AFRL-AFOSR-VA-TR-2023-0207

Wiring Quantum Networks with Mechanical Transducers

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11/28/2022
Final Technical Report

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED	
20221128	Final	START DATE 20141201	END DATE 20220614

4. TITLE AND SUBTITLE
Wiring Quantum Networks with Mechanical Transducers

5a. CONTRACT NUMBER	5b. GRANT NUMBER	5c. PROGRAM ELEMENT NUMBER
	FA9550-15-1-0015	61102F
5d. PROJECT NUMBER	**5e. TASK NUMBER**	**5f. WORK UNIT NUMBER**

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Air Force Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203	AFRL/AFOSR RTB1	AFRL-AFOSR-VA-TR-2023-0207

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
central challenge for realizing large-scale quantum processors is the design and realization of qubit-qubit connectivity. On the one hand, these connections need to be strong enough to enable fast two-qubit gates, while on the other hand, they must be well-confined between modes to avoid extra loss and cross-talk errors. Finally, the scaling to larger systems is greatly simplified if the connections are "detachable" in some way, so that different parts of the processor can be built/tested/replaced individually. The completed work advanced these competing goals using modular reconfigurable microwave networks.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	UU	6

19a. NAME OF RESPONSIBLE PERSON	19b. PHONE NUMBER *(Include area code)*
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Accomplishments

The main objectives of the work were to develop methods to create and test networks of superconducting modular quantum registers, whose connectivity could be dynamically reconfigured. Modules in this context mean high-quality microwave cavities used to store quantum information, and any other elements necessary to control, readout, and communicate the quantum state these stored states. The modules are networked by connecting them to microwave transmission lines or waveguides. A related set of goals sought to develop switches which could isolate and connect different regions of the network.

The primary disseminated accomplishments were
1.) the demonstration of a high-fidelity quantum router based on parametric coupling using so-called SNAIL elements and extended waveguide modes. Universal quantum control over the state of 4 module network was shown via this router.
2.) the demonstration and characterization of error detected quantum state transfer between two modules through a transmission line.
3.) the demonstration and characterization of efficient low-backaction qubit readout without circulators by exploit fast microwave switches.

In addition to these: work progressing towards publication shows a higher fidelity method to entangle remote modules using joint dissipation and cat encoded quantum states, and a high quality interface between 3-dimensional cavities and planar transmission lines using fast switches. Furthermore, two cavities can be coupled through the fast switches. This last item was an explicit goal of the initial proposal which was not completed during the project period.

- How were the results disseminated to communities of interest? If there is nothing significant to report during this reporting period, state “Nothing to Report.”

Results have been disseminated through publications and presentations by project personnel. The major publications or preprints are:

Efficient and Low-Backaction Quantum Measurement Using a Chip-Scale Detector Rosenthal E.I., C.M.F. Schneider, M. Malnou, Z. Zhao, F. Leditzky, B.J. Chapman, W. Wustmann, X. Ma, D.A. Palken, M.F. Zanner, and L.R. Vale, Physical Review Letters **126**, (2021).
https://dx.doi.org/10.1103/physrevlett.126.090503

"Error-Detected State Transfer and Entanglement in a Superconducting Quantum Network," Luke D. Burkhart, James D. Teoh, Yaxing Zhang, Christopher J. Axline, Luigi Frunzio, M.H. Devoret, Liang Jiang, S.M. Girvin, and R.J. Schoelkopf
PRX Quantum **2**, 030321 (2021).
https://doi.org/10.1103/PRXQuantum.2.030321

"A modular quantum computer based on a quantum state router," Chao Zhou, Pinlei Lu, Matthieu Praquin, Tzu-Chiao Chien, Ryan Kaufman, Xi Cao, Mingkang Xia, Roger Mong, Wolfgang Pfaff, David Pekker, Michael Hatridge, arXiv:2109.06848
https://doi.org/10.48550/arXiv.2109.06848

In addition, the work was the primary topic of Eric Rosenthal's PhD.
Efficient and Low-Backaction Quantum Measurement Using a Chip-Scale Detector, University of Colorado, PhD. 2021.

Impacts

Development of the principal discipline(s) of the project

A central challenge for realizing large-scale quantum processors is the design and realization of qubit-qubit connectivity. On the one hand, these connections need to be strong enough to enable fast two-qubit gates, while on the other hand, they must be well-confined between modes to avoid extra loss and cross-talk errors. Finally, the scaling to larger systems is greatly simplified if the connections are "detachable" in some way, so that different parts of the processor can be built/tested/replaced individually. The completed work advanced these competing goals using modular reconfigurable microwave networks.

Other disciplines:

Insights from this research have influenced the search for dark matter. Specifically, the physically remote parametric couplings developed here appear to have application to improved quantum enhanced metrology in searches for axionic dark matter as seen here:

Cavity Entanglement and State Swapping to Accelerate the Search for Axion Dark MatterK Wurtz., B.M. Brubaker, Y. Jiang, E.P. Ruddy, D.A. Palken, and K.W. Lehnert, Prx Quantum 2, 040350 (2021).

https://dx.doi.org/10.1103/prxquantum.2.040350

Bandwidth and visibility improvement in detection of a weak signal using mode entanglement and swapping Yue Jiang, Elizabeth P. Ruddy, Kyle O. Quinlan, Maxime Malnou, Nicholas E. Frattini, Konrad W. Lehnert; arXiv:2211.10403.

https://doi.org/10.48550/arXiv.2211.10403

Describe the impact in this reporting period on the development of human resources

The project trained 6 PhD students in critical question in quantum computing. It exposed undergraduates to impactful highly relevant quantum engineering research.

Describe the impact on teaching and educational experiences

nothing to report

Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.

nothing to report

Impact on society beyond science and technology:

nothing to report

Changes

Changes in approach
Nothing to report

Problems or delays
All components of the project were delayed and disrupted by the pandemic. Perhaps related, the switch portion of the work was delayed, with research goals still in progress due to the failure of the Josephson junction fabrication process. The failure mode has since been identified and fixed.

Expenditure Impacts
Pandemic driven delayed hiring of graduate students led to some non-uniformity in spending.

Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards
nothing to report.

Changes to the primary place of performance from that originally proposed
nothing to report.

Technical Updates

The figures summarize the concepts developed as part of this research.

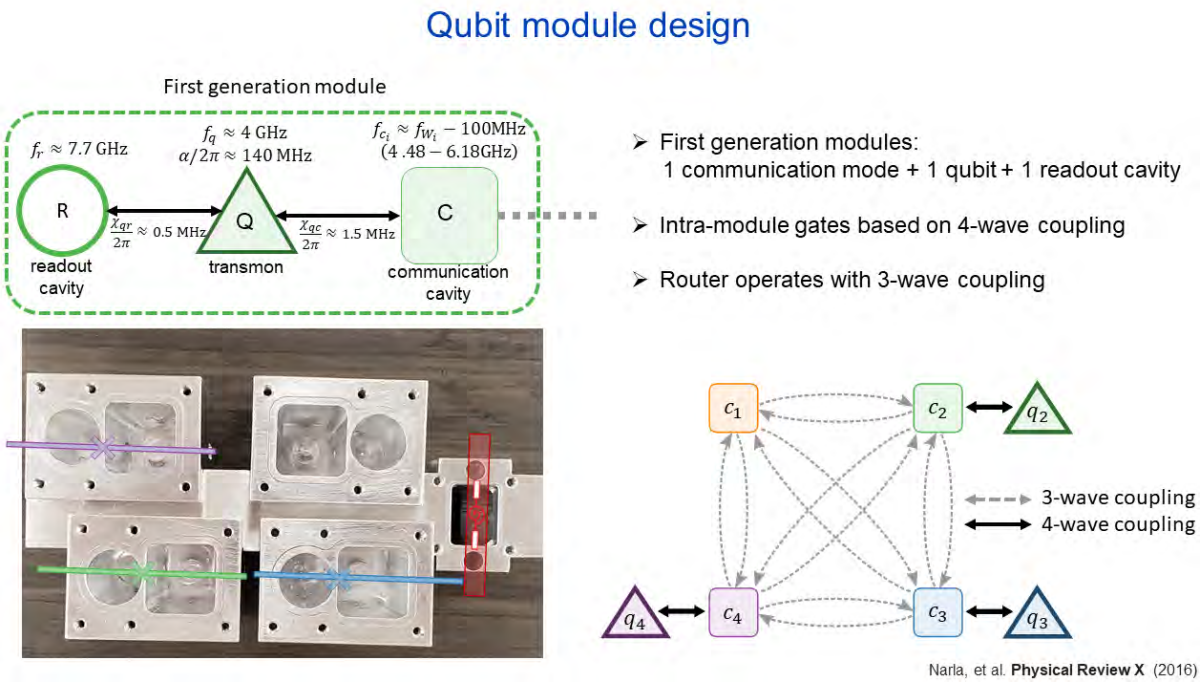
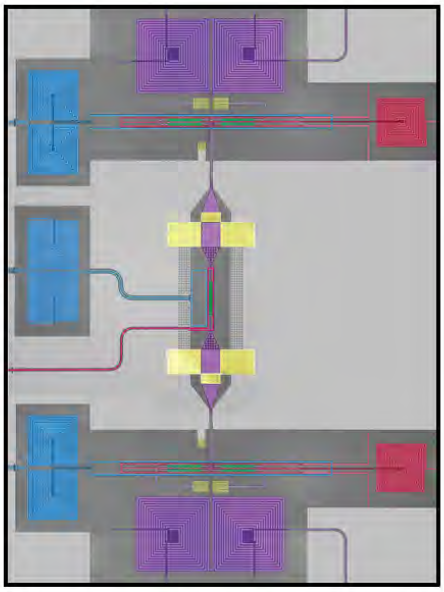


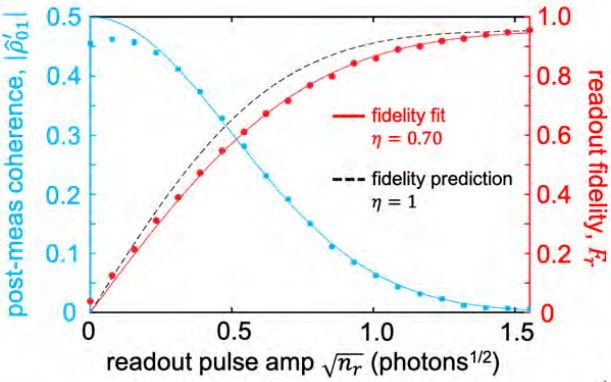
Figure 1: A summary of the parametric router concept and a 4-qubit implementation. A universal gate set is demonstrated in this architecture.

Scalable, efficient and low-backaction readout using a SIMBA



E.I. Rosenthal *et al.*, PRL **126**, 090503 (2021)

Parameter	Value
meas efficiency	$\eta = 70 \pm 1\%$
excess backaction	$n_b = 0.66 \pm 0.01$
max readout fidelity	$F_0 = 95.5 \pm 0.3\%$
meas time	265 ns



JILA

Figure 2: An image of the high-speed losses switches integrated with parametric amplifiers developed as part of this work and a summary of their performance in qubit readout using no circulator elements.

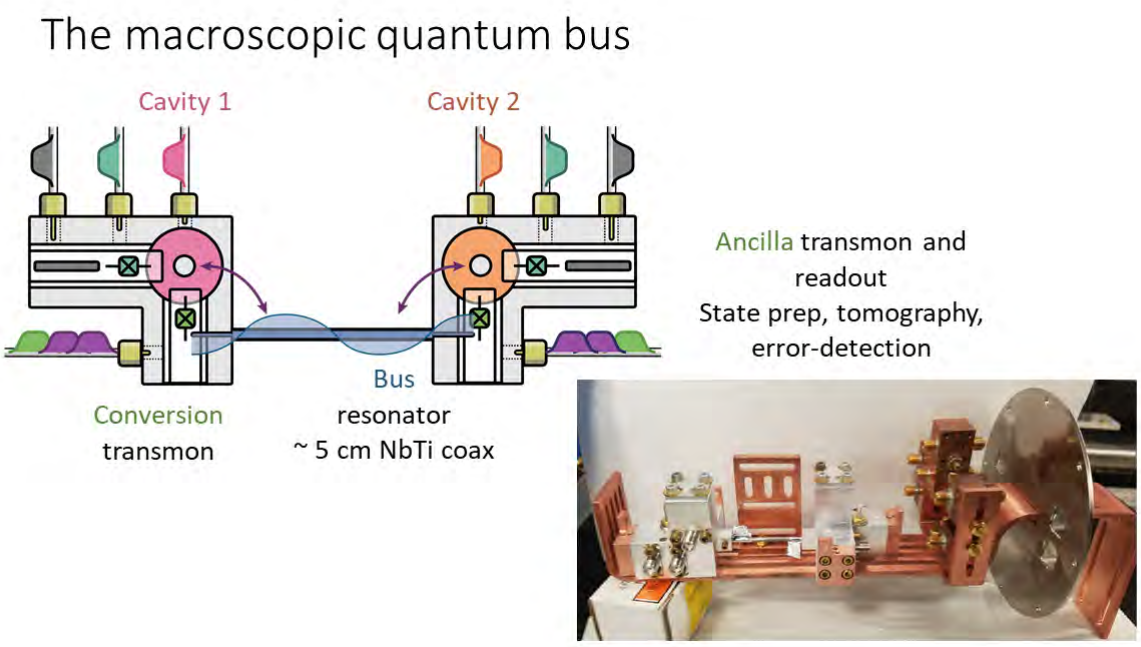


Figure 3: Quantum bus joining two modules through a superconducting microwave transmission, used to test schemes for error-detected and loss protected quantum communication between modules. Note that the modules can be demounted as units from the cable bus.