Bidirectional electro-optic conversion reaching 1% efficiency with thin film lithium niobate

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Abstract: We demonstrate an efficient, bi-directional electro-optic frequency converter based on a hybrid lithium-niobate/superconductor material platform. Through materials and device engineering to mitigate the limiting photorefractive effect, on-chip conversion efficiency of 1% is realized. © 2021 The Author(s)

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1. Introduction

Superconducting cavity electro-optics (EO) presents a promising route to coherently convert microwave and optical photons and distribute quantum information emerging from superconducting qubits over an optical network. The efficiency of cavity EO conversion critically relies on the strength of Pockels effect and optical transparency of the transduction materials. Thin-film lithium niobate (TFLN) offers these desired characteristics however so far has only delivered a limited conversion efficiency on the order of $10^{-5}$, largely impacted by its prominent photorefractive effect at cryogenic temperatures [1, 2]. In this paper, we demonstrate a hybrid superconducting EO device reaching cooperativity of $4.1 \times 10^{-2}$ and on-chip efficiency of 1.0%. Through device engineering to mitigate photorefractive effect and associated charge-screening in TFLN, the conversion efficiency is significantly enhanced with a strong parametric pump meanwhile maintaining stable cryogenic operation. Our on-chip lithium niobate EO converter provide a promising potential toward future demonstration of large scale quantum network.

2. Design

Fig.1 (a) depicts the schematic of our TFLN-superconductor hybrid EO converter design, where a triple-resonant scheme is applied to enhance the conversion process [3]. The optical pump and signal modes and microwave mode are coupled via Pockels nonlinearity. The two optical modes correspond to the symmetric and anti-symmetric supermodes induced by the strong coupling of the fundamental transverse electric (TE) mode in the two ring resonators [4]. The device is fabricated on a 600 nm-thick high quality TFLN bonded on a sapphire substrate. TFLN with a thickness of 350 nm is first etched to define optical waveguides and rings, followed by a second etch to reduce microwave loss induced by the excess LN material. Superconducting niobium nitride (NbN) is deposited directly on sapphire substrate using atomic layer deposition (ALD), followed by a fluorine based etching to define the microwave resonator and electrodes. This uncladded optical structure is critical to suppress photorefractive and associated charge-screening effect in LN. False color scanning electron microscope (SEM) images of the device is shown in Fig.1 (b) and (c). Average intrinsic quality (Q) factor of the fundamental TE mode is $\sim 10^6$ and intrinsic microwave Q of $\sim 10^4$ is obtained immediately after device fabrication. However, the microwave Q drops to $\sim 10^3$ in conversion characterization due to perturbation of microwave mode by the wirebond and cryogenic packaging.

![Fig. 1. (a) Schematic of the LN converter implementation. Two coupled LN ring resonators are co-integrated with a high frequency (7.83 GHz) superconducting microwave resonator. Interconversion of microwave and optical photons is mediated via cavity-enhanced Pockels effect. (b),(c) are the false-color SEM images of the fabricated device. The inset shows the optical and microwave mode profiles utilized in the conversion process.](image-url)
3. Device characterization

The device is loaded in a closed-cycle refrigerator cooled down to 1.9 K base temperature. In the measurement schematic illustrated in Fig.2(a), a pulsed-pump scheme similar to our recent work [5] is utilized to boost the intracavity photon number while remaining low operation temperature. Full spectra of scattering matrix element ($S_{00}$, $S_{ee}$, $S_{oe}$, $S_{eo}$) are measured to calibrate out off-chip gain and loss, thus extracting the on-chip conversion efficiency.

Fig. 2. (a) Illustration of the experimental setup. The signal generated by a vector network analyzer (VNA) is sent to the device either as the microwave input directly or encoded in the optical input through an electro-optic single-sideband modulator (SSBM). The microwave/optical output is sent back to the VNA for bidirectional conversion calibration. (b) The internal conversion efficiency (blue) and cooperativity as a function of on-chip pump power (red). The maximum efficiency of 1.0% is obtained with an on-chip peak pump power of 13 dBm.

The maximum on-chip conversion efficiency of 1.0% is extracted from the spectrum with a peak pump power of 13 dBm in waveguide. The conversion efficiency $\eta$ at different pump power is obtained through a full calibration procedure detailed in [5]. As shown in Fig.2 (b), the internal efficiency as well as the cooperativity $C$ is further calculated based on the extracted microwave and optical cavity loading parameters. A theoretical linear predictions (dashed lines in Fig.2 (b)) is fitted from the data points measured with pulsed pump. The vacuum coupling rate is inferred to be $g_{eo} = 2\pi \times 750Hz$. The nonlinearity in cooperativity can be attributed to the degradation of the superconducting resonator from a combination of light absorption, thermo-optic heating and undesired coupling to environment.

4. Outlook

We note that microwave Q can be further improved by better device packaging. With side-coupling fiber glue technique, the insertion loss could be reduced. Therefore even higher system efficiency can be expected at reduced optical drive power for operation in a dilution refrigerator.

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