REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
31-05-2017	Final Report	1-Mar-2014 - 28-Feb-2017

4. TITLE AND SUBTITLE
Final Report: Scalable Readout of Superconducting Qubits with Novel Superconducting Amplifiers and Metamaterials

5a. CONTRACT NUMBER
W911NF-14-1-0080

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
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8. PERFORMING ORGANIZATION REPORT NUMBER

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)
64904-PH-OC.11

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Superconducting qubit performance has advanced rapidly in recent years with initial multi-qubit implementations leading towards surface code architectures. A truly scalable system requires the ability to perform rapid high-fidelity measurement of both single qubits and multi-qubit parity while minimizing required resources. In our project, we have been developing key tools for the readout of superconducting qubits to serve as building blocks of a scalable architecture. We have worked on utilizing the high bandwidth and large dynamic range of the SLUG amplifier to implement fast, high-fidelity multiplexed readout of up to ten qubits. We have also worked on a

15. SUBJECT TERMS
superconducting qubit, quantum measurement, quantum information

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Britton Plourde
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					315-443-8967

Report Title

Final Report: Scalable Readout of Superconducting Qubits with Novel Superconducting Amplifiers and Metamaterials

ABSTRACT

Superconducting qubit performance has advanced rapidly in recent years with initial multi-qubit implementations leading towards surface code architectures. A truly scalable system requires the ability to perform rapid high-fidelity measurement of both single qubits and multi-qubit parity while minimizing required resources. In our project, we have been developing key tools for the readout of superconducting qubits to serve as building blocks of a scalable architecture. We have worked on utilizing the high bandwidth and large dynamic range of the SLUG amplifier to implement fast, high-fidelity multiplexed readout of up to ten qubits. We have also worked on a readout approach based on microwave photon counting using the Josephson Photomultiplier, providing a natural path for interfacing with low-temperature digital control circuitry. We have worked to implement high-fidelity multi-qubit parity measurements and incorporate novel approaches for engineering cavity modes using metamaterial resonators.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
05/31/2017	6	Luke C. G. Govia, Frank K. Wilhelm. Coherent Feedback Improved Qubit Initialization in the Dispersive Regime, arXiv:1506.05339, (06 2015): 054001. doi: 365,514.00
05/31/2017	10	M. Schöndorf, L. C. G. Govia, M. Vavilov, R. McDermott, F. K. Wilhelm. Optimizing single microwave-photon detection: input-output theory, arXiv, ( ): . doi: 1,042,685.00
08/28/2015	2	Emily J. Pritchett, B. L. T. Plourde, Maxim G. Vavilov, R. McDermott, Luke C. G. Govia, Frank K. Wilhelm. Scalable two- and four-qubit parity measurement with a threshold photon counter, PHYSICAL REVIEW A , (08 2015): 22335. doi: 10.1103/PhysRevA.92.022335 365,505.00
08/28/2015	4	Luke C. G. Govia, Emily J. Pritchett, Canran Xu, B. L. T. Plourde, Maxim G. Vavilov, Frank K. Wilhelm, R. McDermott. High-fidelity qubit measurement with a microwave-photon counter, Physical Review A, (12 2014): 62307. doi: 10.1103/PhysRevA.90.062307 365,507.00
08/31/2016	7	Luke C. G. Govia, Frank K. Wilhelm. Entanglement generated by the dispersive interaction: The dressed coherent state, Physical Review A, ( ): 012316. doi: 1,016,782.00

TOTAL: 5

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL: **1**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Results have been presented by team members at US and International conferences and seminars. Over the 6-month period since our last annual report (Sept. 1, 2016) up to the final date of this project (Feb. 28, 2017), our team has given 4 talks and 4 poster presentations related to this project.

(invited) F. Wilhelm-Mauch, "You have a few qubits, now what?" – Int. Conference on Quantum Coherent Phenomena at Nanoscale, Petrovac, Montenegro, Sept. 4-9, 2016.

Caleb Howington, Matthew D. Hutchings, Guilhem Ribeill, Ivan Pechenezhskiy, Maxim G. Vavilov, Robert McDermott, Britton Plourde, "Qubit parity measurements with a Josephson Photomultiplier" – Applied Superconductivity Conference, 2016, Denver, CO.

(poster) Haozhi Wang, Matthew D. Hutchings, Francisco Rouxinol, Britton Plourde, Bruno Taketani, Frank K. Wilhelm, Sagar Indrajeet, Matthew LaHaye, "Coupling a Transmon Qubit to a Superconducting Metamaterial Resonator" – Applied Superconductivity Conference, 2016, Denver, CO.

M. Kaicher, "Scalable quantum simulation of multi-body interactions in linear time on a superconducting quantum architecture" – Int. Conference for Young Quantum Information Scientists, Barcelona, Spain, Oct. 19-21, 2016.

M. Schöndorf, "Nonlinear Parity readout with a microwave photon counter" – Int. Conference for Young Quantum Information Scientists, Barcelona, Spain, Oct. 19-21, 2016.

(poster) M. Schöndorf, "Nonlinear Parity Readout with a Microwave Photon Counter" – 635 Heraeus-Seminar, Bad Honef, Jan. 29-Feb. 1, 2017.

(poster) L. Theis, "Towards high-fidelity quantum gates using adiabatic techniques"
– 635 Heraeus-Seminar, Bad Honef, Jan. 29-Feb. 1, 2017.

(poster) M. Kaicher, "Scalable composition of many-qubit interactions with linear-size, logarithmic-depth circuits" – 635 Heraeus-Seminar, Bad Honef, Jan. 29-Feb. 1, 2017.

Number of Presentations: 8.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

08/28/2015 3.00 B. L. T. Plourde, Haozhi Wang, Francisco Rouxinol, M. D. LaHaye. Superconducting metamaterials and qubits,
SPIE Sensing Technology + Applications. 20-APR-15, Baltimore, Maryland, United States. : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

None to report from this period

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Overview
Our project has been focused on the development of novel superconducting amplifiers and metamaterials for scalable readout of superconducting qubits. Over the past three years, all team members have worked intensively on the project, as described below.

Syracuse (experimental)
Throughout the three-year period of this project, the Plourde group at Syracuse has worked with the Wisconsin experimental team, as well as the Wisconsin and Saarland theory teams, on the implementation of the new qubit readout protocol based on microwave photon detection with the Josephson PhotoMultiplier (JPM). This technique provides a high-fidelity readout of the qubit state in a cQED architecture with the potential for access to the digital information from the state readout in the cryogenic environment. The configuration of the JPM for this readout scheme has evolved over the course of the project, and the most recent implementation has achieved qubit readout fidelity better than 90% for JPMs that incorporate an on-chip photon-capture cavity. Throughout the project, the Plourde group has worked with the Wisconsin experimental team on various measurements related to the implementation of the JPM readout. In addition, the Syracuse team has performed the fabrication of a range of qubit and cavity devices for this readout project. The most recent devices contain two qubits coupled to a common readout cavity with qubit T1 values in the tens of microseconds and sufficiently strong qubit-cavity coupling to allow for chi-shifts of the order of 10 MHz for mapping the qubit state onto the cavity photon occupation.

Over the course of the project, the Plourde group at Syracuse has worked on the development of superconducting metamaterials for coupling to superconducting qubits. These structures involve lumped-element inductors and capacitors fabricated from superconducting Al and Nb thin films in a cQED architecture. These structures exhibit an unusual left-handed dispersion relation, with the wavelength growing for increasing mode frequency, as well as a dense mode spectrum. The mode separation can be less than 100 MHz in the typical frequency range for a tunable transmon qubit, which allows the qubit to be tuned through resonance with many different metamaterial modes. The Plourde group has been working with the Saarland theory team on a general description of the mode structure in these superconducting metamaterial transmission lines. This effort is based on laser scanning microscope (LSM) imaging measurements from the past year from the Ustinov group in Karlsruhe, Germany on one of the metamaterial devices fabricated in Syracuse, as well as numerical simulations of the microwave mode structure using Sonnet in Syracuse, and also solutions to the general circuit equations by the Saarland group. The team is currently finishing up a manuscript describing these efforts. The Syracuse group has performed a series of experiments investigating the rich pattern of interactions between metamaterial modes that are mediated by the presence of the qubit and the team is continuing to work with the Saarland theory group to model this behavior. The team plans to write up these qubit-metamaterial results in the coming year as well.

The Syracuse group has worked with the McDermott group in Madison throughout the project on the fabrication and testing of qubit-cavity devices for multiplexed SLUG readout. These devices have been designed for fast, multiplexed SLUG readout and most of the latest devices have incorporated grounded-style transmon qubits with on-chip flux-bias lines, similar to those used in the JPM readout efforts.

Wisconsin (experimental)
Over the course of this grant, the Wisconsin group has worked on two parallel approaches to high-fidelity qubit measurement, one based on ultralow noise linear amplification with the Superconducting Low-inductance Undulatory Galvanometer (SLUG) and one based on mapping the qubit state to bright and dark microwave cavity pointer states followed by subsequent photodetection with the Josephson photomultiplier (JPM).

In the SLUG effort, the Wisconsin team developed a novel theoretical framework for thinking about noise in overdamped Josephson junctions in terms of timing jitter of phase slips; this approach offers new insights into the noise properties of a wide range of Josephson devices. The team is finalizing a manuscript on this work and will submit to Physical Review in the coming weeks. On the experimental side, the team optimized the design and layout of the SLUG element and the SLUG die in order to enhance gain*bandwidth product and suppress spurious chip modes at the Josephson frequency. Working with the Syracuse team, they designed, fabricated, and characterized next-generation multiqubit chips for multiplexed SLUG readout. Among the strengths of the SLUG are its intrinsic nonreciprocity and absence of need for high power external pump tones to bias the device; these features make it possible to integrate the SLUG in a qubit measurement chain using a circuit that involves no cryogenic isolators or circulators. The Wisconsin team has performed a detailed theoretical and experimental study of SLUG reverse isolation and backaction. The team has integrated a SLUG amplifier in a qubit measurement chain that involves no commercial magnetic nonreciprocal elements and demonstrated high-fidelity qubit readout with no measurable degradation of qubit performance. This work is described in a recent posting to the arXiv (Thorbeck et al., arXiv:1705.01687); this manuscript is currently under review at Phys. Rev. Appl. Finally, at the request of ARO/LPS the team designed and fabricated high gain, ultralow noise SLUG amplifiers for quantum point contact readout at 1 GHz; a number of these devices were shipped to the group of David Reilly in Sydney.

On the JPM front, the Wisconsin group has worked with the rest of the team to develop and refine a protocol for high-fidelity single qubit measurement and measurement of multiqubit parity operators [Govia et al., PRA 90, 062307 (2014) and PRA 92, 022335 (2015)]. The team has implemented multiple generations of JPM circuits; with the latest generation, the team pursued a strategy of employing an on-chip capture resonator to mediate interaction of a flux-biased JPM with photons emitted from the qubit readout cavity. To date the Wisconsin-Syracuse collaboration has worked with a setup involving separate qubit and JPM chips connected with a coax line, which introduces unavoidable loss between the two chips. Nevertheless, in the most recent cooldown the team achieved single-shot qubit measurement fidelity of 92% using a qubit-JPM pair that were not ideally matched. Current work in this project is focused on an improved approach where the JPM and qubit are integrated on a single chip; the team expects to achieve qubit measurement fidelity in the high 90s with this scheme. Finally, the Wisconsin team has performed experiments to test the QNDness of JPM-based measurement; here, following a single measurement on a qubit superposition state, tomographic reconstruction of the qubit density matrix is performed and the extracted density matrix is correlated with the measurement result. The team finds that JPM-based measurement is highly QND and that repeated, high-fidelity JPM measurement is possible provided that the damping of the JPM itself is exploited to deplete photons rapidly from the capture resonator following qubit measurement. The latest generation JPM experiments will be described in detail in ~2 publications that we expect to submit in late summer/early fall of this year.

Wisconsin (theory)

The Wisconsin theory group included a postdoc Konstantin Nesterov and a student, Zhenyi Qi. The group worked on the estimation of the efficiency of the original design of the JPM coupled to a transmission line through an impedance-matching circuit element. They developed the input-output formalism for such a JPM coupled through a matching network to a transmission line, performed simulations of the measurement contrast for this system, and made a comparison of the contrast for the cases with and without the matching network. The group also developed a theoretical description of the JPM capture scheme, where an additional capture resonator is connected between the transmission line and the JPM device and the JPM is realized as a double-well potential in the phase variable of the JPM. The group then analyzed the ``same-chip'' JPM capture design with the JPM and qubit being on the same chip, formulated a theoretical model to characterize the coupling constant between the qubit and capture resonators and photon losses in this system.

The group was also studying the dynamics of the resonator coupled to a qubit and driven by a microwave field. They developed the code to calculate the evolution of the state of such a system, analyzed effects of multiple anharmonic levels in a qubit. The group focused on studies of effects beyond the dispersive limit on the pointer-state preparation and calculated the fidelity of the pointer-state preparation. They explored the optimization of the pointer state preparation through application of varying frequency microwave drive of the qubit resonator and demonstrated that properly chosen time-dependent frequency of the drive can greatly improve pointer states contrast. The group also analyzed the effects of the measurement on the qubit state, including the QNDness of the measurement.

The Wisconsin theory team developed a theoretical description of tunable dissipators coupled to microwave resonators. They studied the optimal relations between dissipator losses, its coupling strength and frequency detuning for fast relaxation of the resonator to its vacuum state. They also considered the non-linearity of the resonator due to its coupling to the qubit and evaluated the decoherence of the qubit due to the photon shot noise in the resonator.

Saarland (theory)

Research of the Saarland group has covered the JPM and metamaterials. In the area of JPM measurement, the Wilhelm group has applied full input-output theory to describe the continuous wave as well as the pulsed response [Schöndorf et al., arXiv: 1609.08887]. The team has found a simplified ideal matching criterion for weak continuous waves that gets modified for shorter pulses due to their higher instantaneous amplitude. They have extended this work to non-linear driving, an effort that is ongoing.

The Saarland team has also developed a full semiclassical theory (i.e., treating radiation classically) of single qubit and multi-qubit parity measurement [Govia et al., Phys. Rev. A 92, 042333 (2015); Govia et al. Phys. Rev. A 90, 062307 (2014)]. A specific challenge arises from the precision requirements of quantum computing already on the level of faithfully performing the dispersive transformation - independent of the actual measurement protocol for the photons - which the Saarland group has addressed using the tool of dressed coherent states [Govia & Wilhelm, Phys. Rev. A 93, 012316 (2016); Govia & Wilhelm, Phys. Rev. Applied 4, 054001 (2015)]. This also has consequences for the fast preparation of dispersive states [Theis & Wlhelm, Phys. Rev. A 95, 022314 (2017)].

In the area of metamaterials, the Saarland group has collaborated with the Syracuse team. The group has converted all of their closed-cavity mode calculations to transmission calculations, including proper broadening. They have explored ways to design an optimal metamaterial filter for parity measurements [Stefan Ruloff, MSc, February 2017] and they have also developed a scheme to create cluster states by illuminating a Josephson metamaterial with a microwave frequency comb [Anette Messinger, MSc, February 2017].

In addition to the two Masters theses listed above, Luke Govia completed his PhD in 2015 in the Saarland group and postdoc Dr. Bruno G. Taketani, has obtained a faculty position at the Universidade Federal de Santa Catarina in Florianopolis, Brazil.

Personnel: Sept. 1, 2016 - Feb. 28, 2017 (unable to enter information in personnel section)

Faculty:
Britton Plourde (Syracuse University) 0
Robert McDermott (University of Wisconsin) 0
Maxim Vavilov (University of Wisconsin) 0
Frank Wilhelm (University of Saarland) 0.1

Graduate students:
Caleb Howington (Syracuse University) 0.45
Michael Kaicher (University of Saarland) 0.87
Marius Schöndorf (University of Saarland) 1.00
Peter Schuhmacher (University of Saarland) 0.50
Lukas Theis (University of Saarland) 0.50
Haozhi Wang (Syracuse University) 0.45

Postdocs:
Matthew Hutchings (Syracuse University) 0.66
Konstantin Nesteov (University of Wisconsin) 0.15
Ivan Pechenezhskiy (University of Wisconsin) 0.17

Undergraduates:
Sam Carman (University of Wisconsin) 0.04
Nicholas Dupuis (University of Wisconsin) 0.11
Noah Meltzer (University of Wisconsin) 0.02
Anette Messinger – M.S. (University of Saarland) 0.75
Stefan Ruloff – M.S. (University of Saarland) 0.75
Jonathan Stensberg (University of Wisconsin) 0.08
Eric Walsh (University of Wisconsin) 0.01

Technology Transfer

None to report from this period