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RPPR Final Report
as of 17-Jun-2022

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Major Goals: The general objective of the proposed project is to create and demonstrate a fully-functional cQED device (a coherent cavity-qubit coupled system with universal quantum control and readout) that includes nonreciprocal interaction between two or more of its internal quantum components.

To realize such a device, much of the effort is focused on a critical intermediate goal of engineering a low-loss directional transmission channel between two localized qubit or cavity modes. This directional channel is implemented by a waveguide Y-junction style circulator with single crytalline YIG. Distinct from other cQED experiments ubiquitously using a commercial ferrite circulator (for readout), this project aims to "quantize" the circulator. We include its magnon and cavity mode structures, its coupling to the transmission line, etc. in the quantum description of the full cQED system.

As an important application of the proposed non-reciprocal cQED, we envision a cQED device architecture composed of quantum modules with hierarchies, where a lower-tier module can transfer its quantum state to an upper-tier module with high fidelity while maintaining excellent reverse isolation. We will aim to demonstrate a block of this architecture and realize directional quantum state transfer between modules.

Accomplishments: Over the past few years, there has been rising interest in non-reciprocal phenomena in the quantum regime. However, the form of demonstrated non-reciprocal interactions has been limited to the exchange of quantum excitations between linear modes, such as transmission of photons or phonons. These linear non-reciprocal systems are in the correspondence limit of classical dynamics and can be effectively described by a non-Hermitian Hamiltonian.

Superconducting circuit QED provide opportunities where two-level systems can interact with each other or with linear modes in an open-system quantum optics setting, giving rise to new non-reciprocal phenomena with no classical correspondence.

This project is a step towards building a non-reciprocal circuit QED platform by integrating ferromagnetic magnon modes, which allows superconducting qubits and cavities to be coupled in a fully or partially directional manner with high quantum efficiency (i.e. low loss). Such low-loss non-reciprocal interactions enables the study of circuit QED in a regime incorporating time-reversal-symmetry breaking and engineered dissipation, and this paradigm of non-reciprocity may facilitate high-fidelity quantum state transfer and low-crosstalk modularization of a quantum processor.

RPPR Final Report
as of 17-Jun-2022

The main accomplishments under this project are:
1) We demonstrated a low-loss ferrite circulator device as an in-situ tunable chiral quantum system. The circulator is integrated with superconducting cavities at a modest magnetic field, and features an internal loss about a factor of 10 lower than typical circulators in circuit QED. (Phys. Rev. Applied 16, 064066 (2021), “Editor’s suggestion”).
2) We integrated superconducting transmon qubits in this device platform, and realized the first observation of a dispersive type of non-reciprocal interaction between a superconducting qubit and a cavity (manuscript in preparation).
3) On a broader topic (connected to the engineering of open quantum systems but not limited to ferrite-based devices), we completed a theoretical study of non-reciprocal quantum state transfer (Phys. Rev. Research 1, 033198 (2019)) and an experimental demonstration of autonomous quantum error correction (Nature 590, 243 (2021)).

In addition, partially supported by this project, the PI co-authored a tutorial article, “Practical guide for building a superconducting quantum devices” (PRX Quantum, 2, 040202 (2021)).

For more details, see Detailed Research Summary in attached PDF.

Training Opportunities: This project provided training opportunities to many junior researchers, including one postdoc (Juliang Li, part time), two graduate students (Ying-Ying Wang, close to full-time; Sean Van Geldern, part-time), and three undergraduate students (Thomas Connolly, Joshua Carey and Alexander Shilcusky).

Participations in conferences include:
Juliang Li participated and presented in cryogenic engineering conference CEC-ICMC 2019 in Hartford, CT.
Ying-Ying Wang participated and presented in the APS March meeting 2019 in Boston.
Both Ying-Ying Wang and Sean van Geldern participated and presented in the APS March meeting 2021 online.

Notably, this project fostered the career development for several excellent undergraduate students. Thomas Connolly, who was a main contributor at the early stage of the project, was a recipient of the prestigious William F. Field alumni scholar award at U Mass and moved on to graduate school at Yale to join one of the most leading labs in superconducting quantum computing. Alexander Shilcusky, who contributed to the simulations in the project and was a department Hasbrouck scholarship winner, went on to grad school at Northeastern University. Both undergrads are coauthors of our recent paper "Low-loss ferrite circulator as a tunable chiral quantum system".

Results Dissemination: Nothing to Report

Honors and Awards: Awards to PI Chen Wang:
2020 IOP International Quantum Technology Young Scientist Award ‘Highly commended’ top 5 finalist
2020 US Department of Energy Early Career Award
2018 US Air Force Office of Scientific Research (AFOSR) Young Investigator Award

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PARTICIPANTS:

Participant Type: PD/PI
Participant: Chen Wang
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

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

National Academy Member: N

Participant Type: Graduate Student (research assistant)
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Project Contribution:
National Academy Member: N

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Project Contribution:
National Academy Member: N

Participant Type: Undergraduate Student
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National Academy Member: N

Participant Type: Undergraduate Student
Participant: Alexander Shilcusky
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Authors: Chen Wang, Jeffrey Gertler
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Abstract: Quantum state transfer from an information-carrying qubit to a receiving qubit is ubiquitous for quantum information technology. In a closed quantum system, this task requires preciselytimed control of coherent qubit-qubit interactions that are intrinsically reciprocal. Here, breaking reciprocity by tailoring dissipation in an open system, we show that it is possible to autonomously transfer a quantum state between stationary qubits without time-dependent control. We present the general requirements for this directional transfer process, and show that the minimum system dimension for transferring one qubit of information is 3 x 2 (between one physical qutrit and one physical qubit), plus one auxiliary reservoir. We propose realistic implementions in present-day superconducting circuit QED experiments, and further propose transfer schemes across a directional waveguide using impedanced matched dissipation engineering.

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Article Title: Protecting a Bosonic Qubit with Autonomous Quantum Error Correction
Authors: Jeffrey M. Gertler, Brian Baker, Juliang Li, Shruti Shirol, Jens Koch, Chen Wang
Keywords: quantum error correction, dissipation engineering

Abstract: To build a universal quantum computer from fragile physical qubits, effective implementation of quantum error correction (QEC) is an essential requirement and a central challenge. Existing demonstrations of QEC are based on a schedule of discrete error syndrome measurements and adaptive recovery operations. In principle, QEC can be realized autonomously and continuously by tailoring dissipation within the quantum system, but this strategy has remained challenging so far. Here we encode a logical qubit in Schrödinger cat-like multiphoton states of a superconducting cavity, and demonstrate a corrective dissipation process that directly stabilizes an error syndrome operator: the photon number parity. Implemented with continuous-wave control fields only, this passive protocol realizes autonomous correction against single-photon loss and boosts the coherence time of the multiphoton qubit by over a factor of two. Our experiment suggests reservoir engineering as a alternative to active QEC.

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Authors: Yvonne Y. Gao, M. Adriaan Rol, Steven Touzard, Chen Wang
Keywords: Superconducting qubits, quantum computing, circuit QED
Abstract: Quantum computing offers a powerful new paradigm of information processing that has the potential to transform a wide range of industries. In the pursuit of the tantalizing promises of a universal quantum computer, a multitude of new knowledge and expertise has been developed, enabling the construction of novel quantum algorithms as well as increasingly robust quantum hardware. In particular, we have witnessed rapid progress in the circuit quantum electrodynamics (cQED) technology, which has emerged as one of the most promising physical systems that is capable of addressing the key challenges in realizing full-stack quantum computing on a large scale. In this Tutorial, we present some of the most crucial building blocks developed by the cQED community in recent years and a précis of the latest achievements towards robust universal quantum computation. More importantly, we aim to provide a synoptic outline of the core techniques that underlie most cQED experiments and offer a practical
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Article Title: Low-loss ferrite circulator as a tunable chiral quantum system
Authors: Ying-Ying Wang, Sean van Geldern, Thomas Connolly, Yu-Xin Wang, Alexander Shilcusky, Alexander
Keywords: circulator, non-reciprocity, circuit QED, hybrid quantum systems
Abstract: Ferrite microwave circulators allow one to control the directional flow of microwave signals and noise, and thus play a crucial role in present-day superconducting quantum technology. They are typically viewed as a black-box, with their internal structure neither specified nor used as a quantum resource. In this work, we show a low-loss waveguide circulator constructed with single-crystalline yttrium iron garnet (YIG) in a 3D cavity, and analyze it as a multi-mode hybrid quantum system with coupled photonic and magnonic excitations. We show the coherent coupling of its chiral internal modes with integrated superconducting niobium cavities, and how this enables tunable nonreciprocal interactions between the intra-cavity photons. We also probe experimentally the effective non-Hermitian dynamics of this system and its effective nonreciprocal eigenmodes. The device platform provides a test bed for implementing nonreciprocal interactions in open-system circuit QED.
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I certify that the information in the report is complete and accurate:
Signature: Chen Wang
Signature Date: 12/29/21   2:20PM

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Non-reciprocal circuit quantum electrodynamics with ferrites

9/4/2017 – 9/3/2021

Chen Wang, University of Massachusetts-Amherst

A. Executive Summary

Over the past few years, there has been rising interest in non-reciprocal phenomena in the quantum regime. However, the form of demonstrated non-reciprocal interactions has been limited to the exchange of quantum excitations between linear modes, such as transmission of photons or phonons. These linear non-reciprocal systems are in the correspondence limit of classical dynamics and can be effectively described by a non-Hermitian Hamiltonian. Superconducting circuit QED provide opportunities where two-level systems can interact with each other or with linear modes in an open-system quantum optics setting, giving rise to new non-reciprocal phenomena with no classical correspondence.

This project is a step towards building a non-reciprocal circuit QED platform by integrating ferromagnetic magnon modes, which allows superconducting qubits and cavities to be coupled in a fully or partially directional manner with high quantum efficiency (i.e. low loss). Such low-loss non-reciprocal interactions enables the study of circuit QED in a regime incorporating time-reversal-symmetry breaking and engineered dissipation, and this paradigm of non-reciprocity may facilitate high-fidelity quantum state transfer and low-crosstalk modularization of a quantum processor.

The main accomplishments under this project are:

1) We demonstrated a low-loss ferrite circulator device as an in-situ tunable chiral quantum system. The circulator is integrated with superconducting cavities at a modest magnetic field, and features an internal loss about a factor of 10 lower than typical circulators in circuit QED. (Phys. Rev. Applied 16, 064066 (2021), "Editor's suggestion").

2) We integrated superconducting transmon qubits in this device platform, and realized the first observation of a dispersive type of non-reciprocal interaction between a superconducting qubit and a cavity (manuscript in preparation).

3) On a broader topic (connected to the engineering of open quantum systems but not limited to ferrite-based devices), we completed a theoretical study of non-reciprocal quantum state transfer (Phys. Rev. Research 1, 033198 (2019)) and an experimental demonstration of autonomous quantum error correction (Nature 590, 243 (2021)).

In addition, partially supported by this project, the PI co-authored a tutorial article, "Practical guide for building a superconducting quantum devices" (PRX Quantum, 2, 040202 (2021)).

For more details, see Detailed Research Summary in attached PDF.

B. Detailed Descriptions of Research Progress and Results

I. Low-Loss Ferrite Circulator as a Tunable Chiral Quantum System

Ferrite microwave circulators allow one to control the directional flow of microwave signals and noise, and thus play a crucial role in present-day superconducting quantum technology. They are typically viewed as a black box, with their internal structure neither specified nor used as a quantum resource. In this work, we show a low-loss waveguide circulator constructed with single-crystalline yttrium iron garnet (YIG) in a three-dimensional cavity, and analyze it as a multimode hybrid quantum system with coupled photonic and magnonic excitations. We show the coherent coupling of its chiral internal modes with integrated superconducting niobium cavities, and how this enables tunable non-reciprocal interactions between the intra-cavity photons. We also probe experimentally the effective non-Hermitian dynamics of this system and its effective non-reciprocal eigenmodes. The device platform provides a test bed for implementing non-reciprocal interactions in open-system circuit QED.

This work is has been published at Physical Review Applied. This work has implications in several areas. (1) In the context of quantum magnonics, we present a study of polariton modes with a partially magnetized ferrite material, which features a high quality factor and low operating field, both of which are crucial for constructing superconducting-magnonic devices. (2) In the context of modular superconducting quantum computing, we demonstrate a circulator with internal loss well below 1% of the coupling bandwidth, which would enable high-fidelity directional quantum state transfer. (3) Relating to general non-Hermitian physics, we demonstrate an experimental probe of the non-reciprocal eigenvector composition of a non-Hermitian system. Combining these advances, we have established an experimental platform that meets the conditions for future study of nonlinear non-reciprocal interactions with superconducting qubits.

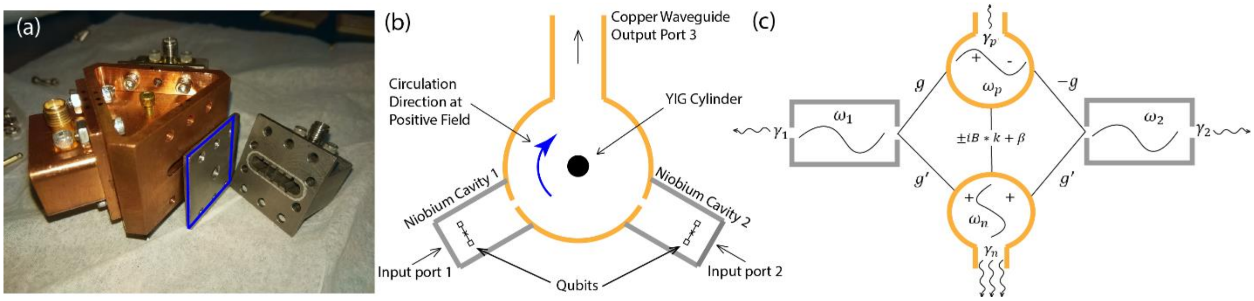

Figure 1. (a) Photo image, (b) schematic top-down view and (c) conceptual Hamiltonian diagram of our non-reciprocal circuit QED device. The device is composed of a Cu waveguide Y-junction loaded with a YIG cylinder, two Nb waveguide segments (converted to cavities using the cover, marked in blue in (a)) with transmon qubits and weakly-coupled drive ports (Port 1 and 2), and an impedance-matched SMA-waveguide transition (Port 3). The relevant part of system can be described by a Hamiltonian of four linear modes (including one strongly dissipative mode) and two two-level systems.

This work combines the bulk of the multi-year effort of hardware development and modeling of the magnon-cavity hybrid system under this project. The various completed tasks and milestones in this thrust are:

I-1. Design and testing of a custom waveguide circulator based on single-crystalline YIG (Year 1-2)

Our reconfigurable non-reciprocal device is ultimately intended for direct coupling of quantum modes, but the first step of the work was to design the device and benchmark it as a low-loss circulator impedance matched to a transmission line. Our constructed circulator operated at a very modest magnetic field of about 25 mT (compatible with superconducting cavity integration), and showed isolation of >20dB over a bandwidth of about 300 MHz. Most importantly, the internal linewidth of the circulator modes was only about 2 MHz, corresponding to a circulator internal loss of less than 1%, which was about 10 times lower than typical circulators in current circuit QED experiments.

Although the classic working principle of microwave circulators has been established since the 1960's, it has been neither an active research area nor described in the modern language of high-Q resonance modes. In order to construct a low-loss circulator integrated in circuit QED, we spent some effort remastering the theoretical model and adapt it to the available geometry of YIG single crystals and the preferred geometry for cavity coupling. While the design of our circulator is by no means fully optimized, the operating condition (frequency and magnetic field) is well described by our theoretical understanding of the magnon modes and their couplings to the cavity photons.

I-2. Study of the damping (decoherence) mechanism of magnon modes in YIG (Year 1-2)

In order to push ferrite devices towards the lossless limit desirable for quantum devices, we investigated the damping mechanisms in single crystalline YIG. This was carried out by a cavity ferromagnetic resonance (FMR) study, where we measure the linewidths of magnon modes of a YIG sphere hybridized with the cavity modes. We systematic analyzed the YIG linewidths as a function of microwave power, temperature, and geometric sensitivity to surface loss, and there were several intriguing observations unexplained by existing knowledge of magnon damping (See Interim report 1&2 for data and discussions). However, we came to believe that the reproducibility of our study is severely limited by the variation of the raw material quality of the single crystalline YIG, even for nominally identical product from the same vendor. As the YIG sample has sufficient Q for our integrated circuit QED device, we later discontinued this line of research to prioritize the study of the non-reciprocal interaction models.

I-3. Development of numerical capability to simulate a ferrite device below magnetic saturation (Year 2-3)

Our experiment operates a ferrite Y-junction circulator at a magnetic field significantly below magnetization saturation of YIG. This modest need of magnetic bias field is important for convenient integration with 3D superconducting circuit QED, but is an unusual regime for circulator design. The regular simulation environment of a commercial E&M solver, such as Ansys HFSS that we use, assumes ferrite materials are always fully magnetized. We developed a custom-defined permeability tensor method in HFSS to model the microwave property of partially magnitzed ferrite. The tensor components are based on the partially saturated permeability model by Sandy and Green [1974]. We further built tools to import the spatial distribution of magnetization and internal fields from magnetostatic simulation into the microwave simulation. This technique allows us to extract the eigenmodes of the cavity-magnon polariton system from raw geometry and plays a major role in quantitative understanding of the system.

I-4. Development and verification of an effective Hamiltonian and input-output model of a multi-mode chiral quantum system (Year 3)

We realized a multi-mode chiral quantum system by coupling the circulator modes directly to superconducting cavity modes and a dissipative reservoir. This device thus implemented a rather complex open quantum system, and we devoted substantial amount of effort on modelling of the system and extract relevant system parameters. We have a non-Hermitian 4x4 Hamiltonian matrix model that is central to this work and successfully captures the linear transmission response of the device:

$$H_{sys} = \begin{pmatrix} \omega_1 - i\gamma_1/2 & 0 & g & g' \\ 0 & \omega_2 - i\gamma_2/2 & -g & g' \\ g & -g & \omega_p & ikB + \beta \\ g' & g' & -ikB + \beta & \omega_n - i\gamma_3/2 \end{pmatrix} \qquad (1)$$

The model includes four principle modes: two niobium mode cavities (ω_1, ω_2) and two magnon-photon polariton modes of the Y-junction circulator (ω_p, ω_n). The latter two modes are coupled to each other with a magnetic-field tunable strength ikB, which breaks the time-reversal symmetry. The three input-output ports of the device are coupled to modes ω_1, ω_2, ω_n respectively with rates $\gamma_1, \gamma_2, \gamma_3$. Using the quantum Langevin equations and the input-output theory, we can compute the scattering matrix of the three-port device as the sum of Lorentzian functions.

We achieve excellent agreement between the experimental spectrum and this theoretical model, as shown in Fig. 2. Notably, non-reciprocity naturally arises from an effective system Hamiltonian that obeys microscopic time-reversal symmetry: The complex eigenvalues of the modes (frequencies ω and linewidths κ) are invariant under reversal of magnetic field, while the eigenvectors (implied by the input-output amplitudes A) are markedly different.

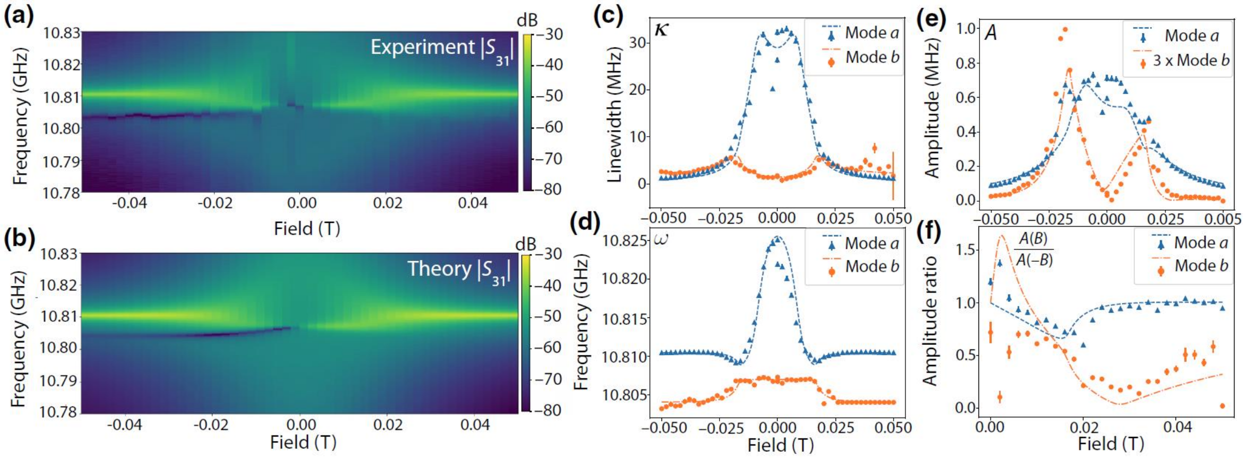

Figure 2. Spectroscopy of the hybridized non-reciprocal modes of a circulator-cavity system. (a) VNA transmission measurement and (b) model prediction of the $|S_{31}|$ frequency spectrum over external magnetic field B. Remaining panels show magnetic field dependence of the system's eigenmodes and wavefunctions: (c) eigenmode linewidths $\kappa_n/2\pi$, (d) eigenmode frequencies $\omega_n/2\pi$, (e) amplitude parameter A_n, and (f) amplitude ratio of experimental data (dots) from two-mode Lorentzian fit and theory predictions (dashed lines).

II. Non-reciprocal Dispersive Interaction in Circuit QED

The dispersive interaction between a qubit and a cavity arises in the detuned limit of the Jaynes-Cumming Hamiltonian and is a hallmark of circuit QED. It is mediated by virtual exchange of excitations, and manifests itself as a frequency shift of the qubit when the cavity is excited and a frequency shift of the cavity when the qubit is excited. By nature of the eigenstate definition in a closed quantum system, the dispersive shift χ in a standard qubit-cavity Hamiltonian H_{qc} is perfectly reciprocal: $\frac{H_{qc}}{\hbar} = \omega_c a^+ a + \left(\omega_q - \chi a^+ a\right)\frac{\sigma_z}{2} = (\omega_c - \chi\frac{\sigma_z}{2})a^+ a + \omega_q\frac{\sigma_z}{2}$. However, in a general non-reciprocal open quantum system, we show that it is possible to realize situations where the dispersive frequency pull χ_{qc} from a qubit to a cavity and χ_{cq} from a cavity to a qubit are different.

Here we implement a dispersive type of non-reciprocal interaction between a transmon qubit and a superconducting cavity, where the system dynamics can be captured by a cavity-qubit nonlinear jump operator in a new effective theory of non-reciprocity. We experimentally measured the qubit dispersive shifts and dephasing rates from both a steady-state photon population and a decaying photon population in the non-reciprocally coupled cavity, in agreement with model predictions. We further explore potential applications of this model such as dissipative gate operations.

This experiment has been carried out in the same device package as in Fig. 1, more specifically on the non-reciprocal interaction between Cavity 1 and a transmon Qubit 2 on the opposite side of the ferrite circulator. Qubit 2 is shielded in a niobium cavity (Cavity 2) which has much broader linewidth and can be adiabatically eliminated. While our work in Section I focuses on understanding the coupled linear dynamics of the system, here our focus shifts to nonlinear non-reciprocal dynamics involving the qubit. In some sense, the Phys. Rev. Appl. paper was dedicated to provide the technical background and introduce the device platform for subsequent studies like this. This new experiment has been completed for one pair of qubits with relatively weak dispersive coupling to the cavity. A manuscript is currently being prepared on this work while we continue to experiment with stronger-coupled qubits. The various completed tasks and milestones are:

II-1. Qubit integration in a non-reciprocal ferrite device (Year 2-3)

Soon after the development of a ferrite circulator at a low field of 25 mT, we started to test the performance of niobium-cavity-shielded transmon qubits under magnetic field. Despite concerns in the literature about flux creep, etc., we found the qubit coherence times are generally unaffected by external field applied at base temperature up to 100 mT, in agreement with the simple picture of Meissner effect and the lower critical field of bulk niobium. Since our device package was not protected by a high-permeability magnetic shield to provide a zero-field environment during the cooldown (as in typical circuit QED experiments), we believed trapped vortices from the cooldown are the limiting factor of transmon coherence. To mitigate this impact, we taped amuneal foil around the niobium part of the device package, and this measure improved the measured transmon coherence times from $T_1 \approx T_2 \approx 1\mu$s up to $T_1 = 15\mu s, T_2^* = 5\mu$s, so far the best record on a superconducting circuit/magnon hybrid platform.

II-2. Measurement of non-reciprocal qubit-cavity dispersive dynamics (Year 3-4)

We developed a comprehensive set of Ramsey protocols to measure the dispersive type of interaction between Qubit 2 and a decaying population of photon numbers in Cavity 1 (Fig. 3). We observed equal frequency pull $\chi_{qc} \approx \chi_{cq}$ at zero field, as expected when the system is reciprocal. When a magnetic field is applied, we observed clear signatures of non-reciprocity in the strength of the dispersive interaction. At the optimal fields of the circulator, B = -25 mT, we measure very small χ_{cq}, in agreement with the sense of circulation. On the other hand, χ_{cq} appears symmetric with respect to field (and crosses zero at B = ±25 mT) because of eigenvalue invariance under the reversal of magnetic field, as we understood from the linear non-reciprocal dynamics. The Ramsey also measures the dephasing of Qubit 2 due to the photon shot noise from Cavity 1.

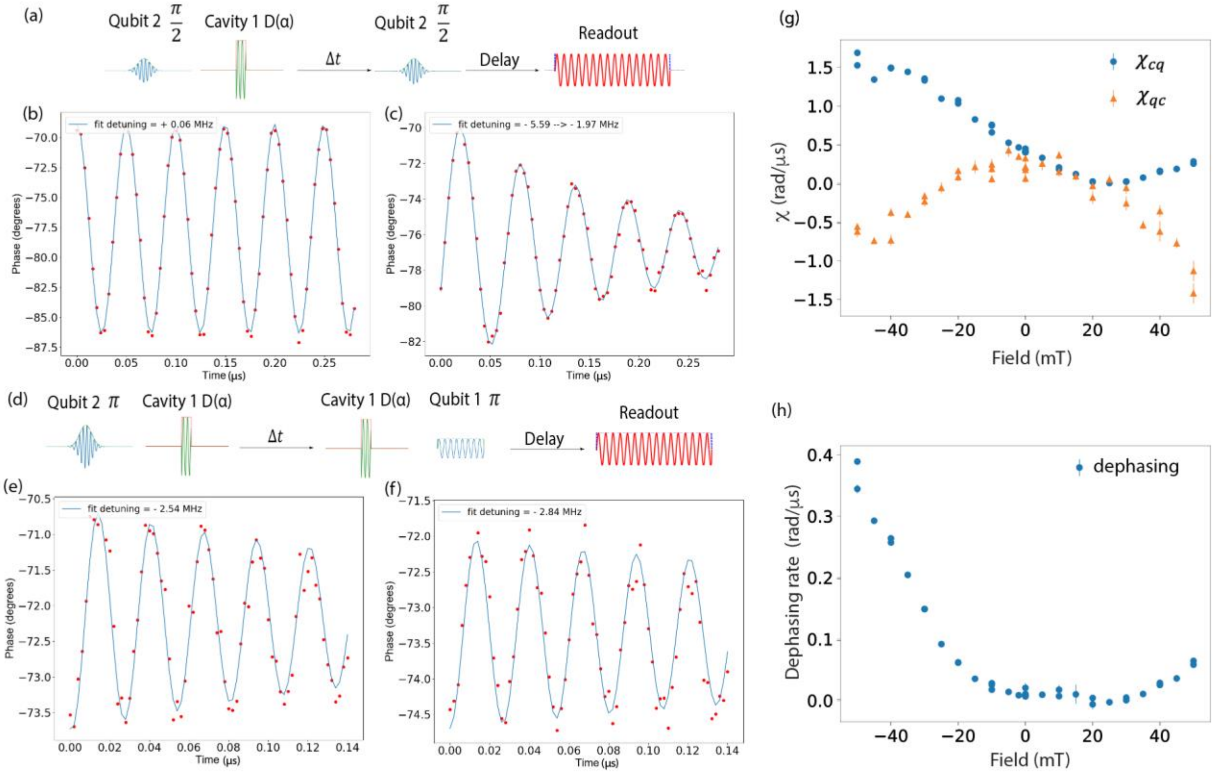

Figure 3. (a) Control sequence diagram for measuring dispersive frequency pull χ_{cq} and photon shot-noise dephasing rate from Cavity 1 to Qubit 2 using qubit Ramsey interference. (b, c) Example data of Qubit 2 Ramsey experiment at B=0 when Cavity 1 is in $|0\rangle$ or is initialized in a coherent state $|\alpha\rangle$. The oscillations are sped up intentionally by 20 MHz, which is subtracted from the fit detuning. (d) Control sequence diagram for measuring the dispersive frequency pull χ_{qc} from Qubit 2 to Cavity 1 using cavity Ramsey interference. (e, f) Example data of Cavity 1 Ramsey experiment at B = 0 when Qubit 2 is prepared in $|g\rangle$ or in $|e\rangle$. The oscillations are sped up intentionally by 40 MHz, which is subtracted from the fit detuning. (g) Measured results of non-reciprocal dispersive interaction χ_{qc} and χ_{cq} as a function of magnetic field. (h) Measured results of photon shot-noise dephasing rate as a function of field.

II-3. Development of theoretical models of qubit-cavity non-reciprocity (Year 3-4)

The defining feature of our study is the ability to tune the degree of reciprocity of qubit-cavity interactions in situ, from fully reciprocal (as in traditional closed-system circuit QED) to fully directional (as in some waveguide QED and photon detection experiments), and most importantly, anywhere in between. In the general scenario that is partially non-reciprocal, the magnetic-field dependence of the dispersive frequency pulls and photon shot-noise dephasing show complex behavior beyond traditional theoretical models.

In collaboration with Aash Clerk group in Univ. of Chicago, we developed two theoretical models to analyze the experimental data. The first model describes a qubit dispersively coupled to a non-reciprocal network of linear modes, with the latter described by a non-Hermitian Hamiltonian (i.e. Eq. (1) for our system). The model connects the dispersive shift and the shot-noise dephasing directly to the susceptibility function of the non-reciprocal network. It accurately captures the experimental data, including the dramatic variation of χ_{qc} near $B = \pm 25$ mT (due to the presence of exceptional points for a non-Hermitian system), but it is limited to coherent states of cavity photons.

The second is a simple effective model between only one qubit and one cavity, as described by the Lindblad master equation:

$$\dot{\rho} = -\frac{i}{\hbar}[\chi \hat{a}^{+}\hat{a}\hat{\sigma}_z, \rho] + \kappa D[\hat{a}] + \Gamma D[(1 + r\hat{\sigma}_z)\hat{a}] \qquad (2)$$

This model arises when other modes of the system are short-lived or far-detuned and therefore can be adiabatically eliminated. It is applicable to arbitrary quantum states of the cavity-qubit system, and it makes the non-reciprocal dispersive type interaction transparent. At the core of this model is a novel form of jump operator $\hat{L} = (1 + r\hat{\sigma}_z)\hat{a}$, where $Im[r]$ encodes the nonlinear non-reciprocal dynamics. A theoretical paper dedicated to the dynamics of this form of jump operator is currently in preparation by Aash Clerk group with input from our experiment.

II-4. Trial experiments on chiral waveguide QED (Year 3)

A separate research thrust based on this device platform we hope to realize is “chiral waveguide QED”: Two artificial atomic emitters are coupled through an open one-dimensional *directional* waveguide without cavities. The directional nature of the waveguide fundamentally changes the nature of interactions: super-radiance and sub-radiance states are no longer present, dissipative stabilization of entanglement has been proposed, etc. It is an interesting regime often discussed but difficult to achieve in quantum optics. In Year 3, we made a few trial runs of such an experiment. We observed resonant florescence of both qubits, and in one cool-down was seemingly able to tune the qubit frequencies on resonance with one another, although not in-band for the circulator (See Interim Report 3). This experiment was challenging due to the poor signal-noise ratio in florescence measurements and a lack of characterization tools of the background microwave modes. While we have identified a promising route forward using a qubit-cavity module (instead of a qubit by itself) as the emitter, we made the decision to prioritize the study of dispersive dynamics in this project.

III. Non-reciprocal Dynamics and Error Correction with Quantum Reservoir Engineering

Apart from the main effort based on ferrite devices, we have carried out theoretical and experimental research more broadly on engineering quantum dynamics in non-reciprocal and/or non-unitary open systems. We report two results partially supported by this project.

III-1. Theoretical study of non-reciprocal quantum state transfer with dissipation engineering (Year 1-2)

Quantum state transfer in a closed quantum system requires precisely-timed control of coherent qubit-qubit interactions that are intrinsically reciprocal. In this 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. 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. 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 autonomous quantum error correction (AQEC). We further devised a cQED experiment that can implement this proposed transfer scheme between a transmon qutrit and a superconducting cavity. This work has been published as Phys. Rev. Research 1, 033198 (2019).

III-2. Demonstration of autonomous quantum error correction with dissipation (Year 3)

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. In this experiment, we encode a logical qubit in Schrödinger cat-like multiphoton states in a superconducting cavity, and demonstrate a corrective dissipation operator – Parity Recovery by Selective Photon Addition (PReSPA) – which performs QEC without time dependent control.

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. This work has been published as Nature 590, 243 (2021).