Quantum Information Processing with Multimode Circuit Quantum Electrodynamics

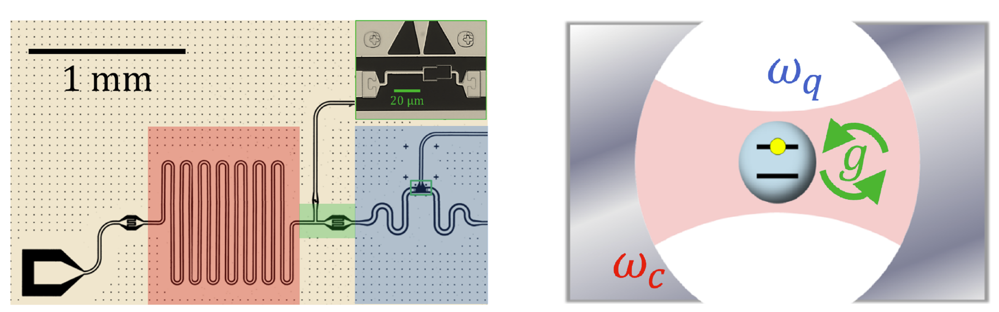
Thomas DiNapoli, Jordan Huang, Eesh Gupta, Shivam Patel, Plamen Kamenov, Srivatsan Chakram

Rutgers, the State University of New Jersey

Introduction

- Superconducting circuits have emerged as versatile and highly-controllable platforms for quantum computing, quantum simulations, and studies of quantum optics.
- Planar superconducting qubits, however, require a large overhead of control resources and have limited coherence times.
- Bosonic modes in superconducting cavity resonators tend to be significantly longer-lived, have fewer error channels, and require fewer control lines per mode.
- With these advantages in mind, we create hardware-efficient quantum information processors that combine high-coherence multimode microwave cavities with superconducting circuits.

Circuit QED



- Quantum control of the cavity modes is achieved using the paradigm of Circuit Quantum Electrodynamics (Circuit QED). Here, the microwave cavity modes are coupled capacitively to a superconducting circuit in a manner similar to an atom coupled to modes of an optical cavity (Cavity QED).
- When the superconducting circuit and the cavity modes are off-resonant, the system is described by the following dispersive Hamiltonian:

$$\mathcal{H}_{\text{disp}} = \frac{\omega_q}{2}\sigma_z + \omega_k b^\dagger b + \underbrace{\frac{g^2}{\triangle}\left(b^\dagger b\right)\sigma_z}_{\text{Dispersive Shift}}$$

- The dispersive interaction shifts the cavity frequency depending on the qubit state, and the qubit frequency depending on the cavity photon number and can be used to perform both qubit and cavity state readout and universal control of the cavity modes.

Errors in Multimode Processors

While the nonlinearity provided by the superconducting circuit allows us to implement universal cavity control, this can lead to (a) unwanted interactions and (b) mode decoherence from coupling to the more lossy superconducting circuit.

(a) These interactions shift the frequencies of the qubit and cavity modes depending on the quantum state of the entire multimode system, resulting in coherent errors during operations on target modes.

(b) The hybridization of the mode with the qubit leads to additional cavity decay via the inverse Purcell effect. Additionally, spurious thermal excitations on the circuit lead to random frequency shifts and additional dephasing of the cavity modes.

We address these challenges in a new hardware design that separates the information storage and processing components using a new tunable coupler circuit.

References

[1] P. Campagne-Ibarcq et al. "Quantum error correction of a qubit encoded in grid states of an oscillator". In: *Nature* (2020).

[2] Srivatsan Chakram et al. "Multimode photon blockade". In: *Nature Physics* (2022).

[3] Alec Eickbusch et al. "Fast Universal Control of an Oscillator with Weak Dispersive Coupling to a Qubit". In: *arXiv:2111.06414v1* (2021).

[4] N. E. Frattini et al. "3-wave mixing Josephson dipole element". In: *Appl. Phys. Lett.* (2017).

[5] Daniel Gottesman, Alexei Kitaev, and John Preskill. "Encoding a qubit in an oscillator". In: *PRA* (2001).

[6] A. Joshi, K. Noh, and Y. Gao. "Quantum information processing with bosonic qubits in circuit QED". In: *Quantum Sci. and Tech.* (2021).

[7] Aidan Zabalo et al. "Critical properties of the measurement-induced transition in random quantum circuits Characterizing phase transitions in the dynamics". In: *PRB* (2020).

Crosstalk-Protected Multimode Random Access Memories

Our new multimode processor advances the state-of-the-art by using separate swap and logic circuits - optimized for each task. Our device consists of **two distinct high-Q cavities**: a **storage cavity** for realizing a multimode quantum memory, and a **processor cavity** for performing crosstalk-free gate operations using a separate ancillary superconducting circuit. This mitigates coherent errors due to quantum state-dependent Stark shifts by a factor of $\sim 10^5$. Quantum information is shuttled between the storage and processor cavities using a tunable coupler circuit based on the SNAIL (Superconducting Nonlinear Asymmetric Inductive eLement) circuit [4]. The SNAIL circuit has the advantage of only needing static magnetic flux to be biased to its optimal point, where it can implement pure 3-wave mixing using charge drives. Operating the SNAIL at this Kerr-free point eliminates coherent errors from inter-mode cross-Kerr interactions inherited from the coupler.

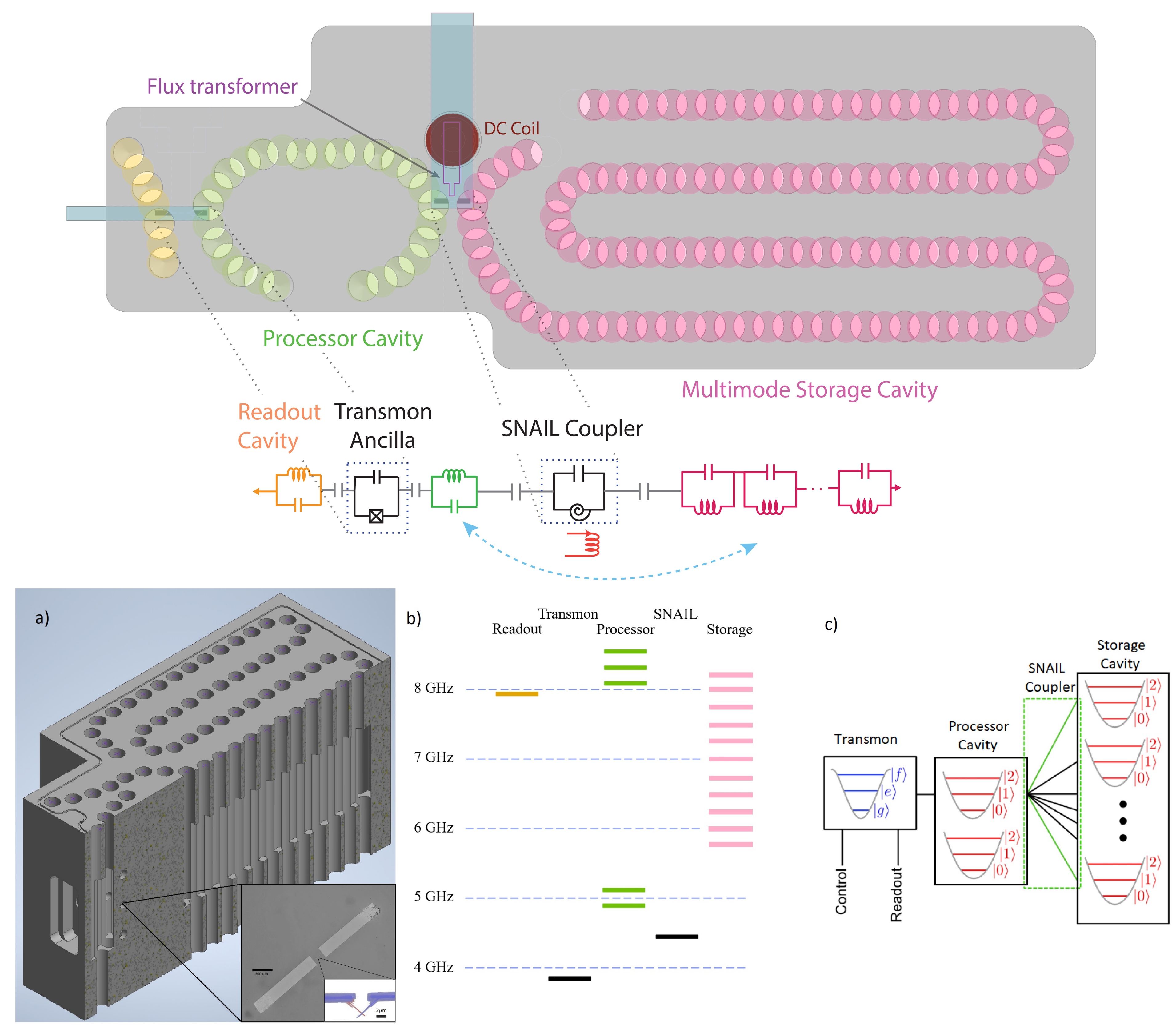


Fig. 2: Top: Schematic of our cross-talk free multimode device and corresponding circuit representation. The storage cavity and processor cavity are coupled by the SNAIL coupler, while the processor and readout cavity are bridged by a transmon ancilla circuit. (a) Cutout of the multimode flute cavity indicating the cavity volume and interface with the transmon circuit. Inset 1: Capacitor pads of the transmon circuit and the Josephson junction (Inset 2). (b) Mode frequencies for the various system elements. (c) Schematic of our processor architecture.

Swapping Quantum States Between the Processor and Memory

Gate operations on target modes of the storage cavity are performed by first swapping the states to the processor cavity - chosen to have two operable modes. The SNAIL coupler generates SWAP (beamsplitter) interactions between cavity modes, when driven at their difference frequency. The coupler will only be virtually occupied and thus its coherence will only contribute to second order, and the swap fidelity can potentially be determined by the high 3D cavity coherences.

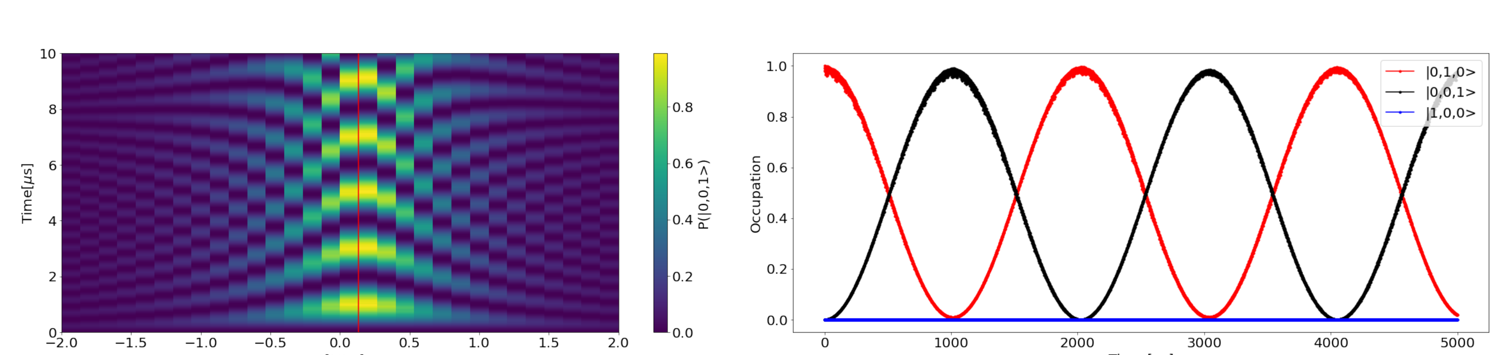
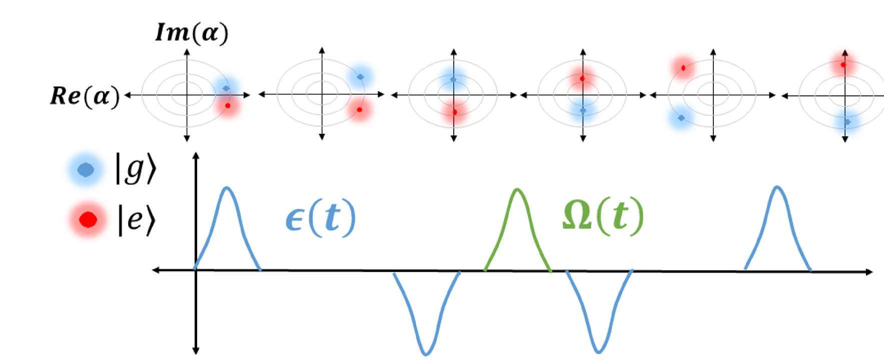


Fig. 3: Inter-mode SWAP operations by driving the SNAIL (a) Population of one of the cavity modes as we vary the frequency of the SNAIL swap tone. The deviation of the drive frequency from the mode frequency difference for the optimal SWAP arises from dressing due to qubit nonlinearities. (b) Resonant exchange of a single photon between two cavity modes.

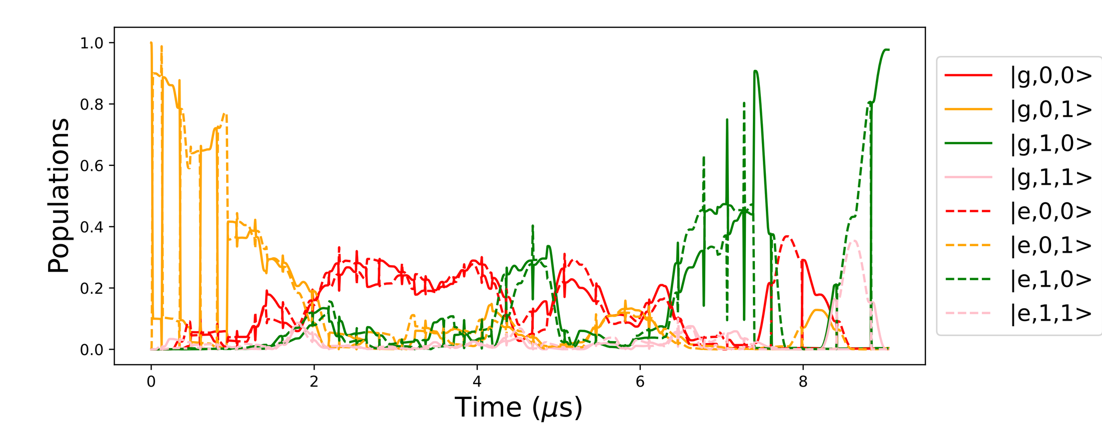
Fast Control with Conditional Displacements

Harnessing the full potential of multimode qRAMs also requires mitigating errors arising from the more error-prone superconducting circuit. We are developing new multimode quantum control schemes, which alleviate crosstalk and ancilla errors by greatly reducing the coupling between the transmon circuit and the multimode memory, while still maintaining fast gate speeds by using large cavity displacements to enhance the native interaction.

- These schemes implement universal control of cavity modes-ancilla qubit systems using series of parameterized Echoed Conditional Displacement (ECD) gates [3] and qubit rotations.
- Phase space and pulse representation of a ECD gate which displaces the oscillator conditioned on the ancilla qubit's state. Cavity drive denoted as $\epsilon(t)$ and qubit drive as $\Omega(t)$.



- Time evolution of an ECD gate optimized to implement beamsplitter operations between modes ($|g01\rangle \rightarrow |g10\rangle$).



Applications of Multimode cQED

This architecture provides a platform for a variety of applications in quantum information and simulation:

- **Quantum error correction (QEC):** Multimode cavities are compatible with both single-mode bosonic codes [6] implemented in the Hilbert space of a single oscillator (such as the GKP code [5] in Figure 6 (a)), as well as distributed qubit codes (Shor, Steane, Surface). We plan to use these systems to explore the rich space of multi-qudit error-correcting codes that lie between these limits, and by concatenating single-mode bosonic codes.
- **Quantum simulation:** Quantum simulators based on multimode cQED are inherently non-equilibrium, have tunable interactions and dissipation, and are amenable to measurement-based feedback control. We plan to leverage this to engineer novel many-body states and study measurement-induced phase transitions (MIPT) in entanglement properties of qudit arrays [7] (Figure 6 (b)), arising by performing projective measurements of varying rates interleaved with entangling gates.
- **Novel quantum control:** We are extending methods such as ECD control; [3], photon blockade [2], and native three-wave mixing [4] for the control of multimode systems.

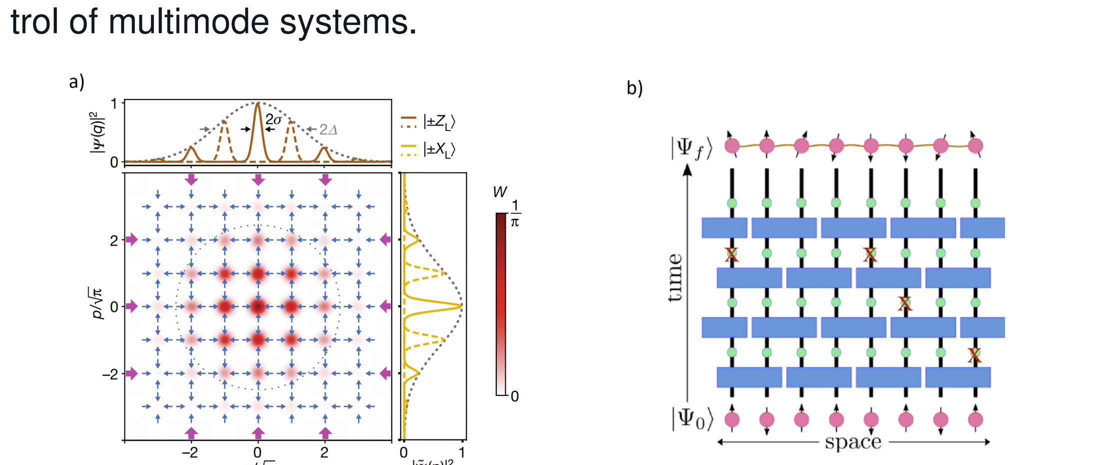


Fig. 6: a) Wigner function representation of the code space of a GKP error correction code [1]. b) Quantum circuit with random entangling gates and projective measurements for probing an MIPT [7].