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(Quantum Accelerator) Superconducting Metamaterial Ring Resonators

**Plourde, Britton
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**03/29/2023
Final Technical Report**

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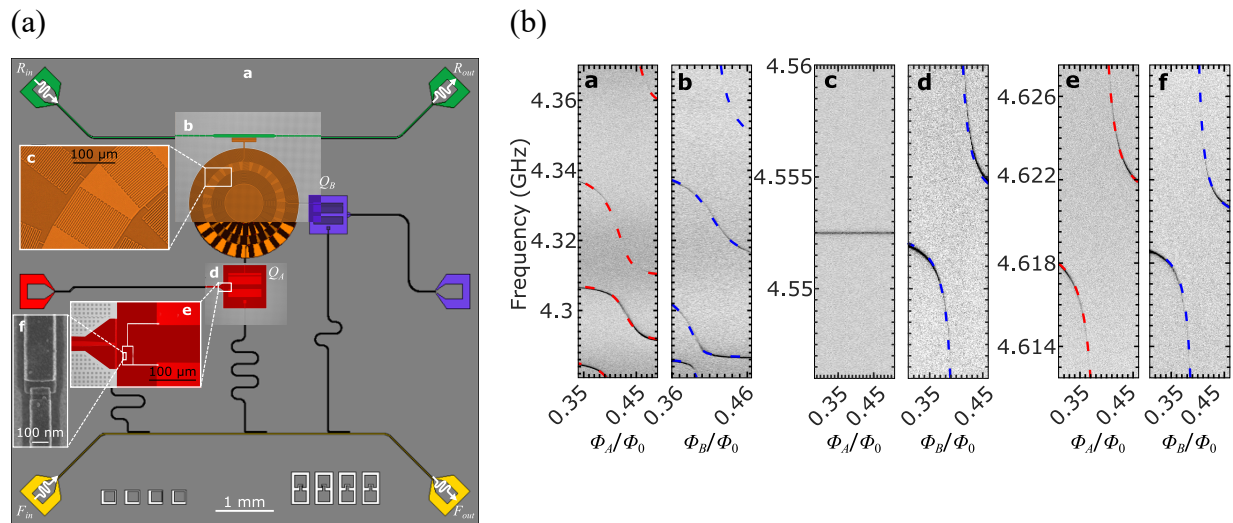


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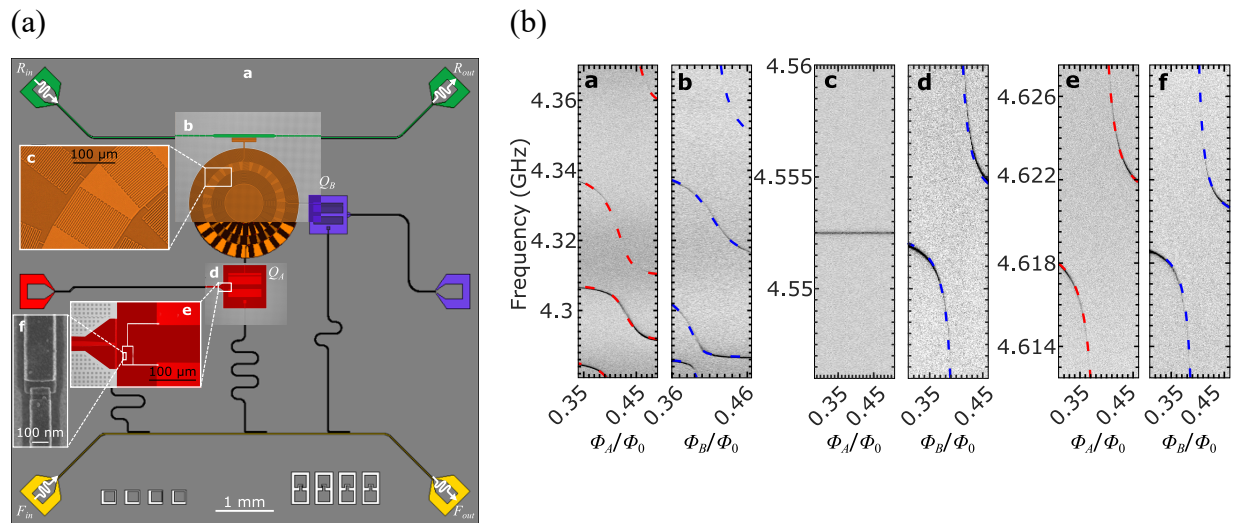


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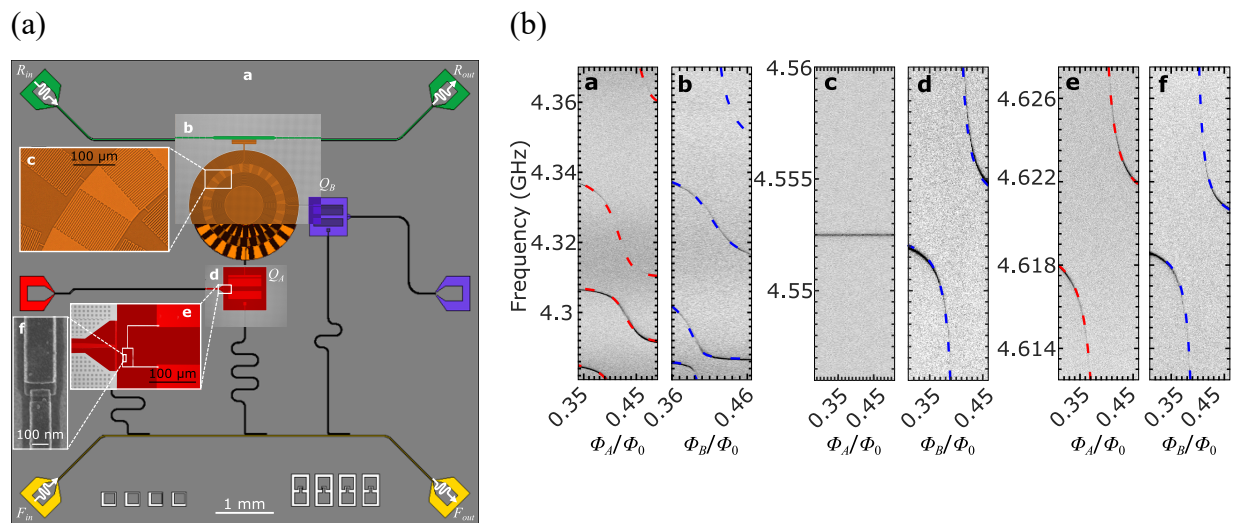


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For low-temperature characterization of these devices, we cooled down several of these chips, including one with a 24-cell metamaterial ring resonator, on one of our adiabatic

demagnetization refrigerators (ADRs). We were able to probe the metamaterial ring resonances with microwave transmission measurements through the feedline coupled to the metamaterial. We observed the expected resonance dips, and by tuning the flux bias for each qubit, we measured vacuum Rabi splittings each time a qubit's bare resonance frequency approached one of the metamaterial ring modes. The size of the splittings provided a measure for the coupling strengths between each qubit and each of the various metamaterial modes. In addition, we were able to perform spectroscopy measurements of the qubits with conventional dispersive readout through the resonators coupled to each qubit. This allowed us to observe the flux-dispersion of each qubit's transition frequency, as well as the splittings due to the coupling to each of the metamaterial ring resonator modes.

Although we made good progress during the first year of the project, the first half of the project year in particular was challenging due to the COVID pandemic. For the first several months of the project, access to the research lab, and also the cleanroom at the Cornell NanoScale Facility, was restricted. Thus, we were not able to measure a metamaterial ring resonator-qubit device on our dilution refrigerator for studying coherent operations with these circuits. We requested a no-cost extension for this project so that we could continue this work for achieving our project goals, and this extension was granted. Thus, in the no-cost extension year of the project, we cooled down a 24-cell metamaterial ring resonator on one of our dilution refrigerators. In this cryostat, we were able to perform higher resolution measurements of the vacuum Rabi splittings with microwave transmission measurements through the feedline coupled to the ring resonator. By fitting these splittings, we were able to extract the coupling strength g for each qubit to each ring resonator mode. These g values varied over a wide range, and at least one mode exhibited a large coupling to one qubit and no coupling to the other qubit.

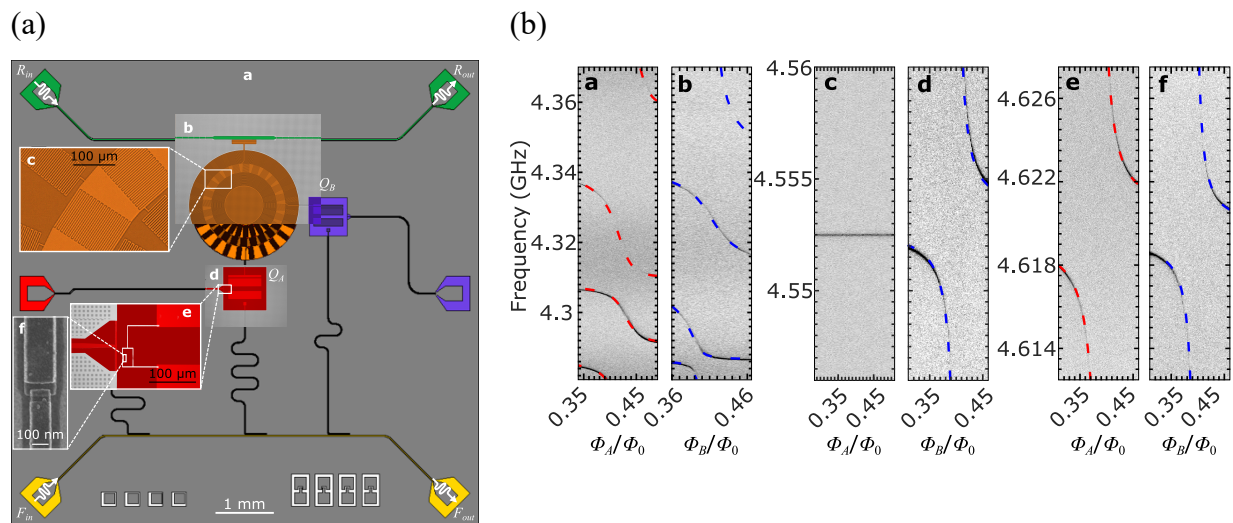


Figure: (a) Metamaterial ring resonator chip layout with two transmon qubits, plus feedline for direct measurements of ring resonator and second feedline for probing readout resonators for each qubit. (b) Measurements of microwave transmission through three different metamaterial modes as a function of each of the two qubit fluxes.

Moving beyond these vacuum Rabi measurements, we also performed spectroscopy of each qubit through their respective readout resonators. In this way, we could again observe the vacuum Rabi splittings each time the bare qubit frequency crossed the bare resonance of a metamaterial mode. In addition, we could observe the J coupling between the two qubits each time one of the qubit bare transition frequencies crossed through the bare frequency of the other qubit. As with single-mode cQED, such a J coupling can be mediated by virtual photon exchange between each qubit and the common mode they both are coupled to. In this multi-mode ring resonator, the J coupling now involves virtual photon exchange with each of the various modes, with different g couplings for each mode to the two qubits. Thus, we observed a significant variation in J depending on the frequency range where the two qubits were brought on resonance with each other. Besides J couplings, we were also able to look at higher-order interactions between the two qubits through measurements of the ZZ energy scale. To study the ZZ interaction for a particular set of bias points for the two qubits, we measured standard Ramsey fringes for one qubit with the other qubit in its ground state. As usual, the center of the fringes identifies the qubit resonance, dressed in this case by the various interactions with metamaterial modes and the other qubit. We then repeated the Ramsey fringe measurement but with the Ramsey sequence preceded by a π -pulse on the other qubit. The shift between the two sets of Ramsey fringes then corresponds to the ZZ term. We observed a significant variation in this ZZ value, including a zero crossing and a change in sign to large negative values, depending on the bias point of the qubits relative to each other and to the various modes.

To understand this complex behavior of the J coupling and ZZ interaction with respect to the qubit bias points, as well as the variations in g coupling between each qubit and each mode, we initiated conversations with the theoretical quantum information group of Prof. Mohammad Ansari at the Jülich Research Center in Germany. Prof. Ansari's group has significant expertise in modeling the detailed level structure of complex cQED systems. They were intrigued by the dense mode spectrum and the rich set of interactions in our metamaterial ring resonator-qubit system. During the no-cost extension year of the project, we started collaborating with the Ansari group on an uncosted basis on the analysis and modeling of our device. This has turned into a fruitful collaboration with beautiful agreement between the g , J , and ZZ experimental data and theoretical modeling. We are currently preparing a joint manuscript describing our experimental measurements and the theoretical analysis that we plan to submit for publication this spring.

Besides this pending publication, during the course of the project, PI Plourde gave invited talks at the Metamaterials 2021 Congress on September 21, 2021 and at the Doolittle Institute Global Future Speaker Series: Quantum Edition on October 27, 2021. Graduate student, Tianna McBroom gave a talk at the American Physical Society (APS) March Meeting in March 2022 on our preliminary measurements. In October 2022, Tianna gave a poster presentation about our measurements of the qubit-mode and qubit-qubit interactions at the Applied Superconductivity Conference in Honolulu, HI. Next month, she will talk again about our work measuring the J and ZZ interactions in this system at the 2023 APS March Meeting. In addition, a graduate student from the Ansari group, Arne Schlabas, will talk in the slot just after Tianna's presentation about the corresponding theoretical analysis.