# Toward Efficient Microwave-Optical Transduction using Cavity Electro-Optics in Thin-Film Lithium Niobate

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**Abstract:** We describe progress toward high-efficiency transduction between microwave and optical radiation using integrated thin-film superconducting microwave resonators and lithium niobate optical resonators. 

## 1. Introduction

Microwave-frequency superconducting circuits are debatably the most promising platform to realize universal quantum computing, but the strong thermal noise and short attenuation lengths of microwave signals make it difficult to transmit quantum information over long distances. Optical-frequency photons are a more robust medium for long-distance quantum information transfer because their high carrier frequency ensures negligible thermal noise, and fiber optics provide long attenuation lengths. For these reasons, large-scale quantum networks of superconducting circuits will likely require quantum transducers capable of mapping quantum information between optical and microwave radiation [1].

Optical modulators based on the Pockels electro-optic effect are widely used for microwave-optical transduction, but low transduction efficiency (of order $10^{-7}$ for a bulk lithium niobate modulator with 1mW optical pump power) makes conventional devices insufficient for quantum networking. Several methods for improving the transduction efficiency of electro-optic devices have been proposed, including resonant enhancement of the interaction using microwave and optical cavities (an approach termed cavity electro-optics) [2,3] and the use of thin-film electro-optic materials, which provide a stronger interaction between optical and microwave fields compared to traditional ion-diffused or bulk devices [4,5]. Here we present progress toward an electro-optic transducer based on a high-efficiency triplet resonance scheme [6] in which one optical resonance is pumped by a laser and modulated by a microwave resonator, which induces resonant scattering of light into a second optical resonance.

## 2. Transducer design

The two optical resonances of our transducer are created by evanescently coupled optical racetrack resonators made from 1.2 um-wide ridge waveguides in thin-film lithium niobate [7]. The waveguides are cladded with 1.5 μm of amorphous silicon dioxide and 40 nm-thick planar superconducting niobium nitride lumped-element microwave resonators are patterned on top of the cladding (Fig. 1a). The optical resonators are addressed by an evanescently coupled bus waveguide that terminates on-chip at grating couplers. The evanescent coupling between near-degenerate modes of the two optical resonators creates hybrid normal modes delocalized between the resonators, with intrinsic quality factors exceeding $10^6$ in our devices, as shown in Fig. 1b. The microwave resonators are capacitively coupled to a bus coplanar waveguide and feature intrinsic quality factors that range between $10^2$ and $10^3$ (Fig. 1c), limited by acoustic radiation loss from piezoelectric coupling in the lithium niobate layer. A combination of improved acoustic radiation engineering and the elimination of the amorphous cladding are likely to improve the microwave quality factor.

## 3. Tuning the transducer

The transduction efficiency is maximized in the triple-resonance condition, where the splitting between the hybrid optical modes is equal to the microwave resonance frequency. To meet this condition, the optical mode splitting can be tuned using a DC bias port on one of the racetrack resonators. However, we have found that this external DC bias decays over time, and that the decay timescale depends strongly on the power of the laser used to interrogate the optical resonances (Fig. 2). We attribute this decay to dielectric relaxation inside the lithium niobate, which allows charge carriers to shield the applied bias electric field. Lithium niobate's well-known photoconductive properties explain the strong optical power dependence of the relaxation rate.

**4. Outlook**

Using the device properties presented here and the simulated single-photon coupling rate $\frac{g_0}{2\pi} \approx 1$ kHz, we estimate that a transduction efficiency of 50% can be achieved with an optical pump power of $\sim 100$ mW. This relatively high optical pump power makes integration with superconducting circuit technology challenging. However, there are several opportunities to reduce the required pump power, including increasing the optical quality factor. To this end, quality factors as high as $10^7$ have already been demonstrated in thin-film lithium niobate, which, if achieved in our devices, would enable a 100-fold reduction in pump power. Cavity electro-optic transducers offer several benefits over alternative transduction schemes such as those based on cavity opto-mechanics, including lower noise and wider bandwidth due the elimination of low-frequency intermediate transduction steps and weaker laser-induced heating due to the high thermal conductance provided by a large and fully clamped device. For these reasons, the cavity electro-optic transducers described here are a promising method to create bidirectional and quantum-coherent transducers between microwave and optical radiation.

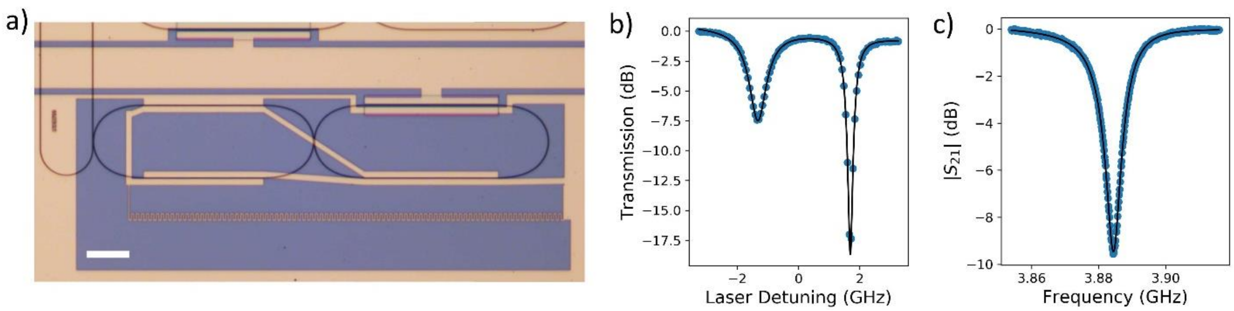


Fig. 1. Device overview. **a)** Optical micrograph of the transducer, showing lithium niobate optical waveguides (black) and thin-film niobium nitride (yellow). Scale bar is 100 $\mu m$. **b)** Optical transmission spectrum measured at $T = 1\ K$, showing evanescently coupled hybridized optical modes with intrinsic quality factor above 1 million. **c)** Microwave transmission spectrum of a niobium nitride resonator on our device measured at $T = 1$ K, showing an intrinsic quality factor above 1,000.

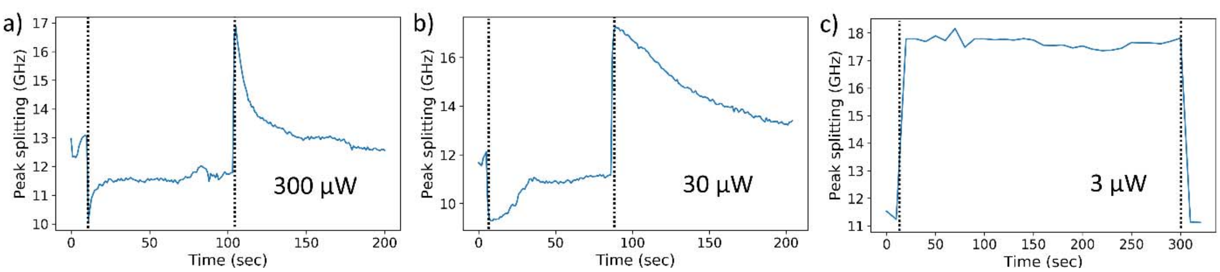


Fig. 2. Relaxation of DC bias at $T = 20$ K. The splitting between hybrid optical modes is tracked over time by repeatedly measuring the optical transmission spectrum using a tunable laser. Each plot shows the results for different on-chip laser powers (shown bottom right). During the monitoring, the DC bias voltage is set to $\pm 20V$ at the time marked by the first vertical dashed line, then set to $0V$ at the time marked by the second vertical dashed line.

**Acknowledgement:** Authors acknowledge support by NSF ECCS-1839197 TAQS grant.

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