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1. REPORT DATE (DD-MM-YYYY) 29-08-2017	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 15-Feb-2014 - 14-Aug-2017
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4. TITLE AND SUBTITLE Final Report: Realization of High-Fidelity, on-Chip Readout of Solid-state Quantum Bits	5a. CONTRACT NUMBER W911NF-14-1-0078
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of California - Berkeley Sponsored Projects Office 2150 Shattuck Avenue, Suite 300 Berkeley, CA 94704 -5940	8. PERFORMING ORGANIZATION REPORT NUMBER
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 64908-PH-OC.2

12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.
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13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	Irfan Siddiqi
	UU		19b. TELEPHONE NUMBER 510-/64-2562

RPPR Final Report

as of 19-Oct-2017

Agency Code:

Proposal Number: 64908PHQC

Agreement Number: W911NF-14-1-0078

INVESTIGATOR(S):

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EIN: 946002123

Report Date: 14-Nov-2017

Date Received: 29-Aug-2017

Final Report for Period Beginning 15-Feb-2014 and Ending 14-Aug-2017

Title: Realization of High-Fidelity, on-Chip Readout of Solid-state Quantum Bits

Begin Performance Period: 15-Feb-2014

End Performance Period: 14-Aug-2017

Report Term: 0-Other

Submitted By: Irfan Siddiqi

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3

STEM Participants: 13

Major Goals: Our research program targets the development of advanced quantum-limited microwave amplifiers, including on-chip implementations, and precision circuitry which makes use of squeezed light and interferometry to boost readout speed and fidelity while reducing hardware complexity over current state-of-the-art.

Accomplishments: The UC Berkeley and MIT teams have developed and characterized Josephson Traveling Wave Parametric Amplifiers (JTWPA or TWPA), superconducting amplifiers providing significantly greater bandwidth and dynamic range than the previous state-of-the-art. This technology enables multiplexed high-fidelity readout of many qubits.

The UC Berkeley team, with theory support from the McGill team, has demonstrated the first use of injected squeezing to increase the signal-to-noise ratio (SNR) of a superconducting qubit measurement. While in principle microwave squeezing provides access to ultimate limits of sensitivity in superconducting qubit measurements, measurement enhancement has remained elusive, in part because integration with standard dispersive readout pollutes the signal channel with antisqueezed noise. In our work, we induced a stroboscopic light-matter coupling with superior squeezing compatibility, and observed an increase in the final signal-to-noise ratio of 24% with applied squeezing. Squeezing the orthogonal phase slowed measurement induced dephasing by a factor of 1.8; the ability to control measurement backaction using squeezing is valuable for proposed multi-qubit gate schemes. Our scheme provides a path to practical microwave squeezing for qubit measurement.

The UC Berkeley team, again with theory support from the McGill team, has also integrated a Josephson Parametric Amplifier (JPA) on-chip with a superconducting qubit, forming a transmon-amplifier circuit ("Trans-Amp"). The on-chip gain mitigates the effect of typically unavoidable microwave loss occurring between a qubit and an off-chip amplifier, enabling detection of the readout signal at room-temperature with increased measurement efficiency greater than 70%, valuable for continuous-measurement based feedback and squeezed-readout protocols. We have investigated measurement backaction and efficiency improvement in this hybrid system for a range of operating points and observed good agreement with our theoretical model. As the Trans-Amp requires minimal additional on-chip circuitry, replacing the standard linear readout resonator with a flux-tunable non-linear resonator and pump line, we expect compatibility with modern multi-qubit architectures.

The theory work at Sherbrooke has focused on three key areas: (i) they have developed a quantum theory for the JTWPA. This was used to predict the device's output field squeezing spectrum. Moreover, they have shown that JTWPAs are powerful resources, allowing to prepare states that are universal for measurement-based quantum computing. (ii) They have extended the study of longitudinal coupling and shown that it could be used for fast and

RPPR Final Report

as of 19-Oct-2017

high-fidelity entangling gates, thus making longitudinal coupling an attractive platform for quantum computing. Moreover, they have shown that squeezing can be used as a resource to obtain exponential improvement in gate fidelity. (iii) They have shown how quantum state engineering of photonic cat states is possible in JPAs. This opens the possibility to use these amplifiers for cat state based quantum computing.

The McGill team has developed a method that allows exponential enhancement of a dispersive measurement using squeezing which is generated in situ, thus avoiding losses associated with transporting and injecting squeezed states. This method builds on their previous work combining two-mode squeezing and dynamical symmetries, and is also related to the "TRANSAMP" integrated amplifier/readout system studied earlier in the program. As an added bonus, the system also features strong intrinsic protection against non-QND backaction effects such as Purcell decay. Other accomplishments at McGill include devising a theory of how impedance engineering can enhance standard paramp bandwidth, and in collaboration with the MIT team, a theory describing how loss mechanisms and noise degrade squeezing generation in TWPA style amplifiers. This work shows that loss that is asymmetric between signal and idler frequencies is particularly damaging; it also suggests methods for mitigating these effects.

During the past year, the MIT team completed characterization of the 2-cavity/1-qubit sample, which will be used for two-mode squeezed readout. They also measured the broadband two-mode correlations in a TWPA as a function of signal frequency and gain. The device will later serve as the source of squeezed light for qubit readout. In support of performing vacuum noise calibrations, they developed data visualization tools including squeezing tomograms (covariance matrix) and reconstruction of Wigner functions. They also developed theoretical tools for studying the effect of distributed vs lumped element loss on achievable squeezing, and investigated the effect of asymmetric loss on squeezing (in collaboration with McGill). They also designed a device consisting of a transmon qubit longitudinally coupled to the readout circuit. The chip is currently in fabrication; they anticipate to perform experiments on this device in the next few months. Finally, they have renovated lab in order to accommodate for a new dilution refrigerator, sponsored by LPS.

Milestone summary:

Accomplished goals:

- Fabricate transamp circuit
- Developed a comprehensive theory of the TRANSAMP integrated qubit/parametric amplifier readout system.
- Develop PARI theory: linear response
- Model squeezing efficiency of Josephson Junction paramps
- Demonstrate fluorescence-based methods for characterizing squeezing
- Experimentally investigate squeezing efficiency of Josephson Junction paramps
- Develop theoretical model of TWPA to account for higher harmonics
- Develop TWPA design to filter harmonics, explore different designs/BW
- Fabricate TWPA's with optimized parameters
- Test TWPA's: gain/bandwidth/backaction/fidelity
- Develop protocols for efficient squeezed light generation
- Model efficiency of squeezed-light readout schemes
- Developed a high-fidelity two-qubit gate based on longitudinal coupling
- Theoretically show that squeezing is a resource for two-qubit gates
- Developed theory of quantum state engineering in JPAs
- Develop a comprehensive understanding of how direct injection of single-mode squeezing into a cavity can enhance standard dispersive measurements.
- Develop a strategy for using two-mode squeezing to exponentially enhance standard dispersive measurements
- Develop a strategy for how squeezing can be generated and used in-situ in a measurement system to enhance the measurement, thus avoiding limitations coming from insertion losses
- Designed, fabricated, and tested TWPA4 with optimized design parameters (with UCB, LL)
- Designed on-chip microwave directional coupler for use with TWPA
- Read out 2D qubits with TPWAs (C-shunt flux qubit, transmon)
- Completed characterization of the two-cavity/one qubit sample for squeezed readout
- Demonstrated two-mode squeezing in TWPA
- Developed detailed understanding of the limiting factors of TWPA two-mode squeezing
- Designed transmon qubit longitudinally coupled to a readout resonator
- Performed initial characterization of qubit longitudinally coupled to readout resonator
- Characterize transamp gain and backaction
- Develop an understanding of how two-tone driving allows one to fully exploit single-mode squeezing to

RPPR Final Report

as of 19-Oct-2017

enhance dispersive measurements.

- Detailed numerical study of readout performance using longitudinal coupling
- Use squeezed light to control measurement backaction
- Use squeezed light to read out transmon

Training Opportunities: Graduate students trained as part of the program:

- UC Berkeley: Christopher Macklin, Mollie Schwartz, Andrew Eddins, John Mark Kreikebaum
- MIT: Moritz Businger
- Sherbrooke: Baptiste Royer
- McGill: Benjamin Levitan

Undergraduates mentored as part of the program:

- UC Berkeley: Aditya Venkatramani, Yanjie Qiu, Nicholas Frattini, Reinhard Lolowang, Dirk Wright

RPPR Final Report

as of 19-Oct-2017

Results Dissemination: Publications/Patents:

2015:

- C. Macklin, et al., “A near-quantum-limited Josephson traveling-wave parametric amplifier”, *Science*, (2015).
- N. Didier et al, “Heisenberg-Limited Readout with Two-Mode Squeezed Light”, *Phys. Rev. Lett.* 115, 093604 (2015). (published on Aug. 28 2015)
- T. Roy et al., “Broadband parametric amplification with impedance engineering: Beyond the gain- bandwidth product”, *App. Phys. Lett.* 107, 262601 (2015).

2016:

- D.M. Toyli*, A.W. Eddins*, et al., “Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum”, *Phys. Rev. X* 6, 031004 (2016)
- M. E. Kimchi-Schwartz et al., “Stabilizing Entanglement via Symmetry-Selective Bath Engineering in Superconducting Qubits”, *Phys. Rev. Lett.* 116, 240503 (2016)
- J. Bourassa, et al., “Parametrically modulated longitudinal coupling,” Provisional patent 62/305,778, United States, March 9. 2016.
- B. Royer, et al., “Fast and High-Fidelity Entangling Gate through Parametrically Modulated Longitudinal Coupling”, arXiv:1603.04424 (2016)
- S. Puri, A. Blais, “Engineering the quantum states of light in a Kerr-nonlinear resonator by two-photon driving”, *Phys. Rev. Lett.* 116, 180501 (2016)
- D.H. Slichter et al., “Quantum Zeno effect in the strong measurement regime of circuit quantum electrodynamics,” *New Journal of Physics* 18, 053031 (2016)

2017:

- S. Boutin, et al., “Effect of higher-order nonlinearities on amplification and squeezing in Josephson parametric amplifiers”, arXiv:1708.00020 (2017)
- A.W. Eddins, et al., “Stroboscopic qubit measurement with squeezed illumination”, arXiv:1708.01674 (2017)
- B. J. Chapman et al., “Widely tunable on-chip microwave circulator for superconducting quantum circuits” arXiv:1707.04565v1 (2017)
- S. Puri and A. Blais “Quantum processor and methods of quantum processing”. Provisional patent 2,968,830, Canada, May 29, 2017.
- A. L. Grimsmo and A. Blais, “Squeezing and quantum state engineering with Josephson travelling wave amplifiers”, *npj Quantum Information* 3, 20 (2017)
- Baptiste Royer et al., Fast and high-fidelity entangling gate through parametrically modulated longitudinal coupling, *Quantum* 1, 11 (2017)
- S. Puri et al., “Engineering the quantum states of light in a Kerr-nonlinear resonator by two-photon driving”, *npj Quantum Information* 3, 18 (2017)
- S. Puri et al., “Quantum annealing with all-to-all connected nonlinear oscillators”, *Nature Communications* 8, 15785 (2017)
- L. C. G. Govia, A. A. Clerk, “Enhanced qubit readout using locally generated squeezing and inbuilt Purcell-decay suppression”, *New. J. Phys.* 19, 023044 (2017).

Presentations:

- B. Royer et al., “Entangling gate by Parametric Modulation of Longitudinal Coupling”, 2016, oral presentation, APS March Meeting, Baltimore
- B. Royer et al., “Entangling gate by Parametric Modulation of Longitudinal Coupling”, 2017, oral presentation, CONFETI (INTRIQ’s student conference), Bromont
- B. Royer et al., “Fast and High-Fidelity Entangling Gate through Parametrically Modulated Longitudinal Coupling”, 2016, ARO program review, Boulder
- B. Royer et al., “Fast and High-Fidelity Entangling Gate through Parametrically Modulated Longitudinal Coupling”, 2017, INTRIQ Quantum Industry Day, Montréal (edited)
- S. Puri, et al., “High-fidelity resonator-induced phase gate with single-mode squeezing”, APS March meeting, Baltimore 2016 (contributed talk)
- S. Puri et al., “Preparation and manipulation of cat states in Josephson parametric amplifiers”, ARO program review, Boulder 2016 (poster)
- S. Puri, et al., “Quantum Ising machines with parametrically modulated nonlinear oscillators?”, Yale Quantum Institute 2016 (invited talk)
- S. Puri, et al., “Quantum annealing with a network of all-to-all connected, two-photon driven Kerr nonlinear oscillators”, Innsbruck Seminar (online) 2017 (invited talk)
- S. Puri, et al., “Quantum annealing with parametrically driven nonlinear resonators”, APS March meeting, New

RPPR Final Report as of 19-Oct-2017

Orleans 2017 (invited talk)

- S. Puri, et al., "Preparation and manipulation of cat states in Josephson parametric amplifiers", INTRIQ Quantum industry day, Montreal 2017 (poster)
- S. Puri, et al., "Quantum Ising machine with a network of nonlinear oscillators", Quantum cavities, Quebec (poster)
- S. Puri, et al., "A quantum Ising machine based on parametrically driven nonlinear oscillators" Adiabatic quantum Computing 2017 (AQC 2017), Tokyo 2017 (contributed talk)
- S. Puri, et al., "Quantum annealers with parametrically modulated nonlinear oscillators" University of Tokyo 2017 (invited talk)
- A. Blais "Quantum Ising machines with parametrically modulated nonlinear oscillators" CIFAR Quantum Information Processing program workshop. Banff, Canada. 2017. Oral presentation.
- A. Blais « Calcul quantique adiabatique dans les circuits supraconducteurs » LIA-Laboratoire circuits et matériaux quantiques. Saint Lambert des Bois, France. 2017. Oral presentation.
- A. Blais "Quantum Ising machines with parametrically modulated nonlinear oscillators" CEA Saclay. Gif-sur-Yvette, France. 2017. Oral presentation.
- A. Blais "Quantum Ising machines with parametrically modulated nonlinear oscillators" Institute for Quantum Optics and Quantum Information. Innsbruck, Austria. 2017. Oral presentation.
- A. Blais. "Quantum Ising machines with parametrically modulated nonlinear oscillators" ETH. Zurich, Switzerland. 2016. Oral presentation.
- A. Blais. "Quantum Ising machines with parametrically modulated nonlinear oscillators" Driven Quantum System Workshop. Bariloche, Argentina. 2016. Oral presentation.
- A. Blais « Superconducting quantum circuits », McGill University Colloquium. Montréal, Canada. 2016. Oral presentation.
- S. Schreppler, "Stroboscopic qubit measurement with injected squeezed light, Part 1: Controlling measurement backaction," 2017, APS March Meeting, New Orleans, LA
- A.W. Eddins, "Stroboscopic qubit measurement with injected squeezed light, Part 2: Enhancing SNR", 2017, APS March Meeting, New Orleans, LA
- S. Schreppler, "Evading quantum backaction via displacement coupling in circuit QED", March 2017, RIKEN Quantum Condensed Matter Research Group Seminar, Wako, Japan
- S. Schreppler, "Evading quantum backaction via displacement coupling in circuit QED", March 2017, Interdisciplinary Workshop on Quantum Devices (IWQD) 2017, Tokyo, Japan
- A.W. Eddins, et al., "Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum", 2016, poster presentation, SQuInT Workshop, Albuquerque, NM.
- A.W. Eddins, et al., "Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum, Part 1: Efficient Fluorescence Detection", 2016, APS March Meeting, Baltimore, MD.
- D.M. Toyli, et al., "Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum, Part 2: Squeezing Characterization Through Fluorescence", 2016, APS March Meeting, Baltimore, MD.
- D.M. Toyli, et al., "Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum", 2016, poster presentation, IMA Quantum and Nano Control Conference, Minneapolis, MN.
- D.M. Toyli, et al., "Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum", 2016, invited talk, University of Minnesota, Condensed Matter Physics Seminar, Minneapolis, MN.
- D.M. Toyli, et al., "Engineering the Electromagnetic Vacuum with Superconducting Circuits", 2016, invited talk, Honeywell Advanced Sensing Technologies Group, Plymouth, MN.
- K. O'Brien, et al., "Strong field dynamics and quantum noise in Josephson traveling wave parametric amplifiers (JTWPAs)", 2016, APS March Meeting, MD
- A. Grimsmo et al., "Engineering Non-Classical Light with Non-Linear Microwaveguides," 2015, poster presentation IBM ThinkQ, NY
- A. Grimsmo et al., "Engineering Non-Classical Light with Non-Linear Microwaveguides," 2016, oral presentation, APS March Meeting, Baltimore, MD.
- S. Puri, A. Blais, "High-fidelity resonator-induced phase gate with single-mode squeezing," 2015, poster presentation, IBM ThinkQ, NY

+ 34 additional presentations

Honors and Awards: Prof. Irfan Siddiqi - Distinguished Teaching Award (2016) - University of California, Berkeley

Protocol Activity Status:

RPPR Final Report as of 19-Oct-2017

Technology Transfer: • S. Puri and A. Blais “Quantum processor and methods of quantum processing”.
Provisional patent 2,968,830, Canada, May 29, 2017.
• J. Bourassa, N. Didier, B. Royer, A.L. Grimsco, A. Blais, “Parametrically modulated longitudinal coupling,”
Provisional patent 62/305,778, United States, March 9, 2016.

PARTICIPANTS:

Participant Type: PD/PI

Participant: Irfan Siddiqi

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co-Investigator

Participant: Alexandre Blais

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co-Investigator

Participant: Aashish Clerk

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co-Investigator

Participant: William Oliver

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Co-Investigator

Participant: Simon Gustavsson

Person Months Worked: 1.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: David Toyli

RPPR Final Report
as of 19-Oct-2017

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Sydney Schreppler

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Arne Grimsmo

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Jerome Bourassa

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Shruti Puri

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Luke Govia

Person Months Worked: 12.00

Funding Support:

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

RPPR Final Report
as of 19-Oct-2017

Participant: Archana Kamal

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Jeffrey Grover

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Philip Krantz

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Andrew Eddins

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: John Mark Kreikebaum

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Christopher Macklin

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

RPPR Final Report
as of 19-Oct-2017

Participant Type: Graduate Student (research assistant)
Participant: Mollie Kimchi-Schwartz
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Moritz Businger
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Baptiste Royer
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Aditya Venkatramani
Person Months Worked: 4.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Yanjie Qiu
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Undergraduate Student
Participant: Nicholas Frattini
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

RPPR Final Report
as of 19-Oct-2017

Participant Type: Undergraduate Student

Participant: Reinhard Lolowang

Person Months Worked: 6.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Undergraduate Student

Participant: Dirk Wright

Person Months Worked: 3.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Benjamin Levitan

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Participant Type: Graduate Student (research assistant)

Participant: Samuel Boutin

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

ARTICLES:

RPPR Final Report as of 19-Oct-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Science

Publication Identifier Type: DOI

Publication Identifier: 10.1126/science.aaa8525

Volume: 350

Issue: 6258

First Page #: 307

Date Submitted: 8/25/17 12:00AM

Date Published: 9/1/15 7:00AM

Publication Location:

Article Title: A near-quantum-limited Josephson traveling-wave parametric amplifier

Authors: C. Macklin, K. O'Brien, D. Hover, M. E. Schwartz, V. Bolkhovskiy, X. Zhang, W. D. Oliver, I. Siddiqi

Keywords: superconducting qubit readout, superconducting parametric amplifier

Abstract: Detecting single-photon level signals—carriers of both classical and quantum information—is particularly challenging for low-energy microwave frequency excitations. Here we introduce a superconducting amplifier based on a Josephson junction transmission line. Unlike current standing-wave parametric amplifiers, this traveling wave architecture robustly achieves high gain over a bandwidth of several gigahertz with sufficient dynamic range to read out 20 superconducting qubits. To achieve this performance, we introduce a subwavelength resonant phase-matching technique that enables the creation of nonlinear microwave devices with unique dispersion relations. We benchmark the amplifier with weak measurements, obtaining a high quantum efficiency of 75% (70% including noise added by amplifiers following the Josephson amplifier). With a flexible design based on compact lumped elements, this Josephson amplifier has broad applicability to microwave metrology and quantum optics.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Applied Physics Letters

Publication Identifier Type:

Publication Identifier:

Volume:

Issue:

First Page #:

Date Submitted: 8/25/17 12:00AM

Date Published: 12/30/15 10:12PM

Publication Location:

Article Title: Broadband parametric amplification with impedance engineering: Beyond the gainbandwidth product

Authors: Tanay Roy, Suman Kundu, Madhavi Chand, A. M. Vadiraj, A. Ranadive, N. Nehra, Meghan P. Patankar

Keywords: Quantum noise, quantum measurement, microwave spectroscopy, oscillators, band models

Abstract: We present an impedance engineered Josephson parametric amplifier capable of providing bandwidth beyond the traditional gain-bandwidth product. We achieve this by introducing a positive linear slope in the imaginary component of the input impedance seen by the Josephson oscillator using a $\pi/2$ transformer. Our theoretical model predicts an extremely flat gain profile with a bandwidth enhancement proportional to the square root of amplitude gain. We experimentally demonstrate a nearly flat 20 dB gain over a 640 MHz band, along with a mean 1-dB compression point of ~ 110 dBm and near quantum-limited noise. The results are in a good agreement with our theoretical model.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report as of 19-Oct-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review X

Publication Identifier Type:

Publication Identifier:

Volume:

Issue:

First Page #:

Date Submitted: 8/25/17 12:00AM

Date Published: 7/11/16 9:14PM

Publication Location:

Article Title: Resonance Fluorescence from an Artificial Atom in Squeezed Vacuum

Authors: D. M. Toyli, A. W. Eddins, S. Boutin, S. Puri, D. Hover, V. Bolkhovskiy, W. D. Oliver, A. Blais, and I. Siddiqi

Keywords: Superconducting qubits, quantum optics, squeezing of quantum noise

Abstract: We present an experimental realization of resonance fluorescence in squeezed vacuum. We strongly couple microwave-frequency squeezed light to a superconducting artificial atom and detect the resulting fluorescence with high resolution enabled by a broadband traveling-wave parametric amplifier. We investigate the fluorescence spectra in the weak and strong driving regimes, observing up to 3.1 dB of reduction of the fluorescence linewidth below the ordinary vacuum level and a dramatic dependence of the Mollow triplet spectrum on the relative phase of the driving and squeezed vacuum fields. Our results are in excellent agreement with predictions for spectra produced by a two-level atom in squeezed vacuum [Phys. Rev. Lett. 58, 2539 (1987)], demonstrating that resonance fluorescence offers a resource-efficient means to characterize squeezing in cryogenic environments.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review Letters

Publication Identifier Type:

Publication Identifier:

Volume:

Issue:

First Page #:

Date Submitted: 8/25/17 12:00AM

Date Published: 6/16/16 9:18PM

Publication Location:

Article Title: Stabilizing Entanglement via Symmetry-Selective Bath Engineering in Superconducting Qubits

Authors: M. E. Kimchi-Schwartz, L. Martin, E. Flurin, C. Aron, M. Kulkarni, H. E. Tureci, and I. Siddiqi

Keywords: Cavity quantum electrodynamics, Entanglement production, Quantum information architectures & platforms

Abstract: Bath engineering, which utilizes coupling to lossy modes in a quantum system to generate nontrivial steady states, is a tantalizing alternative to gate- and measurement-based quantum science. Here, we demonstrate dissipative stabilization of entanglement between two superconducting transmon qubits in a symmetry-selective manner. We utilize the engineered symmetries of the dissipative environment to stabilize a target Bell state; we further demonstrate suppression of the Bell state of opposite symmetry due to parity selection rules. This implementation is resource efficient, achieves a steady-state fidelity $F=0.70$, and is scalable to multiple qubits.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report as of 19-Oct-2017

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: New Journal of Physics
Publication Identifier Type: DOI **Publication Identifier:** 10.1088/1367-2630/aa5f7b
Volume: 19 **Issue:** 2 **First Page #:** 023044
Date Submitted: 8/25/17 12:00AM **Date Published:** 2/1/17 8:00AM
Publication Location:

Article Title: Enhanced qubit readout using locally generated squeezing and inbuilt Purcell-decay suppression

Authors: Luke C G Govia, Aashish A Clerk

Keywords: qubit measurement, squeezed microwaves

Abstract: We introduce and analyze a dispersive qubit readout scheme where two-mode squeezing is generated directly in the measurement cavities. The resulting suppression of noise enables fast, high-fidelity readout of naturally weakly coupled qubits, and the possibility to protect strongly coupled qubits from decoherence by weakening their coupling. Unlike other approaches exploiting squeezing, our setup avoids the difficult task of transporting and injecting with high fidelity an externally generated squeezed state. Our setup is also surprisingly robust against unwanted non-QND backaction effects, as interference naturally suppresses Purcell decay: the system acts as its own Purcell filter. Our setup is compatible with the experimental state-of-the-art in circuit QED systems, but the basic idea could also be realized in other systems.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

DISSERTATIONS:

Publication Type: Thesis or Dissertation

Institution: McGill University

Date Received: 25-Aug-2017

Completion Date: 8/1/15 9:20PM

Title: Dispersive qubit measurement using an on-chip parametric amplifier

Authors: Benjamin Levitan

Acknowledged Federal Support: Y

Publication Type: Thesis or Dissertation

Institution: University of California, Berkeley

Date Received: 25-Aug-2017

Completion Date: 5/31/15 9:52PM

Title: Quantum Feedback and Traveling-wave Parametric Amplification in Superconducting Circuits

Authors: Christopher Macklin

Acknowledged Federal Support: Y

Publication Type: Thesis or Dissertation

Institution: University of California, Berkeley

Date Received: 25-Aug-2017

Completion Date: 1/1/17 6:56AM

Title: Engineering Dissipation to Generate Entanglement Between Remote Superconducting Quantum Bits

Authors: Mollie Kimchi-Schwartz

Acknowledged Federal Support: Y

RPPR Final Report
as of 19-Oct-2017

Nothing to report in the uploaded pdf (see accomplishments)