AFRL-AFOSR-VA-TR-2021-0046

Controlling propagation and entanglement of multi-photon quantum states by driven

Chen Wang
MASSACHUSETTS UNIV AMHERST MA
70 BUTTERFIELD TERRACE
AMHERST, MA,
US

06/10/2021
Final Technical Report

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

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
10-06-2021

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
01 Jan 2018 - 31 Dec 2020

4. TITLE AND SUBTITLE
Controlling propagation and entanglement of multi-photon quantum states by driven

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-18-1-0092

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Chen Wang

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MASSACHUSETTS UNIV AMHERST MA
70 BUTTERFIELD TERRACE
AMHERST, MA
US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB1

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-VA-TR-2021-0046

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Dissipation engineering, which tailors the interaction between a quantum system and the environment bath, has been a valuable tool for stabilizing interesting states for quantum information technology. In this project, we develop techniques to generate more sophisticated nonlinear dissipation operators in superconducting circuit quantum electrodynamics (cQED) for autonomous and efficient control or preservation of multi-photon logical qubits.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT	b. ABSTRACT	c. THIS PAGE		
U	U	U	UU	7

19a. NAME OF RESPONSIBLE PERSON
GRACE METCALFE

19b. TELEPHONE NUMBER *(Include area code)*
(703) 696-9740

Standard Form 298 (Rev.8/98)
Prescribed by ANSI Std. Z39.18

AFOSR Grant No: FA9550-18-1-0092

Final Report

(YIP) Controlling propagation and entanglement of multi-photon quantum states by driven dissipation

Principle Investigator: Chen Wang

Institution: University of Massachusetts, Amherst

AFOSR Program Manager: Grace Metcalfe

Date: 2021/3/31

Reporting period: 2018/1/1 – 2020/12/31

Abstract

Dissipation engineering, which tailors the interaction between a quantum system and the environment bath, has been a valuable tool for stabilizing interesting states for quantum information technology. In this project, we develop techniques to generate more sophisticated nonlinear dissipation operators in superconducting circuit quantum electrodynamics (cQED) for autonomous and efficient control or preservation of multi-photon logical qubits.

The main accomplishment under this project is an experimental demonstration of an autonomous quantum error correction (AQEC) algorithm using continuous dissipation for the first time to our knowledge (Nature 2021). We realized a synthetic dissipation operator – Parity Recovery by Selective Photon Addition (PReSPA) – for microwave photons in a superconducting cavity. Applying this new dissipative process to a Schrodinger-cat-like multiphoton qubit encoded in the cavity, we autonomously correct the dominant physical error – single photon loss – in a passive fashion, boosting the quantum information storage time by over a factor of two. This demonstration positions dissipation engineering as a resource-efficient alternative or supplement to active QEC in future quantum computing architectures.

We also studied dissipation engineering across two distinct superconducting cavity modes. We realized a joint-cavity two-photon loss operator that takes away one photon each from the two high-Q superconducting cavities simultaneously. Preliminarily, we are able to combine this dissipation with two-photon drives to stabilize a pair-coherent state, which is an interesting state in quantum optics context and the basis for multi-cavity AQEC encodings. This research remains ongoing at the conclusion of this project.

In addition, we completed a theoretical work (Phys. Rev. Research 2019) introducing a new functionality of dissipation engineering – autonomous quantum state transfer (AQST). Under the right dissipation condition, quantum information can spontaneously propagate (directionally) from one subsystem to another, with unit fidelity, without using time-dependent control.

Program Objective:

Dissipation engineering has attracted growing interest as a valuable tool for quantum information technology. Past research focused on stabilizing specific quantum states using relatively simple quantum dissipation operators. In this project, we develop techniques to generate more sophisticated nonlinear dissipation operators, with the goal of building and expanding the toolbox of autonomous dissipation for resource-efficient control or preservation of logical qubits for quantum computation tasks.

Scientific Approach:

In this project, we focus on multi-photon bosonic quantum states in 3D superconducting microwave cavities. These cavities, with their long lifetimes and the availability of quantum control using Josephson qubits as ancillas, are a promising storage media for encoding error-correctable logical qubits. More specifically, we use parametric four-wave mixing processes between long-lived storage cavities and lossy reservoirs to engineer exotic dissipation operators acting on the cavity states. The targeted dissipation operators in the proposed research include various first- or second-order combination of photon annihilation operators in two cavity modes. The steady state manifolds arising from these dissipation operators are separable or entangled Schrodinger cat states across two cavities, which are the basis states for a class of bosonic quantum error correction codes.

Changes to originally proposed work:

The originally proposed work primarily focuses on implementing driven dissipation across two superconducting cavity modes. After we engineered and improved a two-cavity device over several iterations, a new exciting opportunity arose for us to implement a highly-specific single-cavity dissipation operator which can autonomously correct the dominant single-photon-loss errors in logical qubits. We decided to shift focus and repurpose our existing device and measurement hardware for this study which has been the main focus for the second half of the project. The end result was the first demonstration of an autonomous quantum error correction (AQEC) algorithm using driven dissipation.

Personnel supported by AFOSR project:

PI: Chen Wang (partial summer support)

Graduate students: Jeffrey M. Gertler, Shruti Shirol (since 2020), Dario Rosenstock (summer 2018)

Postdoc: Juliang Li (2018/11-2019/10, partial support)

Publications:

(1) Jeffrey M. Gertler, Brian Baker, Juliang Li, Shruti Shirol, Jens Koch and Chen Wang, Protecting a bosonic qubit with autonomous quantum error correction, *Nature* **590**, 243 (2021)

(2) Chen Wang and Jeffrey M. Gertler, Autonomous Quantum State Transfer by Dissipation engineering. *Phys. Rev. Research* **1**, 033198 (2019).

Presentations:

1. Chen Wang and Jeffrey M. Gertler, Directional quantum state transfer by dissipation I – Conceptual overview, APS March Meeting 2019, E26.04.

2. Jeffrey M. Gertler and Chen Wang, Directional quantum state transfer by dissipation II – Implementation in circuit QED, APS March Meeting 2019, E26.05.

3. Chen Wang, Autonomous quantum state transfer by dissipation, Condensed Matter seminar, University of Massachusetts, Amherst, April 2019.

4. Juliang Li, Jeffrey Gertler and Chen Wang, Engineering nonlinear dissipation across two super-conducting cavity modes, CEC-ICMC 2019 (International cryogenic engineering and cryogenic materials conference), July 2019.

5. Chen Wang, Autonomous quantum state transfer by dissipation, iQUISE seminar, Massachusetts Institute of Technology, October 2019.

6. Chen Wang, Dissipative quantum error correction of single photon loss in a bosonic qubit, Byron Bay Quantum Workshop (virtual 2020 BBQ), November 2020.

7. Chen Wang, Autonomous quantum error correction of a bosonic qubit with dissipation engineering, Virginia Tech Physics seminar, November 2020.

8. Shruti Shirol, Jeffrey Gertler, Brian Baker, Juliang Li, Jens Koch and Chen Wang, Protecting a bosonic qubit with autonomous quantum error correction I: Parity Recovery by Selective Photon Addition (PReSPA), APS March Meeting 2021, C34.10.

9. Jeffrey Gertler, Brian Baker, Juliang Li, Shruti Shirol, Jens Koch and Chen Wang, Protecting a bosonic qubit with autonomous quantum error correction II: AQEC results, APS March Meeting 2021, C34.11.

10. Chen Wang, Autonomous quantum error correction in a bosonic qubit with dissipation engineering, C^2QA (Co-design Center for Quantum Advantage) colloquium, March 2021.

11. Chen Wang, Protecting a bosonic qubit with autonomous quantum error correction, Unitary Fund invited guest talk, March 2021.

Awards:

Chen Wang: 2020 IOP International Quantum Technology Young Scientist Award – “Highly Commended” (a top 5 finalist)

Summary of major accomplishments during project:

I. Protecting a multi-photon qubit with autonomous quantum error correction (AQEC)

Existing demonstrations of quantum error correction (QEC) are based on a schedule of discrete error syndrome measurements and adaptive recovery operations. These active routines are hardware intensive, prone to introducing and spreading errors, and eventually expected to consume a huge majority of the computation power in a large-scale quantum computer. While QEC is inspired by classical active error correction, notably, robustness in classical computing is primarily accomplished by passive dissipation which acts as a restoring force against environmental perturbation. Its elusive quantum counterpart – autonomous/dissipative quantum error correction (AQEC) – is without doubt a central goal for quantum dissipation engineering. Although stabilization of a quantum manifold with phase-space separation has been demonstrated recently using two-photon driven dissipation, it has remained challenging to achieve the specific form of dissipation required to counter the most prominent errors in a physical system.

In this experiment, we encode a logical qubit in Schrödinger cat-like multiphoton states in a superconducting cavity, and demonstrate a corrective dissipation operator that we call Parity Recovery by Selective Photon Addition (PReSPA):

$$\Pi_{eo} = |1\rangle\langle 0| + |3\rangle\langle 2| + |5\rangle\langle 4| + |7\rangle\langle 6|$$

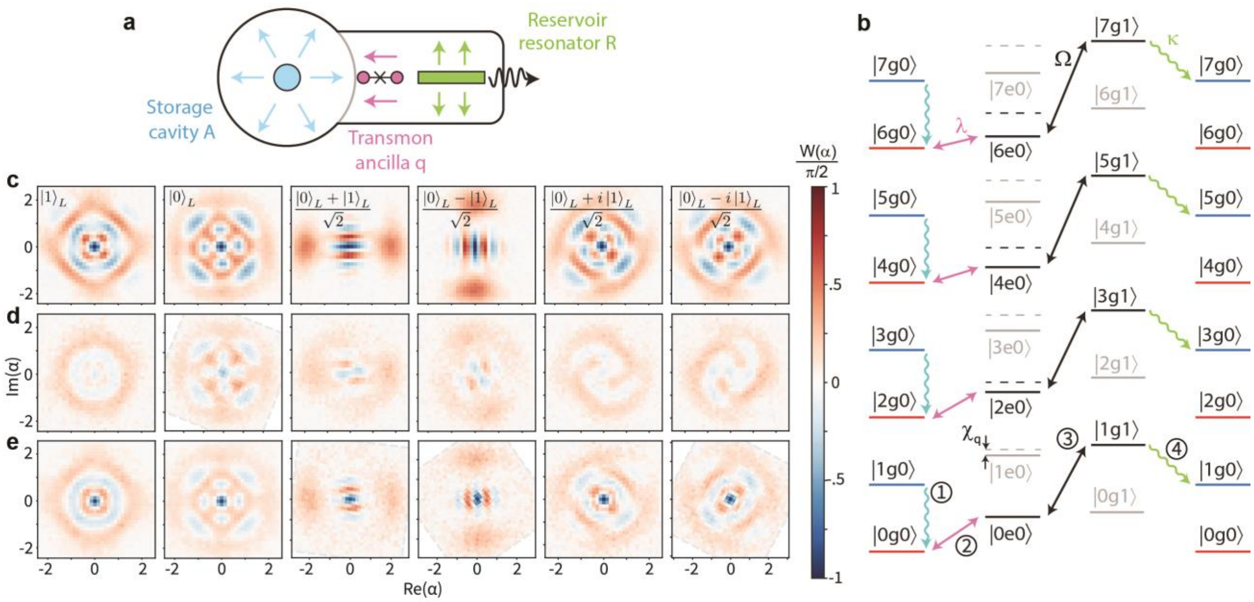

Fig. 1. Experimental demonstration of autonomous quantum error correction against single-photon loss using PReSPA. (a) Schematic of the circuit QED device composed of storage cavity A, transmon ancilla q and reservoir resonator R. (b) AQEC illustrated in a level diagram, with the level indices refer to the quantum Fock states of A, q and R, sequentially. A continuous-wave 'transmon comb' is applied to resonantly excite the transmon ancilla with a Rabi rate λ (magenta arrows), selectively targeting the four even-parity states (red levels). A continuous-wave 'mixing comb' targets the $|2n, e, 0\rangle \leftrightarrow |2n+1, g, 1\rangle$ transitions with an equal Rabi rate Ω (black arrows). Spontaneous decay of the reservoir R converts the quantum state back to the code space (blue levels) without leakage of which-path information. (c-e) Cavity Wigner tomography for the six cardinal-point logical states. We measure the states at t = 0 (c), after 143 μs of free evolution (d) and after 143 μs of AQEC using PReSPA (e). The center points of the Wigner function show a measurement of state parity, which is well preserved under PReSPA.

Our logical qubit is represented by odd-parity superposition states, and a single-photon loss (the dominant error in superconducting cavities) flips the cavity state into the even-parity subspace. This engineered dissipation stabilizes the corresponding error-syndrome operator: the photon number parity. Implemented with continuous-wave control fields only, this passive protocol protects the quantum information by autonomously correcting single-photon-loss errors and boosts the coherence time of the bosonic qubit by over a factor of two (from 130 μs to 288 μs). Notably, QEC is realized in a modest hardware setup with neither high-fidelity readout nor fast digital feedback, in stark contrast to the technological sophistication required for prior QEC demonstrations. Compatible with additional phase-stabilization and fault-tolerant techniques, our experiment suggests quantum dissipation engineering as a resource-efficient alternative or supplement to active QEC in future quantum computing architectures. For more details, please see publication (1).

II. Theory of autonomous quantum state transfer (AQST) by dissipation engineering

Quantum state transfer in a closed quantum system requires precisely-timed control of coherent qubit-qubit interactions that are intrinsically reciprocal. In this theoretical work, we show that by breaking reciprocity using dissipation in an open system, it is possible to autonomously transfer a quantum state between stationary qubits without time-dependent control, i.e. the "free" evolution of a two-qubit state follows:

$$|\psi\rangle_A|\text{vac}\rangle_B \rightarrow |\text{vac}\rangle_A|\psi\rangle_B, \quad |\text{vac}\rangle_A|\psi\rangle_B \rightarrow |\text{vac}\rangle_A|\psi\rangle_B$$

where $|\psi\rangle$ is a logical qubit to be transferred, and $|\text{vac}\rangle$ represents a pre-defined state void of information. This is an example of using dissipation engineering to implement a non-trivial quantum process on (and not just stabilizing) a manifold of quantum states while preserving quantum information.

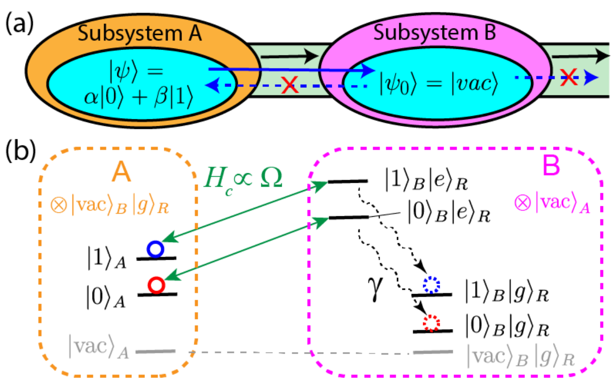

Figure 2. A conceptual diagram of AQST, where an encoded quantum state $|\psi\rangle$ is spontaneously emitted from a subsystem A and fully absorbed by a subsystem B. This is realized via an symmetric coupling channel which is blind to $|\psi\rangle$. (b) Basic construction of AQST using a reservoir mode R. The two dashed boxes encloses quantum states with information stored in A (orange) and in B (magenta) respectively.

We showed that the minimum system dimension for autonomous transfer of one qubit of information is 3×2 (between one physical qutrit and one physical qubit), plus one auxiliary reservoir. We provided the general requirements and strategies for realizing such state transfer and discussed its underlying connection to AQEC. For more details, please see publication (2). The strategies and analysis of the degenerate Raman processes used for AQST directly inspired the PReSPA operator that we use to demonstrate AQEC as discussed above.

We further devised a cQED experiment that can implement this proposed transfer scheme between a transmon qutrit and a superconducting cavity. We have designed, fabricated, and performed initial testing of a first generation of device suitable for demonstrating AQST in circuit QED. However, we did not further pursue experimental progress due to our priority given to the AQEC experiment.

III. Implementation of cross-cavity two-photon driven dissipation (to be completed)

Two-photon driven dissipation, which adds or subtracts photons in pairs, can be used to confine multiphoton states in a quantum manifold spanning distant regions in the phase space of oscillators. This offers protection against phase noise for quantum information tasks. While it does not lead to corrections against parity-flip errors (as we achieved with PReSPA in Part I), it does not perturb the photon number parity and hence the encoded information under parity-based QEC codes. Previous experiments have demonstrated the two-photon dissipation operator $\hat{L} = \hat{a}^2 - \alpha^2$ for a single cavity, which stabilizes a single-mode Schrodinger cat state manifold with exponential suppression of phase flip between the $|\pm\alpha\rangle$ states. Expanding the two-photon dissipation toolbox towards multiple photonic modes is not only pertinent to entanglement and logical operations between single-mode bosonic qubits, but also forms the basis for two-mode QEC codes such as the pair-cat code.

In this experiment, we demonstrate a cross-cavity two-photon dissipation operator in circuit QED. This jump operator, $\hat{L} = \hat{a}\hat{b} - \alpha^2$, adds or takes away one photon each from two high-Q superconducting cavities (with annihilation operators $\hat{a}$ and $\hat{b}$) simultaneously. We realize this process by activating a different four-wave mixing process (at a pump frequency $\omega_p = \omega_a + \omega_b - \omega_r$), which converts one photon each from Alice and Bob into a photon in the reservoir, together with a weak reservoir displacement drive. In the absence of single photon loss, this driven dissipation stabilizes the so-called pair-coherent state $|\psi\rangle_{ab} = \sum_n P_n |n\rangle_A |n\rangle_B$, where the photon numbers in two cavities are uncertain but always equal. Preliminarily, we show this correlation of photon numbers in transmon spectroscopy (Fig. 3), and are in the process of proving the coherence in this state using joint-cavity tomography.

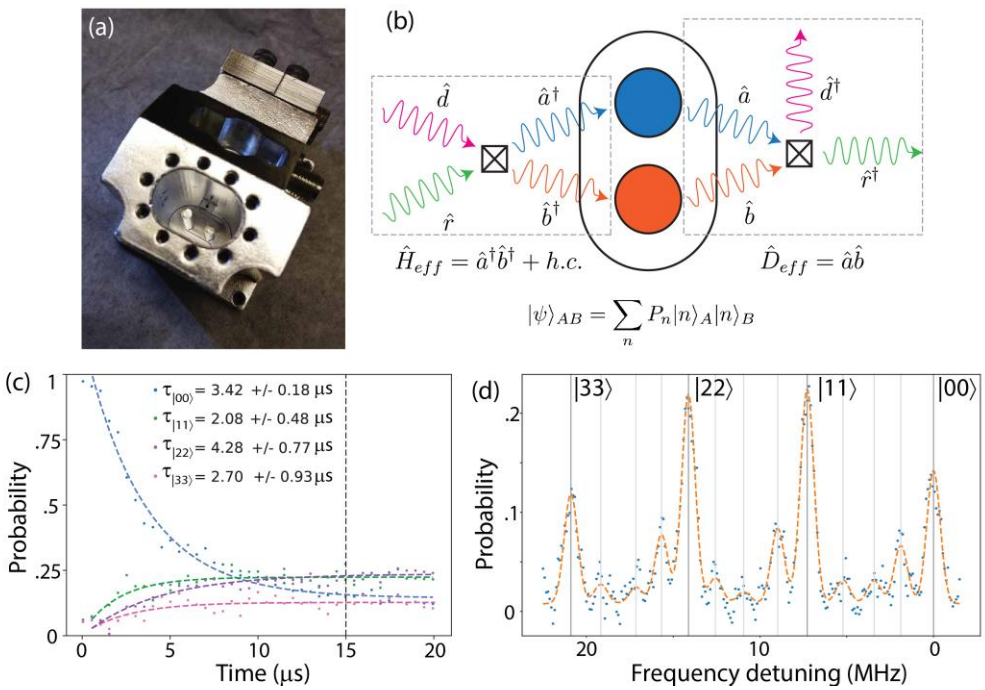

Figure 3. Demonstration of cross-cavity two-photon dissipation. (a) A photograph image of the 3D cQED device with two quantum memory cavity modes defined by the two posts inside the elliptical cylinder. (b) A schematic of the four-wave-mixing activated cross-cavity two-photon drive and dissipation, realizing a combined dissipation operator $\hat{L} = \hat{a}\hat{b} - \alpha^2$. (c) Measured probability of $|00\rangle, |11\rangle, |22\rangle, |33\rangle$ for the two-cavity quantum state after applying $\hat{L}$ to a vacuum state over time. The cavities convergence to a steady state over a time scale of about 3μs, much faster than the single photon lifetimes in the cavities (~300 μs). (d) Measurement of joint-cavity photon number distribution (as probed by spectroscopy of ancilla transmon) after applying $\hat{L}$ to a vacuum state.

Actual Project Timeline and Technical Milestones:

2018/01-2018/10 – Laboratory infrastructure set up: We installed and wired up our dilution fridge after moving the lab into a new building facility; we integrated the cryogenic and room temperature hardware system and quantum control software platform for complex superconducting circuit QED experiments; we developed a working recipe to fabricate transmon qubits locally.

2018/01-2018/10 – Theoretical progress in dissipative quantum control: We completed and submitted the first draft of the autonomous quantum state transfer (AQST) manuscript, and numerically modeled a directional transfer protocol for cat states between cavities using two-photon loss. The AQST theory later went through a substantial extension and further revision over the first half of 2019 to include remote state transfer protocols.

2018/11-2019/08 – Device Fabrication and cryogenic setup improvements: Over 3-4 fabrication cycles and 4-5 fridge cool down cycles we were able to improve the coherence times of our transmon qubit and aluminum cavities to $T_{1q} \approx T_{2Eq} \approx 30\ \mu s,\ T_{1A} \approx T_{2A} \approx 400 \mu s$ respectively, and reduced the excited state populations to ~3% level from much worse values year ago, primarily via improved device thermalization. We also integrated travelling wave parametric amplifiers (TWPA) into the setup for faster readout.

2019/06-2019/08 – Preliminary runs of joint-cavity two-photon dissipation: We obtained some preliminary results demonstrating extraction of photon pairs from two cavities and measured the two-photon loss rate.

2019/08-2020/05 – Demonstration of autonomous quantum error correction: We developed a theoretical protocol of autonomous quantum error correction (AQEC) against single-photon loss, which is suitable for a relatively standard 3D circuit QED device as we already have for the two-photon dissipation experiment. We immediate tested the protocol and carried out the full demonstration on the existing device, and completed and submitted the first draft of the manuscript on AQEC. The manuscript went through revisions over the second half of 2020.

2020/06-2020/12 – Towards demonstration of pair-coherent state using two-photon driven dissipation: We continued work on the two-photon dissipation, and were able to combine it with two-photon drive and two-mode Wigner tomography protocols. We have preliminarily shown that the cavity state converges (before single photon loss sets in) to a pair coherent state with an average photon number of about 2 in each mode. This work has been impacted by the pandemic slowdown and a set-back in our qubit coherence properties. We are continuing on this measurement even though the project has ended.