Optically heralded microwave photons

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Abstract: Interconnecting distant superconducting quantum processors requires optical links. Here, we demonstrate a transducer that generates entangled pairs of microwave and optical photons, achieving a heralding rate of 15 Hz with two added noise photons.

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Networks that distribute entanglement between distant superconducting microwave quantum processors promise breakthroughs in cryptography, quantum computing and distributed sensing [1]. However, interconnecting microwave qubits operating at millikelvin temperatures over large distances requires the use of optical photons. Unlike microwave photons, optical photons have low thermal noise at room temperature and can propagate through low-loss optical fibers. A frequency converter that can bridge the five-orders of magnitude gap in frequency between microwave and optical photons is therefore necessary. Among many approaches [2], transducers based on piezo-optomechanics [3] seem very promising. Through the photoelastic effect, an optical mode is coupled to a mechanical mode which is itself coupled to a microwave mode via the piezoelectric effect (see Fig. 1a). The optical and microwave modes are further coupled to an optical waveguide and a 50 Ω microwave channel respectively. The optomechanical interaction provides the nonlinearity necessary for frequency conversion. Such a transducer can be operated in two regimes: direct transduction and entanglement generation (see Fig. 1b). For the former, a microwave-frequency phonon interacts with a red detuned optical pump photon to generate a slightly higher frequency optical photon. For the latter, a blue-detuned pump photon is parametrically downconverted into an entangled pair consisting of a lower frequency optical photon and a microwave-frequency phonon.

Here, we implement such a transducer in a thin film lithium niobate (LN) on silicon-on-insulator (SOI) platform [4]. We developed this heterogeneous material platform with benefits from the excellent piezoelectric properties of LN as well as the large optomechanical coupling achievable in silicon [3]. The device (see Fig. 1c) consists of a silicon optomechanical crystal which co-confines an optical and mechanical mode at 193.5 THz and 3.6 GHz respectively. The mechanical mode is engineered to be a hybrid silicon/LN mode, allowing it to be piezoelectrically transduced. The optical and mechanical mode profiles are shown in Fig. 1d. To impedance match the piezoelectric resonator to a 50 Ω transmission line, we use a high kinetic inductance microwave resonator which we fabricate on a separate chip and wirebond to the transducer. The microwave resonator can be tuned into resonance with the mechanical mode through an externally applied magnetic field [5].

Fig. 1. a, Mode schematic with the respective coupling rates. b, Simplified device operation principle. c, Left: False color scanning electron micrograph of the transducer showing the silicon (green), LN (purple) and aluminum electrodes (yellow). Scale bar: 2 μm. Right: Optical image of the transducer. d, Simulated optical and mechanical mode profiles of the transducer.
We first characterize the device by extracting the coupling and loss rates. The optical mode is critically coupled with a total loss rate $\kappa_o/2\pi = 1.12$ GHz and we measure a zero-point optomechanical coupling rate of $g_0/2\pi = 413$ kHz and a piezoelectric coupling rate $g_\mu/2\pi = 424$ kHz. With a 10.2 μW continuous-wave red-detuned laser pump, we measure a bidirectional peak conversion efficiency of $(4.9 \pm 0.5)$%, a 3 dB bandwidth of 1.5 MHz and added noise referred to the input of $n_{\text{added}} = 99 \pm 10$ (see Fig. 2a). Finally, we use a blue-detuned pulsed pump laser with on-chip peak power of 5 μW, pulse length of 20 ns which upon arrival, generates a lower frequency sideband photon and a microwave frequency phonon with $\sim 3.6\%$ probability. The pulse repetition rate of 170 kHz leads to a thermal occupation $n_{\text{th}} = 0.68 \pm 0.08$ before the arrival of the pulse. After filtering out the pump photons, the sideband photon reaches a single photon detector (SPD). We demodulate the output microwave field from the device after amplification. When the SPD registers a photon, we store the data in a separate post-selected dataset (see Fig. 2b). We measure the resulting probability distribution of the post-selected data and subtract from it the probability distribution of the full dataset. We obtain the blue curve in Fig. 2c showing that a microwave photon has been added to the output field. Heating from undesired optical absorption of pump photons in the device leads to added thermal noise $n_\text{h} = 1.6 \pm 0.5$. Due to device and measurement setup inefficiencies, the heralding rate is limited to 15 Hz in this experiment. With realistic improvements towards reducing device heating and increasing device and system efficiencies, entangling remote superconducting qubits using piezo-optomechanical transducers is within reach.

Fig. 2. **a**, Continuous-wave bidirectional microwave-to-optical conversion efficiency. **b**, Simplified measurement setup for the optical heralding experiment. **c**, Difference between the radially binned probability distribution of the post-selected dataset and the full dataset (blue). For comparison, we also plot this difference for a randomly selected dataset (black). The points are measurements and the shaded area theory. $\alpha$ is the quadrature-phase amplitude of the microwave mode.

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References

1. H. J. Kimble, “The quantum internet,” Nature **453**, 1023–1030 (2008).
2. X. Han, W. Fu, C.-L. Zou, L. Jiang, and H. X. Tang, “Microwave-optical quantum frequency conversion,” Optica **8**, 1050–1064 (2021).
3. M. Mirhosseini, A. Sipahigil, M. Kalaei, and O. Painter, “Superconducting qubit to optical photon transduction,” Nature **588**, 599–603 (2020).
4. W. Jiang, F. M. Mayor, S. Malik, R. Van Laer, T. P. McKenna, R. N. Patel, J. D. Witmer, and A. H. Safavi-Naeini, “Optically heralded microwave photons,” arXiv preprint arXiv:2210.10739 (2022).
5. M. Xu, X. Han, W. Fu, C.-L. Zou, and H. X. Tang, “Frequency-tunable high-Q superconducting resonators via wireless control of nonlinear kinetic inductance,” Appl. Phys. Lett. **114**, 192601 (2019).
6. C. Eichler, D. Bozyigit, C. Lang, L. Steffen, J. Fink, and A. Wallraff, “Experimental state tomography of itinerant single microwave photons,” Phys. Rev. Lett. **106**, 220503 (2011).