependent losses are shown in Fig. 5(a). As the temperature is increased in all devices, the loss rises exponentially. Devices with more Al have greater loss at all temperatures. This loss is enhanced when the Al is placed in the meandered inductor region. In Fig. 5(b), the loss at 0.5 K in both hybrid L and C devices is plotted and agrees with a linear fit to the percentage of Al's inductance in the circuit. As the temperature dependent loss is in the inductance, it is likely due to thermally activated quasiparticles in the Al.

While the loss in the hybrid C devices at any particular temperature increases with the amount of Al, at higher temperatures the slope of the measured temperature dependent loss vs Al percentage does not intercept the all TiN device at zero Al percentage, i.e. additional loss is measured whenever there exists an Al-TiN interface in the device. Figure 6(a) shows the temperature dependent loss vs Al fraction for the hybrid C devices at temperatures between 0.2 and 0.9 K.

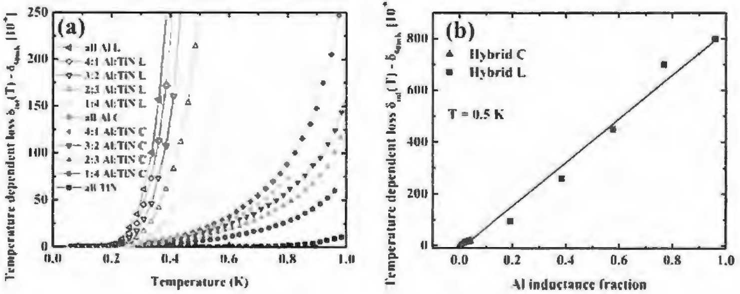

FIG. 5. (a) Temperature dependent loss $\delta_{int}(T) - \delta_{50mK}$ of the hybrid C (closed symbols) and hybrid L (open symbols) devices as a function of temperature. The devices are measured at high power and the 50 mK bath temperature loss is subtracted to reduce the contribution of any other loss terms. The lines are a guide to the eye. (b) The temperature dependent loss of all hybrid L and C resonators at 0.5 K versus Al inductance fraction agrees well to a linear fit.

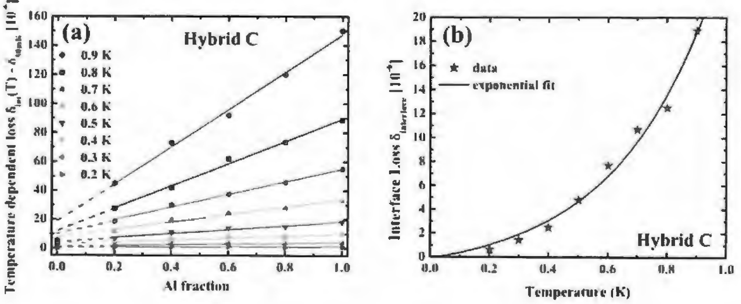

FIG. 6. (a) The temperature dependent loss $\delta_{int}(T) - \delta_{50mK}$ (symbols) in the hybrid C devices versus Al fraction at different temperatures between 0.2-0.9 K. In the hybrid capacitor devices the fit (solid lines) to the temperature dependent loss of the 5 hybrid devices with Al is linear in Al fraction at all temperatures, but the extrapolations of these fits (dashed lines) do not intersect with the loss from the pure TiN device. (b) The interface loss, $\delta_{interface}$, from the y-intercept from (a), plotted vs temperature with an exponential fit (solid line).

While the 5 devices with Al agree closely with linear fits (solid lines) to the Al fraction, the extrapolations of these fits (dashed lines) do not intersect with the measured loss of the all TiN resonator. This implies that there is a relatively small, but additional, loss term whenever any Al is incorporated into the circuit, corresponding to the existence of interfaces between the Al and the TiN. This interfacial or excess loss corresponding to the presence of Al, increases with temperature and is plotted in Fig. 6(b) along with an exponential fit the data. The exponential increase in loss with temperature suggests quasiparticles, and the activation energy scale is similar to the TiN superconducting gap energy, though this interface loss is much greater than the measured temperature dependent loss of the all-TiN device. We speculate that the presence of the TiN-Al interface permits the lower gap Al to act like a quasiparticle trap for the TiN.[22] While quasiparticles in the Al cannot transit to the TiN due to its larger energy gap, quasiparticles generated in the TiN can traverse the interface to the Al, be trapped there and perhaps generate additional loss by subsequently generating additional quasiparticles in the Al. Presumably a similar interfacial effect would be visible in the hybrid L devices, but the comparatively small interface loss term would difficult to distinguish from the roughly 100× larger loss measured in the Al inductors.

In summary, we have shown that the measured losses as a function of power and temperature can be varied by the replacement of Al for TiN in different parts of the resonant circuit. When the lossier Al is placed in capacitive parts of the circuit, the increased TLS loss indicates that the TLSs couple to the capacitive parts of the circuit. However while the Al in the inductor has much less TLS loss, it leads to additional power independent and temperature dependent loss terms. The power independent loss is proportional to the product of the Al area × inductance and likely arises from quasiparticles generated by stray light from the 4 K stage. The temperature dependent loss is related to the Al inductance and is likely from thermally activated quasiparticles. While there is an incremental interface loss between the TiN and Al at higher temperatures, $\delta_{\mathrm{interface}} \leq 1 \times 10^{-6}$ at the base temperature. This lack of interface loss does not preclude future hybrid devices from having low losses. This work suggests that future devices can be designed with their individual circuit elements optimally tuned for their purpose, e.g., low TLS loss, superconducting gap, kinetic inductance, detection efficiency, etc., specifically tuned.[12,23]

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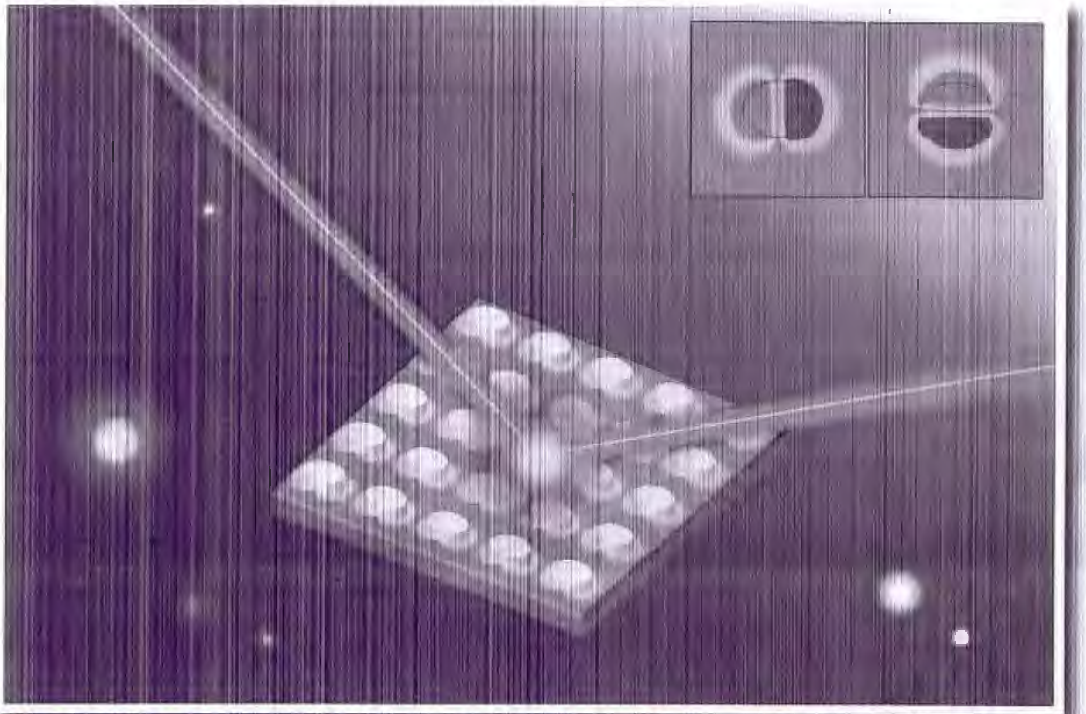

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Dressel, M. (April 2013). Electrodynamics of metallic superconductors. Advances in Condensed Matter Physics, 2013.

Pracht, U. S., Heintze, E., Clauss, C., Hafner, D., Bek, R., Werner, D., ... & Gorshunov, B. (April 2013). Electrodynamics of the superconducting state in ultra-thin films at THz frequencies. IEEE Transactions on Terahertz Science and Technology, 3(3), 269-280.

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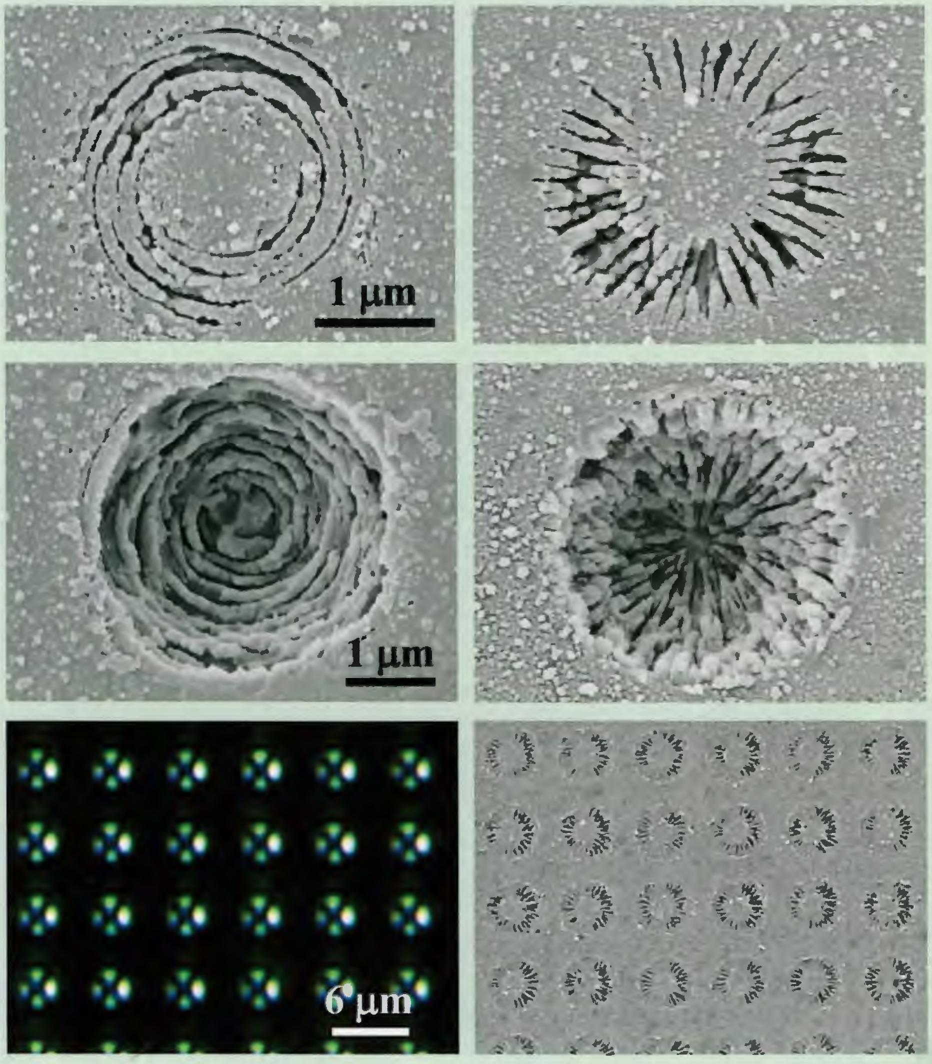

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Measurement-Induced Nonlocality

Shunlong Luo* and Shuangshuang Fu
Academy of Mathematics and Systems Science, Chinese Academy of Sciences, 100190 Beijing, People's Republic of China

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We interpret the maximum global effect caused by locally invariant measurements as measurement-induced nonlocality, which is in some sense dual to the geometric measure of quantum discord [Dakic, Vedral, and Brukner, Phys. Rev. Lett. **105**, 190502 (2010)]. We quantify measurement-induced nonlocality from a geometric perspective in terms of measurements, and obtain analytical formulas for any dimensional pure states and $2 \times n$ dimensional mixed states. We further derive a tight upper bound to measurement-induced nonlocality in general case. The physical significance of measurement-induced nonlocality is discussed in the context of correlations, entanglement, quantumness, and cryptographic communication.

DOI: 10.1103/PhysRevLett.106.120401 PACS numbers: 03.65.Ud, 03.65.Ta, 03.67.Mn

Nonlocality is a controversial, perplexing, and yet fundamental theme in the physical (e.g., gravitational and quantum-theoretical) descriptions of nature, and has many intriguing and subtle manifestations [1]. Classically, the principle of locality dictates that physical effect propagates by a knowable physical mechanism and is limited by the speed of light, and nonlocality usually refers to instantaneous influence of an object on a distant one in gravitation, resulting in violation of this principle. Quantum mechanically, nonlocality arises from at least two different scenarios: One is the Aharonov-Bohm effect related to quantum potential [2], and the other is quantum entanglement involving the Einstein-Podolsky-Rosen type correlations and the so-called "spooky-action-at-a-distance" [3]. Quantum nonlocality usually refers to correlations that cannot be described by any local hidden variable theory, and has been widely studied by means of Bell's inequalities [4–8]. It is intimately related to, but different from, other strange phenomena such as entanglement and quantumness [9].

In this Letter, by nonlocality, we will understand, in a most broad way, as some kind of correlations. This is more general than the conventionally mentioned quantum nonlocality related to entanglement or violation of Bell's inequalities. It is desirable to quantify nonlocality from as many aspects as possible in order to reveal its meaning and properties from different angles. As a particular approach to this program, we will try to quantify nonlocality from a geometric perspective based on von Neumann measurements.

One motivation for this investigation comes from the general consideration of exploiting nonlocality for the purpose of processing quantum information. Many quantum tasks such as superdense coding [10], teleportation [11], remote state preparation [12–15], etc., involve local measurements and comparison between the pre- and post-measurement states. Quantification of nonlocality may shed novel and deep insight into these tasks and their extensions. Moreover, since a bipartite state can be used as a quantum communication channel, and in order to study various capacities of such channels, it may be helpful to quantify the nonlocal resources therein.

Our intuitive setup for quantifying measurement-induced nonlocality is as follows. Consider a bipartite quantum state ρ shared by two parties a and b with respective system Hilbert spaces H^a and H^b. In order to probe the nonlocal feature in ρ, we perform local von Neumann measurements on party a, and investigate the difference between the overall pre- and post-measurement states. To capture the genuine nonlocal effect of measurements on the state, we require the measurements do not disturb the local state $\rho^a := \mathrm{tr}_b \rho$ (partial trace). Based on this idea, we may define the measurement-induced nonlocality (somewhat in contrast to the measurement-induced disturbance [16]) as

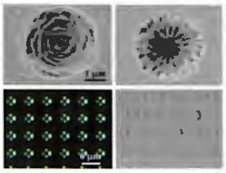
$$N(\rho) := \max_{\Pi^a} \|\rho - \Pi^a(\rho)\|^2, \qquad (1)$$

where the max is taken over the von Neumann measurements $\Pi^a = \{\Pi^a_k\}$ *which do not disturb* ρ^a *locally*, that is, $\sum_k \Pi^a_k \rho^a \Pi^a_k = \rho^a$, and $\|\cdot\|^2$ may be any reasonable norm on states depending on particular applications and contexts. Here we take $\|X\|^2 := \mathrm{tr} X^\dagger X$ to be the Hilbert-Schmidt norm. This quantity is an indicator of the global effect caused by locally invariant measurements [17], which in turn is inspired and motivated by superdense coding consideration and related issues [10,18,19]. Our main purpose here is to illustrate this quantity and evaluate it for several important cases.

The measurement-induced nonlocality $N(\rho)$ is fundamentally different from, and in some sense dual to, the geometric measure of quantum discord [20–22]

$$D(\rho) := \min_{\Pi^a} \|\rho - \Pi^a(\rho)\|^2,$$

which was first introduced in Ref. [20]. Here the min is over *all* local von Neumann measurements Π^a, in sharp contrast to the max over locally invariant ones used in defining the measurement-induced nonlocality $N(\rho)$ in Eq. (1). The geometric measure of quantum discord is



Polarization-sensitive micro-optic structures produced inside fused silica substrates with femtosecond laser pulses. Bottom: A cross-polarized light view (left) of a 2D array of polarization imprints in bulk material (right). [Cyril Hnatovsky, Vladlen Shvedov, Wieslaw Krolikowski, and Andrei Rode, Phys. Rev. Lett. **106**, 123901 (2011)]

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PRL **106,** 120501 (2011) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2011

Decoupling a Cooper-Pair Box to Enhance the Lifetime to 0.2 ms

Z. Kim,[1,2] B. Suri,[1,2] V. Zaretskey,[1,2] S. Novikov,[1,2] K. D. Osborn,[1] A. Mizel,[1] F. C. Wellstood,[2,3] and B. S. Palmer[1]

[1]*Laboratory for Physical Sciences, College Park, Maryland 20740, USA*
[2]*Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[3]*Joint Quantum Institute and Center for Nanophysics and Advanced Materials, College Park, Maryland 20742, USA*

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We present results on a circuit QED experiment in which a separate transmission line is used to address a quasilumped element superconducting microwave resonator which is in turn coupled to an Al/AlO$_x$/Al Cooper-pair box charge qubit. With our device, we find a strong correlation between the lifetime of the qubit and the inverse of the coupling between the qubit and the transmission line. At the smallest coupling we measured, the lifetime of the Cooper-pair box was $T_1 = 200\ \mu$s, which represents more than a twentyfold improvement in the lifetime of the Cooper-pair box compared with previous results. These results imply that the loss tangent in the AlO$_x$ junction barrier must be less than about 4×10^{-8} at 4.5 GHz, about 4 orders of magnitude less than reported in larger area Al/AlO$_x$/Al tunnel junctions.

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The use of high quality factor superconducting resonators has many applications in solid-state and atomic physics including microwave kinetic inductance detectors [1] and in the quantum information sciences in the form of circuit quantum electrodynamics [2–4]. Understanding and minimizing the sources of energy loss in these systems has a general technological importance for all of these topics to improve the sensitivities of microwave kinetic inductance detectors and coherence times for qubits. For superconducting qubits, energy loss has been attributed to various mechanisms, including discrete charge two-level fluctuators coupled to the qubit [5,6], dielectric loss [7], nonequilibrium quasiparticles [8], and lossy higher order electromagnetic modes of the electromagnetic field which are coupled to the qubit [9].

Here, we report the observation of relaxation times in a Cooper-pair box (CPB) that are 1 order of magnitude larger than previously reported. Our design builds on the circuit quantum electrodynamics approach [2,10,11]: We coupled the CPB to a resonator and used perturbations of the resonator frequency to read out the state of the CPB over one octave in frequency. In contrast to previous work, however, we used a lumped element design for the resonator and addressed it by using a separate transmission line. In our experiment, we find that a key reason for obtaining the long lifetimes was decoupling the CPB from the transmission line.

Our CPB consists of a small (100 nm × 2 μm × 30 nm thick) superconducting Al island connected to superconducting leads by two ultrasmall Josephson junctions [see Fig. 1(c)]. By applying a dc voltage V_g that is capacitively coupled to the island with capacitance C_g^*, we can change the system's electrostatic charging energy, and by varying the magnetic flux through the superconducting loop, we can modulate the critical current I_0 and therefore the Josephson energy $E_J = \hbar I_0/2e$. Restricting consideration to the two lowest levels, the Hamiltonian of the CPB can be written as

$$H_{\mathrm{CPB}} = \frac{\hbar\omega_a}{2}\sigma_z, \tag{1}$$

where $\hbar\omega_a = \sqrt{[4E_c(1-n_g)]^2 + E_J^2}$, $E_c = e^2/2C_\Sigma$ is the electrostatic charging energy constant, $n_g = C_g^* V_g/e$ is the reduced gate voltage, and σ_z is a Pauli spin matrix.

We coupled our CPB to a quasilumped element resonator [Fig. 1(a)] and measured the CPB at the charge degeneracy point while it was tuned over one octave in frequency. When the CPB is coupled to a resonator and the detuning between the qubit and the resonator ($\Delta = \omega_a - \omega_r$) is large compared to the strength of the coupling g between them, the Hamiltonian for the combined system is approximately

$$H \cong \hbar\left(\omega_r + \frac{g^2}{\Delta}\sigma_z\right)\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\omega_a}{2}\sigma_z, \tag{2}$$

where $\hbar g = (eC_g/C_\Sigma)\sqrt{\hbar\omega_r/2C}$, C is the capacitance of the resonator with resonance frequency ω_r, and C_g is the capacitance between the resonator and the island of the CPB [10,11]. Depending on the state of the qubit, Eq. (2) predicts that the bare resonance frequency ω_r is shifted by $\pm g^2/\Delta$. For $g/2\pi = 5$ MHz and $\Delta/2\pi = 1$ GHz, we find that the maximum dispersive frequency shift of the resonator's resonance frequency is $g^2/2\pi\Delta = 25$ kHz.

To measure these small frequency shifts we have designed and fabricated, using photolithographic lift-off techniques, a high-Q superconducting resonator made from a 100 nm thick film of Al on a c-plane sapphire wafer. The resonator consists of a coplanar meander-line inductor (~ 2 nH) and an interdigital capacitor (~ 400 fF) coupled to a transmission line [see Fig. 1(a)]. The resonance frequency of our resonator was $\omega_r/2\pi = 5.44$ GHz,

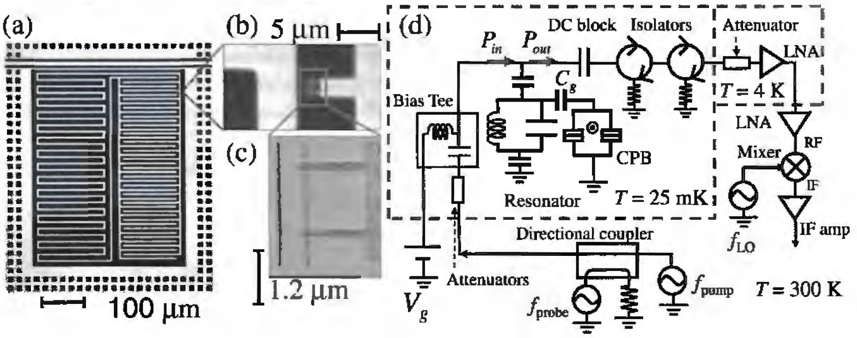

FIG. 1 (color online). (a) Optical image of a quasilumped element resonator coupled to a transmission line and surrounded by a ground plane. White regimes are aluminum, and black regimes are sapphire. (b) Optical image of the CPB close to the interdigital capacitor. (c) Scanning electron micrograph of the CPB. (d) Schematic of the measurement setup. Two microwave tones are sent to the device on the mixing chamber through microwave lines and attenuators at different temperatures. On the mixing chamber the microwave tones are combined with a dc voltage before the device. After the device the signal passes through two isolators, is amplified at both 4 and 300 K, mixed to a smaller intermediate frequency, and then digitized on an oscilloscope.

the loaded quality factor was $Q_L = 22\,000$, and the internal quality factor was $Q_i = 32\,000$. Subsequently, the CPB was fabricated by using e-beam lithography and double-angle evaporation (with an oxidation in between the two evaporations) to form the small Josephson junctions [12]. We used a bilayer of MMA(8.5)MMA copolymer (mixture of polymethyl methacrylate and 8.5% methacrylic acid) and ZEP520A (methylstyrene/chloromethyl acrylate copolymer) as the electron beam resist and the 30 nm thick Al island and 50 nm thick Al leads were deposited in an electron beam evaporator [see Figs. 1(b) and 1(c)].

The device was packaged in an rf-tight Cu box and bolted to the mixing chamber of an Oxford Instruments Kelvinox 100 dilution refrigerator. To reduce Johnson-Nyquist noise from higher temperatures, we used cold attenuators on the input microwave line and two isolators on the output line [see Fig. 1(d)]. The input microwave power had 10 dB of attenuation at 4 K, 20 dB at 0.7 K, and 30 dB on the mixing chamber at 25 mK. On the output line, both isolators on the mixing chamber had a minimum isolation of 18 dB between 4 and 8 GHz. The output microwave signal was amplified with a high-electron-mobility transistor amplifier sitting in the He bath. To allow a dc gate voltage bias to be applied to the island of the CPB from the transmission line, a bias tee was placed on the transmission line before the device and a dc block was placed on the transmission line after the device [see Fig. 1(d)].

Figure 2(a) shows a plot of the transition spectrum of the CPB qubit. This spectrum was taken by measuring the phase of the transmitted microwaves at the resonator's bare resonance frequency ($f_r = 5.44$ GHz) while sweeping the dc gate voltage and stepping the frequency of a second microwave source from 6.2 to 8.4 GHz. When the second microwave source is resonant with the transition between the two lowest states of the CPB, the CPB is excited. This causes a change in ω_r [see Eq. (2)] and a change in the phase of the transmitted signal. For these measurements the average number of photons in the resonator was $\bar{n} = 20$ photons. From fitting this spectrum, we extract $E_c/h = 6.24$ GHz and $E_J/h = 6.35$ GHz. Using these parameters and the measured dispersive shift ($g^2/2\pi\Delta \simeq 27$ kHz), we extracted the coupling between the resonator and the CPB: $g/2\pi = 5$ MHz.

To measure Rabi oscillations, we applied magnetic flux to set $E_J/h = 6.15$ GHz, dc biased the gate voltage at the charge degeneracy point $n_g = 1$, and delivered a short pulse of microwaves at $f = 6.15$ GHz while continuously monitoring the phase of the resonator with an average of $\bar{n} = 20$ photons. Figure 2(b) shows a false color plot of the measured phase (which has been calibrated in terms of the probability of occupancy of the excited state) as a function of time after sending the pulse and as a function of the length of the pulse. Figure 2(c) presents a line cut through 2(b): we see clear driven oscillations of the state of the qubit.

Figure 2(d) shows a plot of the probability P_e of occupying the excited state as a function of time after sending a π pulse to the qubit at $f = 6.15$ GHz and $n_g = 1$. For $P_e > 5\%$, the relaxation is well fit by an exponential with a decay time of $T_1 = 30$ μs. We also varied the Josephson energy from a maximum of $E_J/h = 19$ GHz and measured T_1 at the charge degeneracy point over one octave in the CPB transition frequency, from 3.8 to 8.5 GHz [black squares in Fig. 3(b)]. While $T_1 \sim 30$ μs for frequencies above f_r, we discover that the CPB attains a striking lifetime of $T_1 = 200$ μs below f_r at $f = 4.5$ GHz.

Some of the qualitative features in Fig. 3(b) can be understood. In particular, the depressions in T_1 at $f = 4.18$ GHz and $f = 5.67$ GHz correlate to changes in the measured transmission of microwaves through the transmission line [see Fig. 3(a)] and are likely due to the packaging of our device ($f = 4.18$ GHz) or imperfections in a microwave component ($f = 5.67$ GHz). Also, the dip near

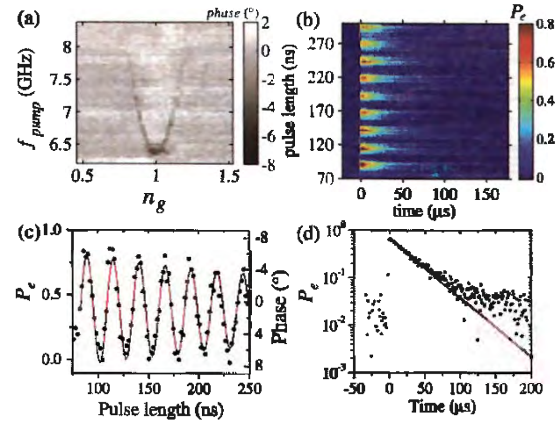

FIG. 2 (color). (a) Measured spectrum of the CPB. The gray-scale plot shows the change in phase of the transmitted microwaves at the probe frequency as a function of the pump frequency and n_g. (b) Rabi oscillation of the CPB qubit for microwave drive at $f = 6.15$ GHz. (c) Line cut of (b) along the pulse length at a measurement time of 2 μs. The maximum measured population in the excited state was about 80%. From the fit (red curve), the extracted Rabi frequency was 39 MHz. (d) Energy relaxation measurement of the CPB from the excited state. The red line shows a fit with $T_1 \simeq 30$ μs.

$f_r = 5.44$ GHz is consistent with enhanced spontaneous emission at the resonator frequency due to the Purcell effect [see the dashed blue curve in Fig. 3(b)] [9].

Next, we studied the coupling between the qubit and the microwave drive to understand the steady change in T_1 below f_r. At several values of f, we measured the change in the frequency f_{Rabi} of the Rabi oscillations with microwave drive voltage V. The red triangles in Fig. 3(b) show dV/df_{Rabi} versus f. This quantity indicates how decoupled the transmission line is from the qubit; when dV/df_{Rabi} is large, the qubit responds only weakly to a change in V, and when dV/df_{Rabi} is small, the qubit responds strongly to a change in V. While the simple model for our system [Fig. 1(d)] does not predict this behavior of the coupling, we note that the coupling is changing near and between additional resonances in the system which can produce a nontrivial dependence of dV/df_{Rabi} on f. We find that we can achieve good agreement between the experimental dV/df_{Rabi} and a theoretical calculation that augments the simple circuit of Fig. 1(d) with an additional LC circuit which is coupled to the transmission line and the qubit to model the microwave packaging resonance at $f = 4.18$ GHz.

A close relationship between T_1 and the decoupling dV/df_{Rabi} is evident in the figure. If we assume that the qubit is capacitively coupled to a $Z_0 = 50\ \Omega$ quantum dissipative environment at the input and output microwave lines, then the decay rate is given by [13]

$$T_1^{-1} = \left(\frac{df_{\mathrm{Rabi}}}{dV}\right)^2 8\pi^2 Z_0 h f. \qquad (3)$$

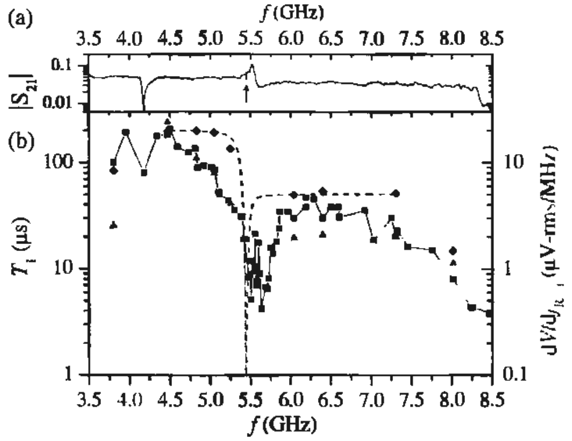

FIG. 3 (color online). (a) Plot of the ratio of the transmitted output voltage before the mixer in Fig. 1 to input voltage (S_{21}) versus frequency through the system. The arrow at 5.44 GHz identifies the resonance of the resonator. (b) Log plot of measured T_1 versus frequency (filled squares) and model for T_1 (filled diamonds) based on the measured coupling to quantum noise from 50 Ω. The dashed blue curve shows the contribution to loss from coupling to the resonator plus an additional decay rate of $T_1^{-1} = 5 \times 10^3$ s^{-1} below f_r and $T_1^{-1} = 2 \times 10^4$ s^{-1} above f_r. Right axis: Inverse of the measured coupling (Rabi frequency divided by applied rms voltage) between the transmission line and the CPB versus f (red filled triangles).

The filled diamonds in Fig. 3(b) show that Eq. (3) with an additional unknown fixed decay rate of $T_1^{-1} = 5 \times 10^3$ s^{-1} is in reasonably good qualitative agreement with the data (filled squares). This relationship suggests that decoupling the qubit from the noisy transmission line in our experiment was essential to allowing T_1 to reach 30 μs at most values of f and to attain 200 μs at $f = 4.5$ GHz.

The measured lifetime also places a bound on charge noise in the CPB. If charge noise is the dominant mechanism producing relaxation, then the spectral density of charge noise S_Q at positive frequencies is related to T_1 at the charge degeneracy point by [13–15]

$$S_Q(+f) = \left(\frac{e\hbar}{2E_c}\right)^2 \frac{1}{T_1}. \qquad (4)$$

Using Eq. (4) and the measured value of T_1 at 4.5 GHz, we get an upper bound on the spectral density of charge noise of $S_Q(f = 4.5\ \mathrm{GHz}) \leq 10^{-18}\ e^2/\mathrm{Hz}$. This level of charge noise is approximately an order of magnitude smaller than the bound measured by Vion *et al.* [16]. If we assume that S_Q has a $1/f$ dependence, then the symmetrized *classical* spectral density of charge noise at 1 Hz would be approximately $S_Q(f = 1\ \mathrm{Hz}) = 2(10^{-4})^2\ e^2/\mathrm{Hz}$, a value that is 2 orders of magnitude smaller than is typically measured at low frequencies [17,18] and similar to the best values reported in stacked single electron transistors [19].

Our T_1 measurements also place a bound on dielectric loss in the Josephson junctions. If T_1 is limited by dissipation in the junction, then the effective resistance of the tunnel junctions is related to the charge noise S_Q by

$$R = \frac{2\hbar}{\omega S_Q} = \frac{T_1}{C_\Sigma}\left(\frac{4E_c}{E_J}\right). \quad (5)$$

At $E_J/h = 4.5$ GHz, where $T_1 = 200\ \mu$s, this yields $R \sim 3 \times 10^{11}\ \Omega$. If this dissipation were due to dielectric loss in the amorphous AlO_x tunnel junction barrier, then one would find $\tan\delta = (R\omega C_\Sigma)^{-1} = 4 \times 10^{-8}$, which appears to be 4 orders of magnitude smaller than most amorphous dielectrics at both low temperatures and low microwave powers [7]. A possible explanation is that the loss is due to a few discrete two-level fluctuators in the ultrasmall junctions. Spectroscopic measurements on CPB devices have shown anomalous avoided level crossings with splitting sizes on the order of 50 MHz and decay rates due to the two-level fluctuator on the order of 10 $\mu\mathrm{s}^{-1}$ [6]. If we take these parameters and assume that the two-level fluctuator resonance is detuned by 2 GHz from the CPB resonance, then the T_1 from a single fluctuator would be approximately 160 μs.

Another metric of charge noise can be found from dephasing measurements. To minimize dephasing from photons in the resonator [10], the power at f_r was pulsed on only after the state of the CPB was manipulated. At $E_J/h = 6.4$ GHz we find a Ramsey decay time of $T_2^* = 70$ ns. Assuming $1/f$ charge noise is the dominant free induction dephasing mechanism [14], then at $n_g = 1$ the standard deviation of the charge noise (σ_Q) obeys [14]

$$\sigma_Q^2 = \frac{1}{T_2^*}\frac{E_J}{(4E_c)^2}\frac{2e^2\hbar}{\eta}, \quad (6)$$

where $\eta = \ln(f_{\max}/f_{\min})$ and $f_{\min}$ and $f_{\max}$ are the minimum and maximum bandwidth of the measurement, respectively. Using Eq. (6) we find $\sigma_Q = (2 \times 10^{-3}e)^2$, which is a fairly typical value for the amplitude of $1/f$ charge noise [17,18]. Measurements of the decay of Rabi oscillations showed a maximum decay time of $T' \simeq 1\ \mu$s.

We also obtained some measurements on a second device with a charging energy of $E_c/h = 12.48$ GHz. The lifetime of that device at $f = E_J/h = 7.5$ GHz was $T_1 = 8\ \mu$s, which from Eq. (4) gives $S_Q(f = 7.5\ \mathrm{GHz}) = 5 \times 10^{-18}\ e^2/\mathrm{Hz}$. This value is within a factor of 2 of the device discussed in this Letter at $f = 7.5$ GHz. Unfortunately, we did not obtain T_1 measurements on this second device over a wide range of frequency before the device stopped functioning.

In conclusion, we have measured the spectrum, excited state lifetime, and Rabi oscillations of a CPB qubit over one octave in transition frequency. We find T_1 varies from 4 μs at $f = 8$ GHz up to 200 μs at $f = 4.5$ GHz. The longest lifetime places an upper bound on the spectral density of charge noise which is $S_Q(f = 4.5\ \mathrm{GHz}) \leq 10^{-18}\ e^2/\mathrm{Hz}$ at 4.5 GHz. Our measurements place a remarkably small upper bound on dielectric loss in the junction barrier. While the exact source of improvement in the lifetime of our CPB compared with other results [11,14,16] is unknown, our measurements suggest that the coupling between the qubit and the transmission line can play a key role.

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973			|**a** AC |**b** avail_circ
974			|**z** v.118:no.1(2017:Jan. 06) |**a** 4528039-7350 |**b** FLINT |**c** PERI |**f** 08
974			|**z** v.118:no.10(2017:Mar. 10) |**a** 4528039-7440 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.11(2017:Mar. 17) |**a** 4528039-7450 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.12(2017:Mar. 24) |**a** 4528039-7460 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.13(2017:Mar. 31) |**a** 4528039-7470 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.14(2017:April 07) |**a** 4528039-7480 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.15(2017:April 14) |**a** 4528039-7490 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.16(2017:April 21) |**a** 4528039-7500 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.17(2017:April 28) |**a** 4528039-7510 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.18(2017:May 05) |**a** 4528039-7520 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.19(2017:May 12) |**a** 4528039-7530 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.2(2017:Jan. 13) |**a** 4528039-7360 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.20(2017:May 19) |**a** 4528039-7540 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.21(2017:May 26) |**a** 4528039-7550 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.118:no.22(2017:Jun. 02) |**a** 4528039-7560 |**b** FLINT

	|**c** PERI |**f** 08
974	|**z** v.118:no.23(2017:Jun. 09) |**a** 4528039-7570 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.24(2017:Jun. 16) |**a** 4528039-7580 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.25(2017:Jun. 23) |**a** 4528039-7590 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.26(2017:Jun. 30) |**a** 4528039-7600 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.3(2017:Jan. 20) |**a** 4528039-7370 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.4(2017:Jan. 27) |**a** 4528039-7380 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.5(2017:Feb. 03) |**a** 4528039-7390 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.6(2017:Feb. 10) |**a** 4528039-7400 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.7(2017:Feb. 17) |**a** 4528039-7410 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.8(2017:Feb. 24) |**a** 4528039-7420 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.118:no.9(2017:Mar. 03) |**a** 4528039-7430 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.1(2017:Jul. 07) |**a** 4528039-7610 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.10(2017:Sep. 08) |**a** 4528039-7700 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.11(2017:Sep. 15) |**a** 4528039-7710 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.12(2017:Sep. 22) |**a** 4528039-7720 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.13(2017:Sep. 29) |**a** 4528039-7730 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.14(2017:Oct. 06) |**a** 4528039-7740 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.15(2017:Oct. 13) |**a** 4528039-7750 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.16(2017:Oct. 20) |**a** 4528039-7760 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.17(2017:Oct. 27) |**a** 4528039-7770 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.18(2017:Nov. 03) |**a** 4528039-7780 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.19(2017:Nov. 10) |**a** 4528039-7790 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.2(2017:Jul. 14) |**a** 4528039-7620 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.20(2017:Nov. 17) |**a** 4528039-7800 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.119:no.21(2017:Nov. 24) |**a** 4528039-7810 |**b** FLINT

	|**c** PERI |**f** 08
974	|**z** v.119:no.22(2017:Dec. 01) |**a** 4528039-7820 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.23(2017:Dec. 08) |**a** 4528039-7830 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.24(2017:Dec. 15) |**a** 4528039-7840 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.25(2017:Dec. 22) |**a** 4528039-7850 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.26(2017:Dec. 29) |**a** 4528039-7860 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.3(2017:Jul. 21) |**a** 4528039-7630 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.4(2017:Jul. 28) |**a** 4528039-7640 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.5(2017:Aug. 04) |**a** 4528039-7650 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.6(2017:Aug. 11) |**a** 4528039-7660 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.7(2017:Aug. 18) |**a** 4528039-7670 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.8(2017:Aug. 25) |**a** 4528039-7680 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.119:no.9(2017:Sep. 01) |**a** 4528039-7690 |**b** FLINT |**c** PERI |**f** 08

974	|**z** v.120:no.1(2018:Jan. 05) |**a** 4528039-7870 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.10(2018:Mar. 09) |**a** 4528039-7960 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.11(2018:Mar. 16) |**a** 4528039-7970 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.12(2018:Mar. 23) |**a** 4528039-7980 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.13(2018:Mar. 30) |**a** 4528039-7990 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.14(2018:April 06) |**a** 4528039-8000 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.15(2018:April 13) |**a** 4528039-8010 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.16(2018:April 20) |**a** 4528039-8020 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.17(2018:April 27) |**a** 4528039-8030 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.18(2018:May 04) |**a** 4528039-8040 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.19(2018:May 11) |**a** 4528039-8050 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.2(2018:Jan. 12) |**a** 4528039-7880 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.120:no.20(2018:May 18) |**a** 4528039-8060 |**b** FLINT

|**c** PERI |**f** 08

974 |**z** v.120:no.21(2018:May 25) |**a** 4528039-8070 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.22(2018:Jun. 01) |**a** 4528039-8080 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.23(2018:Jun. 08) |**a** 4528039-8090 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.24(2018:Jun. 15) |**a** 4528039-8100 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.3(2018:Jan. 19) |**a** 4528039-7890 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.4(2018:Jan. 26) |**a** 4528039-7900 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.5(2018:Feb. 02) |**a** 4528039-7910 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.6(2018:Feb. 09) |**a** 4528039-7920 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.7(2018:Feb. 16) |**a** 4528039-7930 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.8(2018:Feb. 23) |**a** 4528039-7940 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.120:no.9(2018:Mar. 02) |**a** 4528039-7950 |**b** FLINT |**c** PERI |**f** 08

974 |**z** v.121:no.1(2018:Jul. 06) |**a** 4528039-8130 |**b** FLINT |**c** PERI |**f** 08

974	|**z** v.121:no.10(2018:Sep. 07) |**a** 4528039-8220 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.11(2018:Sep. 14) |**a** 4528039-8230 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.12(2018:Sep. 21) |**a** 4528039-8240 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.13(2018:Sep. 28) |**a** 4528039-8250 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.14(2018:Oct. 05) |**a** 4528039-8260 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.15(2018:Oct. 12) |**a** 4528039-8270 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.16(2018:Oct. 19) |**a** 4528039-8280 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.17(2018:Oct. 26) |**a** 4528039-8290 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.18(2018:Nov. 02) |**a** 4528039-8300 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.19(2018:Nov. 09) |**a** 4528039-8310 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.2(2018:Jul. 13) |**a** 4528039-8140 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.20(2018:Nov. 16) |**a** 4528039-8320 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.21(2018:Nov. 23) |**a** 4528039-8330 |**b** FLINT

	|**c** PERI |**f** 08
974	|**z** v.121:no.22(2018:Nov. 30) |**a** 4528039-8340 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.23(2018:Dec. 07) |**a** 4528039-8350 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.24(2018:Dec. 14) |**a** 4528039-8360 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.26(2018:Dec. 28) |**a** 4528039-8380 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.3(2018:Jul. 20) |**a** 4528039-8150 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.4(2018:Jul. 27) |**a** 4528039-8160 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.5(2018:Aug. 03) |**a** 4528039-8170 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.6(2018:Aug. 10) |**a** 4528039-8180 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.7(2018:Aug. 17) |**a** 4528039-8190 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.8(2018:Aug. 24) |**a** 4528039-8200 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.121:no.9(2018:Aug. 31) |**a** 4528039-8210 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.1(2019:Jan. 11) |**a** 4528039-8390 |**b** FLINT |**c** PERI |**f** 08

974	|**z** v.122:no.10(2019:Mar. 15) |**a** 4528039-8480 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.11(2019:Mar. 22) |**a** 4528039-8490 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.12(2019:Mar. 29) |**a** 4528039-8500 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.13(2019:April 05) |**a** 4528039-8510 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.14(2019:April 12) |**a** 4528039-8520 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.15(2019:April 19) |**a** 4528039-8530 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.16(2019:April 26) |**a** 4528039-8540 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.17(2019:May 03) |**a** 4528039-8550 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.18(2019:May 10) |**a** 4528039-8560 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.19(2019:May 17) |**a** 4528039-8570 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.2(2019:Jan. 18) |**a** 4528039-8400 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.20(2019:May 24) |**a** 4528039-8580 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.21(2019:May 31) |**a** 4528039-8590 |**b** FLINT

	|**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.22(2019:Jun. 07) |**a** 4528039-8600 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.23(2019:Jun. 14) |**a** 4528039-8610 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.24(2019:Jun. 21) |**a** 4528039-8620 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.25(2019:Jun. 28) |**a** 4528039-8630 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.26(2019:Jul. 05) |**a** 4528039-8640 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.3(2019:Jan. 25) |**a** 4528039-8410 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.4(2019:Feb. 01) |**a** 4528039-8420 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.122:no.5(2019:Feb. 08) |**a** 4528039-8430 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.6(2019:Feb. 15) |**a** 4528039-8440 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.7(2019:Feb. 22) |**a** 4528039-8450 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.8(2019:Mar. 01) |**a** 4528039-8460 |**b** FLINT |**c** PERI |**f** 08
974	|**z** v.122:no.9(2019:Mar. 08) |**a** 4528039-8470 |**b** FLINT |**c** PERI |**f** 08

974	|**z** v.123:no.1(2019:Jul. 12) |**a** 4528039-8650 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.10(2019:Sep. 13) |**a** 4528039-8740 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.11(2019:Sep. 20) |**a** 4528039-8750 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.12(2019:Sep. 27) |**a** 4528039-8760 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.13(2019:Oct. 04) |**a** 4528039-8770 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.14(2019:Oct. 11) |**a** 4528039-8780 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.15(2019:Oct. 18) |**a** 4528039-8790 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.16(2019:Oct. 25) |**a** 4528039-8800 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.17(2019:Nov. 01) |**a** 4528039-8810 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.18(2019:Nov. 08) |**a** 4528039-8820 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.19(2019:Nov. 15) |**a** 4528039-8830 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.2(2019:Jul. 19) |**a** 4528039-8660 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.20(2019:Nov. 22) |**a** 4528039-8840 |**b** FLINT

	|**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.21(2019:Nov. 29) |**a** 4528039-8850 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.22(2019:Dec. 06) |**a** 4528039-8860 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.23(2019:Dec. 13) |**a** 4528039-8870 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.24(2019:Dec. 20) |**a** 4528039-8880 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.25(2019:Dec. 27) |**a** 4528039-8890 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.26(2020:Jan. 03) |**a** 4528039-8900 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.3(2019:Jul. 26) |**a** 4528039-8670 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.4(2019:Aug. 02) |**a** 4528039-8680 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.5(2019:Aug. 09) |**a** 4528039-8690 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.6(2019:Aug. 16) |**a** 4528039-8700 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.7(2019:Aug. 23) |**a** 4528039-8710 |**b** FLINT |**c** PERI |**f** 08 |**s** NA
974	|**z** v.123:no.8(2019:Aug. 30) |**a** 4528039-8720 |**b** FLINT |**c** PERI |**f** 08 |**s** NA

974 |**z** v.123:no.9(2019:Sep. 06) |**a** 4528039-8730 |**b** FLINT |**c** PERI |**f** 08 |**s** NA

974 |**z** v.92-117 (2004-2016) LOOSE |**a** B2284368 |**b** FLINT |**c** PERI |**f** 05

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APPENDIX 1011-D

Copyright
United States Copyright Office

Help Search History Titles Start Over

Public Catalog

Copyright Catalog (1978 to present)
Search Request: Left Anchored Title = physical review letters
Search Results: Displaying 223 of 635 entries

previous next

Labeled View

PHYSICAL REVIEW LETTERS.

Type of Work: Serial
Registration Number / Date: TX0007418640 / 2011-08-24
Application Title: PHYSICAL REVIEW LETTERS
Title: PHYSICAL REVIEW LETTERS. [Published: 2011-04-04. Issue: vol. 106, no. 12, 25 March 2011]
Serial Publication Year: 2011
ISSN: 0031-9007
Frequency: Weekly.
Copyright Claimant: The American Physical Society. Address: 1 Research Road, Ridge, NY 11961-2701, United States.
Nation of First Publication: United States
Authorship on Application: The American Physical Society, employer for hire; Citizenship: United States. Authorship: compilation.
Issues Registered: vol. 106, no. 12, 25 March 2011. Created 2011; Pub. 2011-04-04. Reg. 2011-08-24; TX0007418640
Names: The American Physical Society

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RAPID COMMUNICATIONS

PHYSICAL REVIEW A **69**, 060701(R) (2004)

Observation of interference effects in ejected electrons from 16.0-keV e^--SF_6 collisions

S. Mondal and R. Shanker*

Atomic Physics Laboratory, Department of Physics, Banaras Hindu University, Varanasi 221 005, India

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The relative energy- and angle- dependent cross sections for emission of electrons from SF_6 molecule by impact of 16 keV electrons have been measured. The angular distributions of ejected electrons are shown to exhibit an oscillatory structure which is suggested to arise due to an interference effect. The condition for interference effect for the present collision system has been examined and it is shown that the appearance of interference pattern takes place above a threshold energy of 65 eV for the ejected electrons. The ejected electrons producing an interference structure are suggested to originate from two atomic centers of a transiently formed doubly ionized parent molecule, namely, SF_6^{2+}. This extremely unstable ion suffers a Coulomb explosion and gives rise to many singly charged stable radical and atomic ions. The time of flight mass spectrometric results of our earlier work [Phys. Rev. A **67**, 022704 (2003)] on partial ionization of SF_6 molecule by impact of 16 keV electrons are found to support the existence of these stable ions.

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Ionization processes in molecular collisions with energetic charged particles provide an ideal test ground to describe the fundamental interactions occurring in a multiparticle system. These interactions are found to play an important role in astrophysics, plasma physics, thermonuclear fusion, and in studies of surface and materials [1]. In the present work an effort is made to understand the ionization processes occurring in molecules by impact of energetic electrons. Study of energy- and angular distributions of ejected electrons from molecules by impact of energetic charged particles is one of the commonly used techniques to shed light on ionization processes in such collisions [2–5]. Depending on the projectile's velocity, structures in energy and angular distributions of ejected electrons are found to change according to different roles played by various collision processes in electron ejection from the target molecules [6,7]. The soft collision at high projectile energies can be attributed to three body collisions [8]. These fast projectiles may be regarded as a source of virtual photons which gives rise to the dipole transitions involving the transfer of a unit angular momentum. The violent collisions at low projectile velocities give rise to binary encounter collision due to a large momentum transfer of the projectile to the target electrons. A general understanding of the electron ejection processes in collisions with low velocity charged particles with simple diatomic molecules is available [9–14], wherein a "binary collision process" plays a dominant role. When momentum transfer by the incident particle to the target electrons assumes a minimum value, the peaking approximation in the dipole interaction is generally applied. Under these conditions, the ejected electrons carry the momentum transfer in the backward direction in order to conserve the total momentum of the collision system. On one hand, the simultaneous ejection of electrons from constituent atoms of a molecule via soft collisions may add coherently and produce an interference pattern at the backward angles $\theta(\pi/2<\theta<\pi)$. Hence for high velocity of incident particles $v_p\sim 50$ a.u. [6], the momentum transfer becomes minimum to the target electrons and the soft collision gives rise to an oscillatory structure due to interference effect among the ejected electrons. On other hand, as the binary encounter process involves a large momentum transfer to a "single" individual electron of the target and produces a peak structure in the forward direction $(\theta<\pi/2)$ in the angular distributions, obviously, it is not expected to produce two coherent electrons to cause an interference effect.

60 MeV/u Kr^{34+}-ion-induced interference effect has been observed experimentally by Stolterfoht *et al.* [6] in the double differential ionization cross sections of ejected electrons from H_2 molecule. In their work, they have shown that an oscillatory pattern on the energy distributions of the double differential cross sections of the ejected electrons arises due to the interference effect and that it is independent of the ejection angle of the electrons. They have been able to see this oscillatory pattern when they divided their double differential cross sections by the corresponding theoretical results of Fainstein *et al.* [15]. In contrary to their own observation, recently Stolterfoht *et al.* [16] have shown that the double differential ionization cross section of H_2 molecule by impact of 68-MeV/u Kr^{33+} ions follows an oscillatory pattern due to the interference effect among the ejected electrons from the target. This pattern was found to vary with the ejection angle of the electrons in agreement with their own theoretical predictions [16].

The origin of interference effect of electrons ejected from a diatomic molecule can be explained by considering the fact that two atomic centers in a diatomic molecule represent a double slit assembly. When electrons of same energy are ejected simultaneously from two atomic centers separated by a finite distance $\mathbf{R}_0$, they may interfere with each other, giving rise to an oscillatory structure in their angular distributions. Such an electron interference pattern may be compared with Young's double slit experiment. The visibility of such an interference effect has been discussed in detail by Walter

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*Corresponding author; electronic address: rshankerin2003@yahoo.com

PHYSICAL REVIEW A **69**, 062320 (2004)

Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation

Alexandre Blais,[1] Ren-Shou Huang,[1,2] Andreas Wallraff,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]
[1]*Departments of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*

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We propose a realizable architecture using one-dimensional transmission line resonators to reach the strong-coupling limit of cavity quantum electrodynamics in superconducting electrical circuits. The vacuum Rabi frequency for the coupling of cavity photons to quantized excitations of an adjacent electrical circuit (qubit) can easily exceed the damping rates of both the cavity and qubit. This architecture is attractive both as a macroscopic analog of atomic physics experiments and for quantum computing and control, since it provides strong inhibition of spontaneous emission, potentially leading to greatly enhanced qubit lifetimes, allows high-fidelity quantum nondemolition measurements of the state of multiple qubits, and has a natural mechanism for entanglement of qubits separated by centimeter distances. In addition it would allow production of microwave photon states of fundamental importance for quantum communication.

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I. INTRODUCTION

Cavity quantum electrodynamics (CQED) studies the properties of atoms coupled to discrete photon modes in high Q cavities. Such systems are of great interest in the study of the fundamental quantum mechanics of open systems, the engineering of quantum states, and measurement-induced decoherence [1–3] and have also been proposed as possible candidates for use in quantum information processing and transmission [1–3]. Ideas for novel CQED analogs using nanomechanical resonators have recently been suggested by Schwab and collaborators [4,5]. We present here a realistic proposal for CQED via Cooper pair boxes coupled to a one-dimensional (1D) transmission line resonator, within a simple circuit that can be fabricated on a single microelectronic chip. As we discuss, 1D cavities offer a number of practical advantages in reaching the strong-coupling limit of CQED over previous proposals using discrete LC circuits [6,7], large Josephson junctions [8–10], or 3D cavities [11–13]. Besides the potential for entangling qubits to realize two-qubit gates addressed in those works, in the present work we show that the CQED approach also gives strong and controllable isolation of the qubits from the electromagnetic environment, permits high-fidelity quantum nondemolition (QND) readout of multiple qubits, and can produce states of microwave photon fields suitable for quantum communication. The proposed circuits therefore provide a simple and efficient architecture for solid-state quantum computation, in addition to opening up a new avenue for the study of entanglement and quantum measurement physics with macroscopic objects. We will frame our discussion in a way that makes contact between the language of atomic physics and that of electrical engineering.

We begin in Sec. II with a brief general overview of CQED before turning to a discussion of our proposed solid-state realization of cavity QED in Sec. III. We then discuss in Sec. IV the case where the cavity and qubit are tuned in resonance and in Sec. V the case of large detuning which leads to lifetime enhancement of the qubit. In Sec. VI, a quantum nondemolition readout protocol is presented. Realization of one-qubit logical operations is discussed in Sec. VII and two-qubit entanglement in Sec. VIII. We show in Sec. IX how to take advantage of encoded universality and decoherence-free subspace in this system.

II. BRIEF REVIEW OF CAVITY QED

Cavity QED studies the interaction between atoms and the quantized electromagnetic modes inside a cavity. In the optical version of CQED [2], schematically shown in Fig. 1(a), one drives the cavity with a laser and monitors changes in the cavity transmission resulting from coupling to atoms falling through the cavity. One can also monitor the spontaneous emission of the atoms into transverse modes not confined by the cavity. It is not generally possible to directly determine the state of the atoms after they have passed through the cavity because the spontaneous emission lifetime is on the scale of nanoseconds. One can, however, infer information about the state of the atoms inside the cavity from real-time monitoring of the cavity optical transmission.

In the microwave version of CQED [3], one uses a very-high-Q superconducting 3D resonator to couple photons to transitions in Rydberg atoms. Here one does not directly monitor the state of the photons, but is able to determine with high efficiency the state of the atoms after they have passed through the cavity (since the excited state lifetime is of the order of 30 ms). From this state-selective detection one can infer information about the state of the photons in the cavity.

The key parameters describing a CQED system (see Table I) are the cavity resonance frequency ω_r, the atomic transition frequency Ω, and the strength of the atom-photon coupling g appearing in the Jaynes-Cummings Hamiltonian [14]

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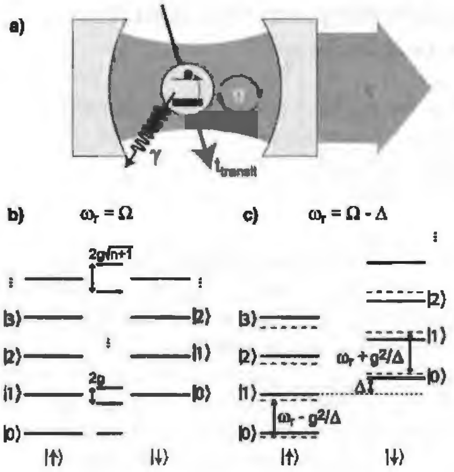

FIG. 1. (Color online) (a) Standard representation of a cavity quantum electrodynamic system, comprising a single mode of the electromagnetic field in a cavity with decay rate κ coupled with a coupling strength $g=\mathcal{E}_{\rm rms}d/\hbar$ to a two-level system with spontaneous decay rate γ and cavity transit time $t_{\rm transit}$. (b) Energy spectrum of the uncoupled (left and right) and dressed (center) atom-photon states in the case of zero detuning. The degeneracy of the two-dimensional manifolds of states with $n-1$ quanta is lifted by $2g\sqrt{n+1}$. (c) Energy spectrum in the dispersive regime (long-dashed lines). To second order in g, the level separation is independent of n, but depends on the state of the atom.

$$H=\hbar\omega_r\left(a^\dagger a+\frac{1}{2}\right)+\frac{\hbar\Omega}{2}\sigma^z+\hbar g(a^\dagger\sigma^-+\sigma^+a)+H_\kappa+H_\gamma. \tag{1}$$

Here H_κ describes the coupling of the cavity to the continuum which produces the cavity decay rate $\kappa=\omega_r/Q$, while H_γ describes the coupling of the atom to modes other than the cavity mode which cause the excited state to decay at rate γ (and possibly also produce additional dephasing effects). An additional important parameter in the atomic case is the transit time $t_{\rm transit}$ of the atom through the cavity.

In the absence of damping, exact diagonalization of the Jaynes-Cumming Hamiltonian yields the excited eigenstates (dressed states) [15]

$$|\overline{+,n}\rangle=\cos\theta_n|\downarrow,n\rangle+\sin\theta_n|\uparrow,n+1\rangle, \tag{2}$$

$$|\overline{-,n}\rangle=-\sin\theta_n|\downarrow,n\rangle+\cos\theta_n|\uparrow,n+1\rangle, \tag{3}$$

and ground state $|\uparrow,0\rangle$ with corresponding eigenenergies

$$E_{\overline{\pm,n}}=(n+1)\hbar\omega_r\pm\frac{\hbar}{2}\sqrt{4g^2(n+1)+\Delta^2}, \tag{4}$$

$$E_{\uparrow,0}=-\frac{\hbar\Delta}{2}. \tag{5}$$

In these expressions,

$$\theta_n=\frac{1}{2}\tan^{-1}\left(\frac{2g\sqrt{n+1}}{\Delta}\right), \tag{6}$$

and $\Delta\equiv\Omega-\omega_r$ the atom-cavity detuning.

Figure 1(b) shows the spectrum of these dressed states for the case of zero detuning, $\Delta=0$, between the atom and cavity. In this situation, degeneracy of the pair of states with $n+1$ quanta is lifted by $2g\sqrt{n+1}$ due to the atom-photon interaction. In the manifold with a single excitation, Eqs. (2) and (3) reduce to the maximally entangled atom-field states $|\pm,0\rangle=(|\uparrow,1\rangle\pm|\downarrow,0\rangle)/\sqrt{2}$. An initial state with an excited atom and zero photons $|\uparrow,0\rangle$ will therefore flop into a photon $|\downarrow,1\rangle$ and back again at the vacuum Rabi frequency g/π. Since the excitation is half atom and half photon, the decay rate of $|\pm,0\rangle$ is $(\kappa+\gamma)/2$. The pair of states $|\pm,0\rangle$ will be resolved in a transmission experiment if the splitting $2g$ is larger than this linewidth. The value of $g=\mathcal{E}_{\rm rms}d/\hbar$ is determined by the transition dipole moment d and the rms zero-point electric field of the cavity mode. Strong coupling is achieved when $g\gg\kappa,\gamma$ [15].

TABLE I. Key rates and CQED parameters for optical [2] and microwave [3] atomic systems using 3D cavities, compared against the proposed approach using superconducting circuits, showing the possibility for attaining the strong cavity QED limit ($n_{\rm Rabi}\gg 1$). For the 1D superconducting system, a full-wave ($L=\lambda$) resonator, $\omega_r/2\pi=10$ GHz, a relatively low Q of 10^4, and coupling $\beta=C_g/C_\Sigma=0.1$ are assumed. For the 3D microwave case, the number of Rabi flops is limited by the transit time. For the 1D circuit case, the intrinsic Cooper-pair box decay rate is unknown; a conservative value equal to the current experimental upper bound $\gamma\leq 1/(2\ \mu s)$ is assumed.

Parameter	Symbol	3D optical	3D microwave	1D circuit
Resonance or transition frequency	$\omega_r/2\pi$, $\Omega/2\pi$	350 THz	51 GHz	10 GHz
Vacuum Rabi frequency	g/π, g/ω_r	220 MHz, 3×10^{-7}	47 kHz, 1×10^{-7}	100 MHz, 5×10^{-3}
Transition dipole	d/ea_0	~1	1×10^3	2×10^4
Cavity lifetime	$1/\kappa, Q$	10 ns, 3×10^7	1 ms, 3×10^8	160 ns, 10^4
Atom lifetime	$1/\gamma$	61 ns	30 ms	2 μs
Atom transit time	$t_{\rm transit}$	≥50 μs	100 μs	∞
Critical atom number	$N_0=2\gamma\kappa/g^2$	6×10^{-3}	3×10^{-6}	$\leq6\times10^{-5}$
Critical photon number	$m_0=\gamma^2/2g^2$	3×10^{-4}	3×10^{-8}	$\leq1\times10^{-6}$
Number of vacuum Rabi flops	$n_{\rm Rabi}=2g/(\kappa+\gamma)$	~10	~5	$\sim10^2$

For large detuning, $g/\Delta \ll 1$, expansion of Eq. (4) yields the dispersive spectrum shown in Fig. 1(c). In this situation, the eigenstates of the one excitation manifold take the form [15]

$$\overline{|-,0\rangle} \sim -(g/\Delta)|\downarrow,0\rangle + |\uparrow,1\rangle, \tag{7}$$

$$\overline{|+,0\rangle} \sim |\downarrow,0\rangle + (g/\Delta)|\uparrow,1\rangle. \tag{8}$$

The corresponding decay rates are then simply given by

$$\Gamma_{\overline{-,0}} \simeq (g/\Delta)^2\gamma + \kappa, \tag{9}$$

$$\Gamma_{\overline{+,0}} \simeq \gamma + (g/\Delta)^2\kappa. \tag{10}$$

More insight into the dispersive regime is gained by making the unitary transformation

$$U = \exp\left[\frac{g}{\Delta}(a\sigma^{+} - a^{\dagger}\sigma^{-})\right] \tag{11}$$

and expanding to second order in g (neglecting damping for the moment) to obtain

$$UHU^{\dagger} \approx \hbar\left[\omega_r + \frac{g^2}{\Delta}\sigma^z\right]a^{\dagger}a + \frac{\hbar}{2}\left[\Omega + \frac{g^2}{\Delta}\right]\sigma^z. \tag{12}$$

As is clear from this expression, the atom transition is ac Stark/Lamb shifted by $(g^2/\Delta)(n+1/2)$. Alternatively, one can interpret the ac Stark shift as a dispersive shift of the cavity transition by $\sigma^z g^2/\Delta$. In other words, the atom pulls the cavity frequency by $\pm g^2/\kappa\Delta$.

III. CIRCUIT IMPLEMENTATION OF CAVITY QED

We now consider the proposed realization of cavity QED using the superconducing circuits shown in Fig. 2. A 1D transmission line resonator consisting of a full-wave section of superconducting coplanar waveguide plays the role of the cavity and a superconducting qubit plays the role of the atom. A number of superconducting quantum circuits could function as artificial atom, but for definiteness we focus here on the Cooper-pair box [6,16–18].

A. Cavity: Coplanar stripline resonator

An important advantage of this approach is that the zero-point energy is distributed over a very small effective volume ($\approx 10^{-5}$ cubic wavelengths) for our choice of a quasi-one-dimensional transmission line "cavity." As shown in Appendix A, this leads to significant rms voltages $V_{\text{rms}}^0 \sim \sqrt{\hbar\omega_r/cL}$ between the center conductor and the adjacent ground plane at the antinodal positions, where L is the resonator length and c is the capacitance per unit length of the transmission line. At a resonant frequency of 10 GHz ($h\nu/k_B \sim 0.5$ K) and for a 10 μm gap between the center conductor and the adjacent ground plane, $V_{\text{rms}} \sim 2$ μV corresponding to electric fields $\mathcal{E}_{\text{rms}} \sim 0.2$ V/m, some 100 times larger than achieved in the 3D cavity described in Ref. [3]. Thus, this geometry might also be useful for coupling to Rydberg atoms [19].

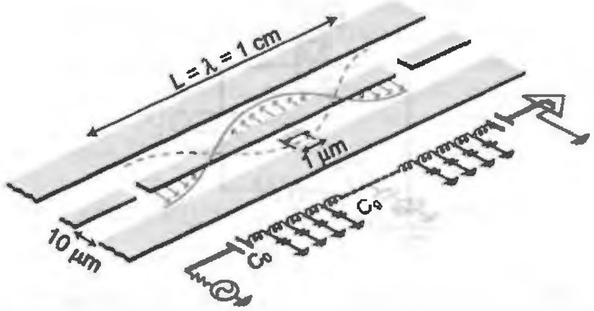

FIG. 2. (Color online). Schematic layout and equivalent lumped circuit representation of proposed implementation of cavity QED using superconducting circuits. The 1D transmission line resonator consists of a full-wave section of superconducting coplanar waveguide, which may be lithographically fabricated using conventional optical lithography. A Cooper-pair box qubit is placed between the superconducting lines and is capacitively coupled to the center trace at a maximum of the voltage standing wave, yielding a strong electric dipole interaction between the qubit and a single photon in the cavity. The box consists of two small (~ 100 nm $\times$ 100 nm) Josephson junctions, configured in a ~ 1 μm loop to permit tuning of the effective Josephson energy by an external flux Φ_{ext}. Input and output signals are coupled to the resonator, via the capacitive gaps in the center line, from 50Ω transmission lines which allow measurements of the amplitude and phase of the cavity transmission, and the introduction of dc and rf pulses to manipulate the qubit states. Multiple qubits (not shown) can be similarly placed at different antinodes of the standing wave to generate entanglement and two-bit quantum gates across distances of several millimeters.

In addition to the small effective volume and the fact that the on-chip realization of CQED shown in Fig. 2 can be fabricated with existing lithographic techniques, a transmission-line resonator geometry offers other practical advantages over lumped LC circuits or current-biased large Josephson junctions. The qubit can be placed within the cavity formed by the transmission line to strongly suppress the spontaneous emission, in contrast to a lumped LC circuit, where without additional special filtering, radiation and parasitic resonances may be induced in the wiring [20]. Since the resonant frequency of the transmission line is determined primarily by a fixed geometry, its reproducibility and immunity to $1/f$ noise should be superior to Josephson junction plasma oscillators. Finally, transmission-line resonances in coplanar waveguides with $Q \sim 10^6$ have already been demonstrated [21,22], suggesting that the internal losses can be very low. The optimal choice of the resonator Q in this approach is strongly dependent on the intrinsic decay rates of superconducting qubits which, as described below, are presently unknown, but can be determined with the setup proposed here. Here we assume the conservative case of an overcoupled resonator with a $Q \sim 10^4$, which is preferable for the first experiments.

B. Artificial atom: The Cooper-pair box

Our choice of "atom," the Cooper-pair box [6,16], is a mesoscopic superconducting island. As shown in Fig. 3, the

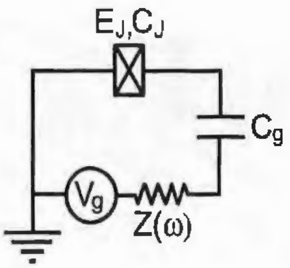

FIG. 3. Circuit diagram of the Cooper-pair box. The gate voltage is connected to the island through an environmental impedance $Z(\omega)$.

island is connected to a large reservoir through a Josephson junction with Josephson energy E_J and capacitance C_J. It is voltage biased from a lead having capacitance C_g to the island. If the superconducting gap is larger than both the charging energy $E_c = e^2/2C_\Sigma$ (where $C_\Sigma = C_J + C_g$ is the total box capacitance) and temperature, the only relevant degree of freedom is the number of Cooper pairs N on the island. In this basis, the Hamiltonian describing the superconducting island takes the form

$$H_Q = 4E_c \sum_N (N - N_g)^2 |N\rangle\langle N| - \frac{E_J}{2} \sum_N (|N+1\rangle\langle N| + \text{H.c.}), \tag{13}$$

where $N_g = C_g V_g / 2e$ is the dimensionless gate charge representing the total polarization charge injected into the island by the voltage source.

In the charge regime $4E_c \gg E_J$ and restricting the gate charge to the range $N_g \in [0,1]$, only a pair of adjacent charge states on the island are relevant and the Hamiltonian then reduces to a 2×2 matrix

$$H_Q = -\frac{E_{\text{el}}}{2}\bar{\sigma}^z - \frac{E_J}{2}\bar{\sigma}^x, \tag{14}$$

with $E_{\text{el}} = 4E_C(1 - 2N_g)$. The Cooper-pair box can in this case be mapped to a pseudospin-1/2 particle, with effective fields in the x and z directions.

Replacing the Josephson junction by a pair of junctions in parallel, each with energy $E_J/2$, the effective field in the x direction becomes $E_J \cos(\pi\Phi_{\text{ext}}/\Phi_0)/2$. By threading a flux Φ_{ext} in the loop formed by the pair of junctions and changing the gate voltage V_g, it is possible to control the effective fields acting on the qubit. In the setup of Fig. 2, application of dc gate voltage on the island can be conveniently achieved by applying a bias voltage to the center conductor of the transmission line. The resonator coupling capacitance C_0, the gate capacitance C_g (the capacitance between the center conductor of the resonator and the island), and the capacitance to ground of the resonator then act as a voltage divider.

C. Combined system: Superconducting cavity QED

For a superconducting island fabricated inside a resonator, in addition to a dc part V_g^{dc}, the gate voltage has a quantum part v. As shown in Appendix A, if the qubit is placed in the center of the resonator, this latter contribution is given by $v = V_{\text{rms}}^0 (a^\dagger + a)$. Taking into account both V_g^{dc} and v in Eq. (14), we obtain

$$H_Q = -2E_C(1 - 2N_g^{\text{dc}})\bar{\sigma}^z - \frac{E_J}{2}\bar{\sigma}^x - e\frac{C_g}{C_\Sigma}\sqrt{\frac{\hbar\omega_r}{Lc}}(a^\dagger + a) \times (1 - 2N_g - \bar{\sigma}^z). \tag{15}$$

Working in the eigenbasis $\{|\uparrow\rangle, |\downarrow\rangle\}$ of the first two terms of the above expression [23] and adding the Hamiltonian of the oscillator mode coupled to the qubit, the Hamiltonian of the interacting qubit and resonator system takes the form

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z - e\frac{C_g}{C_\Sigma}\sqrt{\frac{\hbar\omega_r}{Lc}}(a^\dagger + a) \times [1 - 2N_g - \cos(\theta)\sigma^z + \sin(\theta)\sigma^x]. \tag{16}$$

Here, σ^x and σ^z are Pauli matrices in the eigenbasis $\{|\uparrow\rangle, |\downarrow\rangle\}$, $\theta = \arctan[E_J/4E_C(1 - 2N_g^{\text{dc}})]$ is the mixing angle, and the energy splitting of the qubit is $\Omega = \sqrt{E_J^2 + [4E_C(1 - 2N_g^{\text{dc}})]^2}/\hbar$ [23]. Note that contrary to the case of a qubit fabricated outside the cavity where the N_g^2 term in Eq. (13) has no effect, here this term slightly renormalizes the cavity frequency ω_r and displaces the oscillator coordinate. These effects are implicit in Eq. (16).

At the charge degeneracy point (where $N_g^{\text{dc}} = C_g V_g^{\text{dc}}/2e = 1/2$ and $\theta = \pi/2$), neglecting rapidly oscillating terms and omitting damping for the moment, Eq. (16) reduces to the Jaynes-Cummings Hamiltonian (1) with $\Omega = E_J/\hbar$ and coupling

$$g = \frac{\beta e}{\hbar}\sqrt{\frac{\hbar\omega_r}{cL}}, \tag{17}$$

where $\beta \equiv C_g/C_\Sigma$. The quantum electrical circuit of Fig. 2 is therefore mapped to the problem of a two-level atom inside a cavity. Away from the degeneracy point, this mapping can still be performed, but with a coupling strength reduced by $\sin(\theta)$ and an additional term proportional to $(a^\dagger + a)$.

In this circuit, the "atom" is highly polarizable at the charge degeneracy point, having transition dipole moment $d \equiv \hbar g/\mathcal{E}_{\text{rms}} \sim 2 \times 10^4$ atomic units (ea_0), or more than an order of magnitude larger than even a typical Rydberg atom [15]. An experimentally realistic [18] coupling $\beta \sim 0.1$ leads to a vacuum Rabi rate $g/\pi \sim 100$ MHz, which is three orders of magnitude larger than in corresponding atomic microwave CQED experiments [3] or approximately 1% of the transition frequency. Unlike the usual CQED case, these artificial "atoms" remain at fixed positions indefinitely and so do not suffer from the problem that the coupling g varies with position in the cavity.

A comparison of the experimental parameters for implementations of cavity QED with optical and microwave atomic systems and for the proposed implementation with superconducting circuits is presented in Table I. We assume here a relatively low $Q = 10^4$ and a worst case estimate, con-

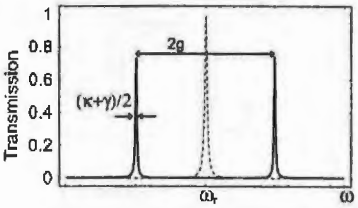

FIG. 4. Expected transmission spectrum of the resonator in the absence (dashed line) and presence (solid line) of a superconducting qubit biased at its degeneracy point. Parameters are those presented in Table I. The splitting exceeds the line width by two orders of magnitude.

sistent with the bound set by previous experiments with superconducting qubits (discussed further below), for the intrinsic qubit lifetime of $1/\gamma \gtrsim 2\ \mu\text{s}$.

The standard figures of merit [24] for strong coupling are the critical photon number needed to saturate the atom on resonance, $m_0 = \gamma^2/2g^2 \lesssim 1\times 10^{-6}$, and the minimum atom number detectable by measurement of the cavity output, $N_0 = 2\gamma\kappa/g^2 \lesssim 6\times 10^{-5}$. These remarkably low values are clearly very favorable and show that superconducting circuits could access the interesting regime of very strong coupling.

IV. ZERO DETUNING

In the case of a low-Q cavity ($g<\kappa$) and zero detuning, the radiative decay rate of the qubit into the transmission line becomes strongly *enhanced* by a factor of Q relative to the rate in the absence of the cavity [15]. This is due to the resonant enhancement of the density of states at the atomic transition frequency. In electrical engineering language, the $\sim 50\Omega$ external transmission-line impedance is transformed on resonance to a high value which is better matched to extract energy from the qubit.

For strong coupling $g>\kappa,\gamma$, the first excited state becomes a doublet with linewidth $(\kappa+\gamma)/2$, as explained in Sec. II. As can be seen from Table I, the coupling in the proposed superconducting implementation is so strong that, even for the low $Q=10^4$ we have assumed, $2g/(\kappa+\gamma)\sim 100$ vacuum Rabi oscillations are possible. Moreover, as shown in Fig. 4, the frequency splitting ($g/\pi \sim 100$ MHz) will be readily resolvable in the transmission spectrum of the resonator. This spectrum, calculated here following Ref. [25], can be observed in the same manner as employed in optical atomic experiments, with a continuous-wave measurement at low drive, and will be of practical use to find the dc gate voltage needed to tune the box into resonance with the cavity.

Of more fundamental importance than this simple avoided level crossing, however, is the fact that the Rabi splitting scales with the square root of the photon number, making the level spacing anharmonic. This should cause a number of novel nonlinear effects [14] to appear in the spectrum at higher drive powers when the average photon number in the cavity is large ($\langle n\rangle > 1$).

A conservative estimate of the noise energy for a 10 GHz cryogenic high-electron-mobility (HEMT) amplifier is $n_{\text{amp}} = k_B T_N/\hbar\omega_r \sim 100$ photons, where T_N is the noise temperature of the amplification circuit. As a result, these spectral features should be readily observable in a measurement time $t_{\text{meas}} = 2n_{\text{amp}}/\langle n\rangle\kappa$ or only $\sim 32\ \mu\text{s}$ for $\langle n\rangle \sim 1$.

V. LARGE DETUNING: LIFETIME ENHANCEMENT

For qubits *not* inside a cavity, fluctuation of the gate voltage acting on the qubit is an important source of relaxation and dephasing. As shown in Fig. 3, in practice the qubit's gate is connected to the voltage source through external wiring having, at the typical microwave transition frequency of the qubit, a real impedance of value close to the impedance of free space ($\sim 50\ \Omega$). The relaxation rate expected from purely quantum fluctuations across this impedance (spontaneous emission) is [18,23]

$$\frac{1}{T_1} = \frac{E_J^2}{E_J^2 + E_{el}^2}\left(\frac{e}{\hbar}\right)^2 \beta^2 S_V(+\Omega), \tag{18}$$

where $S_V(+\Omega) = 2\hbar\Omega\ \mathrm{Re}[Z(\Omega)]$ is the spectral density of voltage fluctuations across the environmental impedance (in the quantum limit). It is difficult in most experiments to precisely determine the real part of the high-frequency environmental impedance presented by the leads connected to the qubit, but reasonable estimates [18] yield values of T_1 in the range of $1\ \mu\text{s}$.

For qubits fabricated inside a cavity, the noise across the environmental impedance does not couple directly to the qubit, but only indirectly through the cavity. For the case of strong detuning, coupling of the qubit to the continuum is therefore substantially reduced. One can view the effect of the detuned resonator as filtering out the vacuum noise at the qubit transition frequency or, in electrical engineering terms, as providing an impedance transformation which strongly *reduces* the real part of the environmental impedance seen by the qubit.

Solving for the normal modes of the resonator and transmission lines, including an input impedance R at each end of the resonator, the spectrum of voltage fluctuations as seen by the qubit fabricated in the center of the resonator can be shown to be well approximated by

$$S_V(\Omega) = \frac{2\hbar\omega_r}{Lc}\frac{\kappa/2}{\Delta^2 + (\kappa/2)^2}. \tag{19}$$

Using this transformed spectral density in Eq. (18) and assuming a large detuning between the cavity and qubit, the relaxation rate due to vacuum fluctuations takes a form that reduces to $1/T_1 \equiv \gamma_\kappa = (g/\Delta)^2\kappa \sim 1/(64\ \mu\text{s})$, at the qubit's degeneracy point. This is the result already obtained in Eq. (10) using the dressed-state picture for the coupled atom and cavity, except for the additional factor γ reflecting a loss of energy to modes outside of the cavity. For large detuning, damping due to spontaneous emission can be much less than κ.

One of the important motivations for this CQED experiment is to determine the various contributions to the qubit decay rate so that we can understand their fundamental physical origins as well as engineer improvements. Besides γ_κ evaluated above, there are two additional contributions to the total damping rate $\gamma = \gamma_\kappa + \gamma_\perp + \gamma_{\rm NR}$. Here $\gamma\_$ is the decay rate into photon modes other than the cavity mode and $\gamma_{\rm NR}$ is the rate of other (possibly nonradiative) decays. Optical cavities are relatively open and $\gamma_\perp$ is significant, but for 1D microwave cavities, $\gamma_\perp$ is expected to be negligible (despite the very large transition dipole). For Rydberg atoms the two qubit states are both highly excited levels and $\gamma_{\rm NR}$ represents (radiative) decay out of the two-level subspace. For Cooper-pair boxes, $\gamma_{\rm NR}$ is completely unknown at the present time, but could have contributions from phonons, two-level systems in insulating [20] barriers and substrates, or thermally excited quasiparticles.

For Cooper box qubits *not* inside a cavity, recent experiments [18] have determined a relaxation time $1/\gamma = T_1 \sim 1.3\ \mu$s despite the backaction of continuous measurement by a SET electrometer. Vion *et al.* [17] found $T_1 \sim 1.84\ \mu$s (without measurement backaction) for their charge-phase qubit. Thus, in these experiments, if there are nonradiative decay channels, they are at most comparable to the vacuum radiative decay rate (and may well be much less) estimated using Eq. (18). Experiments with a cavity will present the qubit with a simple and well-controlled electromagnetic environment, in which the radiative lifetime can be enhanced with detuning to $1/\gamma_\kappa > 64\ \mu$s, allowing $\gamma_{\rm NR}$ to dominate and yielding valuable information about any nonradiative processes.

VI. DISPERSIVE QND READOUT OF QUBITS

In addition to lifetime enhancement, the dispersive regime is advantageous for readout of the qubit. This can be realized by microwave irradiation of the cavity and then probing the transmitted or reflected photons [26].

A. Measurement protocol

A drive of frequency $\omega_{\mu\rm w}$ on the resonator can be modeled by [15]

$$H_{\mu\rm w}(t) = \hbar\varepsilon(t)(a^\dagger e^{-i\omega_{\mu\rm w}t} + a e^{+i\omega_{\mu\rm w}t}), \qquad (20)$$

where $\varepsilon(t)$ is a measure of the drive amplitude. In the dispersive limit, one expects from Fig. 1(c) peaks in the transmission spectrum at $\omega_{\rm r} - g^2/\Delta$ and $\Omega + 2g^2/\Delta$ if the qubit is initially in its ground state. In a frame rotating at the drive frequency, the matrix elements for these transitions are, respectively,

$$\langle\uparrow,0|H_{\mu\rm w}|\overline{-,n}\rangle \sim \varepsilon,$$

$$\langle\uparrow,0|H_{\mu\rm w}|\overline{+,n}\rangle \sim \frac{\varepsilon g}{\Delta}. \qquad (21)$$

In the large detuning case, the peak at $\Omega + 2g^2/\Delta$, corresponding approximatively to a qubit flip, is highly suppressed.

The matrix element corresponding to a qubit flip from the excited state is also suppressed and, as shown in Fig. 5, depending on the qubit being in its ground or excited states, the transmission spectrum will present a peak of width κ at $\omega_{\rm r} - g^2/\Delta$ or $\omega_{\rm r} + g^2/\Delta$. With the parameters of Table I, this dispersive pull of the cavity frequency is $\pm g^2/\kappa\Delta = \pm 2.5$ linewidths for a 10% detuning. Exact diagonalization (4) shows that the pull is power dependent and decreases in magnitude for cavity photon numbers on the scale $n = n_{\rm crit} \equiv \Delta^2/4g^2$. In the regime of nonlinear response, single-atom optical bistability [14] can be expected when the drive frequency is off resonance at low power but on resonance at high power [29].

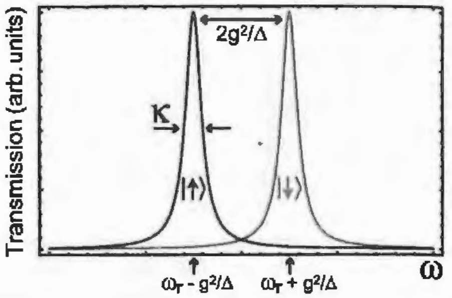

FIG. 5. (Color online) Transmission spectrum of the cavity, which is "pulled" by an amount $\pm g^2/\Delta = \pm 2.5\omega_{\rm r} \times 10^{-4}$, depending on the state of the qubit (red for the excited state, blue for the ground state). To perform a measurement of the qubit, a pulse of microwave photons, at a probe frequency $\omega_{\mu\rm w} = \omega_{\rm r}$ or $\omega_{\rm r} \pm g^2/\Delta$, is sent through the cavity. Additional peaks near Ω corresponding to qubit flips are suppressed by g/Δ.

The state-dependent pull of the cavity frequency by the qubit can be used to entangle the state of the qubit with that of the photons transmitted or reflected by the resonator. For $g^2/\kappa\Delta > 1$, as in Fig. 5, the pull is greater than the linewidth, and irradiating the cavity at one of the pulled frequencies $\omega_{\rm r} \pm g^2/\Delta$, the transmission of the cavity will be close to unity for one state of the qubit and close to zero for the other [30].

Choosing the drive to be instead at the bare cavity frequency $\omega_{\rm r}$, the state of the qubit is encoded in the phase of the reflected and transmitted microwaves. An initial qubit state $|\chi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$ evolves under microwave irradiation into the entangled state $|\psi\rangle = \alpha|\uparrow,\theta\rangle + \beta|\downarrow,-\theta\rangle$, where $\tan\theta = 2g^2/\kappa\Delta$ and $|\pm\theta\rangle$ are (interaction representation) coherent states with the appropriate mean photon number and opposite phases. In the situation where $g^2/\kappa\Delta \ll 1$, this is the most appropriate strategy.

It is interesting to note that such an entangled state can be used to couple qubits in distant resonators and allow quantum communication [31]. Moreover, if an independent measurement of the qubit state can be made, such states can be turned into photon Schrödinger cats [15].

To characterize these two measurement schemes corresponding to two different choices of the drive frequency, we compute the average photon number inside the resonator $\bar{n}$ and the homodyne voltage on the 50Ω impedance at the output of the resonator. Since the power coupled to the outside of the resonator is $P = \langle n\rangle\hbar\omega_{\rm r}\kappa/2 = \langle V_{\rm out}\rangle^2/R$, the homodyne voltage can be expressed as $\langle V_{\rm out}\rangle = \sqrt{R\hbar\omega_{\rm r}\kappa}\langle a + a^\dagger\rangle/2$ and is proportional to the real part of the field inside the cavity.

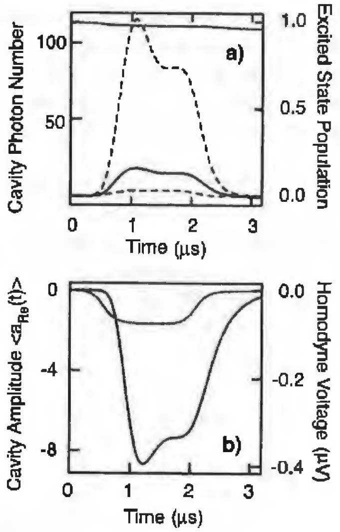

FIG. 6. (Color online) Results of numerical simulations using the quantum-state diffusion method. A microwave pulse of duration $\sim 15/\kappa$ and centered at the pulled frequency $\omega_r + g^2/\Delta$ drives the cavity. (a) The occupation probability of the excited state (right axis, solid lines), for the case in which the qubit is initially in the ground (blue) or excited (red) state and intracavity photon number (left axis, dash lines), are shown as a function of time. Though the qubit states are temporarily coherently mixed during the pulse, the probability of real transitions is seen to be small. Depending on the qubit's state, the pulse is either on or away from the combined cavity-qubit resonance and therefore is mostly transmitted or mostly reflected. (b) The real component of the cavity electric field amplitude (left axis) and the transmitted voltage phasor (right axis) in the output transmission line for the two possible initial qubit states. The parameters used for the simulation are presented in Table I.

In the absence of dissipation, the time dependence of the field inside the cavity can be obtained in the Heisenberg picture from Eqs. (12) and (20). This leads to a closed set of differential equations for a, σ^z, and $a\sigma^z$ which is easily solved. In the presence of dissipation, however [i.e., performing the transformation (11) on H_κ and H_γ and adding the resulting terms to Eqs. (12) and (20)], the set is no longer closed and we resort to numerical stochastic wave function calculations [32]. See Appendix B for a brief presentation of this numerical method.

Figures 6 and 7 show the numerical results for the two choices of drive frequency and using the parameters of Table I. For these calculations, a pulse of duration $\sim 15/\kappa$ with a hyperbolic tangent rise and fall is used to excite the cavity. Figure 6 corresponds to a drive at the pulled frequency $\omega_r + g^2/\Delta$. In Fig. 6(a) the probability $P_\uparrow$ to find the qubit in its excited state (right axis) is plotted as a function of time for the qubit initially in the ground (blue) or excited state (red). The dashed lines represent the corresponding number of photons in the cavity (left axis). Figure 6(b) shows, in a frame rotating at the drive frequency, the real part of the cavity electric field amplitude (left axis) and transmitted voltage phase (right axis) in the output transmission line, again for the two possible initial qubit states. These quantities are shown in Fig. 7 for a drive at the bare frequency ω_r.

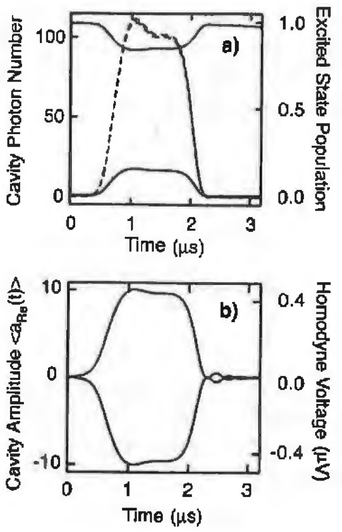

FIG. 7. (Color online) Same as Fig. 6 for the drive at the bare cavity frequency ω_r. Depending on the qubit's state, the pulse is either above or below the combined cavity-qubit resonance and so is partly transmitted and reflected but with a large relative phase shift that can be detected with homodyne detection. In (b), the opposing phase shifts cause a change in sign of the output, which can be measured with high signal to noise to realize a single-shot, QND measurement of the qubit.

As expected, for the first choice of drive frequency, the information about the state of the qubit is mostly stored in the number of transmitted photons. When the drive is at the bare frequency, however, there is very little information in the photon number, with most of the information being stored in the phase of the transmitted and reflected signal. This phase shift can be measured using standard heterodyne techniques. As also discussed in Appendix C, both approaches can serve as a high-efficiency quantum nondemolition dispersive readout of the state of the qubit.

B. Measurement time and backaction

As seen from Eq. (12), the backaction of the dispersive CQED measurement is due to quantum fluctuations of the number of photons n within the cavity. These fluctuations cause variations in the ac Stark shift $(g^2/\Delta)n\sigma^z$, which in turn dephase the qubit. It is useful to compute the corresponding dephasing rate and compare it with the measurement rate—i.e., the rate at which information about the state of the qubit can be acquired.

To determine the dephasing rate, we assume that the cavity is driven at the bare cavity resonance frequency and that the pull of the resonance is small compared to the linewidth κ. The relative phase accumulated between the ground and excited states of the qubit is

$$\varphi(t) = 2\frac{g^2}{\Delta}\int_0^t dt' n(t'), \tag{22}$$

which yields a mean phase advance $\langle\varphi\rangle = 2\theta_0 N$ with $\theta_0 = 2g^2/\kappa\Delta$ and $N = \kappa\bar{n}t/2$ the total number of transmitted photons [14]. For weak coupling, the dephasing time will greatly exceed $1/\kappa$ and, in the long-time limit, the noise in φ induced by the ac Stark shift will be Gaussian. Dephasing can then be evaluated by computing the long-time decay of the correlator

$$\langle\sigma^+(t)\sigma^-(0)\rangle = \left\langle \exp\left(i\int_0^t dt'\varphi(t')\right)\right\rangle \simeq \exp\left[-\frac{1}{2}\left(2\frac{g^2}{\Delta}\right)^2\int_0^t\int_0^t dt_1dt_2\langle n(t_1)n(t_2)\rangle\right]. \tag{23}$$

To evaluate this correlator in the presence of a continuous-wave (cw) drive on the cavity, we first perform a canonical transformation on the cavity operators $a^{(\dagger)}$ by writing them in terms of a classical $\alpha^{(*)}$ and a quantum part $d^{(\dagger)}$:

$$a(t) = \alpha(t) + d(t). \tag{24}$$

Under this transformation, the coherent state obeying $a|\alpha\rangle = \alpha|\alpha\rangle$ is simply the vacuum for the operator d. It is then easy to verify that

$$\langle[n(t)-\bar{n}][n(0)-\bar{n}]\rangle = \alpha^2\langle d(t)d^\dagger(0)\rangle = \bar{n}e^{-\kappa|t|/2}. \tag{25}$$

It is interesting to note that the factor of 1/2 in the exponent is due to the presence of the coherent drive. If the resonator is not driven, the photon number correlator rather decays at a rate κ. Using this result in Eq. (23) yields the dephasing rate

$$\Gamma_\varphi = 4\theta_0^2\frac{\kappa}{2}\bar{n}. \tag{26}$$

Since the rate of transmission on resonance is $\kappa\bar{n}/2$, this means that the dephasing per transmitted photon is $4\theta_0^2$.

To compare this result to the measurement time T_{meas}, we imagine a homodyne measurement to determine the transmitted phase. Standard analysis of such an interferometric setup [14] shows that the minimum phase change which can be resolved using N photons is $\delta\theta = 1/\sqrt{N}$. Hence the measurement time to resolve the phase change $\delta\theta = 2\theta_0$ is

$$T_{\mathrm{m}} = \frac{1}{2\kappa\bar{n}\theta_0^2}, \tag{27}$$

which yields

$$T_{\mathrm{m}}\Gamma_\varphi = 1. \tag{28}$$

This exceeds the quantum limit [33] $T_{\mathrm{m}}\Gamma_\varphi = 1/2$ by a factor of 2. Equivalently, in the language of Ref. [34] (which uses a definition of the measurement time twice as large as that above) the efficiency ratio is $\chi \equiv 1/(T_{\mathrm{m}}\Gamma_\varphi) = 0.5$.

The failure to reach the quantum limit can be traced [35] to the fact that that the coupling of the photons to the qubit is not adiabatic. A small fraction $R \approx \theta_0^2$ of the photons incident on the resonator are reflected rather than transmitted. Because the phase shift of the reflected wave [14] differs by π between the two states of the qubit, it turns out that, despite its weak intensity, the reflected wave contains precisely the same amount of information about the state of the qubit as the transmitted wave which is more intense but has a smaller phase shift. In the language of Ref. [34], this "wasted" information accounts for the excess dephasing relative to the measurement rate. By measuring also the phase shift of the reflected photons, it could be possible to reach the quantum limit.

Another form of possible backaction is mixing transitions between the two qubit states induced by the microwaves. First, as seen from Fig. 6(a) and 7(a), increasing the average number of photons in the cavity induces mixing. This is simply caused by dressing of the qubit by the cavity photons. Using the dressed states (2) and (3), the level of this coherent mixing can be estimated as

$$P_{\downarrow,\uparrow} = \frac{1}{2}\langle\overline{\pm,n}|\mathbb{1} \pm \sigma^z|\overline{\pm,n}\rangle \tag{29}$$

$$= \frac{1}{2}\left(1 \pm \frac{\Delta}{\sqrt{4g^2(n+1)+\Delta^2}}\right). \tag{30}$$

Exciting the cavity to $n = n_{\mathrm{crit}}$ yields $P_\downarrow \sim 0.85$. As is clear from the numerical results, this process is completely reversible and does not lead to errors in the readout.

The drive can also lead to real transitions between the qubit states. However, since the coupling is so strong, large detuning $\Delta = 0.1\ \omega_r$ can be chosen, making the mixing rate limited not by the frequency spread of the drive pulse, but rather by the width of the qubit excited state itself. The rate of driving the qubit from ground to excited state when n photons are in the cavity is $R \approx n(g/\Delta)^2\gamma$. If the measurement pulse excites the cavity to $n = n_{\mathrm{crit}}$, we see that the excitation rate is still only 1/4 of the relaxation rate. As a result, the main limitation on the fidelity of this QND readout is the decay of the excited state of the qubit during the course of the readout. This occurs (for small γ) with probability $P_{\mathrm{relax}} \sim \gamma t_{\mathrm{meas}} \sim 15\gamma/\kappa \sim 3.75\%$ and leads to a small error $P_{\mathrm{err}} \sim 5\gamma/\kappa \sim 1.5\%$ in the measurement, where we have taken $\gamma = \gamma_\kappa$. As confirmed by the numerical calculations of Fig. 6 and 7, this dispersive measurement is therefore highly nondemolition.

C. Signal to noise

For homodyne detection in the case where the cavity pull $g^2/\Delta\kappa$ is larger than 1, the signal-to-noise ratio (SNR) is given by the ratio of the number of photons, $n_{\mathrm{sig}} = n\kappa\Delta t/2$, accumulated over an integration period Δt, divided by the detector noise $n_{\mathrm{amp}} = k_BT_N/\hbar\omega_r$. Assuming the integration time to be limited by the qubit's decay time $1/\gamma$ and exciting the cavity to a maximal amplitude $n_{\mathrm{crit}} = 100 \sim n_{\mathrm{amp}}$, we obtain SNR $= (n_{\mathrm{crit}}/n_{\mathrm{amp}})(\kappa/2\gamma)$. If the qubit lifetime is longer than a few cavity decay times ($1/\kappa = 160$ ns), this SNR can be very large. In the most optimistic situation where $\gamma = \gamma_\kappa$, the signal-to-noise ratio is SNR $= 200$.

When taking into account the fact that the qubit has a finite probability to decay during the measurement, a better strategy than integrating the signal for a long time is to take advantage of the large SNR to measure quickly. Simulations have shown that in the situation where $\gamma = \gamma_\kappa$, the optimum

TABLE II. Figures of merit for readout and multiqubit entanglement of superconducting qubits using dispersive (off-resonant) coupling to a 1D transmission-line resonator. The same parameters as Table I and a detuning of the Cooper-pair box from the resonator of 10% ($\Delta=0.1\omega_r$) are assumed. Quantities involving the qubit decay γ are computed both for the theoretical lower bound $\gamma=\gamma_\kappa$ for spontaneous emission via the cavity and (in parentheses) for the current experimental upper bound $1/\gamma \geq 2\ \mu$s. Though the signal to noise of the readout is very high in either case, the estimate of the readout error rate is dominated by the probability of qubit relaxation during the measurement, which has a duration of a few cavity lifetimes [$\sim(1-10)\kappa^{-1}$]. If the qubit nonradiative decay is low, both high-efficiency readout and more than 10^3 two-bit operations could be attained.

Parameter	Symbol	1D circuit
Dimensionless cavity pull	$g^2/\kappa\Delta$	2.5
Cavity-enhanced lifetime	$\gamma_\kappa^{-1}=(\Delta/g)^2\kappa^{-1}$	64 μs
Readout SNR	SNR = $(n_{\text{crit}}/n_{\text{amp}})\kappa/2\gamma$	200 (6)
Readout error	$P_{\text{err}}\sim 5\times\gamma/\kappa$	1.5%(14%)
One-bit operation time	$T_\pi > 1/\Delta$	>0.16 ns
Entanglement time	$t_{\sqrt{\text{iSWAP}}}=\pi\Delta/4g^2$	~0.05 μs
Two-bit operations	$N_{\text{op}}=1/[\gamma\, t_{\sqrt{\text{iSWAP}}}]$	>1200(40)

integration time is roughly 15 cavity lifetimes. This is the pulse length used for the stochastic numerical simulations shown above. The readout fidelity, including the effects of this stochastic decay, and related figures of merit of the single-shot high efficiency QND readout are summarized in Table II.

This scheme has other interesting features that are worth mentioning here. First, since nearly all the energy used in this dispersive measurement scheme is dissipated in the remote terminations of the input and output transmission lines, it has the practical advantage of avoiding quasiparticle generation in the qubit.

Another key feature of the cavity QED readout is that it lends itself naturally to operation of the box at the charge degeneracy point ($N_g=1/2$), where it has been shown that T_2 can be enormously enhanced [17] because the energy splitting has an extremum with respect to gate voltage and isolation of the qubit from $1/f$ dephasing is optimal. The derivative of the energy splitting with respect to gate voltage is the charge difference in the two qubit states. At the degeneracy point this derivative vanishes and the environment cannot distinguish the two states and thus cannot dephase the qubit. This also implies that a charge measurement cannot be used to determine the state of the system [4,5]. While the first derivative of the energy splitting with respect to gate voltage vanishes at the degeneracy point, the second derivative, corresponding to the difference in charge *polarizability* of the two quantum states, is *maximal*. One can think of the qubit as a nonlinear quantum system having a state-dependent capacitance (or in general, an admittance) which changes sign between the ground and excited states [36]. It is this change in polarizability which is measured in the dispersive QND measurement.

In contrast, standard charge measurement schemes [37,18] require moving away from the optimal point. Simmonds *et al.* [20] have recently raised the possibility that there are numerous parasitic environmental resonances which can relax the qubit when its frequency Ω is changed during the course of moving the operating point. The dispersive CQED measurement is therefore highly advantageous since it operates best at the charge degeneracy point. In general, such a measurement of an ac property of the qubit is strongly desirable in the usual case where dephasing is dominated by low-frequency ($1/f$) noise. Notice also that the proposed quantum nondemolition measurement would be the inverse of the atomic microwave CQED measurement in which the state of the photon field is inferred nondestructively from the phase shift in the state of atoms sent through the cavity [3].

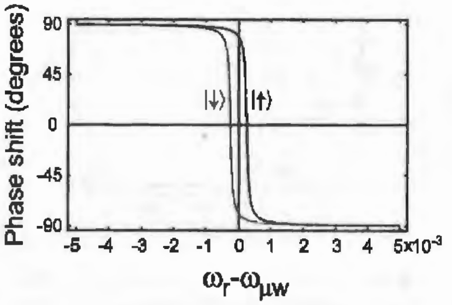

FIG. 8. (Color online) Phase shift of the cavity field for the two states of the qubit as a function of detuning between the driving and resonator frequencies. Obtained from the steady-state solution of the equation of motion for $a(t)$ while only taking into account damping on the cavity and using the parameters of Table I. Readout of the qubit is realized at, or close to, zero detuning between the drive and resonator frequencies where the dependence of the phase shift on the qubit state is largest. Coherent manipulations of the qubit are realized close to the qubit frequency which is 10% detuned from the cavity (not shown on this scale). At such large detunings, there is little dependence of the phase shift on the qubit's state.

VII. COHERENT CONTROL

While microwave irradiation of the cavity at its resonance frequency constitutes a measurement, irradiation close to the qubit's frequency can be used to coherently control the state of the qubit. In the former case, the phase shift of the transmitted wave is strongly dependent on the state of the qubit and hence the photons become entangled with the qubit, as shown in Fig. 8. In the latter case, however, driving is *not* a measurement because, for large detuning, the photons are largely reflected with a phase shift which is independent of the state of the qubit. There is therefore little entanglement between the field and qubit in this situation and the rotation fidelity is high.

To model the effect of the drive on the qubit, we add the microwave drive of Eq. (20) to the Jaynes-Cumming Hamiltonian (1) and apply the transformation (11) (again neglecting damping) to obtain the effective one-qubit Hamiltonian

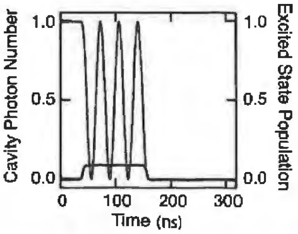

FIG. 9. (Color online) Numerical stochastic wave function simulation showing coherent control of a qubit by microwave irradiation of the cavity at the ac Stark- and Lamb-shifted qubit frequency. The qubit (red line) is first left to evolve freely for about 40 ns. The drive is turned on for $t=7\pi\Delta/2g\varepsilon\sim 115$ ns, corresponding to 7π pulses, and then turned off. Since the drive is tuned far away from the cavity, the cavity photon number (black line) is small even for the moderately large drive amplitude $\varepsilon=0.03\ \omega_r$ used here.

$$H_{1q}=\frac{\hbar}{2}\left[\Omega+2\frac{g^2}{\Delta}\left(a^\dagger a+\frac{1}{2}\right)-\omega_{\mu w}\right]\sigma^z+\hbar\frac{g\varepsilon(t)}{\Delta}\sigma^x$$
$$+\hbar(\omega_r-\omega_{\mu w})a^\dagger a+\hbar\varepsilon(t)(a^\dagger+a) \tag{31}$$

in a frame rotating at the drive frequency $\omega_{\mu w}$. Choosing $\omega_{\mu w}=\Omega+(2n+1)g^2/\Delta$, H_{1q} generates rotations of the qubit about the x axis with Rabi frequency $g\varepsilon/\Delta$. Different drive frequencies can be chosen to realize rotations around arbitrary axes in the $x-z$ plane. In particular, choosing $\omega_{\mu w}=\Omega+(2n+1)g^2/\Delta-2g\varepsilon/\Delta$ and $t=\pi\Delta/2\sqrt{2}g\varepsilon$ generates the Hadamard transformation H. Since $H\sigma^xH=\sigma^z$, these two choices of frequency are sufficient to realize any one-qubit logical operation.

Assuming that we can take full advantage of lifetime enhancement inside the cavity (i.e., that $\gamma=\gamma_\kappa$), the number of π rotations about the x axis which can be carried out is $N_\pi=2\varepsilon\Delta/\pi g\kappa\sim 10^5\varepsilon$ for the experimental parameters assumed in Table I. For large ε, the choice of drive frequency must take into account the power dependence of the cavity frequency pulling.

Numerical simulation shown in Fig. 9 confirms this simple picture and that single-bit rotations can be performed with very high fidelity. It is interesting to note that since detuning between the resonator and the drive is large, the cavity is only virtually populated, with an average photon number $\bar{n}\approx\varepsilon^2/\Delta^2\sim 0.1$. Virtual population and depopulation of the cavity can be realized much faster than the cavity lifetime $1/\kappa$ and, as a result, the qubit feels the effect of the drive rapidly after the drive has been turned on. The limit on the speed of turn on and off of the drive is set by the detuning Δ. If the drive is turned on faster than $1/\Delta$, the frequency spread of the drive is such that part of the drive's photons will pick up phase information (see Fig. 8) and dephase the qubit. As a result, for large detuning, this approach leads to a fast and accurate way to coherently control the state of the qubit.

To model the effect of the drive on the resonator an alternative model is to use the cavity-modified Maxwell-Bloch equations [25]. As expected, numerical integration of the Maxwell-Bloch equations reproduce very well the stochastic numerical results when the drive is at the qubit's frequency but do *not* reproduce these numerical results when the drive is close to the bare resonator frequency (Figs. 6 and 7)—i.e., when entanglement between the qubit and photons cannot be neglected.

VIII. RESONATOR AS QUANTUM BUS: ENTANGLEMENT OF MULTIPLE QUBITS

The transmission-line resonator has the advantage that it should be possible to place multiple qubits along its length ($\sim$1 cm) and entangle them together, which is an essential requirement for quantum computation. For the case of two qubits, they can be placed closer to the ends of the resonator but still well isolated from the environment and can be separately dc biased by capacitive coupling to the left and right center conductors of the transmission line. Additional qubits would have to have separate gate bias lines installed.

For the pair of qubits labeled i and j, both coupled with strength g to the cavity and detuned from the resonator but in resonance with each other, the transformation (11) yields the effective two-qubit Hamiltonian [3,38,39]

$$H_{2q}\approx\hbar\left[\omega_r+\frac{g^2}{\Delta}(\sigma_i^z+\sigma_j^z)\right]a^\dagger a+\frac{1}{2}\hbar\left[\Omega+\frac{g^2}{\Delta}\right](\sigma_i^z+\sigma_j^z)$$
$$+\hbar\frac{g^2}{\Delta}(\sigma_i^+\sigma_j^-+\sigma_i^-\sigma_j^+). \tag{32}$$

In addition to ac Stark and Lamb shifts, the last term couples the qubits through virtual excitations of the resonator.

In a frame rotating at the qubit's frequency Ω, H_{2q} generates the evolution

$$U_{2q}(t)=\exp\left[-i\frac{g^2}{\Delta}t\left(a^\dagger a+\frac{1}{2}\right)(\sigma_i^z+\sigma_j^z)\right]$$
$$\times\begin{pmatrix}1 & & & \\ & \cos\frac{g^2}{\Delta}t & i\sin\frac{g^2}{\Delta}t & \\ & i\sin\frac{g^2}{\Delta}t & \cos\frac{g^2}{\Delta}t & \\ & & & 1\end{pmatrix}\otimes\mathbb{1}_r, \tag{33}$$

where $\mathbb{1}_r$ is the identity operator in resonator space. Up to phase factors, this corresponds at $t=\pi\Delta/4g^2\sim 50$ ns to a $\sqrt{\text{iSWAP}}$ logical operation. Up to one-qubit gates, this operation is equivalent to the controlled-NOT gate. Together with one-qubit gates, the interaction H_{2q} is therefore sufficient for universal quantum computation [40]. Assuming again that we can take full advantage of the lifetime enhancement inside the cavity, the number of $\sqrt{\text{iSWAP}}$ operations which can be carried out is $N_{2q}=4\Delta/\pi\kappa\sim 1200$ for the parameters assumed above. This can be further improved if the qubit's nonradiative decay is sufficiently small and higher Q cavities are employed.

When the qubits are detuned from each other, the off-diagonal coupling provided by H_{2q} is only weakly effective and the coupling is for all practical purposes turned off. Two-qubit logical gates in this setup can therefore be controlled by individually tuning the qubits. Moreover, single-qubit and two-qubit logical operations on different qubits and pairs of qubits can both be realized simultaneously, a requirement to reach presently known thresholds for fault-tolerant quantum computation [41].

It is interesting to point out that the dispersive QND readout presented in Sec. VI may be able to determine the state of multiple qubits in a single shot without the need for additional signal ports. For example, for the case of two qubits with different detunings, the cavity pull will take four different values $\pm g_1^2/\Delta_1 \pm g_2^2/\Delta_2$, allowing single-shot readout of the coupled system. This can in principle be extended to N qubits provided that the range of individual cavity pulls can be made large enough to distinguish all the combinations. Alternatively, one could read them out in small groups at the expense of having to electrically vary the detuning of each group to bring them into strong coupling with the resonator.

IX. ENCODED UNIVERSALITY AND DECOHERENCE-FREE SUBSPACE

Universal quantum computation can also be realized in this architecture under the encoding $\mathcal{L}=\{|\uparrow\downarrow\rangle,|\downarrow\uparrow\rangle\}$ by controlling only the qubit's detuning and, therefore, by turning on and off the interaction term in H_{2q} [42].

An alternative encoded two-qubit logical operation to the one suggested in Ref. [42] can be realized here by tuning the four qubits forming the pair of encoded qubits in resonance for a time $t=\pi\Delta/3g^2$. The resulting effective evolution operator can be written as $\hat{U}_{2q}=\exp[-i(\pi\Delta/3g^2)\hat{\sigma}_{x1}\hat{\sigma}_{x2}]$, where $\hat{\sigma}_{xi}$ is a Pauli operator acting on the ith encoded qubit. Together with encoded one-qubit operations, $\hat{U}_{2q}$ is sufficient for universal quantum computation using the encoding $\mathcal{L}$.

We point out that the subspace $\mathcal{L}$ is a decoherence-free subspace with respect to global dephasing [43] and use of this encoding will provide some protection against noise. The application of $\hat{U}_{2q}$ on the encoded subspace $\mathcal{L}$, however, causes temporary leakage out of this protected subspace. This is also the case with the approach of Ref. [42]. In the present situation, however, since the Hamiltonian generating $\hat{U}_{2q}$ commutes with the generator of global dephasing, this temporary excursion out of the protected subspace does not induce noise on the encoded qubit.

X. SUMMARY AND CONCLUSIONS

In summary, we propose that the combination of one-dimensional superconducting transmission-line resonators, which confine their zero-point energy to extremely small volumes, and superconducting charge qubits, which are electrically controllable qubits with large electric dipole moments, constitutes an interesting system to access the strong-coupling regime of cavity quantum electrodynamics. This combined system is an advantageous architecture for the coherent control, entanglement, and readout of quantum bits for quantum computation and communication. Among the practical benefits of this approach are the ability to suppress radiative decay of the qubit while still allowing one-bit operations, a simple and minimally disruptive method for readout of single and multiple qubits, and the ability to generate tunable two-qubit entanglement over centimeter-scale distances. We also note that in the structures described here, the emission or absorption of a single photon by the qubit is tagged by a sudden large change in the resonator transmission properties [29], making them potentially useful as single-photon sources and detectors.

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APPENDIX A: QUANTIZATION OF THE 1D TRANSMISSION-LINE RESONATOR

A transmission line of length L, whose cross-section dimension is much less then the wavelength of the transmitted signal, can be approximated by a 1D model. For relatively low frequencies it is well described by an infinite series of inductors with each node capacitively connected to ground, as shown in Fig. 2. Denoting the inductance per unit length l and the capacitance per unit length c, the Lagrangian of the circuit is

$$\mathcal{L}=\int_{-L/2}^{L/2} dx\left(\frac{l}{2}j^2-\frac{1}{2c}q^2\right), \tag{A1}$$

where $j(x,t)$ and $q(x,t)$ are the local current and charge density, respectively. We have ignored for the moment the two semi-infinite transmission lines capacitively coupled to the resonator. Defining the variable $\theta(x,t)$,

$$\theta(x,t)\equiv\int_{-L/2}^{x} dx' q(x',t), \tag{A2}$$

the Lagrangian can be rewritten as

$$L=\int_{-L/2}^{L/2} dx\left(\frac{l}{2}\dot{\theta}^2-\frac{1}{2c}(\nabla\theta)^2\right). \tag{A3}$$

The corresponding Euler-Lagrange equation is a wave equation with the speed $v=\sqrt{1/lc}$. Using the boundary conditions due to charge neutrality,

$$\theta(-L/2,t)=\theta(L/2,t)=0, \tag{A4}$$

we obtain

$$\theta(x,t) = \sqrt{\frac{2}{L}} \sum_{k_o=1}^{k_{o,\mathrm{cutoff}}} \phi_{k_o}(t) \cos\frac{k_o \pi x}{L} + \sqrt{\frac{2}{L}} \sum_{k_e=2}^{k_{e,\mathrm{cutoff}}} \phi_{k_e}(t) \sin\frac{k_e \pi x}{L}. \tag{A5}$$

for odd and even modes, respectively. For finite length L, the transmission line acts as a resonator with resonant frequencies $\omega_k = k\pi v/L$. The cutoff is determined by the fact that the resonator is not strictly one dimensional.

Using the normal-mode expansion (A5) in (A3), one obtains, after spatial integration, the Lagrangian in the form of a set of harmonic oscillators:

$$\mathcal{L} = \sum_k \frac{l}{2}\dot{\phi}_k^2 - \frac{1}{2c}\left(\frac{k\pi}{L}\right)^2 \phi_k^2. \tag{A6}$$

Promoting the variable ϕ_k and its canonically conjugated momentum $\pi_k = l\dot{\phi}_k$ to conjugate operators and introducing the boson creation and annihilation operators $a_k^\dagger$ and a_k satisfying $[a_k, a_{k'}^\dagger] = \delta_{kk'}$, we obtain the usual relations diagonalizing the Hamiltonian obtained from the Lagrangian (A6):

$$\hat{\phi}_k(t) = \sqrt{\frac{\hbar\omega_k c}{2}} \frac{L}{k\pi}[a_k(t) + a_k^\dagger(t)], \tag{A7}$$

$$\hat{\pi}_k(t) = -i\sqrt{\frac{\hbar\omega_k l}{2}}[a_k(t) - a_k^\dagger(t)]. \tag{A8}$$

From these relations, the voltage on the resonator can be expressed as

$$\begin{aligned} V(x,t) &= \frac{1}{c}\frac{\partial\theta(x,t)}{\partial x} \\ &= -\sum_{k_o=1}^{\infty} \sqrt{\frac{\hbar\omega_{k_o}}{Lc}} \sin\left(\frac{k_o\pi x}{L}\right)[a_{k_o}(t) + a_{k_o}^\dagger(t)] \\ &\quad + \sum_{k_e=1}^{\infty} \sqrt{\frac{\hbar\omega_{k_e}}{Lc}} \cos\left(\frac{k_e\pi x}{L}\right)[a_{k_e}(t) + a_{k_e}^\dagger(t)]. \end{aligned} \tag{A9}$$

In the presence of the two semi-infinite transmission lines coupled to the resonator, the Lagrangian (A3) and the boundary conditions (A4) are modified to take into account the voltage drop on the coupling capacitors C_0. Assuming no spatial extent for the capacitors C_0, the problem is still solvable analytically. Due to this coupling, the wave function can now extend outside of the central segment which causes a slight redshift, of order C_0/Lc, of the cavity resonant frequency.

As shown in Fig. 2, we assume the qubit to be fabricated at the center of the resonator. As a result, at low temperatures, the qubit is coupled to the mode $k=2$ of the resonator, which as an antinode of the voltage in its center. The rms voltage between the center conductor and the ground plane is then $V_{\mathrm{rms}}^0 = \sqrt{\hbar\omega_r/cL}$ with $\omega_r = \omega_2$ and the voltage felt by the qubit is $V(0,t) = V_{\mathrm{rms}}^0[a_2(t) + a_2^\dagger(t)]$. In the main body of this paper, we work only with this second harmonic and drop the mode index on the resonator operators.

APPENDIX B: TREATMENT OF DISSIPATION

The evolution of the total density matrix, including the qubit, cavity mode, and baths, is described by the von Neuman equation

$$\dot{\rho}_{tot} = -\frac{i}{\hbar}[H_{\mathrm{sys}} + H_\kappa + H_\gamma, \rho_{\mathrm{tot}}], \tag{B1}$$

where H_{sys} stands for the first three terms of Eq. (1) plus the drive Hamiltonian of Eq. (20). An explicit expression for H_κ can be found in Ref. [14]. When the coupling between the system (qubit plus cavity mode) and the baths is weak, the reduced density operator for the system can be shown to obey the master equation [14]

$$\dot{\rho} = -\frac{i}{\hbar}[H_{\mathrm{sys}}, \rho] - \frac{1}{2}\sum_{m=\{\kappa,\gamma\}} (L_m^\dagger L_m \rho + \rho L_m^\dagger L_m - 2L_m \rho L_m^\dagger) \tag{B2}$$

in the Markov approximation. Here, L_m are Lindblad operators describing the effect of the baths on the system and can be expressed as $L_\kappa = \sqrt{\kappa a}$ and $L_\gamma = \sqrt{\gamma\sigma^-}$. The effect of finite temperature and pure dephasing, for example, can also be taken into account easily by introducing additional Lindblad operators.

The master equation is solved numerically by truncating the cavity Hilbert space to N photons. This leads to $(2N)^2$ coupled differential equations which, for large N, can be difficult to solve in practice. An alternative approach is to write an equivalent stochastic differential equation for the wave function [32,44]. There exist different such "unravelings" of the master equation and here we use the quantum state diffusion equation [32,44]

$$\begin{aligned} |d\psi\rangle = &-\frac{i}{\hbar}H_{\mathrm{sys}}|\psi\rangle dt + \sum_m (L_m - \langle L_m\rangle_\psi)|\psi\rangle d\xi_m \\ &- \frac{1}{2}\sum_m (L_m^\dagger L_m + \langle L_m^\dagger\rangle_\psi \langle L_m\rangle_\psi - 2\langle L_m^\dagger\rangle_\psi L_m)|\psi\rangle dt. \end{aligned} \tag{B3}$$

The $d\xi_m$ are complex independent Wiener processes satisfying for their ensemble averages

$$\overline{d\xi_m} = \overline{d\xi_m d\xi_n} = 0, \tag{B4}$$

$$\overline{d\xi_m^* d\xi_n} = \delta_{mn} dt. \tag{B5}$$

An advantage of this approach is that now only $2N$ coupled differential equations have to be solved. A drawback is that the results must be averaged over many realizations of the noise to obtain accurate results. Still, this leads to much less important memory usage and to speedup in the numerical calculations [32,45].

APPENDIX C: QUANTUM NONDEMOLITION MEASUREMENTS

Readout of a qubit can lead to both mixing and dephasing [23,33]. While dephasing is unavoidable, mixing of the measured observable can be eliminated in a QND measurement by choosing the qubit-measurement apparatus interaction such that the measured observable is a constant of motion. In that situation, the measurement-induced mixing is rather introduced in the operator conjugate to the operator being measured.

In the situation of interest in this paper, the operator being probed is σ^z and, from Eq. (12), the qubit-measurement apparatus interaction Hamiltonian is given for large detuning by $H_{\mathrm{int}}=(g^2/\Delta)\sigma^z a^\dagger a$, such that $[\sigma^z,H_{\mathrm{int}}]=0$. For σ^z to be a constant of motion also requires that it commute with the qubit Hamiltonian. This condition is also satisfied in Eq. (12).

That the measured observable is a constant of motion implies that repeated observations will yield the same result. This allows for the measurement result to reach arbitrary large accuracy by accumulating signal. In practice, however, there are always environmental dissipation mechanisms acting on the qubit independently of the readout. Even in a QND situation, these will lead to a finite mixing rate $1/T_1$ of the qubit in the course of the measurement. Hence, high fidelity can only be achieved by a strong measurement completed in a time $T_{\mathrm{m}} \ll T_1$. This simple point is not as widely appreciated as it should be.

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Blais, A., Huang, R. S., Wallraff, A., Girvin, S. M., & Schoelkopf, R. J. (2004). Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation. *Physical Review A*, vol. 69, no. 6, article 062320. (14 pages)

Early Citations Selected from 2004 (in chronological order)

Zhu, S. L., Wang, Z. D., & Zanardi, P. (February 2004). Geometric quantum computation and multi-qubit entanglement with superconducting charge qubits inside a cavity. *arXiv preprint quant-ph/0403004*.

Camalet, S., Schriefl, J., Degiovanni, P., & Delduc, F. (October 2004). Quantum impurity approach to a coupled qubit problem. *EPL (Europhysics Letters)*, *68*(1), 37.

Pritchett, E. J., & Geller, M. R. (October 2004). Nanomechanical quantum memory for superconducting qubits. *arXiv preprint quant-ph/0410029*.

Strauch, F. W. (2004). *Theory of superconducting phase qubits*(Doctoral dissertation).

Xu, H. (2004). *Quantum computing with Josephson junction circuits* (Doctoral dissertation).

APPENDIX 1019-A

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Coherent Josephson Qubit Suitable for Scalable Quantum Integrated Circuits

R. Barends, J. Kelly, A. Megrant, D. Sank, E. Jeffrey, Y. Chen, Y. Yin,* B. Chiaro, J. Mutus, C. Neill, P. O'Malley, P. Roushan, J. Wenner, T. C. White, A. N. Cleland, and John M. Martinis

Department of Physics, University of California, Santa Barbara, California 93106, USA

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We demonstrate a planar, tunable superconducting qubit with energy relaxation times up to 44 μs. This is achieved by using a geometry designed to both minimize radiative loss and reduce coupling to materials-related defects. At these levels of coherence, we find a fine structure in the qubit energy lifetime as a function of frequency, indicating the presence of a sparse population of incoherent, weakly coupled two-level defects. We elucidate this defect physics by experimentally varying the geometry and by a model analysis. Our "Xmon" qubit combines facile fabrication, straightforward connectivity, fast control, and long coherence, opening a viable route to constructing a chip-based quantum computer.

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One of the outstanding challenges in building a quantum computer is to balance coherence, connectivity, and control in the qubits. Superconductivity provides an appealing platform because it allows for scalability: the conduction electrons condense into a macroscopic quantum state, and large quantum integrated circuits can be made with many elements having individual control lines. However, quantum coherence in superconducting circuits has proven to be very delicate, as it is easily disturbed by material defects, electron system excitations, and radiative coupling to external wiring [1–8]. To minimize these and other effects, many groups have recently begun embedding qubits in three-dimensional superconducting cavities. These 3D qubits show high coherence, with energy relaxation times in 3D transmon qubits between 30 and 140 μs [9,10].

Here, we demonstrate a new design for a fully planar superconducting qubit, based on the planar transmon [11,12], with energy coherence times in excess of 40 μs. Our approach balances coherence, connectivity, as well as fast control. The qubits are frequency tunable, which allows the implementation of fast two-qubit gates: a CONTROLLED-Z gate [13–15] can then be implemented with high fidelity in 25 ns [16]. With the coherence time exceeding single- and two-qubit gate times by 3 orders of magnitude, we believe that our device provides a key ingredient for implementing a surface code quantum computer [17].

We also identify an incoherent decoherence mechanism, arising from a sparse bath of weakly coupled defects. This incoherent regime is made accessible by the long coherence of our qubits. We explore this physics by visualizing these defects in the measured quantum time-resolved spectroscopy, by varying the qubit geometry, and by a model analysis. These defects give rise to frequency-dependent variations in the lifetime; our results may also explain the variations observed in lifetimes of 3D transmon qubits.

Our device is shown in Fig. 1(a), formed by patterning the Al metal (light areas) and exposing the sapphire substrate (dark areas). The qubit is the cross-shaped device. We design the qubit with high-quality coplanar waveguide capacitors, motivated by the recent advances with superconducting resonators, yielding a modular design with straightforward connectivity. Its four arms connect to separate elements, each having a different function: a coplanar waveguide resonator for readout on the top, a quantum bus resonator on the right to mediate coupling to other qubits, XY control on the left to excite the qubit state, and Z control on the bottom to tune the qubit frequency. The cross is the qubit capacitor, which connects at the bottom to the tunable Josephson junction, formed by the rectangular

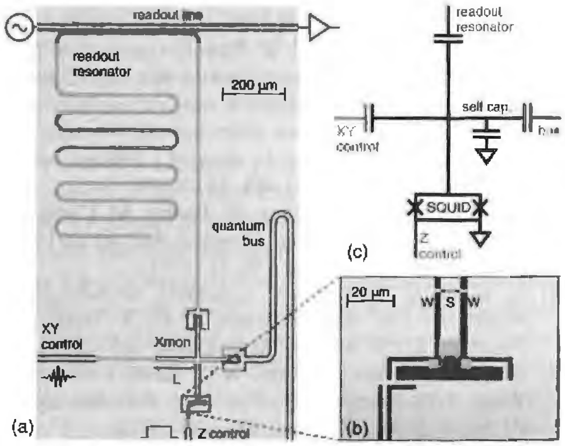

FIG. 1 (color online). (a) Optical micrograph of the planar Xmon qubit, formed by the Al superconducting film (light) and the exposed sapphire substrate (dark). The qubit is capacitively coupled to a quarter wave readout resonator (top), a quantum bus resonator (right), and an XY control line (left), and inductively coupled to a Z control line (bottom). The Xmon arm length is L. (b) The inset shows the shadow evaporated Al junction layer in false color (blue regions). The junction size is $0.30 \times 0.20\ \mu\text{m}^2$. The capacitor central linewidth is S, and the gap width is W. (c) The electrical circuit of the qubit.

ring-shaped superconducting quantum interference device (SQUID); see Fig. 1(b). The rectangular ring is intersected by two identically sized Al tunnel junctions [blue regions in Fig. 1(b)]. The electrical circuit is equivalent to that of a grounded transmon [11], with the capacitor in parallel with the tunable junction [Fig. 1(c)]. In a clear departure from the traditional floating transmon with an interdigitated capacitor [12], we chose to form the qubit capacitor by intersecting two coplanar waveguide lines.

In prior work, we showed that highly coherent coplanar waveguide resonators can be fabricated, having quality factors of about 1.5×10^6 at the single photon occupation level. These resonators were made from molecular beam epitaxy (MBE) Al on oxygen-cleaned sapphire [18]. This shows that a straightforward path to high coherence comes from a combination of (I) MBE Al as high-quality material, (II) coplanar waveguides having low radiative loss, and (III) embedding in a ground plane. We therefore embed the qubit in an uninterrupted ground plane, with thin Al lines at the capacitor ends tying the ground planes together; this suppresses parasitic slot line modes in the control lines and resonators as well.

Connectivity is accomplished by coupling each of the qubit's arms to a distinct element with specific functionality. Three of the connections are easily made with a coupling capacitor, as the qubit is connected to ground. An advantage of this approach is that each coupling can be individually tuned and optimized. To this end, we have also separated out qubit control. The XY control drive line is connected with a coupling $C_c = 60$ aF, which allows us to excite the qubit state in 10 ns but hardly affects coherence, with an estimated T_1 of 0.3 ms. The Z control also combines speed and coherence. The drive line is galvanically connected to the SQUID to allow for a large inductive coupling with a mutual inductance of $M = 2.2$ pH. We are able to rapidly detune the qubit on the time scale of a nanosecond [19]. The measured parasitic coupling between the Z line and the qubit gives an estimated T_1 of $\sim$30 ms [20].

We believe that the large increase in the qubit coherence relies critically on the *combination* of changes to the qubit design; implementing just one or two of these changes in isolation would not yield a significant improvement. With this experimental nature in mind, we name our qubit the "Xmon." While the cross-shaped qubit capacitor may emphasize this name, more arms can be added to allow for more connectivity.

We find a dramatic increase in Xmon energy coherence compared to the traditional planar transmon, measuring decay times up to $T_1 = 44\ \mu s$; see Fig. 2(a). We find Ramsey and spin echo phase coherence times up to $T_2^* = 15\ \mu s$ and $T_2 = 20\ \mu s$ at the flux insensitive point, respectively [see Fig. 2(b)]; $T_1 = 18\ \mu s$ at this point. The dephasing envelopes follow an exponential decay, measured using tomography. The first pulse is $X_{\pi/2}$, followed by $X_{\pi/2}$, $X_{-\pi/2}$, $Y_{\pi/2}$, or $Y_{-\pi/2}$ (see the inset), producing fringes with different phases. The limit of $T_2 = 2T_1$ has not been reached [11], indicating additional dephasing. This, as well as dephasing away from the flux insensitive point, is presently under investigation.

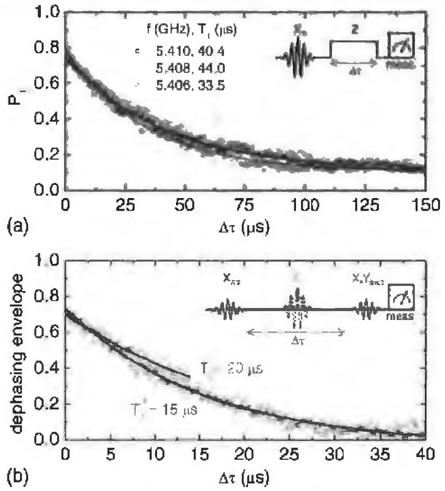

FIG. 2 (color online). (a) Qubit energy decay at three nearby frequencies ($S = W = 16\ \mu$m [43]). The qubit frequency is adjusted by applying a rectangular pulse with length $\Delta\tau$ on the Z line. The pulse sequence is shown in the inset. (b) Ramsey T_2^* and spin echo T_2 dephasing envelopes at the flux insensitive point ($T_1 = 18\ \mu s$), measured by phase tomography ($S = W = 24\ \mu$m). The inset shows the pulse sequence; for the spin echo, we apply a refocusing pulse (dashed line). We apply four phases to the last pulse for phase tomography, to measure the decay envelope. Spin echo measurements are limited by electronics to 14 μs.

The qubits had ground to excited state transition frequencies around 6 GHz when unbiased, nonlinearities around 230 MHz, and a ratio of Josephson to charging energy $E_J/E_C \sim 95$. We employ a dispersive, high-power single-shot readout scheme with a 70%–85% fidelity [21]. The readout resonator frequencies used are 6.4–6.7 GHz, the loaded quality factor is $Q_l = 10^4$, and the resonator-qubit coupling strength is approximately 40 MHz. Measurements were done in a dilution refrigerator with a base temperature of 30 mK, with multistage infrared shielding [22]. Magnetic fields were reduced by room temperature and cryogenic magnetic shields, with nonmagnetic microwave connectors [23].

The results in Fig. 2 show that tunable superconducting qubits with a planar geometry can have T_1 values in excess of 40 μs. In fact, this T_1 corresponds to the MBE Al resonator quality factors [18], for which $T_1 = Q/\omega$ is also about 40 μs. The combination of long energy and phase coherence times compares well with previously reported values for planar superconducting Al qubits: for transmons $T_1 = 9.7\ \mu s$ and $T_2^* = 10\ \mu s$ [24], for charge qubits $T_1 = 200\ \mu s$ and $T_2^* = 0.07\ \mu s$ [25], for flux qubits $T_1 = 12\ \mu s$ and $T_2^* = 2.5\ \mu s$ [26], and for the fluxonium $T_1 = 10\ \mu s$ and $T_2^* = 2\ \mu s$ [27]. In fact, the Xmon approaches the long coherence found in 3D transmons [9,10]. Very recently, TiN planar devices have shown long coherence [28,29], encouraging using Xmon geometries with this material.

We find that the energy relaxation depends on qubit frequency. As shown in Fig. 2(a), we find T_1 values from 34 to 44 μs in a 4 MHz band near 5.4 GHz. In order to elucidate this further, we performed a spectroscopic scan on the qubit, shown in Fig. 3(a). The qubit frequency displays the expected dependence on applied flux Φ [11], varying smoothly without visible splittings, indicating that strongly coupled defects, which manifest as avoided level crossings [1], are virtually absent. We then performed a quantum analogue of time-resolved spectroscopy (swap spectroscopy [30]), shown in Fig. 3(b). The pulse sequence is shown in Fig. 2(a). The probability of the excited state (color) is plotted for $\Delta\tau$ from 100 ns to 150 μs (logarithmic vertical scale) and qubit frequencies from 4 to 6 GHz. We find that the probability decays exponentially, but with a fine structure of variable energy relaxation and distinct peaks in the energy decay rate [Fig. 3(c)]. We do not observe any "chevron" interference patterns [30], where the quantum state coherently swaps back and forth, implying no defects interact coherently with the qubit. After cycling the temperature to 4.2 K, the fine structure is altered, but the overall image remains unchanged. We count approximately 30 regions with reduced coherence ($T_1 < 8$ μs) per GHz in Fig. 3(b).

We explored the dependence of the qubit coherence time on capacitor geometry, using six different designs; the width S of the central line, gap width W, and arm length L were varied, while the capacitance value [31] and junction parameters are kept the same. The parameters are listed in Table I; see Ref. [19] for a micrograph. We find that the swap spectroscopy measurements of the different designs share the same characteristics as shown in Fig. 3(b): a fine structure with varying exponential decay. The energy relaxation times extracted from the measurements are shown in Fig. 4. The overall energy relaxation time increases with width: when changing S,W from 8, 4 μm to 16, 8 μm and 24, 12 μm, the T_1 improves from a band of values between 8 and 15 to 10 and 20, and 20 and 40 μs, respectively. Importantly, both the upper and lower bounds on T_1 increase. This is repeated in the qubits with S,W ranging from 8,8 to 16,16 and 24, 24 μm. The reduction of T_1 at frequencies approaching 6 GHz is due to Purcell decay into the readout resonator [32]. We emphasize that these T_1 values are obtained in multiqubit chips with control wiring.

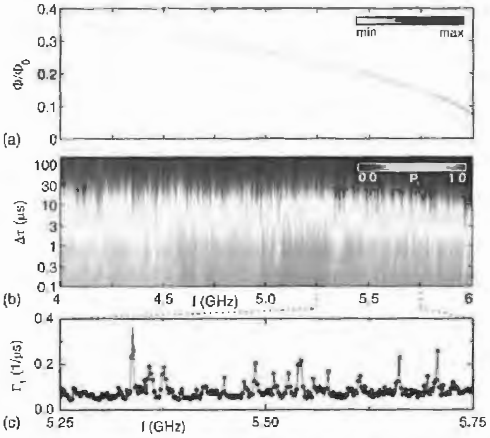

FIG. 3 (color online). (a) Qubit spectroscopy for a device with S, $W = 8$, 8 μm. A smooth curve is formed by the high transmission (gray line), measured on resonance with the readout resonator, which indicates when the qubit is excited. (b) Swap spectroscopy of the same qubit. The qubit is detuned from 4 to 6 GHz (step size 2 MHz), and the delay time is varied from 100 ns to 150 μs. See the inset of Fig. 2(a) for the pulse sequence. (c) Qubit relaxation rates, extracted from the data in (b). The peaks are fitted to Eq. (1) (solid lines).

The improvement of T_1 with increasing width is consistent with previous experiments on superconducting resonators [33,34]. Loss arises from the electric fields coupling to two-level systems with dipole moments [35], which reside predominantly in surface oxides and interfaces. This loss depends on the participation ratio, which depends on the electric field distribution [36]. Widening the capacitor reduces the surface participation, a natural explanation for the approximately linear increase in average T_1 with width in Fig. 4. On the other hand, the peaks in the decay rate are reminiscent of experiments with phase qubits [1], where localized features in the frequency dependence occur when the qubit couples strongly to two-level defects, often giving rise to splitting of the qubit frequency and the chevron-shaped signature of coherent swapping. However, the exponential decay in the Xmon qubit, with no signatures of swapping or splitting, suggests a different energy relaxation mechanism.

Here, we show how surface defects near the metal edges of the capacitor provide a natural explanation for the peaks in the energy decay. As indicated by the data, the key point is that loss arises from the qubit interacting with a sparse bath of incoherent, weakly coupled defects, giving rise to incoherent decay [37]. The sharp frequency dependence as well as the changes in fine structure when cycling to 4.2 K are consistent with defects. The absence of chevrons and qubit frequency splittings corresponds to incoherent interaction. The lower and upper bounds of T_1 increasing with capacitor dimension indicate that the defects reside in the capacitor.

We model a quantum system consisting of a qubit, with a frequency-independent loss rate $\Gamma_{1,Q}$ and pure dephasing rate $\Gamma_{\phi,Q}$, and a two-level defect with decoherence rate

TABLE I. Geometric parameters for the Xmon qubit capacitors as defined in Fig. 1 along with their frequencies. Groups of three qubits indicate that the devices are on the same chips.

S (μm)	8	16	24	8	16	24
W (μm)	4	8	12	8	16	24
L (μm)	130	130	130	165	165	165
$f_{10,\max}$ (GHz)	6.094	6.158	6.071	6.080	5.883	5.846
Nonlinearity (MHz)	224	228	222	220	225	223

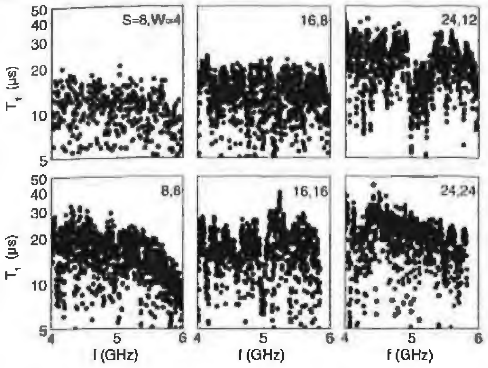

FIG. 4. Frequency dependence of T_1 for six qubits with different S and W (see Table I). The frequency step size is 5 MHz for $S, W = 8, 4$ μm and 2 MHz otherwise. See Ref. [19] for the corresponding decay rates.

$\Gamma_{1,D}$ and dephasing rate $\Gamma_{\phi,D}$ [19]; we assume Markovian decoherence. When $\Gamma_{1,D}$ exceeds the coupling strength g, coherent swapping vanishes and an incoherent, exponential decay appears. From a two-spin Hamiltonian [19], we derive the qubit energy relaxation rate Γ_1 (in the limit $\Gamma_{1,D} > g > \Gamma_{1,Q}$)

$$\Gamma_1 = \frac{2g^2\Gamma}{\Gamma^2 + \Delta^2} + \Gamma_{1,Q}, \tag{1}$$

with detuning Δ, and $\Gamma = \Gamma_{1,D}/2 + \Gamma_{\phi,D} + \Gamma_{1,Q}/2 + \Gamma_{\phi,Q}$. Hence, each uncorrelated defect adds a single Lorentzian to the energy decay rate. We can roughly estimate g for a surface defect with dipole moment $p \sim 1$ Debye at a distance x away from the metal edge. With the electric field given by $E = B/\sqrt{x}$ [38] and B from numerical simulations [39], we arrive at $g/2\pi \sim 0.1$ MHz ($g = pE$) for $x = 3$ nm. We apply our model to Fig. 3(c). The peaks in decay rate can be described by a set of Lorentzians, with $1/(\Gamma_{1,D}/2 + \Gamma_{\phi,D}) \sim 50$–$100$ ns, consistent with defect decay rates measured in similar systems [1,40] and with $g/2\pi \gtrsim 0.2$ MHz, agreeing with incoherent loss.

We can also estimate the number of individually resolvable defects using two-level system physics developed for junctions. The substrate-metal interface in our devices was thoroughly cleaned [18]; hence, we assume that the bulk of strongly coupled defects resides in the metal- and substrate-air interfaces, as they have the highest participation ratios [36]. The defect density for AlO_x in tunnel barriers has been established in measurements with phase qubits [1], with the distribution over dipole moment given by $\rho_0\sqrt{1 - p^2/p^2_{\max}}/p$, with $\rho_0 \approx 10^2/\mu\mathrm{m}^3/\mathrm{GHz}$, and the maximum dipole moment $p_{\max} = 6$ Debye. We take these numbers as representative and assume a 3 nm thick dielectric layer with defects [41]. The number of defects with coupling strength greater than $g_{\min}$ is then given by

$$N = \iint \rho_0 \frac{\sqrt{1 - p^2/p^2_{\max}}}{p} \Theta[p|E(\vec{r})| - g_{\min}]dpd\vec{r}, \tag{2}$$

with Θ the unit step function and $E(\vec{r})$ the electric field at position $\vec{r}$. Simulations using Eq. (2) as well as Monte Carlo simulations indicate $N \sim 30$–50/GHz, for $g_{\min}/2\pi \sim 0.2$ MHz; see Ref. [19]. We emphasize that the simulations connect $g_{\min}$ to N with values which are close to what is observed experimentally. The simulations also indicate that the bulk of strongly coupled defects reside within a $\sim$100 nm distance from the etched edges, where the electric fields are largest. In addition, the simulated qubit decay rate reproduces the experimentally observed features, showing both the peaks and background variation.

The good quantitative comparison between model and experiment gives compelling evidence that a sparse bath of incoherent defects plays a major role in loss in highly coherent qubits. Our results may also explain previously reported anomalous behavior in planar transmon qubits with long coherence, for which the T_1 has been reported to vary significantly between qubits, even on the same chip [24,42]. This is consistent with a sparse bath of incoherent defects limiting the coherence, as in Fig. 3.

In conclusion, we demonstrate energy coherence times exceeding 40 μs in tunable, planar superconducting qubits. We have achieved this using a geometry with low radiative dissipation and high-quality materials. At these high coherence levels, we identify a novel decoherence mechanism, loss from a sparse bath of incoherent defects, which is apparent in the swap spectroscopy. Our qubits combine long coherence, easy interconnectivity, and fast control, providing a key ingredient for the implementation of an on-chip surface code quantum computer.

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*Present address: Department of Physics, Zhejiang University, Hangzhou 310027, China.

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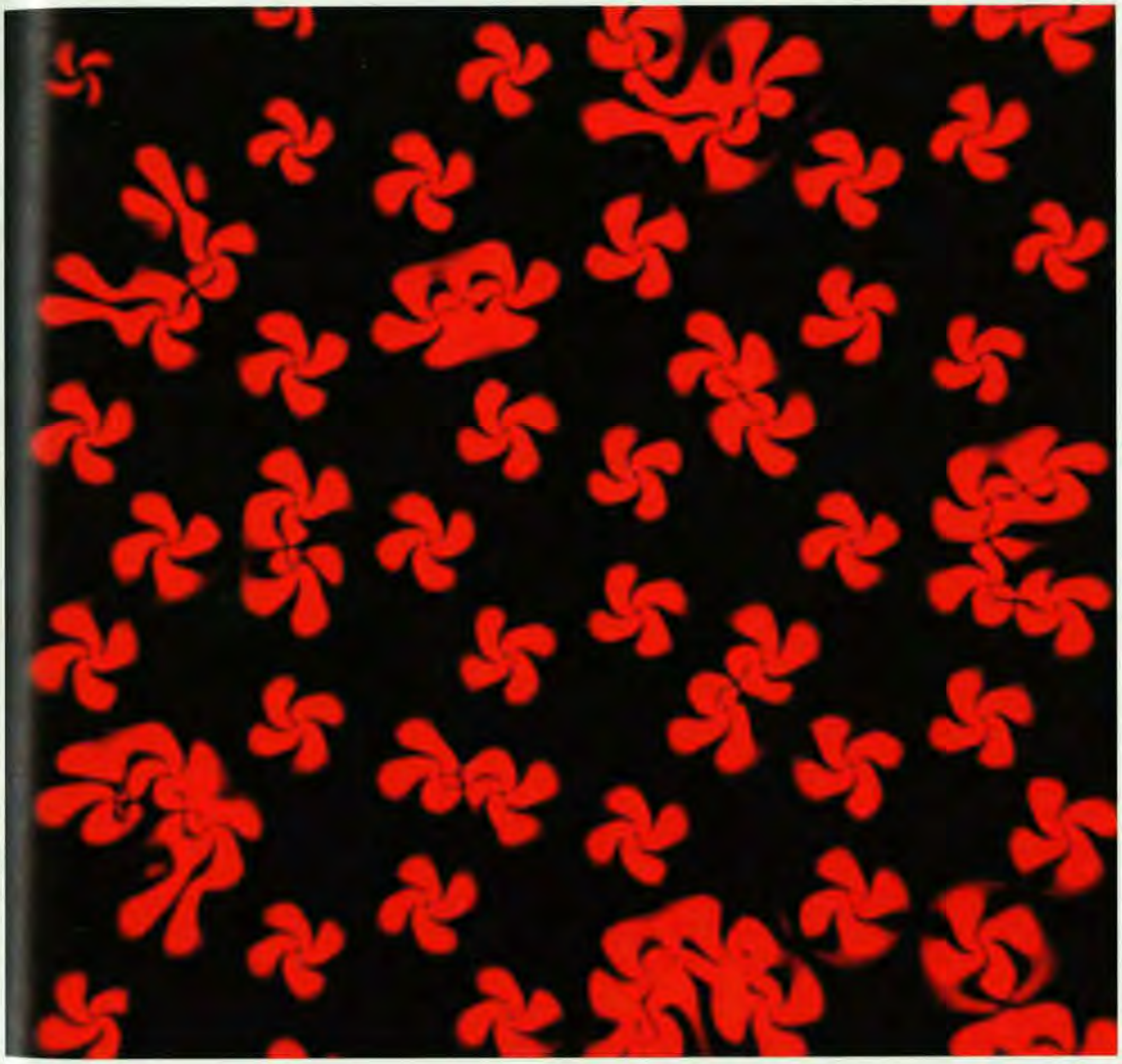

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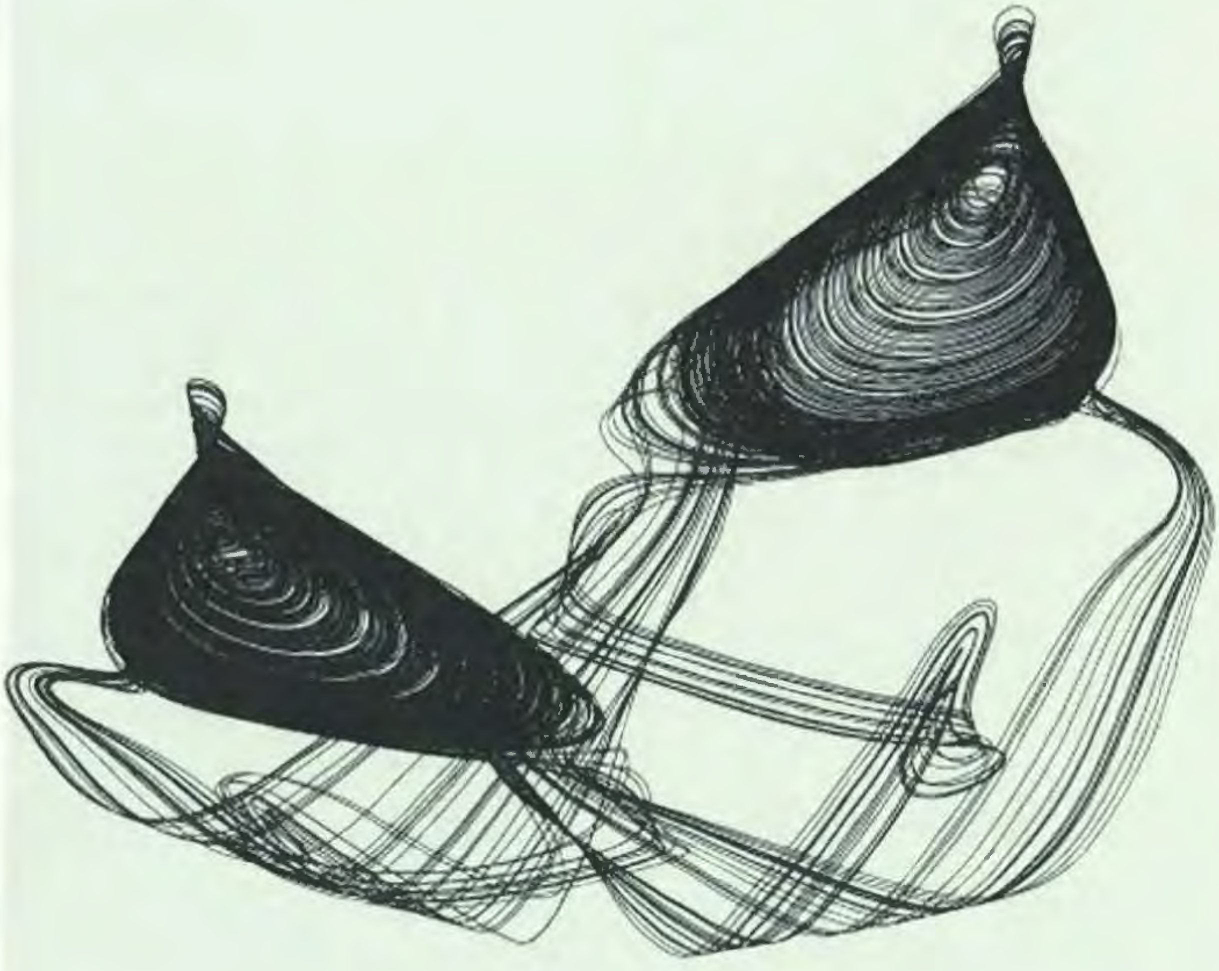

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Observation of High Coherence in Josephson Junction Qubits Measured in a Three-Dimensional Circuit QED Architecture

Hanhee Paik,[1] D. I. Schuster,[1,2] Lev S. Bishop,[1,3] G. Kirchmair,[1] G. Catelani,[1] A. P. Sears,[1] B. R. Johnson,[1,4] M. J. Reagor,[1] L. Frunzio,[1] L. I. Glazman,[1] S. M. Girvin,[1] M. H. Devoret,[1] and R. J. Schoelkopf[1]

[1]*Department of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics and James Franck Institute, University of Chicago, Chicago, Illinois 60637, USA*
[3]*Joint Quantum Institute and Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742, USA*
[4]*Raytheon BBN Technologies, Cambridge, Massachusetts 02138, USA*

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Superconducting quantum circuits based on Josephson junctions have made rapid progress in demonstrating quantum behavior and scalability. However, the future prospects ultimately depend upon the intrinsic coherence of Josephson junctions, and whether superconducting qubits can be adequately isolated from their environment. We introduce a new architecture for superconducting quantum circuits employing a three-dimensional resonator that suppresses qubit decoherence while maintaining sufficient coupling to the control signal. With the new architecture, we demonstrate that Josephson junction qubits are highly coherent, with $T_2 \sim 10$ to $20\ \mu$s without the use of spin echo, and highly stable, showing no evidence for $1/f$ critical current noise. These results suggest that the overall quality of Josephson junctions in these qubits will allow error rates of a few 10^{-4}, approaching the error correction threshold.

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Superconducting circuits are a promising technology for quantum information processing with solid-state devices. Several different types of qubits [1,2] have been developed, which all rely on the nonlinearity of one or more Josephson junctions. Ideally, the Josephson junctions should be dissipationless and highly stable to avoid decoherence, while providing the crucial anharmonicity that allows individual energy levels to be separately addressed. In the past decade, the coherence time of superconducting qubits has increased from initially only a few nanoseconds to typically about a microsecond today. This has permitted experiments where two or three qubits are controlled, entangled [3–6], and used to demonstrate simple algorithms [7]. However, scaling more than three qubits with an acceptable level of fidelity and coherence will require higher coherence times than the current state of art. Two major outstanding questions are whether superconducting qubit coherence can improve further and whether there are fundamental limits on coherence imposed by the Josephson junctions.

The coherence can either be limited by possible imperfections in the Josephson junctions or by unintended interactions with the environment. Even if the junctions were perfectly coherent, achieving a long coherence time also requires understanding and controlling the Hamiltonian such that the terms coupling the qubit to the outside world can be made small. For example, in the hydrogen atom a coupling of only 40 parts per billion (ppb) to the electromagnetic continuum gives rise to spontaneous emission and a quality factor Q of about 25 million (25×10^6). Building a scalable quantum computer using superconducting qubits therefore requires engineering a Hamiltonian where the undesirable couplings that lead to decoherence are kept at the part per million (ppm) to ppb level. Can a man-made, macroscopic quantum system based on Josephson junctions have well-defined quantum states that approach this level of coherence?

Here we present results on a new implementation of a superconducting qubit where we carefully control the coupling to the environment, obtaining an increase in coherence by over an order of magnitude. We observe reproducible qubit lifetimes for relaxation (T_1) up to 60 μs, and lifetimes of coherent superpositions (T_2) of 10–20 μs, corresponding to quality factors for both dissipation ($Q_1 = \omega_{01} T_1 \sim 2 \times 10^6$, where ω_{01} is the transition frequency of the qubit) and decoherence ($Q_2 = \omega_{01} T_2 \sim 7 \times 10^5$) of about 1×10^6. The high quality factors observed imply that the instability in the parameters of our system, the intrinsic dissipation in the Josephson junction, and the size of the undesired couplings are all in fact smaller than 1 ppm. Together with the fast gate time ($t_{\text{gate}} \sim 10$ ns) previously demonstrated in superconducting qubits [8], we estimate the error rate will be approximately $t_{\text{gate}}/T_2 \sim 5 \times 10^{-4}$. These results suggest that existing Josephson junction technology should allow superconducting circuits to achieve coherence levels compatible with scalable quantum computing in the solid state.

Our experiment employs a particularly simple transmon qubit [9,10], consisting of just two superconducting electrodes connected with a single small aluminum Josephson junction, that requires no bias circuitry and has minimal sensitivity to $1/f$ noises in charge or flux, coupled to a

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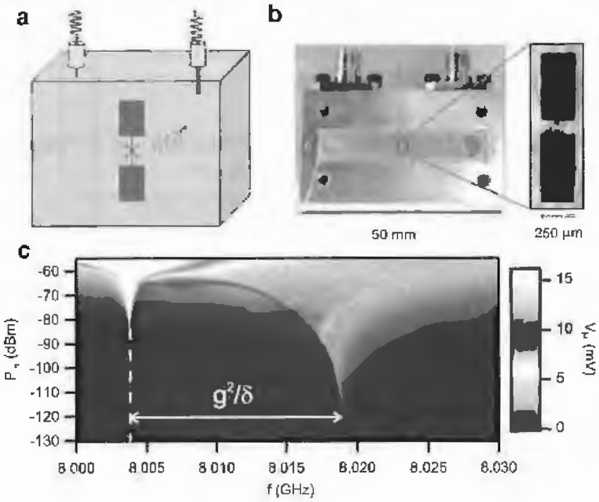

FIG. 1 (color online). Qubit coupled to a 3D cavity. (a) Schematic of a transmon qubit inside a 3D cavity. The qubit is coupled to the cavity through a broadband dipole antenna that is used to receive and emit photons. (b) Photograph of a half of the 3D aluminum waveguide cavity. An aluminum transmon qubit with the dipole antenna is fabricated on a c-plane sapphire substrate and is mounted at the center of the cavity. (Inset) Optical microscope image of a single-junction transmon qubit. The dipole antenna is 1 mm long. (c) Transmission of a 3D cavity (cavity D) coupled to a transmon ($J1$) measured as a function of power and frequency. The cavity response above -80 dBm occurs at the bare cavity frequency $f_c = 8.003$ GHz. At lower powers, the cavity freqnency shifts by g^2/δ.

microwave resonant cavity that can act as an entanglement bus and readout circuit. Neglecting the interactions with its environment, the transmon is described by the simple Hamiltonian [9,11] $\hat{H} = 4E_C(\hat{n} - n_0)^2 - E_J \cos\hat{\phi}$ where $\hat{n}$ and $\hat{\phi}$ are the normalized operators for the pair charge and phase (obeying $[\hat{\phi}, \hat{n}] = i$), $E_J = \hbar I_c/2e$ and $E_C = e^2/2C_\Sigma$ are the Josephson and Coulomb energies, e is the electron's charge, I_c is the junction critical current, C_Σ is the total capacitance between the electrodes, and n_0 is the offset charge.

The experiments are performed using a circuit QED architecture [12,13], a circuit implementation of a cavity QED [14], to isolate, couple, and measure the qubit. A novel aspect is the use of a three-dimensional waveguide cavity machined from superconducting aluminum (alloy 6061 T6), as shown in Figs. 1(a) and 1(b). This type of cavity offers several advantages over the planar transmission-line cavities used in previous circuit QED experiments. First, the cavity has a larger mode volume (approximately 3 cm^3 or one tenth of a cubic wavelength, compared to the 10^{-6} cubic wavelengths for a conventional transmission-line resonator), and is much less sensitive to the surface dielectric losses that are suspected as the limiting source of dissipation in transmission-line resonators to date [15,16]. Indeed, we have observed reproducible quality factors of these cavities [17] of 2×10^6 to 5×10^6, corresponding to photon storage times in excess of 50 μs (not shown) in the quantum regime ($k_B T \ll \hbar\omega_c$ and $\langle n \rangle < 1$, where ω_c is the cavity frequency), without the power dependence [15,16] indicative of the presence of two-level systems. Second, the geometry presents the qubit with a well-controlled electromagnetic environment, limiting the possibility of relaxation through spontaneous emission into the multiple modes that may be possible with a complicated chip and its associated wiring [18]. The qubit is placed in the center of the cavity, maximizing the coupling to the lowest frequency TE101 mode at $\omega_c/2\pi \sim 8$ GHz, which is used for readout and control. This location also nulls the coupling to the second mode (TE102 at approximately 10 GHz).

Despite the larger mode volume of the three-dimensional cavity, we are able to achieve the strong-coupling limit of cavity QED in this system, with vacuum Rabi frequencies, $g/2\pi$, greater than 100 MHz. As seen in Fig. 1(b), the electrodes of the qubit are significantly larger [~ 0.5 mm] than in a conventional transmon qubit, so that the increased dipole moment of the qubit compensates for the reduced electric field that a single photon creates in the cavity. We note that due to the large dipole moment, the expected lifetime from spontaneous emission in free space would be only ~ 100 ns, so that a high-Q cavity is required to maintain the qubit lifetime. The electrodes also form the shunting capacitance ($C_\Sigma \sim 70$ fF) of the transmon, giving it the same anharmonicity and the same insensitivity to $1/f$ charge noise as in the conventional design. An advantage of this qubit design is that the large electrode size reduces the sensitivity of the qubit to surface dielectric losses, which may be responsible for the improved relaxation times. In this experiment, the qubits cannot be tuned into resonance with the cavity, so the vacuum Rabi coupling is not observed directly. The system is rather operated in the dispersive limit ($|\delta| \approx |\omega_c - \omega_{01}| \gg g$) [13]. Here the qubit induces a state-dependent shift on the cavity, which is the basis of the readout mechanism. The dispersive shifts are typically several tens of MHz (see Table I), and can approach 1000 times the linewidths of qubit and cavity, so that all devices are well within the strong dispersive limit [19]. The transmission through the cavity as a function of microwave power, which demonstrates the ground-state shift of the cavity and the reemergence of the bare cavity frequency at sufficiently high powers (see Refs. [20,21]) is shown in Fig. 1(c). Single-shot readout of the qubit (with fidelities greater than 70%) is performed using the technique previously described [20].

The dramatically improved coherence properties of these qubits are confirmed via the standard time-domain measurements of the relaxation time (T_1) and Ramsey experiments (T_2) (see Fig. 2 and Table I). We employ the same techniques used in the previous conventional

TABLE I. Parameters of four transmon qubits (labeled as J's for single-junction qubits and S's for SQUID) measured in four different 3D cavities (labeled as A, B, C and D respectively). The data of $J1a$ and Sa are data on qubits $J1$ and S following cycling to room temperature. Here, $f_{01} = \omega_{01}/2\pi$ is the dressed qubit transition frequency between ground-state $|0\rangle$ and the first excited state $|1\rangle$, $g/2\pi$ is the coupling strength, $g^2/2\pi\delta$ is the cavity frequency shift from the bare cavity frequency due to the qubit, $f_c = \omega_c/2\pi$ is the bare cavity frequency, Q_c is the quality factor of the shifted cavity resonance at single-photon power, T_1 is the relaxation time from $|1\rangle$ to $|0\rangle$, T_2 is the coherence time measured by Ramsey experiment, and $T_{\rm echo}$ is the coherence time measured by a spin-echo experiment.

Qubit (cavity)	f_{01} (GHz)	E_J (GHz)	E_C (GHz)	$g/2\pi$ (MHz)	$g^2/2\pi\delta$ (MHz)	f_c (GHz)	Q_c ($x10^3$)	T_1 (μs)	T_2 (μs)	$T_{\rm echo}$ (μs)
$J1$ (D)	6.808	21.1	0.301	138	15.9	8.0035	340	60	18	25
$J1a$ (D)	6.769	21.0	0.301	140	15.8	8.003 75	340	50	20	24
$J2$ (C)	7.772	28.6	0.292	152	99.8	8.0020	360	25	15	21
$J3$ (B)	7.058	22.5	0.304	141	21.5	7.9835	320	42	12	12
S (D)	7.625	34.4	0.227	136	48.2	8.061 69	340	35	7.3	11
Sa (A)	7.43	32.5	0.228	123	24.1	8.061 69	100	20	6	8

transmon experiment (see Refs. [8,18,22]) performed in a cryogen-free dilution refrigerator at 10 mK. The qubits have an anharmonicity $\alpha/2\pi = f_{12} - f_{01} \sim -200$ MHz to -300 MHz which allows fast single-qubit operations in $\sim$10 ns. There are several surprising features in the time-domain data. First, while T_2's are typically in the range of 15–20 μs, they do not yet attain the limit twice T_1 which is reproducibly in the range 25–50 μs corresponding to $Q_1 = 1\text{–}2 \times 10^6$. This indicates that there is still significant dephasing. At the same time, both the Ramsey decay envelope and the echo coherence (which has an artificial phase rotation as a function of the delay added) can be fit well by an exponential decay, indicating that contrary to the previous predictions [23,24], $1/f$ noise is not dominant [22] in our experiment. This is consistent with the expectation that these simple qubits should avoid dephasing due to both $1/f$ flux noise (since there are no superconducting loops) and charge noise (since the total charge variation of the transition frequency [9] for these transmon parameters is less than 1 kHz). The observed phase coherence factor, $Q_2 \sim 700\,000$, is an order of magnitude larger than previous superconducting devices [10,25]. Since the transition frequency of the transmon qubit ($\omega_{01} \sim \sqrt{8E_J E_C}$) is set by a combination of the Josephson and charging energies, this allows us to place stringent limits on the amount of critical current noise in Josephson junctions, or dielectric fluctuations in the shunt capacitance. We find that any critical current noise must have a total variance of less than about 1 ppm ($\delta I/I_c < 10^{-6}$). In fact, the observed Ramsey and echo decays are more consistent with frequency-independent noise in the qubit transition frequency (or critical current) of about $\sqrt{S_{\omega/\omega_{01}}} \sim 10$ ppb/$\sqrt{\rm Hz}$ or $\sqrt{S_{I/I_c}} \sim 20$ ppb/$\sqrt{\rm Hz}$. The improvement by approximately a factor of 2 with echo indicates either a characteristic correlation time in this noise of about 10 μs, or an additional low-frequency noise (but not $1/f$ in character) component with a variance of about 1 ppm.

The high stability of the qubit transition frequency is exhibited in Fig. 2(c), which shows the deviations observed

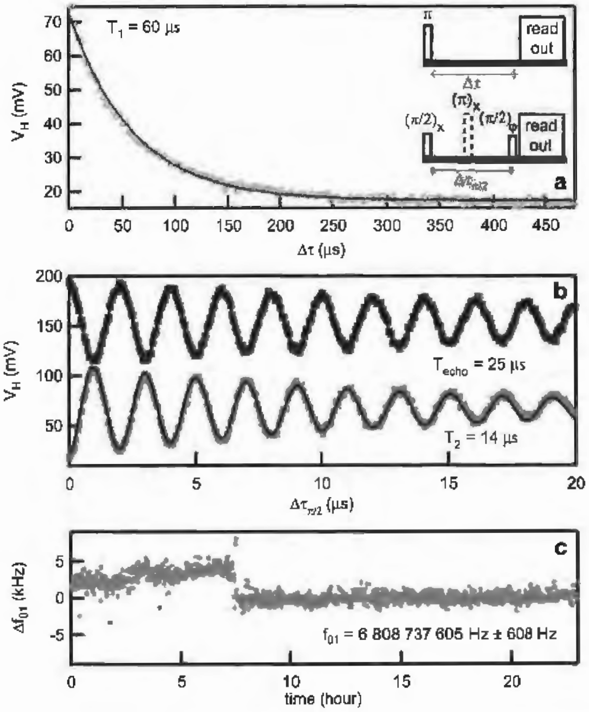

FIG. 2 (color online). Time-domain measurement of the qubit coherence (a) Relaxation from $|1\rangle$ of qubit $J1$. T_1 is 60 μs for this measurement. (Inset) The pulse sequences used to measure relaxation (upper) and Ramsey experiments with and without echo (lower). The pulse shown in dashed line is an echo signal applied at one half of the delay between two $\pi/2$ pulses. (b) Ramsey fringes measured on resonance with (blue squares online or upper curve) and without (red squares online or lower curve) echo sequence. The pulse width for the π and $\pi/2$ pulses used in the experiments is 20 ns. An additional phase is added to the rotation axis of the second $\pi/2$ pulse for each delay to give the oscillatory feature to the Ramsey fringes. (c) Qubit frequency f_{01} measured over 23 h by repeated Ramsey measurements.

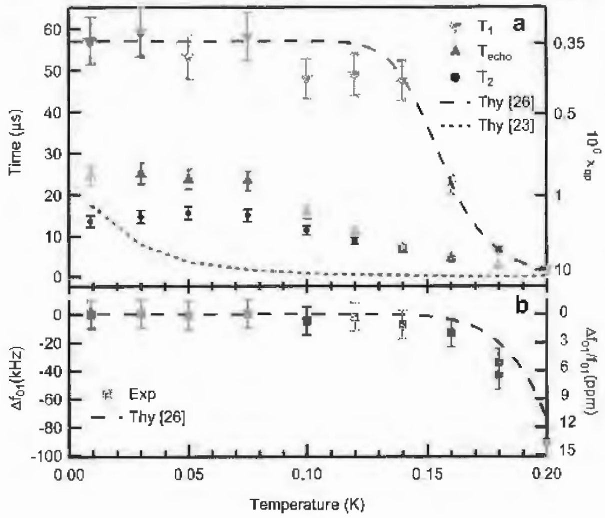

FIG. 3 (color online). Temperature dependence of qubit properties. (a) Measurement of T_1, $T_{\rm echo}$, and T_2. (b) Shift of the transition frequency f_{01}. Black dashed curves in (a) and (b) are theoretical T_1 and f_{01} calculated from the model in Ref. [26] plus a temperature-independent relaxation rate with the same fitting parameter of $\Delta = 194\ \mu$eV for both T_1 and f_{01}. (See Supplemental Material [22] for details.) The blue small-dashed curve is the theoretical T_2 from $1/f$ critical current fluctuations predicted by Ref. [23].

in the Ramsey detuning compared to the microwave generator over 1 d. The parameters in the Hamiltonian of this artificial quantum system are seen to be stable for long periods to within ~600 Hz or ~80 ppb over many hours. Discrete jumps of a few kHz (or about 1 ppm) are occasionally observed, which are consistent in size with that expected by single atomic rearrangements in the tunnel junction barrier. On subsequent thermal cycling of two devices, a slow telegraph switching behavior (with $\delta f \sim 5$–50 kHz) was also observed. These observations confirm the ability of this type of experiment to reveal tiny variations in junction parameters which would be undetectable in previous superconducting qubit experiments.

It is still not clear what mechanisms limit the coherence in these new qubits, but some information can be obtained by measuring the dependence of coherence times on sample temperature, as shown in Fig. 3. The most striking effect is the rapid decrease in the relaxation time, T_1, once the temperature exceeds about 130 mK, which is in good quantitative agreement with a recent theory on the effects of quasiparticles [22,26], using only a single fit parameter which is the gap of the superconductor ($\Delta = 194\ \mu$eV). The saturation of the relaxation times below this temperature means that either the qubits are limited by the presence of out-of-equilibrium quasiparticles, or other mechanisms such as spontaneous emission (the Purcell effect) or dielectric losses in the sapphire. The observed times place a stringent upper bound on the density of these quasiparticles, which is less than one quasiparticle per cubic micron, or a normalized quasiparticle density $x_{\rm qp} = n_{\rm qp}/n_{\rm pairs} < 5 \times 10^{-7}$ (where $n_{\rm qp}$ is the density of quasiparticles and $n_{\rm pairs}$ is the density of Cooper pairs). This is an order of magnitude lower density than reported in recent measurements on phase qubits [27] or transmission-line resonators [28]. We also observe a frequency shift of the qubit transition due to the induced thermal quasiparticles [Fig. 3(b)], again in quantitative agreement with the predictions of Ref. [26]. The coherence times T_2 and $T_{\rm echo}$ are observed to decrease slowly with temperature, inconsistent with either the quadratic [23] or linear [24] temperature scalings reported previously for critical current noise. Another mechanism for relaxation is spontaneous emission of the qubit via the cavity (the Purcell effect), which is consistent with the general trend that qubits with smaller detunings from the cavity tend to have shorter lifetimes. Our estimates of the multimode Purcell effect [18] for these cavities predict only a small contribution to T_1 for most devices measured so far, but the data do not yet allow a detailed test of the Purcell model. Further experiments which vary qubit and cavity parameters will be required to identify and hopefully further reduce decoherence. Nonetheless, the current results already indicate that the intrinsic quality factor of Josephson junctions is greater than 1×10^6.

We have presented a new implementation of superconducting qubits coupled to a 3D microwave cavity with an order of magnitude improved coherence. While there have been recent observations of individual devices with comparable T_1 [29] or $T_{\rm echo}$ times [30], we have reproducibly obtained both relaxation (T_1) and coherence (T_2, without echo) times in excess of 10 μs. Our qubits demonstrate remarkable long-term stability, indicating that critical current fluctuations are much smaller than previously predicted. The dissipation and the frequency shift as a function of temperature confirm recent theoretical predictions on the effects of thermally induced quasiparticles. The lifetimes at low temperatures imply that the intrinsic quality factor of Josephson junctions can be greater than 1×10^6 and enable us to place significantly more stringent limits on any possible background density of nonequilibrium quasiparticles.

Our new architecture provides a particularly simple electromagnetic environment for the qubits, and thereby reduces the sources of decoherence. The good stability and long coherence times obtained from the new architecture enable us to detect couplings of the qubit to any low-energy degrees of freedom, at the level of a fraction of only a ppm. The improved coherence was achieved without reducing either the anharmonicity or the coupling strength between the qubit and cavity which should still permit fast one and two-qubit operations. Scaling this architecture to multiple qubits is not harder than for conventional superconducting circuits. For example, more qubits can be added inside a 3D cavity such that they couple to each other. These results are therefore encouraging for all experiments with superconducting quantum circuits. The evolution of this architecture could allow future devices to approach the error levels required to achieve the quantum error correction threshold and make it possible to realize larger entangled states and more complex algorithms with superconducting quantum systems.

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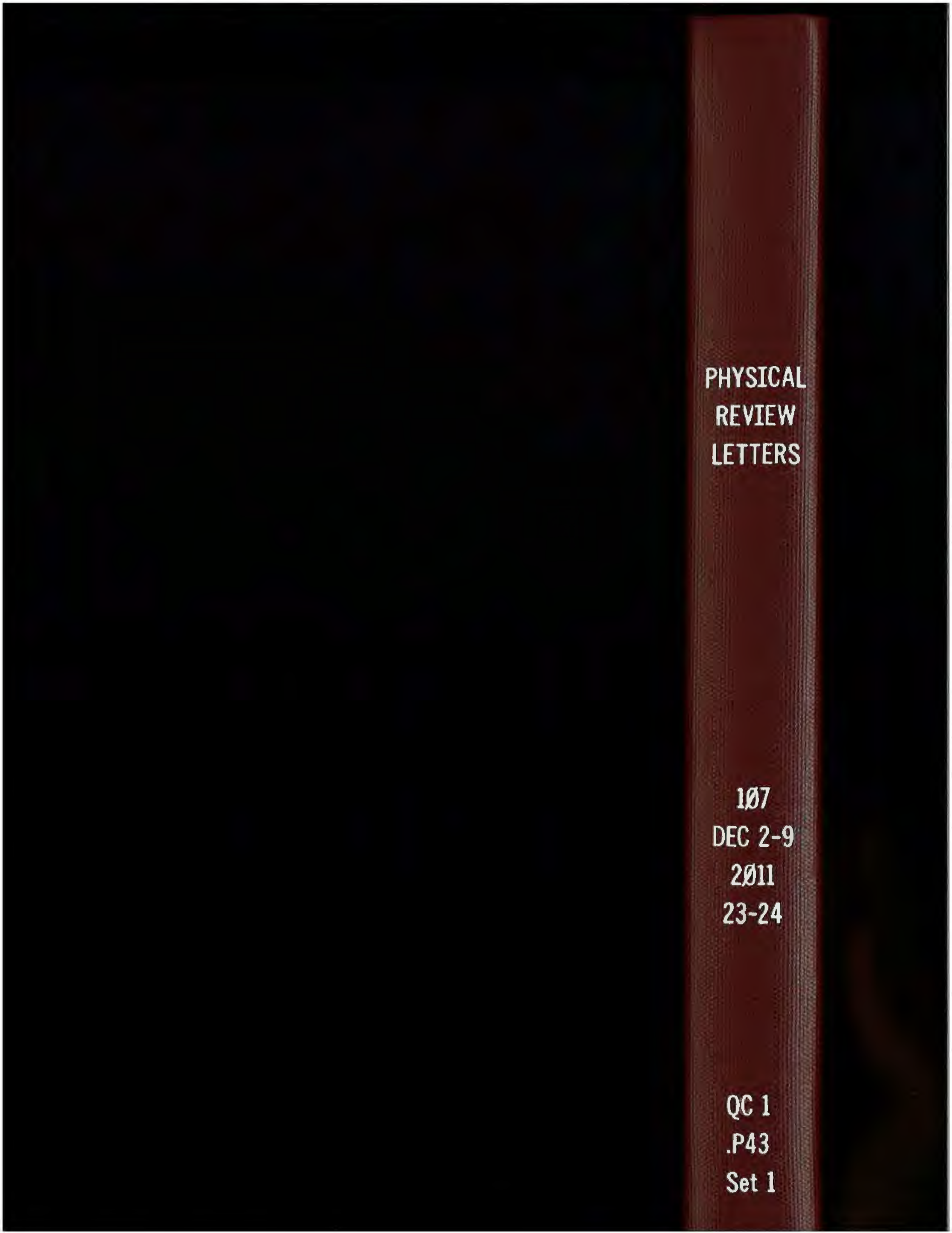

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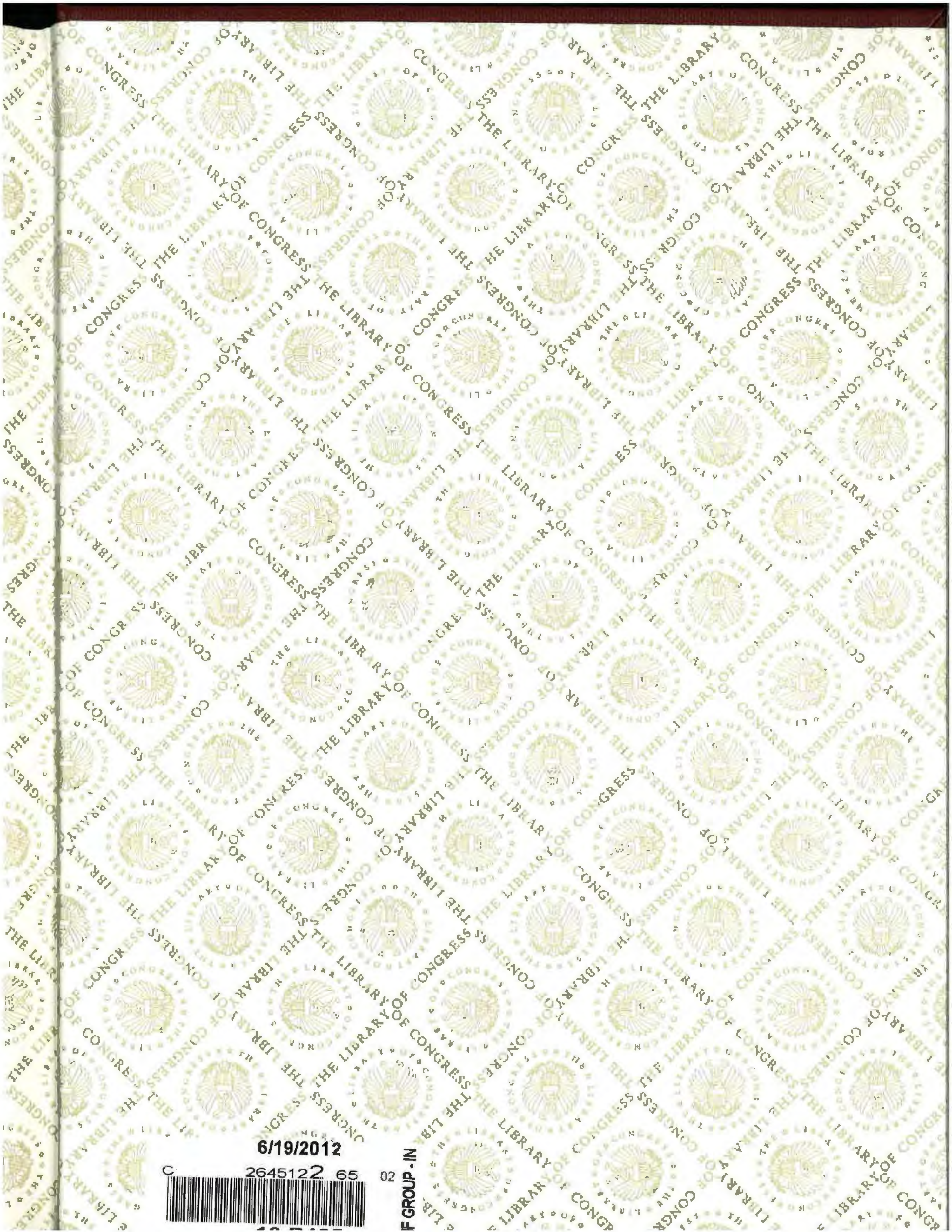

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Life after charge noise: recent results with transmon qubits

A. A. Houck · Jens Koch · M. H. Devoret ·
S. M. Girvin · R. J. Schoelkopf

Abstract We review the main theoretical and experimental results for the transmon, a superconducting charge qubit derived from the Cooper pair box. The increased ratio of the Josephson to charging energy results in an exponential suppression of the transmon's sensitivity to 1/f charge noise. This has been observed experimentally and yields homogeneous broadening, negligible pure dephasing, and long coherence times of up to 3 μs. Anharmonicity of the energy spectrum is required for qubit operation, and has been proven to be sufficient in transmon devices. Transmons have been implemented in a wide array of experiments, demonstrating consistent and reproducible results in very good agreement with theory.

Keywords Superconducting qubits · Transmon · Quantum computation

PACS 03.67.Lx · 85.25.-j · 42.50.-p

1 Introduction

The idea of harnessing the power of quantum mechanics for specific computational tasks, first proposed in the early 1980s (see e.g. [1] for an early review), has inspired physicists, engineers, and computer scientists alike. It continues to act as a prime driving force behind the ongoing research on quantum control, measurement, decoherence,

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A. A. Houck
Department of Electrical Engineering, Princeton University,
Princeton, NJ 08544, USA

J. Koch (✉) · M. H. Devoret · S. M. Girvin · R. J. Schoelkopf
Departments of Physics and Applied Physics, Yale University,
New Haven, CT 06520, USA
e-mail: jens.koch@yale.edu

and quantum information. The basic building blocks of a universal quantum computation scheme [2] are quantum bits (qubits), which are quantum coherent two-level systems. Despite some impressive progress, the last decades have clearly established the difficulty of implementing even just a few qubits.

Nature offers only a few true two-level systems, such as spin-1/2 systems, or massless spin-1 systems (e.g. polarization of photons). As an alternative, sufficiently anharmonic multi-level systems can be used as effective qubits. In principle, they also offer the possibility of multi-level quantum logic [3]. All such systems bear in common discrete energy spectra and can be understood as generalized atoms. Superconducting circuits have been established as promising systems for tunable artificial atoms: they utilize the quantum coherence of the superconducting state to minimize undesired dissipation, and employ Josephson junctions as the fundamental nonlinear and dissipationless element to obtain an anharmonic spectrum [4–6]. Moreoever, fabrication of superconducting qubits benefits from the existence of well-established microfabrication techniques, spurring hope that the required scaling towards multi-qubit systems will not pose a fundamental obstacle.

Here, we review the characteristics of the transmon qubit [7], a superconducting charge qubit derived from the Cooper pair box (CPB) [8,9], with minimal sensitivity to 1/f noise. The transmon made its debut in an experiment demonstrating the photon-number dependent qubit frequency shift in the strongly dispersive limit [10]. Since then it has been successfully employed in a growing number of experiments, and has demonstrated an excellent level of agreement with theory. Coherent coupling between two transmon qubits via virtual microwave photons was reported by Majer et al. [11]. A comprehensive verification of predicted transmon properties with high accuracy has been presented in Ref. [12], with relaxation and dephasing times in the microsecond range. The coherence times of seven different transmon devices have been analyzed and shown to be both reproducible and predictable over more than an octave in qubit frequency [13]. Transmons have further been involved in recent studies of the $\sqrt{n}$ anharmonicity of the Jaynes-Cummings ladder [14,15], and benchmarks of single-qubit operations [16].

The scope of this paper is to provide a comprehensive review of the transmon basics, together with a summary of its fabrication and its overall performance as observed in recent experiments.

2 General idea of the transmon

Most naturally, the transmon qubit is understood as a modified version of the prototypical charge qubit, the CPB [8,9]. As depicted in Fig. 1, the transmon shares with the CPB the same underlying circuit topology. More specifically, its circuit is most closely related to the differential single CPB [17], which is composed of two superconducting islands and no reservoirs. Because the circuit provides no external connection between the two islands, the operator for the charge difference n between the two islands has a discrete spectrum, and the superconducting phase difference φ is only defined modulo 2π, i.e., it is a compact variable for which φ and $\varphi + 2\pi z$

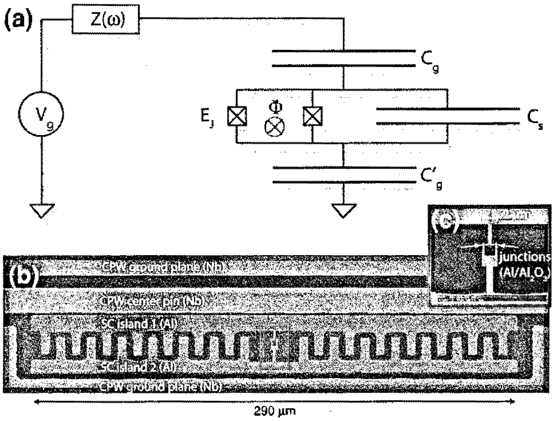

Fig. 1 The transmon qubit. **a** The circuit of the transmon is identical to the circuit of a differential single Cooper pair box, consisting of two superconducting islands coupled by two Josephson junctions. The coupling to ground is purely capacitive. The use of two Josephson junctions allows for tuning of the effective Josephson energy via the external magnetic flux penetrating the superconducting loop. **b** and **c** show the optical and SEM image of a transmon device positioned inside a coplanar waveguide. While the size of the junctions and the superconducting loop is very similar to CPB devices, the inter-island capacitance C_s is increased drastically due to the large size of the islands and the interdigitated finger structure. This capacitance is matched by comparably large capacitances C_g and C'_g to the ground plane and centerpin of the transmission line resonator

are considered as identical for any integer z.[1] The corresponding Hamiltonian is given by

$$H = 4E_C(n - n_g)^2 - E_J \cos\varphi, \qquad (1)$$

where the two terms describe the contribution from charging effects and Josephson tunneling, respectively. The magnitudes of these terms are set by the single-electron charging energy $E_C = e^2/2C_\Sigma$ with $C_\Sigma = C_s + (C_g^{-1} + C_g'^{-1})^{-1}$, and the Josephson energy E_J, which is set by the junction's normal-state conductance G_t and the supeconducting gap Δ via the Ambegaokar-Baratoff relation $E_J = hG_t\Delta/8e^2$ [18]. The offset charge is denoted by n_g and can be tuned by the external gate voltage.

While the CPB and transmon share the same Hamiltonian, they belong to different parameter regimes: the CPB is typically operated with $E_J \approx E_C$, and the transmon with $E_J \gg E_C$. This transmon regime is reached primarily by lowering the charging energy E_C. In practice, this is achieved by increasing the island sizes,[2] thus adding a large shunt capacitance as shown in Fig. 1b. Shunt capacitances have also been

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[1] It is important to note that these points underline the principle difference between the CPB/transmon system and the phase qubit.

[2] The island area is increased by a factor of ~1000.

independently proposed to improve dephasing times in flux qubits by a factor of 3 [19], and have been implemented in phase qubits to avoid spurious resonances [20].

Both the principle benefits and drawbacks of the transmon are evident from examining how the energy spectrum changes as one increases the ratio of Josephson energy and charging energy E_J/E_C from the charge regime to the transmon regime, cf. Fig. 2a. In the charge regime, the spectrum of the CPB is dominated by charge parabolas with avoided crossings at the charge degeneracy points due to Josephson tunneling. If operated away from a charge degeneracy point, it is readily apparent that the qubit transition energy E_{01} varies rapidly with gate charge n_g, thus resulting in fast dephasing due to random fluctuations in the local electrostatic potential (1/f charge noise). To some extent, this can be combatted by careful biasing of the qubit at a charge degeneracy point, where the levels are first-order insensitive to charge noise, a special operating point termed "sweet spot" [21]. When biased at such a point, dephasing decreases; however, second-order effects of charge noise can still limit dephasing rates. As confirmed in an experiment by Metcalfe et al. [22], second-order charge noise can indeed be identified as the clear limitation on dephasing times in the CPB charge regime. As an additional complication, drifts in the offset charge can quickly result in a departure from the sweet spot.

The main idea of the transmon is to eliminate these problems by making the charge-dependence of energy levels negligibly small. This is achieved precisely by an increase of the E_J/E_C ratio, as shown in the sequence of plots in Fig. 2a. The graphs demonstrate that the energy levels become increasingly flat, i.e., independent of charge, as E_J/E_C is increased. We note, however, that the energy spectrum always remains $2e$ periodic in the offset charge, illustrating that the transmon is still a charge qubit. (No such periodicity exists, e.g. for the phase qubit where φ is not a compact variable.) The increased flatness of levels at $E_J/E_C \gg 1$ effectively generates a "sweet spot everywhere" so that sensitivity to charge noise is suppressed to high order, and device performance is not strongly dependent on a particular bias point anymore. A detailed analysis [7] shows that the suppression of charge sensitivity is exponential in the parameter $\sqrt{8E_J/E_C}$.

The effect of this exponential suppression can be recast into a statement about the dephasing induced by 1/f charge noise. A useful order-of-magnitude estimate of the dephasing time T_φ can be obtained by using characteristic amplitudes of charge noise and evaluating the fluctuations in qubit frequency in terms of a Taylor expansion. Assuming a Gaussian process for the offset charge, the root-mean-square fluctuations in the qubit frequency are given by

$$\delta\omega_{\mathrm{rms}} = \left[n_{\mathrm{rms}}^2 \left(\frac{\partial \omega_{01}}{\partial n_g} \right)^2 + \frac{3 n_{\mathrm{rms}}^4}{4} \left(\frac{\partial^2 \omega_{01}}{\partial n_g^2} \right)^2 \right]^{1/2}. \qquad (2)$$

To obtain a finite variance, the 1/f spectrum has to be cut off, and all results depend weakly (logarithmically) on the specific choice of the cutoff. Here, we use a typical value of $n_{\mathrm{rms}} = 0.5 \times 10^{-3}$ [23]. The estimate predicts a six orders of magnitude improvement in dephasing time due to charge noise $T_\varphi \approx 1/\delta\omega_{\mathrm{rms}}$ by changing E_J/E_C by a factor of 50, cf. Fig. 2b.

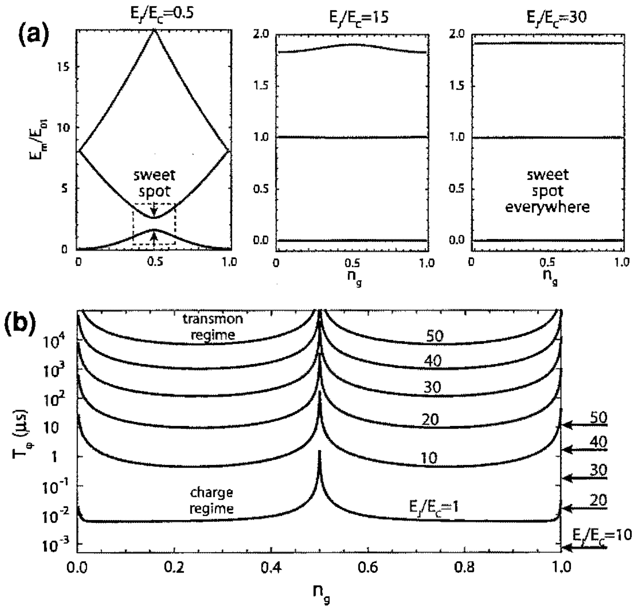

Fig. 2 Level spectrum and charge sensitivity of the Cooper pair box in the charge and transmon regime. **a** Eigenenergies E_m (first three levels, $m = 0, 1, 2$) of the CPB Hamiltonian (1) as a function of the effective offset charge n_g for different ratios E_J/E_C. All energies are given in units of the transition energy E_{01} (evaluated at the degeneracy point $n_g = 1/2$). The zero point of energy is chosen as the bottom of the $m = 0$ level. The sequence of plots highlights the exponentially increasing flatness of energy levels and the slow loss of anharmonicity as E_J/E_C is increased. **b** Order-of-magnitude estimates of dephasing times T_φ caused by charge noise, assuming Gaussian fluctuations around a fixed offset charge, cf. Eq. 2. Arrows on the right-hand side mark the worst-case estimates for T_φ, as determined by the total charge dispersion. The results demonstrate the exponential gain in the dephasing time due to charge noise under an increase of E_J/E_C

A worst-case estimate of the dephasing time can also be obtained by considering the maximum possible variation of the qubit transition energy, known as the charge dispersion ϵ_{01}. Dephasing cannot occur faster than $T_\varphi \sim \hbar/\epsilon_{01}$, independent of the amplitude of 1/f charge noise. This scenario is depicted by arrows in Fig. 2b. Due to the exponential suppression of level variation in the transmon regime, dephasing remains negligible even with this worst case estimate. Furthermore, a detailed analysis [7] shows that the increase in E_J/E_C does not heighten sensitivity to any of the other known 1/f noise mechanisms of dephasing, such as flux or critical current noise. In fact, as is evident from Table 1, by operating in the transmon instead of the charge regime, one gains a factor of 2 in both the insensitivity with respect to critical current and flux noise.

The only drawback of the E_J/E_C increase is revealed by examining the level spacings in Fig. 2a. Although the charge dependence has been suppressed exponentially, the level spectrum approaches that of a pure harmonic oscillator, which would prevent the system from acting as a qubit. However, the anharmonicity α, determined

Table 1 Comparison of dephasing times for the transmon and Cooper pair box qubit with $\omega_{01}/2\pi = 7$ GHz. Contributions to T_φ are theoretical predictions based on [7]

Noise source	$1/f$ amplitude, A	Transmon $E_J/E_C = 100$ T_φ (μs)	CPB $E_J/E_C = 1$ T_φ (μs)
Charge	10^{-4}–$10^{-3}e$ [23]	24,600	**1.1**^{a}
Flux	10^{-6}–$10^{-5}\Phi_0$ [30,31]	3,600^{a}	1,800^{a}
Crit. current	10^{-7}–$10^{-6}I_0$ [32]	**35**	17

Note: Entries in bold face mark the dominant noise channel. For the CPB, second-order charge noise at the sweet spot limits the performance of the qubit. In contrast, for the transmon dephasing is suppressed to an extent that coherence times are limited by relaxation (T_1) processes only

[a] These values are evaluated at a sweet spot (i.e., second-order noise)

by the difference between the fundamental qubit transition and the next higher transition frequency, decreases only slowly as function of the E_J/E_C ratio, following $\alpha/\omega_{01} \sim (E_J/E_C)^{-1/2}$ [7]. Thus, increasing the E_J/E_C ratio from 1 to 50 can virtually eliminate the effects of charge noise, and still maintain sufficient anharmonicity for the transmon to act as an effective two-level system. We illustrate this statement by considering the concrete example of a device with transition frequency $\omega_{01}/2\pi = 7$ GHz and $E_J/E_C = 100$. For these parameters, one obtains an absolute anharmonicity of 260 MHz and a dephasing time due to charge noise of $T_\varphi \geq 25$ ms (worst-case estimate).

At the large E_J/E_C ratios characteristic for the transmon regime, readout of the qubit state via charge detection or measurement of the quantum capacitance [24] as in the CPB is not possible. In fact, the transmon does not possess any dc measurable state-dependent parameters (charge, flux, etc.). However, the transmon still exhibits a strong coupling between charge and ac voltage, rendering it an ideal candidate for an artificial atom in the circuit QED architecture [25]. A full derivation of the coupling strength is given in [7], which can be intuitively understood from adding an ac component to the offset charge to describe the quantized resonator field, $n_g \to n_g^{\mathrm{dc}} + C_g V_{\mathrm{rms}}(a + a^\dagger)/2e$. Here, V_{rms} denotes the root-mean-square voltage of the resonator at the transmon position, and a, $a^\dagger$ are the annihilation and creation operators for microwave photons in the relevant resonator mode. Carrying out the square in Eq. 1 generates the coupling term, from which one obtains the coupling strength $g_{ij} = 2eV_{\mathrm{rms}}\langle i\,|\,n\,|\,j\,\rangle C_g^{\mathrm{eff}}/C_\Sigma$ with $C_g^{\mathrm{eff}} = (C_g^{-1} + C_g'^{-1})^{-1}$. In the transmon regime, the matrix elements are significant only between nearest-neighbor transmon levels, $i = j \pm 1$, and their overall magnitude is larger by a factor of typically $3 - 5$ than for the CPB, due to the participation of more than one Cooper pair. In all transmons fabricated so far, the ratio C_g/C_Σ is also ~3 times larger than in the CPB, leading to a total increase in coupling strength of more than an order of magnitude.

3 Transmon fabrication

All transmons have thus far been fabricated in a circuit QED architecture, as the cavity offers a convenient means of reading out the qubit state. The cavity consists of a 50 Ω niobium coplanar waveguide cavity with a 4.2 μm gap between the center pin and ground planes. Standing waves form between transverse capacitors at either end of the waveguide, designed with a 3 μm spacing and a range of capacitances to vary the cavity Q from 100 to 500, 000. Cavities are patterned with photolithography and reactive ion etching of 180 nm films of sputtered niobium. Transmon qubits are patterned with electron beam lithography, and consist of two layers (20 and 80 nm thick) of lifted-off aluminum, deposited with an angle evaporation process without venting samples to air. Samples have been fabricated on bare and oxidized silicon and sapphire substrates, with a common $Q \sim 70,000$ limit on relaxation in the devices on sapphire. Details of fabrication and processing are likely to prove important for future improvements in coherence, especially given that all transmon qubits now achieve a common limit to T_1.

4 Transmon performance

The major transmon features have been confirmed by experiments, which have been published in Refs. [12] and [13]. Here, we summarize these results and provide an overview of the most current transmon data.

To establish that the anharmonicity is still sufficient to treat the transmon as an effective two-level system, the level spectrum of the lowest two transitions is measured by spectroscopy, as depicted in Fig. 3a. It is immediately apparent that the transitions $0 \rightarrow 1$ and $1 \rightarrow 2$ are well resolved in frequency space. The observed 455 MHz anharmonicity allows for single-qubit manipulation with pulse durations of only a few nanoseconds without occupying the third level.

The insensitivity of the transmon to charge noise, which should lead to long coherence, can directly be verified by probing the charge dependence of the transmon level spectrum. The suppression of this dependence is quantified by using the notion of charge dispersion, defined as the total variation of the qubit transition frequency (as a function of gate charge). As demonstrated by spectroscopic data in Fig. 3b, this exponential suppression agrees well with theoretical prediction and results in virtually charge-independent qubit frequencies at sufficiently large E_J/E_C. Instead of a single, nearly sinusoidal curve, the data displayed in Fig. 3b shows two such curves with a relative displacement of half a period. This can be explained by the presence of one or several quasiparticles, which tunnel between the two islands. At low E_J/E_C this phenomenon has been termed quasiparticle-poisoning [26], and it leads to complete dephasing of the device [27]. However, the frequency shift due to such a tunneling event is bounded from above by the charge dispersion, and therefore becomes exponentially small in the transmon regime. Hence, these data confirm that the transmon is insensitive to fluctuations in local charge, including the special fluctuations due to quasiparticle poisoning.

Since charge noise was the limiting source of dephasing in charge qubits, the transmon has lead to dramatically improved dephasing times. Currently, the best T_2^* for a transmon is measured at a flux sweet spot where $T_2^* = 2.94 \pm 0.04\,\mu\text{s}$ (without any echoing) and $T_1 = 1.57 \pm 0.04\,\mu\text{s}$, see Fig. 4a and b [28]. Here, T_2^* is close to identical to $2T_1$, indicating a homogeneously broadened qubit, and a very long pure dephasing time of $T_\varphi \geq 35\,\mu\text{s}$, consistent with our predictions.

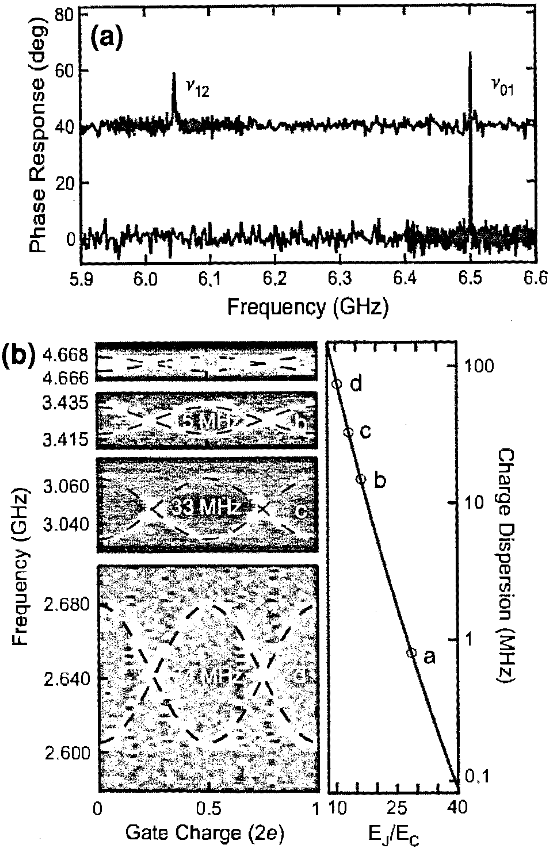

Fig. 3 **a** Anharmonicity of a transmon qubit. Data presented for a transmon qubit at $E_J/E_C = 40$. The qubit transitions measured are the 01 transition in a single tone spectroscopic measurement (bottom), and the 12 transition (top, offset) while populating transmon excited state with a second drive on the 01 transition. The second excited state of the transmon is not populated with the 12 transition at normal spectroscopy powers (bottom). The 01 and 12 transitions are separated by 455 MHz; the transmon can therefore be treated as a two-level system even during fast control operations. **b** Exponential suppression of charge dispersion. Data presented for four different values of E_J, where a $E_J/E_C = 28.6$, b 16.3, c 13.3, and d 10.4. Spectroscopic measurements of qubit frequency while changing a gate voltage reveal the expected sinusoidal frequency bands. The width of the band (charge dispersion) is decreased from 74 to 0.8 MHz. Two sinusoids are evident as random quasiparticle tunneling events cause the frequency curve to shift by one electron. The measured charge dispersion agrees well with the theoretical prediction (right). Reprinted from [12]

These recent results of long coherence times are to be contrasted with the performance of the first generation of transmons [10,11], which showed shorter relaxation times of ~200 ns. The improved times shown in Fig. 4 are the result of a more complete understanding of relaxation, and by now have been reproduced in a number of samples. Over more than an octave in frequency, the current limit on transmon coherence has been shown to be imposed by spontaneous emission of photons through the

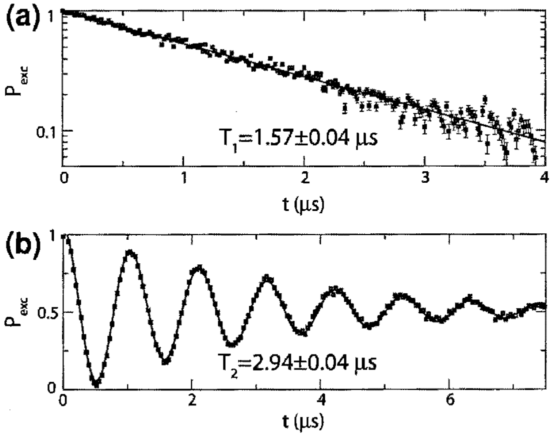

Fig. 4 Long coherence times in a transmon. Data measured at the flux sweet spot for a transmon qubit with $E_C = 380\,\mathrm{MHz}$, $E_J/E_C = 52$. **a** Relaxation from excited state. Measurements of the occupation probability P_{exc} of the excited qubit state while varying the time delay after a π pulse yield an exponential decay with $T_1 = 1.57 \pm 0.04\,\mu\mathrm{s}$. **c** Ramsey fringes, measured by varying the time delay between two $\pi/2$ pulses, show a long dephasing time $T_2^* = 2.94 \pm 0.04\,\mu\mathrm{s}$ (no echo)

cavity, a process known as the Purcell effect [29]. This requires proper modeling of the cavity impedance including all higher modes of the resonator, which serves as a filter between the qubit and the evironment [13]. In fact, all transmon qubits now reach the same limit on intrinsic T_1, as shown in Fig. 5. Towards the lowest frequencies where the Purcell effect is least severe, a non-Purcell T_1 limitation is observed to set in, which is possibly due to dielectric loss with a Q value of 70,000.

A separate issue for qubit control and usability of the qubit spectrum for operation regards the presence of coupling to unwanted degrees of freedom, such as spurious two-level systems. We have performed systematic searches of transmon spectra for such spurious resonances, which have revealed both very good agreement with theory predictions with errors as low as one part in 10^4, and have enabled us to estimate the average number of spurious resonances in current transmon devices to be 1 per 5 GHz per qubit [12].

5 Summary

In summary, the transmon is a robust superconducting qubit for use in the circuit QED architecture. Its primary feature is an insensitivity to 1/f charge noise, the dominant source of dephasing in other charge qubits, without any detrimental effects on the sensitivity to other known noise channels. Experiments have directly verified the predicted exponential suppression of the sensitivity to charge fluctuations by monitoring the transmon energy levels, and have confirmed the resulting gain in dephasing times with current devices reaching the $T_2 = 2T_1$ limit and dephasing times of up to 3 μs. Due to the limitation of T_2 by relaxation, future improvements may become easier as

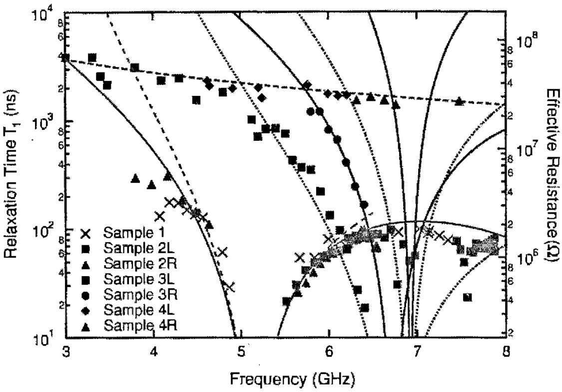

Fig. 5 Relaxation times for seven transmon qubits. Predictions for qubit lifetime (colored lines) agree well with observed relaxation times (points). Solid lines represent predictions for input side qubits located at the resonator input side (L), while dashed lines correspond to output side (R) qubits. All sapphire qubits (blue and green) reach the same common intrinsic limits (black line), with lifetimes limited to a constant $Q \sim 70,000$. Qubit lifetimes are accurately predicted over a wide range of frequencies and more than two orders of magnitude in time. Reprinted from [13]

they will focus on removing sources of dissipation. The fact that all recent transmon qubits reach a consistent T_1 limit suggests that relaxation is caused by a single source, giving hope that it can be identified and eliminated in the near future.

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APPENDIX 1025-F

US008642998B2

(12) **United States Patent**
Gambetta et al.

(10) **Patent No.: US 8,642,998 B2**
(45) **Date of Patent: Feb. 4, 2014**

(54) **ARRAY OF QUANTUM SYSTEMS IN A CAVITY FOR QUANTUM COMPUTING**

(75) Inventors: **Jay M. Gambetta**, Yorktown Heights, NY (US); **Mark B. Ketchen**, Hadley, MA (US); **Chad T. Rigetti**, Hopewell Junction, NY (US); **Matthias Steffen**, Cortlandt Manor, NY (US)

(73) Assignee: **International Business Machines Corporation**, Armonk, NY (US)

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H03K 19/195 (2006.01)

(52) **U.S. Cl.**
USPC **257/31**; 326/4

(58) **Field of Classification Search**
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See application file for complete search history.

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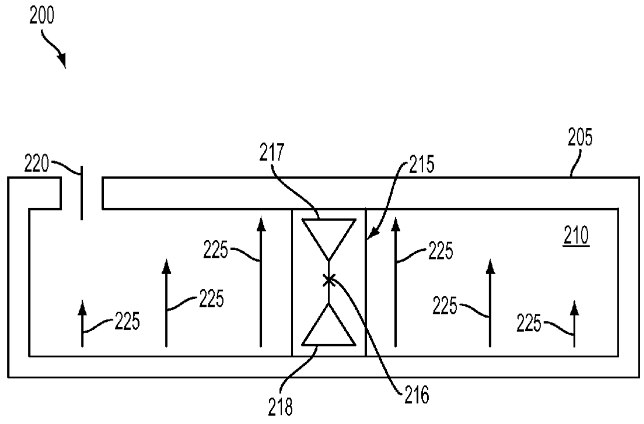
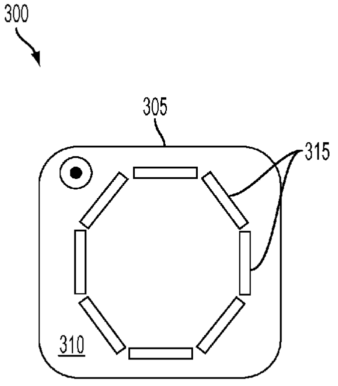
(57) **ABSTRACT**

A device includes a volume bounded by electromagnetically conducting walls, an aperture in a bounding wall of the electromagnetically conducting walls, a plurality of quantum systems disposed within the volume and an electromagnetic field source coupled to the volume via the aperture.

25 Claims, 4 Drawing Sheets





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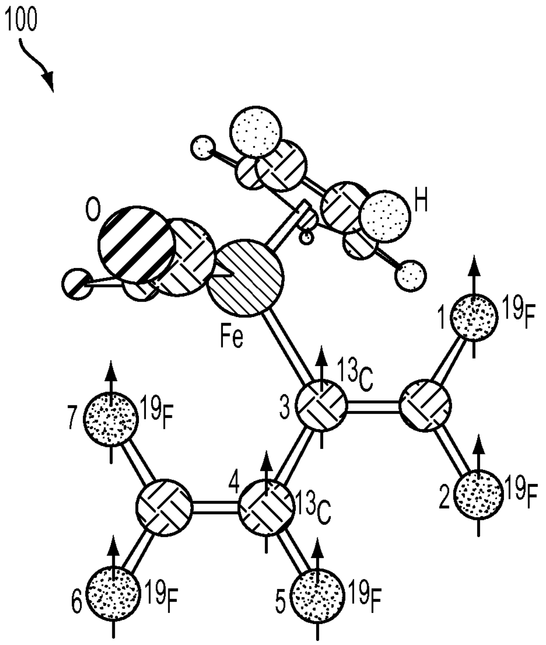

FIG. 1

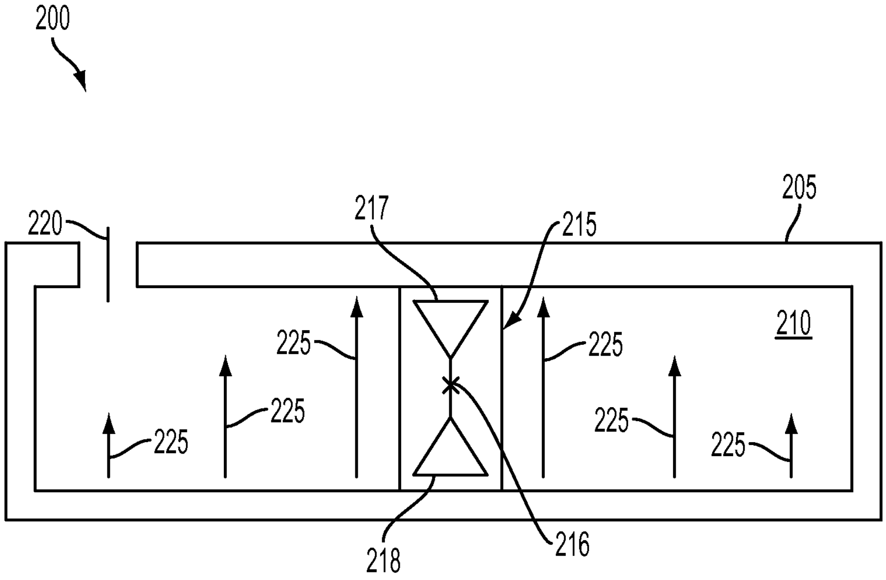

FIG. 2

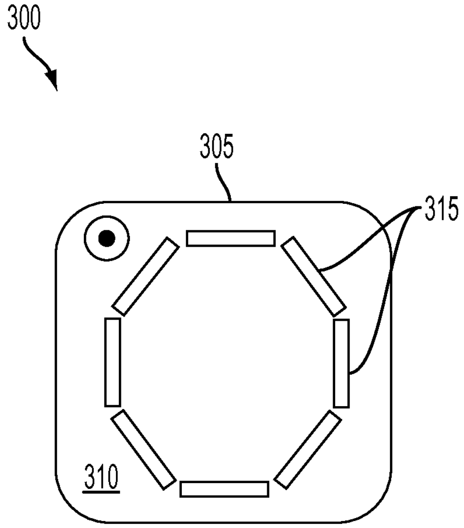

FIG. 3

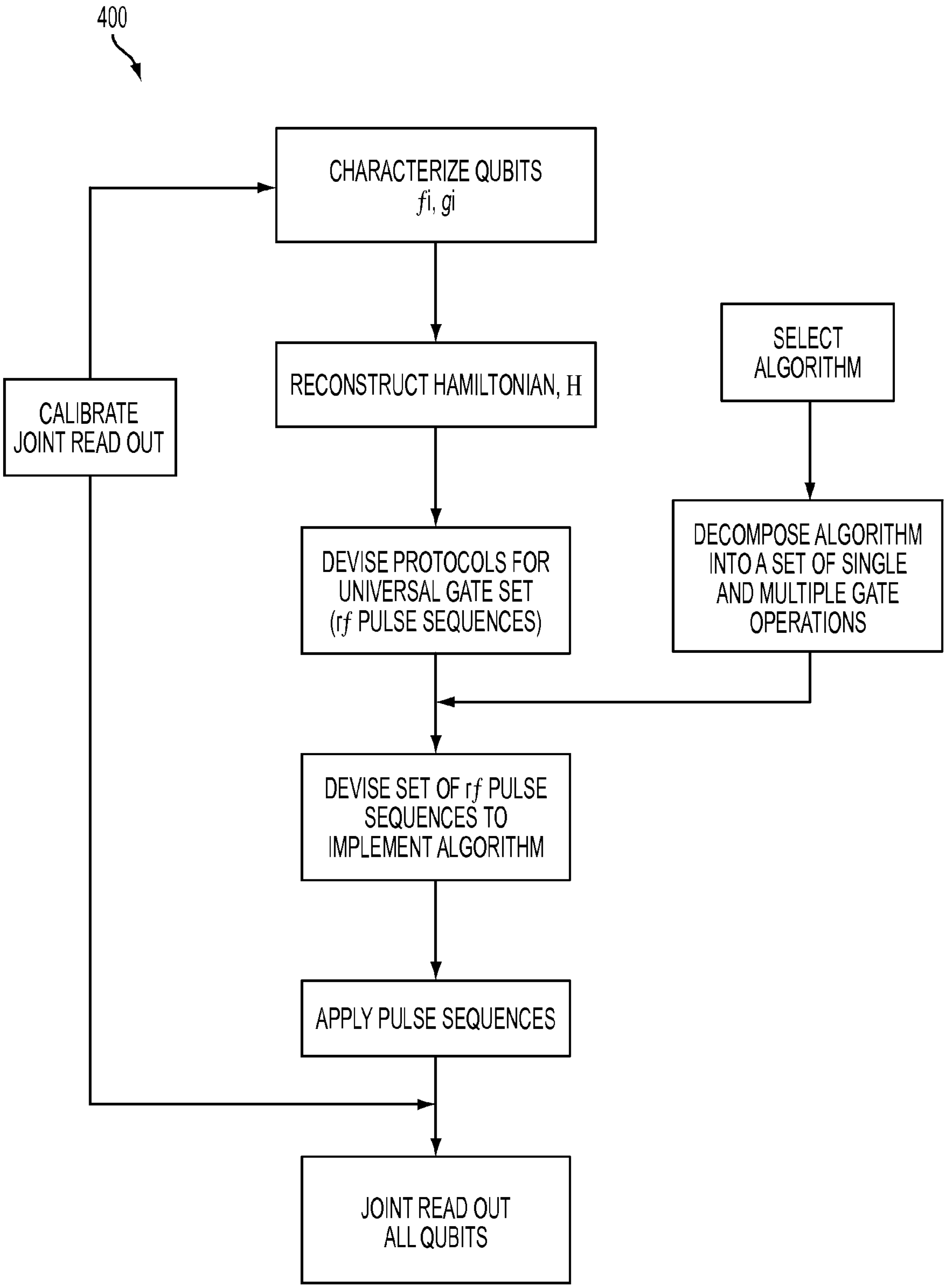
400
CHARACTERIZE QUBITS
fi, *gi*
RECONSTRUCT HAMILTONIAN, H
SELECT ALGORITHM
CALIBRATE JOINT READ OUT
DEVISE PROTOCOLS FOR UNIVERSAL GATE SET (r*f* PULSE SEQUENCES)
DECOMPOSE ALGORITHM INTO A SET OF SINGLE AND MULTIPLE GATE OPERATIONS
DEVISE SET OF r*f* PULSE SEQUENCES TO IMPLEMENT ALGORITHM
APPLY PULSE SEQUENCES
JOINT READ OUT ALL QUBITS

FIG. 4

ARRAY OF QUANTUM SYSTEMS IN A CAVITY FOR QUANTUM COMPUTING

CROSS-REFERENCE TO RELATED APPLICATIONS

Priority based on U.S. Provisional Patent Application, Ser. No. 61/497,018, filed Jun. 14, 2011, and entitled, "ARRAY OF THREE DIMENSIONAL SUPERCONDUCTING QUBIT/CAVITY CLUSTERS FOR QUANTUM COMPUTING", is claimed, the disclosure of which is incorporated by reference herein in its entirety. This application is related to co-pending U.S Pat. applications entitled "MODULAR ARRAY OF FIXED-COUPLING QUANTUM SYSTEMS FOR QUANTUM INFORMATION PROCESSING", filed on Sep. 2, 2011, having and accorded Ser. No. 13/224768, which is entirely incorporated herein by reference.

BACKGROUND

The present invention relates generally to quantum systems and more particularly to an array of quantum systems within a volume bounded by conducting walls with applications to quantum information processing.

Quantum information processing is new paradigm of information processing wherein explicit quantum mechanical states and quantum mechanical phenomena and behavior are exploited for information processing applications. This feat is enabled by several peculiar properties found in quantum systems that are impossible to achieve in classical systems: the ability for a quantum system to be in a superposition of several of its eigenstates and the ability for several quantum systems to be entangled with one another. As such, quantum physics provides a basis for achieving computational power to address certain categories of mathematical problems that are intractable with current machine computation. Similarly to a classical bit where the state of a transistor in a processor, the magnetization of a surface in a hard disk and the presence of current in a cable can all be used to represent bits in the same computer, qubits represent different states. However, for a classical bit it is understood that its state must be 0 or 1. A qubit can be 0 or 1 or a superposition of both.

Several types of physical systems are possibly best suited for building a quantum computer. Such physical systems include, but are not limited to: silicon-based nuclear spins, trapped ions, cavity quantum-electrodynamics, nuclear spins, electron spins in quantum dots, superconducting loops and Josephson junctions, liquid state nuclear magnetic resonance (NMR), and electrons suspended above the surface of liquid Helium.

Historically, a liquid state NMR quantum computer (NMRQC) was the first physical system demonstrating many of the main concepts of quantum computing. In such a system the nuclear spins are placed in a strong magnetic field, creating "up" and "down" states of the nuclear spin (similar to a bar magnet) representing the logical |0> and |1> states. Subsequent quantum algorithms were identified allowing implementation of a three-qubit quantum search algorithm, a five-qubit order finding algorithm, the realization of an adiabatic quantum optimization algorithm, and a demonstration of Shor's factoring algorithm (factoring the number 15 using a 7-spin molecule). FIG. **1** illustrates a prior art NMR seven-spin molecule used to factor the number 15 into its prime factors 3 and 5. The NMRQC is very well-characterized and has several advantages including the seven spin states. However, NMRQC has several drawbacks including qubit systems limited to those nature naturally provides and also limited scalability. Currently, several types of physical systems are being pursued for quantum computing, including implementation of Josephson Junctions, superconducting loops, superconducting capacitors, and superconducting qubits. In addition to various approaches based on superconducting qubits, the most active areas of research involve trapped ions, and quantum dots. The largest quantum computer built in any of these systems to date consists of around 10 qubits, and most implementations are focused on the demonstration of a specific quantum algorithm or quantum state. However, there remain limitations on the number of collections of superconducting qubits possible in current physical systems.

SUMMARY

Exemplary embodiments include a device, including a volume bounded by electromagnetically conducting walls, an aperture in a bounding wall of the electromagnetically conducting walls, a plurality of quantum systems disposed within the volume and an electromagnetic field source coupled to the volume via the aperture.

Additional exemplary embodiments include an apparatus, including a volume bounded by conductive surfaces having an aperture, an arrangement of quantum systems disposed within the volume and an electromagnetic field source coupled to the volume.

Further exemplary embodiments include a qubit apparatus, including a housing defining a cavity therein, a plurality of qubit devices arranged in the cavity and an electromagnetic field source coupled to the housing and configured to apply an electromagnetic field within the cavity.

Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with the advantages and the features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The forgoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** illustrates a prior art NMR seven-spin molecule;

FIG. **2** illustrates an example of a qubit apparatus; and

FIG. **3** illustrates an example of an exemplary three dimensional qubit cluster apparatus.

FIG. **4** illustrates a flow chart of a method for a quantum computing method in accordance with exemplary embodiments.

DETAILED DESCRIPTION

In exemplary embodiments, the systems and methods described herein implement large collections (e.g., on the order of thousands and more) of coupled superconducting qubits that can be used for quantum computing applications. In exemplary embodiments, any suitable physical qubit system can be implemented. For example, any two-level system can be used as a qubit. Multilevel systems can be used as well, if they possess two states that can be effectively decoupled from the rest (e.g., ground state and first excited state of a nonlinear oscillator). Such systems can include but are not limited to: silicon-based nuclear spins, trapped ions, cavity quantum-electrodynamics, nuclear spins, electron spins in quantum dots, superconducting loops and Josephson junctions, liquid state NMR, and electrons suspended above the surface of liquid Helium.

There are several quantum mechanical properties that are considered in building quantum computers. One distinguishing feature between a qubit and a classical bit is that multiple qubits can exhibit quantum entanglement, which is a nonlocal property that allows a set of qubits to express higher correlation than is possible in classical systems. Take, for example, two entangled qubits in the Bell state, which is called an equal superposition. Entanglement also allows multiple states (i.e., the Bell state mentioned above) to be acted on simultaneously, unlike classical bits that can only have one value at a time. Entanglement is a necessary ingredient of any quantum computation that cannot be done efficiently on a classical computer. Many of the successes of quantum computation and communication, such as quantum teleportation and superdense coding, make use of entanglement, suggesting that entanglement is a resource that is unique to quantum computation. Another quantum mechanical property is quantum teleportation, or entanglement-assisted teleportation, which is a process by which a qubit state can be transmitted exactly (in principle) from one location to another, without the qubit being transmitted through the intervening space. It is useful for quantum information processing; however, it does not immediately transmit classical information, and therefore cannot be used for communication at superluminal (faster than light) speed. Quantum teleportation is unrelated to the common term teleportation—it does not transport the system itself, and does not concern rearranging particles to copy the form of an object.

The requirements for building a practical quantum computer are more intricate than quantum mechanical properties such as superposition and entanglement alone. There is a set of requirements that must be fulfilled in order to build a practical quantum computer. One requirement is to have a system of qubits that can be initialized to a known state. Another requirement is the ability to manipulate this state by applying single and multi-qubit gate operations such that any arbitrary logic operation can be implemented. Finally, the outcome of the computation must be measured through known techniques. In addition, for a quantum system to retain the delicately created superposition and entangled states for sufficiently long times (i.e., coherence times) it must be well isolated from the environment. However, in order to manipulate the quantum system according to the steps of the desired algorithm it must inherently also be coupled to the external environment thereby introducing noise mechanisms that reduce coherence times.

However, as described herein, significant research has been conducted on the NMRQC. The exemplary systems and methods described herein implement a cluster of qubits that behave and can be characterized much like an NMRQC. As such, in characterizing the exemplary systems and methods, several features of the NMRQC can be analyzed as further described herein.

In exemplary embodiments the systems and methods described herein include a housing or volume having a cavity defined within the housing or volume. Quantum systems are disposed within the cavity and can be coupled to one another by electromagnetic field modes excited by an electromagnetic field source. In exemplary embodiments, the cavity includes resonant modes that are each characterized by a resonant frequency. In addition, the quantum systems include a number of eignestates, which have an associated frequency. The electromagnetic field has a number of modes, such that each quantum system can couple to other quantum systems via the mutual coupling of the of the quantum systems to the electromagnetic field.

It will be appreciated that the quantum systems can be any variety of devices that can support qubits for information processing, such as electronic circuits (e.g., Josephson junctions). The quantum systems can represent composite quantum systems, formed for example by a resonant mode of the cavity and the plurality of quantum systems. In exemplary embodiments, the electromagnetic field source is configured to induce a measurement of an eigenstate of at least one of one or more of the quantum systems and the composite quantum systems. In addition, the electromagnetic field source is configured to induce transitions between eigenstates among the plurality of quantum systems. As such, each quantum system has an associated transition frequency that enables the quantum system to transition between eignstates when induced with different modes of the electromagnetic field.

FIG. **2** illustrates an example of a qubit apparatus **200**. The apparatus **200** provides an illustrative basis for describing the exemplary systems and methods herein. The apparatus includes a housing **205** with a cavity **210** defined therein. The apparatus **200** can further include a qubit **215** disposed within the cavity **210**. The apparatus **200** can further include an external electromagnetic source **220** (e.g., a coaxial cable) coupled to the housing **205** and providing an electromagnetic field, represented by arrows **225**. As such, it can be appreciated that the housing **205** is an electromagnetic waveguide for the electromagnetic field applied to the housing. It can further be appreciated that the housing **205** can support several modes of the electromagnetic field. For illustrative purposes, the qubit **215** is circuit having a Josephson junction **216** defined with other circuit elements **217**, **218** such as capacitors and inductors as known in the art. The qubit **215** can be advantageously coupled to a transmission line or other suitable connector (not shown) configured to measure the quantum state induced in the qubit **215** from the electromagnetic field. Measurements can be performed by applying signals to the cavity **210** through an interconnect and looking at either the reflected or transmitted signals. If measuring in transmission, a second port—(an output port) can be added. If measuring in reflection, measurements can be made via the port supporting the external magnetic source **220**. For further illustrative purposes, the housing **205** can be any suitable superconducting material such as aluminum (Al) and the qubit **215** can be a transom-style superconducting Josephson junction. A transom qubit is a superconducting qubit that is made insensitive to charge by making the qubit capacitance large. By adjusting the capacitance and Josephson inductance (both are determined through fabrication and device geometry), the characteristic energies associated with the qubit capacitance (Ec) and qubit inductance (Ej) satisfy Ej>>Ec. It can be appreciated that other types of qubits are contemplated in other exemplary embodiments. The apparatus **200** can therefore be a three-dimensional waveguide cavity and qubit that form a valid circuit quantum electrodynamic (cQED) system capable of coherence times in the 50 μs range. Coherence times in this range are desirable for the cQED system to retain the delicately created superposition and entangled states as further described herein. Current cQED systems typically implement coplanar waveguide resonators and planar qubits with interdigitated capacitors. In exemplary embodiments, the apparatus **200** is three dimensional in terms of both its physical structure and the associated electromagnetic (EM) fields to which the qubit **215** is coupled.

Several observations can be made of the apparatus **200**. First, the electromagnetic modes occupy a free-space region defined by cavity **210**. The mode volumes can be considered large with respect to the cavity **210**, but also well-defined and have predictable quality factors and frequencies. For example, measurements indicate that the modes are entirely controlled up to our maximum characterization frequency of 27 GHz. The presence of only understood and predictable modes that occupy a free-space region means the possible sources of loss within the system are far more limited than in the planar geometry. By placing the qubit **215** inside the cavity **210**, the profile and location of the electromagnetic fields associated with the qubit mode can be adjusted in addition to the electromagnetic field modes. It can be appreciated that appropriate modifications have to be made to the geometry of the qubit capacitance to obtain suitable shunting and coupling capacitances.

In addition, the internal quality factor (i.e., Q factor) of the apparatus has been measured to be as high as 4.4 million. The Q factor characterizes a resonator's bandwidth relative to its center frequency. Higher Q indicates a lower rate of energy loss relative to the stored energy of the cavity **210**, and thus the oscillations die out more slowly. Furthermore, the Q factor is easily tuned and can be increased for readout performance or for Purcell Effect qubit relaxation. The Purcell Effect in this case defines the rate at which the qubits relax (i.e., lose their current quantum state). For example, the apparatus has been measured to have a Purcell-limited qubit lifetime of 2.7 μs in the cavity **210** with a loaded Q of 20,000. In addition, the coupling factor, g, between the qubit and the cavity **210** has been measured to be g=475 MHz. Such coupling indicates a strong interaction between the cavity **210** and the qubit **215**. As such, the applied electromagnetic field can easily adjust the quantum state of the qubit **215**, which in turn will relax slow enough to allow for suitable measurement. Such measurements indicate that many-qubit systems as described herein can provide meaningful measurements for quantum computing to perform high-fidelity multi-qubit logic.

The apparatus **200** of FIG. **2** is a single three-dimensional (3D) configuration in that the coupling of the qubit **215** to the electromagnetic field in the cavity **210** occurs in three dimensions. In exemplary embodiments, the single 3D qubit **215** of FIG. **2** can be scaled up to a larger array of coupled 3D qubits for quantum computing as now described.

FIG. **3** illustrates an example of an exemplary 3D qubit cluster apparatus **300**. The apparatus **300** includes a housing **305** with a cavity **310** defined therein. The apparatus **300** can further include a cluster of qubits **315** disposed within the cavity **310**. As described herein, an example of a superconducting Josephson junction is described as each of the qubits **315**. However, as described herein, it is appreciated that any type of qubit can be implemented including, but not limited to, quantum dots, electron or nuclear spins or collections thereof. The apparatus **300** can further include an external electromagnetic source **320** (e.g., a coaxial cable) coupled to the housing **305** and providing an electromagnetic field within the cavity **310**. As such, it can be appreciated that the housing **205** is an electromagnetic waveguide for the electromagnetic field applied to the housing **305**. The qubits **315** can be arranged in a wide variety of ways within the cavity **310**. The location and orientation of a qubit within the cavity can affect how strongly coupled it is to the modes of the cavity. Each qubit **315** can be viewed as a dipole, with an associated dipole moment vector. The strength of its interaction with the cavity **310** is determined predominantly by the dot product of the dipole moment vector with the electric field vector at the location of the qubit **315**. As such, adjustments of the qubit location and orientation relative to the electric field profile of the mode of interest can be used to adjust the strength of qubit-cavity coupling, and in turn the qubit-qubit coupling, as the qubits acquire a direct qubit-qubit effective interaction through their mutual interaction with the cavity mode. The apparatus **300** exhibits similar physical qualities as the apparatus described with respect to FIG. **2**. The apparatus **300** is thus a scaled apparatus including multiple qubits **315**. As such, the cavity **310** can support a high volume of electromagnetic modes, with strong coupling between the cavity **310** and the qubits. Furthermore, there is also strong coupling among the individual qubits **315** within the cavity that can be controlled and tuned by adjusting the electromagnetic field from the electromagnetic source **320**. The apparatus **300** is therefore scaled up from the single 3D qubit to a large platform of coupled 3D qubits for quantum computing. In exemplary embodiments, the scaling up process is modular. FIG. **3** illustrates a single qubit cluster **300** as described. In exemplary embodiments, eight qubits **315** are illustrated and can be arranged in a variety of ways in order to achieve desired coupling among the qubits. It will be appreciated that there are numerous ways and manners in which the qubits **315** can couple. The qubits **315** are illustrated in an octagonal pattern but in no way are other exemplary embodiments limited to this pattern. Furthermore, there can be fewer or more than eight qubits **315** arranged in the cavity **310**. Eight qubits **315** are illustrated because they behave much like a conventional NMR molecule, as further described herein, and therefore are well-understood and characterized.

As such, FIG. **3** illustrates eight transom-style qubits inside the cavity **315**, which, as described is an ultra-high Q superconducting waveguide resonator, to form the qubit cluster apparatus **300**.

In exemplary embodiments, as described herein, the coupling of qubits within a cluster as well can be achieved by the application of electromagnetic fields. Measurements of the qubits can be subsequently taken in order to determine the quantum states of the qubits. The application of the electromagnetic fields as well as the subsequent quantum state measurements described an overall quantum computing method. First all the qubits within the cluster are characterized in terms of their frequencies f_i and coupling strengths g_i to the cavity by known techniques. Through an iterative process with this qubit characterization joint readout of the qubits is then calibrated. With the values of f_i and g_i the Hamiltonian H of the qubit/cavity system can then be reconstructed. And protocols for a universal gate set devised—consisting of rf pulse sequences. In parallel an algorithm to be implemented is selected and decomposed into a set of single and multiple gate operations consistent with the resources available in the cluster. A set of rf pulse sequences is then devised to implement the algorithm based on those determined for the universal gate set. These RF pulse sequences are next applied to the system and a joint readout of all the qubits is done to determine the outcome.

Several properties of the exemplary systems and methods are now further described. As discussed herein, the physics of a system with multiple transmon style qubits dispersively coupled to a single bosonic resonator mode is well understood (e.g., an NMRQC). In exemplary embodiments, the systems and methods described herein are implemented with fixed qubit frequencies and fixed qubit-qubit coupling. In this way, known NMR control techniques can be implemented. In NMR technology, Larmor frequencies are implemented in which the qubits tend to align with the applied electromagnetic fields. In addition, chemical shifts, which describe the dependence of energy levels in on the electronic environment in a molecule, can be implemented to determine the dependence of the energy levels in a given cavity in the exemplary qubit clusters described herein. By implementing such known techniques, universal control of the exemplary qubit clusters described herein can be attained. In exemplary embodiments, qubit frequencies could be controlled via wires introduced into the cavity. By judicious selection of qubit frequencies and anharmonicities, Hamiltonians identical to Hamiltonians in NMR can be attained, where there are both secular and non-secular coupling terms of comparable strength, but only the secular portion is important because it enters to first order in perturbation theory. In exemplary embodiments, spins can be selected on individual qubits within a cavity.

In NMRQC, ZZ exchange and interaction describes the spin exchange between adjacent molecules. This concept can be extended to describe spin exchange in qubits as described in exemplary embodiments. An NMR-style Hamiltonian emerges when the effective ZZ interaction between qubits in a particular cavity is significant compared with the off-diagonal J-coupling term, that is, coupling of angular momentum of interacting qubits. This ZZ interaction has two physical origins. First, ZZ interaction emerges in the two-level approximation when the cavity-qubit coupling is treated to fourth-order in perturbation theory. Second, it emerges when additional qubit levels outside the computational subspace are properly modeled. The two effects can be made to add rather than cancel. In exemplary embodiments, the systems and methods described herein that include circuits that implement an NMR-type Hamiltonian requires understanding and exploiting both these origins of the ZZ interaction term. The strength of the effect increases rapidly as the 1-->2 transition of one qubit in a cluster approaches the 0-->1 transition of another. By exploiting these physical phenomena, the qubit clusters described herein can be scaled as described.

In exemplary embodiment, in order to produce the NMR-type Hamiltonian characterized by: a) fixed qubit transition frequencies, and b) fixed qubit-qubit couplings dominated by a ZZ interaction, the systems described herein possess the following qualities: 1) Each qubit is controlled and manipulated in such a manner that it behaves as an effective two-level system; 2) Each qubit interacts with at least one other qubit with a coupling energy that is much greater than the qubit relaxation and decoherence rates; 3) The system allows for the application to the qubits of a frequency and amplitude modulated microwave control field; and 4) The system allows for the readout of the quantum state of all qubits such as joint readout via reflection or transmission.

In exemplary embodiments, two qubit gates are performed by doing nothing to the two qubits that are to be entangled, while interactions between all other pairs are refocused. In recent liquid state NMR experiments on multi-spin molecules, very-high fidelity control of $E_{1q}=1.3\times10^{-4}$ and $E_{2q}=4.7\times10^{-3}$ has been demonstrated. It is believed that these are limited by the difficulty to polarize the spins at the outset. In contrast, in exemplary embodiments, the qubits described herein (i.e., superconducting qubits can be easily initialized. However, due to the higher Larmor frequencies (roughly 1-10 GHz as compared to 50-500 MHz), additional steps must be taken to carry out accurate numerical pulse optimization.

In exemplary embodiments, qubits within the exemplary cluster described herein are measured through the application of resonant or near-resonant signals to the cavity that houses them. The readouts can be done according to the established methods of joint dispersive readout. Single shot readouts can be realized by also applying drive signals to a neighboring coupling element, whose non-linearity makes it suitable for signal amplification.

As such, it can be appreciated that the exemplary cluster described herein combines known and well-characterized features of NMRQC and desirable attributes of qubits such as superconducting attributes.

In exemplary embodiments, as described herein, the coupling of qubits within a cluster as well can be achieved by the application of electromagnetic fields. Measurements of the qubits can be subsequently taken in order to determine the quantum states of the qubits. The application of the electromagnetic fields as well as the subsequent quantum state measurements described an overall quantum computing method. FIG. **4** illustrates a flow chart of a method **400** for a quantum computing method in accordance with exemplary embodiments. First all the qubits within the cluster are characterized in terms of their frequencies f; and coupling strengths g_i to the cavity by known techniques. Through an iterative process with this qubit characterization joint readout of the qubits is then calibrated. With the values of f_i and g_i the Hamiltonian H of the qubit/cavity system can then be reconstructed. And protocols for a universal gate set devised—consisting of rf pulse sequences. In parallel an algorithm to be implemented is selected and decomposed into a set of single and multiple gate operations consistent with the resources available in the cluster. A set of rf pulse sequences is then devised to implement the algorithm based on those determined for the universal gate set. These rf pulse sequences are next applied to the system and a joint readout of all the qubits is done to determine the outcome.

The flow diagram depicted herein is just one example. There may be many variations to this diagram or the steps (or operations) described therein without departing from the spirit of the invention. For instance, the steps may be performed in a differing order or steps may be added, deleted or modified. All of these variations are considered a part of the claimed invention.

While the preferred embodiment to the invention had been described, it will be understood that those skilled in the art, both now and in the future, may make various improvements and enhancements which fall within the scope of the claims which follow. These claims should be construed to maintain the proper protection for the invention first described.

What is claimed is:

1. A device, comprising:

a volume bounded by electromagnetically conducting walls;

an aperture in a bounding wall of the electromagnetically conducting walls;

a plurality of quantum systems disposed within the volume; and

an electromagnetic field source coupled to the volume via the aperture,

wherein each of the plurality of quantum systems is arranged at a location in the volume, which is relative to an electric field profile of a mode of interest from the electromagnetic filed source, the location determining coupling strength between each of the plurality of quantum systems to the cavity and to other quantum systems.

2. The device as claimed in claim **1** wherein the volume supports a plurality of electromagnetic resonant modes, each of the plurality of resonant modes characterized by a resonant frequency.

3. The device as claimed in claim **1** wherein each of the plurality of quantum systems includes a plurality of eignestates.

4. The device as claimed in claim **1** wherein the electromagnetic field source produces an electromagnetic field within the volume.

5. The device as claimed in claim **1** wherein a plurality of the quantum systems disposed within the volume is coupled to the electromagnetic field within the volume.

6. The device as claimed in claim **5** wherein a particular quantum system from among the plurality disposed within the volume interacts with a different particular quantum system from among the plurality disposed within the volume by way of the electromagnetic field within the volume.

7. The device as claimed in claim **2** wherein a particular quantum system from among the plurality disposed within the volume interacts with a different particular quantum system from among the plurality disposed within the volume by way of the electromagnetic resonant modes supported by the bounded volume.

8. The device as claimed in claim **1** wherein each of the plurality of quantum systems is an electronic circuit.

9. The device as claimed in claim **8** wherein each of the plurality of quantum systems includes a Josephson junction.

10. The device as claimed in claim **1** wherein each of the plurality of quantum systems is a qubit.

11. The device as claimed in claim **1** wherein each of the plurality of quantum systems is a composite quantum system.

12. The device as claimed in claim **1** wherein a resonant mode of the cavity and the plurality of quantum systems is a composite quantum system.

13. The device as claimed in claim **1** wherein the electromagnetic field source is configured to induce a measurement of an eigenstate of at least one of one or more of the plurality of quantum systems and the composite quantum system.

14. The device as claimed in claim **1** wherein the electromagnetic field source is configured to induce an electromagnetic field within the cavity.

15. The device as claimed in claim **14** wherein each of the plurality of quantum systems includes a transition frequency.

16. The device as claimed in claim **15** wherein the electromagnetic field source is configured to induce transitions between eigenstates among the plurality of quantum systems.

17. The device as claimed in claim **15** wherein the electromagnetic field source is configured to induce transitions between eigenstates of one or more quantum systems among the plurality of quantum systems.

18. The array as claimed in claim **2** wherein each of the one or more quantum states includes a measurable feature.

19. The array as claimed in claim **1** wherein the housing is a closed section of electromagnetic waveguide.

20. The array as claimed in claim **1** wherein each of the plurality of quantum systems is a transmon-style superconducting qubit.

21. The device as claimed in claim **2** wherein the electromagnetic field source is configured to induce an electromagnetic field within the cavity at one or more of the resonant frequencies associated with the volume.

22. An apparatus, comprising:

a volume bounded by conductive surfaces having an aperture;

an arrangement of quantum systems disposed within the volume; and

an electromagnetic field source coupled to the volume,

wherein individual quantum systems from the arrangement of quantum systems is arranged at a location in the volume, which is relative to an electric field profile of a mode of interest from the electromagnetic filed source, the location determining coupling strength between individual quantum systems to the volume and to other individual quantum systems.

23. The apparatus as claimed in claim **22** wherein an electromagnetic field generated from the electromagnetic field source within the volume is applied through the aperture.

24. An qubit apparatus, comprising:

a housing defining a cavity therein;

a plurality of qubit devices arranged in the cavity; and

an electromagnetic field source coupled to the housing and configured to apply an electromagnetic field within the cavity,

wherein each of the plurality of qubit devices is arranged at a location in the cavity, which is relative to an electric field profile of a mode of interest from the electromagnetic filed source, the location determining coupling strength between each of the plurality of qubit devices to the cavity and to other qubit devices.

25. The array as claimed in claim **24** wherein each of the plurality of qubits includes a resonance frequency and wherein the electromagnetic field is configured to generate one or more quantum states in each of the plurality of qubits, and wherein the plurality of qubits are arranged in the cavity such that modes associated with each of the plurality of qubits couple with one another.

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