Toward Microwave-to-Optical Conversion using Erbium Doped Crystals and Integrated Resonators

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Abstract: We present progress towards a bidirectional coherent microwave-to-optical photon converter using an ensemble of rare-earth ions coupled to integrated photonic and microwave resonators.

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1. Introduction

Future quantum networks will benefit from an optical interconnect to entangle distant superconducting circuits via optical photons. An ensemble of rare-earth ions (REIs) simultaneously coupled to an optical and microwave cavity at dilution refrigerator temperatures offers a promising system to achieve bidirectional coherent conversion between microwave and optical photons. Conversion can be realized by utilizing isolated three level systems within the energy structure of the REIs, where the coherence of the ensemble generated from incoming microwave (optical) photons with frequency ω_μ (ω_o) can be mapped to optical (microwave) photons using an optical pump with Rabi frequency, Ω_o, as shown in Figure 1a.

A high-efficiency converter using REI ensembles can be achieved by using a Raman heterodyne scheme when the system has sufficiently large optical and microwave cooperativities, mode overlap and optical pump power [1]. REI ensembles have previously been shown to have strong coupling to both optical and microwave fields independently [2,3].

Here, we present an integrated platform using microwave and optical resonators fabricated on top of our REI doped substrate in order to optimize the mode overlap and cavity mode volumes to achieve high-efficiency conversion with low optical pump power. We show preliminary results of the platform fabricated on sapphire substrates to characterize the performance of the resonators.

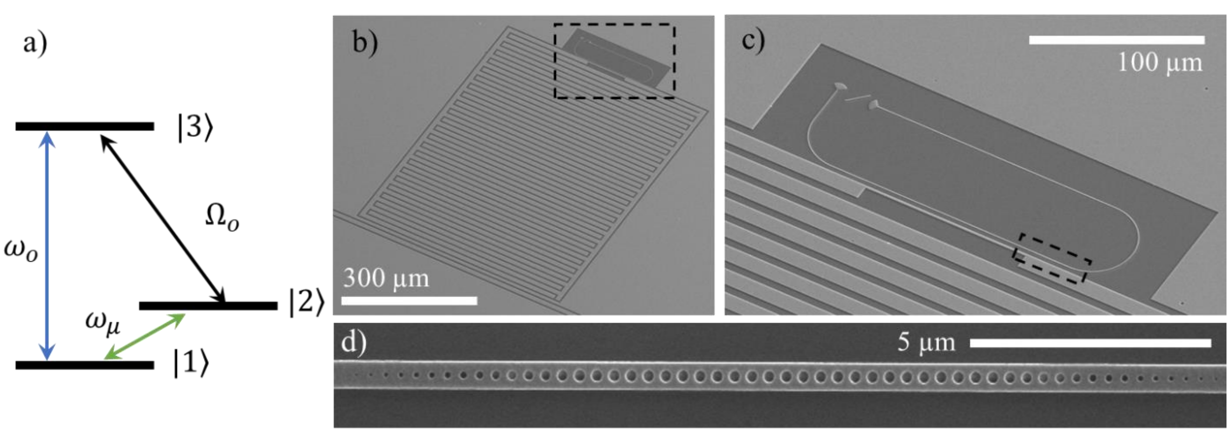

Figure 1: (a) An energy diagram of the microwave to optical converter. An incoming microwave photon at frequency ω_μ induces a coherence between $|1\rangle$ and $|2\rangle$. This coherence is upconverted to the optical frequency ω_o using the pump with Rabi frequency Ω_o. (b) An SEM image of the optical and microwave resonators. (c) A higher magnification image of the inductive component of the microwave resonator next to the optical resonator (rectangle indicated in (b)). The two photonic crystal mirrors of the optical resonator are at the ends of the inductive component. (d) A zoom in image of one of the photonic crystal mirrors located at the ends of the cavity (rectangle indicated in (c)).

2. Results

For our microwave to optical converter, the integrated platform is composed of a superconducting microwave resonator and an amorphous silicon photonic resonator coupled to an erbium ensemble doped in a yttrium orthosilicate (YSO) substrate. In order to maximize the field overlap, we arrange the optical cavity next to the inductive component of the microwave cavity such that the two resonators couple to a similar ensemble of ions.

Erbium's optical transitions are at telecom wavelengths (~1540 nm), which enables the use of silicon photonics to make an optical resonator on the YSO surface for evanescent coupling to the REIs [4]. The optical resonator consists of a long waveguide between two photonic crystal mirrors (Figure 1c). The photonic crystal mirrors consist of periodic holes etched into the waveguide structure (Figure 1d). Gratings couplers are used to couple light from free-space optics.

The microwave resonator consists of an interdigitated capacitor and a narrow waveguide with high inductance. Next to the high inductance waveguide is a metal-free gap where the optical circuit can be positioned in close proximity. The size of the capacitor is tuned to reach a resonant frequency of ~5 GHz. Coupling to the resonator is achieved using a bus waveguide that capacitively couples to the resonator.

In order to test the platform and the fabrication process, the resonators were first fabricated on a sapphire substrate, which has similar permittivities to YSO at both optical and microwave frequencies and low losses. Both resonators are fabricated on top of the substrate permitting the capability of transferring the process to different substrates. Niobium films are first sputtered on the substrate and patterned via dry etching with a SF_6-based chemistry. Next, amorphous silicon films are deposited with plasma enhanced chemical vapor deposition and patterned using with a pseudo-Bosch process.

The quality factors of the both the optical and microwave resonators were measured. The optical resonators were measured at room temperature using a confocal microscope and the microwave resonators were measured in dilution fridge at <30 mK using a network analyzer. Optical resonances show quality factors of ~110,000 at a wavelength of 1531 nm (Figure 2a). Microwave resonances show internal quality factors of ~90,000 at a frequency of 5 GHz (Figure 2b).

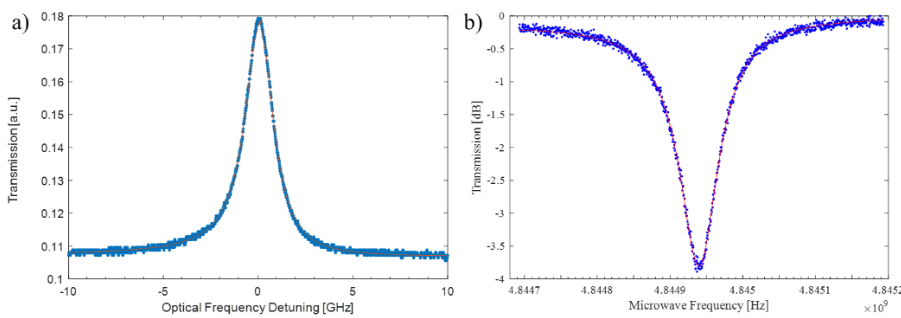

Figure 2: (a) The transmission spectrum of a high-Q mode of the photonic crystal cavity. Resonance fitting of the under-coupled cavity gives a total Q of 110,000. (b) The transmission spectrum of the bus waveguide coupled to the microwave resonator. Resonance fitting gives an internal Q of 91,000.

3. Conclusion

Our platform enables resonators with high quality factors in both the optical and microwave domain, while maintaining sufficient overlap between the optical and microwave fields required for the magneto-optical converter to achieve high efficiency.

4. References

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