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Tunable Microwave Resonators for Superconducting Electro-optic Devices

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Abstract: We present frequency-tunable, photolithography compatible superconducting microwave resonators designed for integration with electro-optic devices. We demonstrate >500 MHz of tuning with a bulk permanent magnet and >100 MHz of tuning with planar coils under moderate (<5 mT) magnetic fields. © 2024 The Author(s)

1. Introduction

Superconducting-photonic hybrid devices are an important building block in many quantum systems, including solid-state memories [1], detectors [2], and superconducting processors [3]. In many cases, readout or device sensitivity can be enhanced by coupling an optical transition to a superconducting microwave resonator. In others, frequency mixing can be resonantly enhanced by the introduction of the microwave resonator. However, achieving resonance across multiple system modes can pose challenges in frequency matching, potentially suppressing desired transitions. Here, we present a tunable superconducting microwave resonator to serve as a reconfigurable link in these hybrid systems in order to facilitate meeting resonance conditions and improve the performance of electro-optic devices.

2. Microwave Resonator Characterization

In an LC superconducting resonator, the resonant frequency can be tuned by adjusting the inductance (L). In our design, the holes patterned within the meander inductor facilitate magnetic flux penetration, enabling us to tune the kinetic inductance, and thus the resonant frequency, of the resonator.

We use niobium as our superconducting material due to its compatibility with microwave-optical devices and electro-optic platforms [4]. For characterization at 4K, 60 nm of Nb is sputtered onto a silicon substrate, patterned via photolithography, and etched using CF4 ion milling (Fig. 1a). During the patterning process, 2 µm holes with a 2 µm street width (Fig. 1b) are introduced in the inductor mask. Transmission through a device above and below critical temperature (Tc~ 9 K) is plotted in Fig. 1c, where there is a clear resonant mode around 6.57 GHz. We note that several devices with identical meander dimensions and various hole geometries were used to characterize tuning performance.

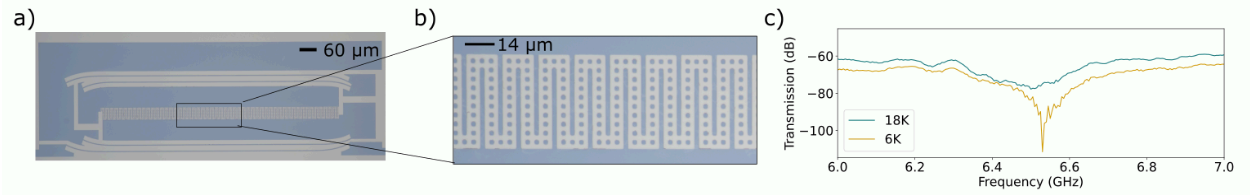

Figure 1. (a) Optical micrograph of niobium LC resonator (tan) on silicon (blue). (b) Magnified optical micrograph of LC resonator (meander inductor). 2 µm width square holes are etched into the meander inductor to allow tuning via magnetic flux. (c) Transmission through a niobium microwave resonator above Tc (18K) and below Tc (6K).

The microwave resonator performance is characterized at 4K using an open-loop helium cryostat (Fig. 2a). Two tuning mechanisms are explored in the work presented here. First, we demonstrate tuning with a permanent magnet fixed to a movable rod within the cryostat. The resonator transmission at different magnetic fields is shown in Fig. 2b. The change in lineshape is attributed to coupling to box modes within the silicon substrate. We demonstrate over 500 MHz of tuning with less than 5 mT of estimated applied magnetic field using a permanent magnet (Fig 2c).

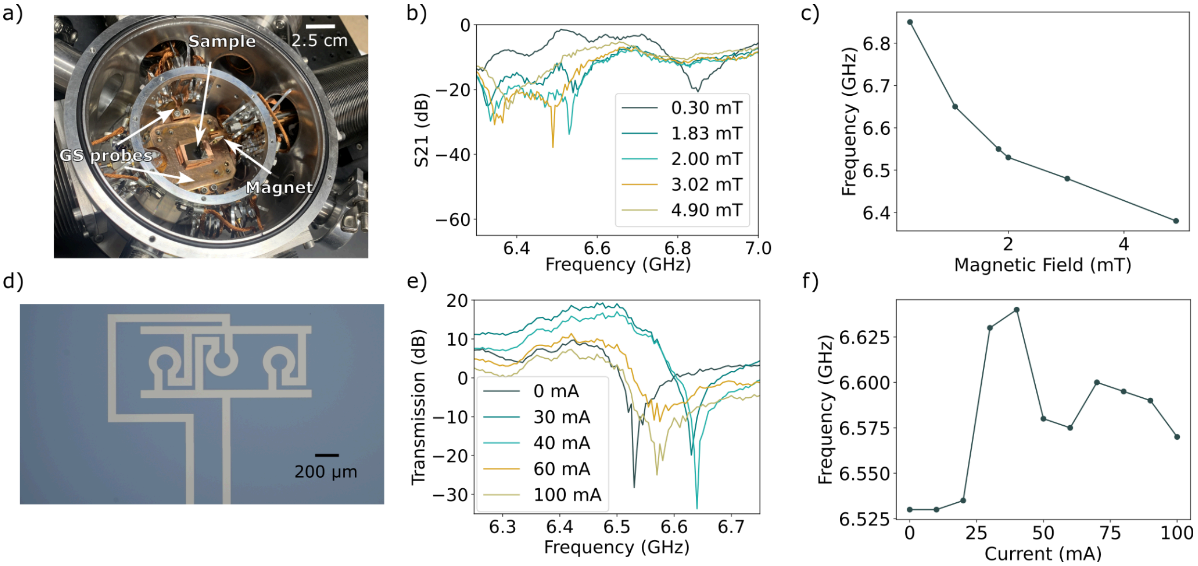

Figure 2. (a) Setup for characterizing device tuning. A magnet (right) mounted on a movable arm is used to inject magnetic field into the inductor. (b) Microwave resonator transmission taken at different estimated magnetic fields applied by a permanent magnet. (c) Microwave resonant frequency as a function of estimated magnetic field. (c) Planar LC tuning coils, where three niobium loops in parallel (tan) are placed below the tunable microwave resonator to induce magnetic field in the inductor. (d) Microwave resonator transmission at different injected currents, and thus magnetic field, in the planar tuning coils. (e) Microwave resonant frequency as a function of injected current into the planar coil positioned beneath the resonator chip.

Next, we fabricate planar magnetic tuning coils from niobium deposited on silicon (Fig. 2d), with the same fabrication techniques as those used for the microwave resonators. The planar tuning chip is positioned directly beneath the microwave resonator chip and coarsely aligned using alignment marks. The backside of the microwave resonator chip is polished to reduce the substrate thickness, resulting in a blue-shifting of the resonant frequency. Current is injected via DC probes to induce magnetic field in the tuning coils. The corresponding transmission through the microwave resonator is plotted in Fig. 2e. A maximum current of 100 mA is applied, resulting in 100 MHz of tuning (Fig. 2f). The tuning curve is a sinusoid with a spike around 40 mA. We expect that this is due to the injected current locally tuning the kinetic inductance of the niobium, which can be mitigated by increasing the nanowire width or thickness, although this requires further investigation.

3. Outlook

We demonstrate over 500 MHz of tuning under less than 5 mT of applied magnetic field for electro-optic compatible microwave resonators using photolithography techniques. While the work presented here is demonstrated on silicon, the resonators are designed for co-operation with optical racetrack resonators fabricated in an electro-optic material (eg. lithium niobate [5], aluminum nitride [6], etc), although modifications can be made to couple the microwave resonators to other optical structures, including ring resonators and traveling-waveguides. Interfacing the tunable microwave resonator with electro-optic waveguides can allow for DC- and magnetic tuning, permitting arbitrary frequency control within tuning bandwidths. The low required magnetic field allows placement of the resonator near other magnetic flux-sensitive devices with minimal crosstalk. Fields can be further localized by placing devices inside of a package with integrated Helmholtz superconducting coils. Future work will involve evaluating device performance in packaged electro-optic devices used to directly interface microwave and optical frequencies.

4. Acknowledgements

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