Fabrication of Nanoscale Josephson Junctions for Quantum Coherent Superconducting Circuits

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Primary CNF Tools Used: ASML Photostepper, JEOL 6300, Plasma-Therm 770

Abstract:

We fabricate nanoscale superconductor tunnel junctions and other structures for experiments involving quantum coherent circuits. Such circuits have shown great promise in recent years for explorations of quantum mechanics at the scale of circuits on a chip and for forming qubits, the foundational elements of a quantum computer. The quantum state of these superconducting qubits can be manipulated with microwave radiation at low temperatures. We are currently developing superconducting metamaterial structures with novel microwave mode spectra for coupling to superconducting qubits.

Summary of Research:

The unique properties of nanoscale Josephson junctions enable a wide range of novel superconducting circuits for investigations in many diverse areas. In recent years, circuits composed of such junctions have emerged as promising candidates for the element of a quantum computer, due to the low intrinsic dissipation from the superconducting electrodes and the possibility of scaling to many such qubits on a chip [1]. The quantum coherent properties of the circuits are measured at temperatures below 50 mK with manipulation of the qubit state through microwave excitation.

We are developing multimode microwave resonators using combinations of superconducting lumped-circuit elements to engineer metamaterial transmission lines, including metamaterial ring resonator devices. These structures exhibit novel mode structures characteristic of left-handed materials [2]. We are fabricating such metamaterial transmission lines from Al and Nb films on Si and characterizing these at low temperatures [2]. We are working on experiments to couple these left-handed lines and ring resonators to superconducting qubits for experiments involving the exchange of microwave photons [2-4].

We pattern these circuits at the CNF with nanoscale structures defined with electron-beam lithography on the JEOL 6300 integrated with photolithographically defined large-scale features. The junctions are fabricated using the standard double-angle shadow evaporation technique, in which a resist bilayer of copolymer and PMMA is used to produce a narrow PMMA airbridge suspended above the substrate. Evaporation of aluminum from two different angles with an oxidation step in between forms a small Al-AlOx-Al tunnel junction from the deposition shadow of the airbridge. We have developed a process for defining these junctions with electron-beam lithography and we perform the aluminum evaporations in a dedicated chamber at Syracuse. We pattern large-scale features using the ASML stepper, with electron-beam evaporation of Al and sputter-deposition of Nb. Measurements of these circuits are performed in cryogenic systems at Syracuse University, including dilution refrigerators for achieving temperatures below 30 mK.

References:

[1] Clarke, J. and Wilhelm, F.K.; "Superconducting quantum bits"; Nature, 453, 1031 (2008).

[2] Wang, H., Zhuravel, A., Indrajeet, S., Taketani, B., Hutchings, M., Hao, Y., Rouxinol, F., Wilhelm,F., LaHaye, M.D., Ustinov, A., Plourde, B.; "Mode Structure in Superconducting Metamaterial Transmission Line Resonators"; Physical Review Applied 11, 054062 (2019).

[3] Indrajeet, S., Wang, H., Hutchings, M.D., Taketani, B.G., Wilhelm, F.K., LaHaye, M.D., Plourde, B.L.T.; "Coupling a Superconducting Qubit to a Left-Handed Metamaterial Resonator"; Physical Review Applied 14, 064033 (2020).

[4] McBroom, T.A., Schlabes, A., Xu, X., Ku, J., Cole, B.G., Ansari, M., Plourde, B.; "Multimode entangling interactions between transmons coupled through a metamaterial ring-resonator: experiment"; Bull. Am. Phys. Soc. 2023, https://meetings.aps.org/Meeting/MAR23/Session/A73.7.

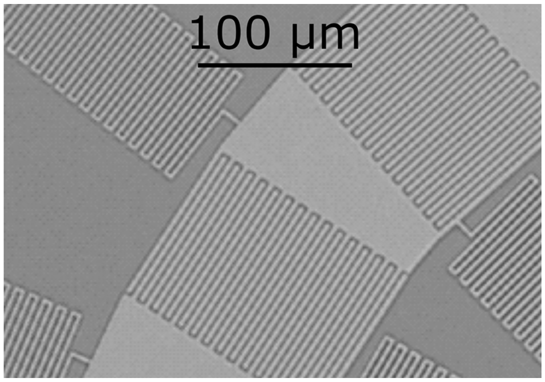

Figure 1: Optical micrograph of unit cell of left-handed metamaterial ring resonator fabricated from Nb on Si with interdigitated capacitor and meander-line inductors.

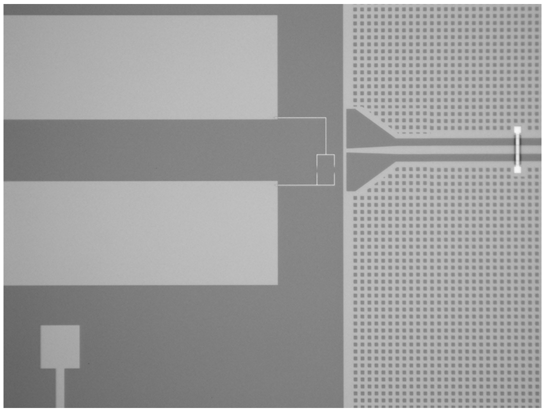

Figure 2: Zoomed-in optical micrograph of transmon qubit with Al-AlOx-Al junctions and Nb capacitor pads coupled to metamaterial ring resonator with on-chip Nb flux-bias line.

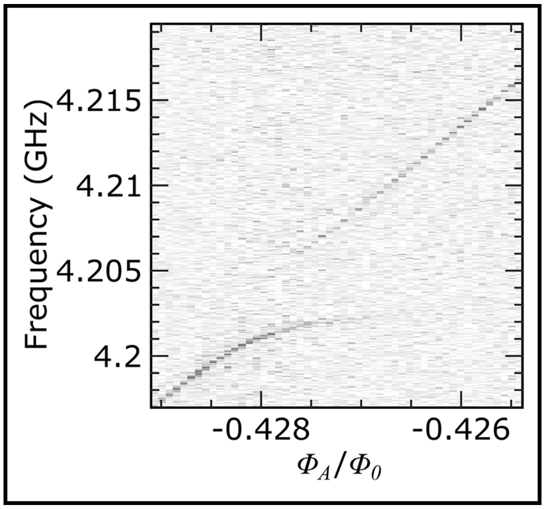

Figure 3: Measurement of qubit spectroscopy on metamaterial ring resonator with two qubits while tuning magnetic flux bias of one qubit. Splitting feature corresponds to exchange coupling between qubits when bare frequency of qubit being tuned approaches resonance with second qubit.

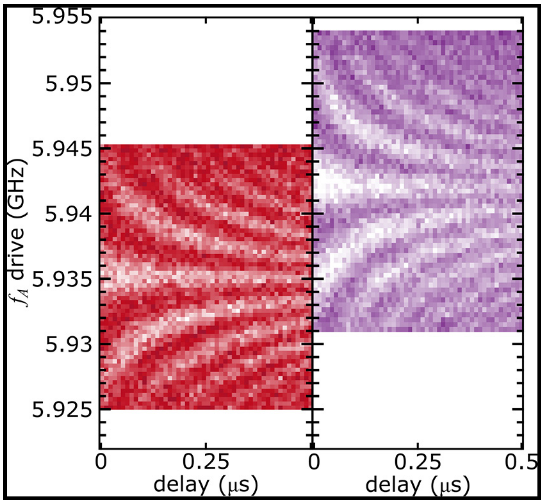

Figure 4: Measurement of Ramsey fringe oscillations on one qubit coupled to metamaterial ring resonator with and without an X pulse on second qubit.

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