Integrated Lithium Niobate Acousto-optic Cavities for Microwave-to-optical Conversion

Linbo Shao[1], Mengjie Yu[1], Smarak Maity[1], Neil Sinclair[1,2], Lu Zheng[3], Cleaven Chia[1], Amirhassan Shams-Ansari[1], Cheng Wang[1,4], Mian Zhang[1], Keji Lai[3], and Marko Loncar[1]

[1]John A. Paulson School of Engineering and Applied Sciences, Harvard University, 29 Oxford Street, Cambridge, MA 02138, USA
[2]Division of Physics, Mathematics and Astronomy, and Alliance for Quantum Technologies (AQT), California Institute of Technology, 1200 E. California Blvd., Pasadena, California 91125, USA
[3]Department of Physics, University of Texas at Austin, Austin, Texas 78712, USA and
[4]Department of Electrical Engineering & State Key Lab of THz and Millimeter Waves, City University of Hong Kong, Kowloon, Hong Kong, China
Email: shaolb@seas.harvard.edu

Abstract: Using integrated acousto-optic cavities on thin-film lithium niobate, we demonstrate efficient conversion of GHz microwaves to 1.5 μm wavelength light via the piezoelectric effects and the optomechanical interactions. © 2020 The Author(s).

1. Introduction

Efficient microwave-to-optical converters and filters are desired for microwave photonic signal processing and long-distance data transmission [1-3]. They could also be used as quantum transducers enabling coherent transfer of quantum information from electrical to optical domains, thus enabling efficient optical links between cryogenic quantum computers. Integrated lithium niobate photonics has emerged as a promising platform for realization of microwave-to-optical converters. Examples include efficient electro-optic modulators with bandwidth above 100 GHz [4], and optomechanical crystals that benefit from materials strong piezoelectric and photoelastic effects [5]. Here, we demonstrate an alternative approach based on integrated acousto-optic cavities realized in integrated lithium niobate photonic platform [6]. A high-quality (Q) acoustic resonator [7, 8] is used as a bridge since it can couple to microwave signals by piezoelectric effect and to optical signals by moving boundaries, photoelasticity, and electro-optics. we also demonstrate a microwave photonic link with unitary gain, which refers to a 0-dB microwave power transmission over an optical channel.

2. Lithium niobate acousto-optic cavities

Our device consists of an optical racetrack cavity partially embedded within an acoustic resonator, fabricated in suspended thin-film lithium niobate (Fig. 1**a**). The optical cavity, with loaded optical Q factor exceeding 2×10^6, is coupled by on-chip waveguide (Fig. 1**b**), and the acoustic resonator, with loaded acoustic Q factors of 3,600 is electrically excited by using interdigital transducers (IDTs) (Fig. 1**c**). Due to strong piezoelectric effect of lithium niobate, acoustic waves generate microwave electric fields, which in turn couple to optical waves via strong electro-optic effect. This effect enhances the overall acousto-optic coupling mediated by photo-elastic and moving boundary effects. Numerical simulations reveal that this effect contributes constructively to the moving boundaries and photoelastic components, resulting in large acousto-optic effect (Fig. 1**d**). We note that in our devices the contribution of the moving boundary component is an order of magnitude weaker than the other two effects.

3. Experimental characterization

The characterization setup used in our experiments is shown in Fig. 2**a** and consists of vector network analyzer (VNA), a tunable telecom laser, Erbium-doped fiber amplifier (EDFA), and a photodiode (Finisar Ultra-High-Power Photodetector VPDV2120). When microwave signal is applied to resonantly excite the acoustic cavity, the sidebands (additional transmission dips) are observed in the optical transmission spectra. Second-order sideband dips could be generated with microwave power as low as 10 dBm, indicating a strong modulation of the optical cavity by the acoustic modes (Fig. 2**b**). To investigate the potential of our acousto-optic cavities in microwave photonics, we measure the S parameters of our system by sweeping the frequency of input microwave signal (Fig. 2**c**). The microwave photonic link is measured to be a unitary gain at 1.57 GHz frequency, which is achieved without the need of an optical amplifier within the link (after acousto-optic device). In these experiments, about 500 mW of optical power was delivered to the device with overall optical insertion loss of 10 dB, resulting in as little as 50 mW of optical power on the detector.

4. Conclusion

We demonstrate integrated acousto-optic cavities on thin-film lithium niobate platform. Unitary gain microwave photonic link is achieved by high-Q acoustic resonators and acousto-optic interactions in lithium niobate. Potential applications include microwave-to-optical quantum coherent converters, where mechanical resonance promotes conversion efficiency, and radar systems [9], where a spectral bandwidth of the pulse repetition frequency is enough to get information of moving targets.

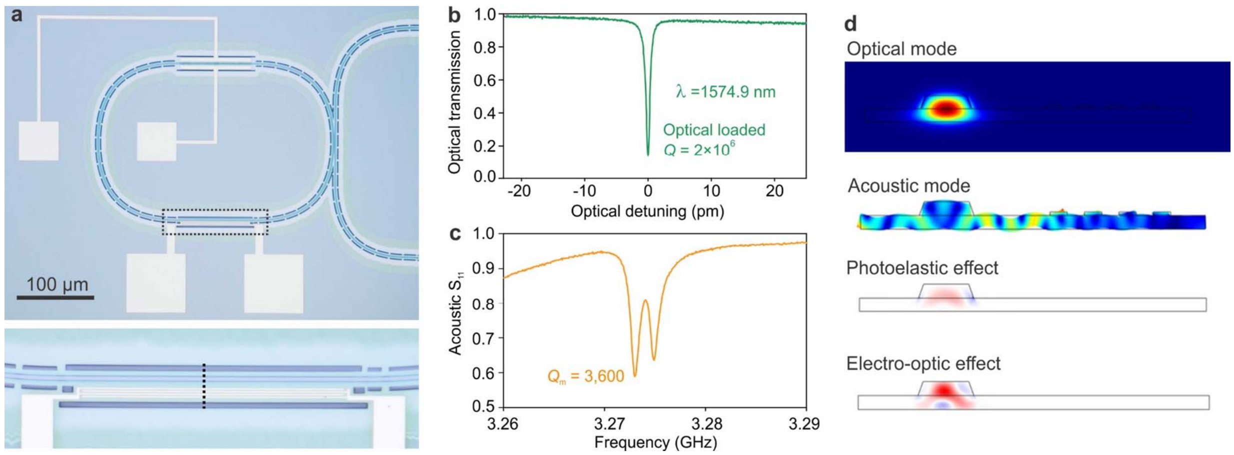

Fig. 1 Lithium niobate acousto-optic cavities. **a**, Microscopic image of optical racetrack cavity with thin-film acoustic resonators. The acoustic resonator is excited by the IDT. The zoom-in region is marked in the dash box. **b**, Optical transmission spectrum of a high-*Q* optical mode. **c**, Electrical S_{11} measurements of an acoustic mode. **d**, Acousto-optic simulation of the cross-section (marked in red line in inset in **a**) showing coupling between optical and acoustic modes via combined photoelastic and electro-optic effect.

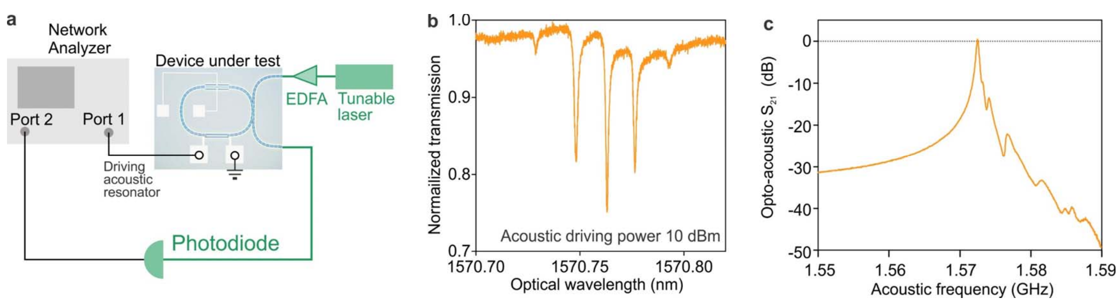

Fig. 2 Measurements of the acousto-optic RF link. a, Schematic of the experimental setup used for device characterization. **b,** The optical transmission spectrum showing optical sidebands due to a 10 dBm resonant acoustic wave driving. **c**, Microwave S parameter spectra of the acousto-optic microwave photonic link.

Acknowledgment

This work was supported by National Science Foundation (DMR-1707372, DMR-1231319, ECCS-1740296, ECCS-1810233); Office of Naval Research (N00014-15-1-2761); Natural Sciences and Engineering Research Council of Canada; U.S. Department of Energy (DE-SC0019219), Natural Sciences and Engineering Research Council of Canada (NSERC), the AQT Intelligent Quantum Networks and Technologies (INQNET) research program, and by the DOE/HEP QuantISED program grant, QCCFP (Quantum Communication Channels for Fundamental Physics).

References

1. D. Marpaung, et al., "Integrated microwave photonics," Nat. Photonics **13**, 80-90 (2019).
2. J. S. Fandiño, et al., "A monolithic integrated photonic microwave filter," Nat. Photonics **11**, 124-129 (2016).
3. D. Marpaung, et al., "Low-power, chip-based stimulated Brillouin scattering microwave photonic filter with ultrahigh selectivity," Optica **2**, 76-83 (2015).
4. C. Wang, et al., "Integrated lithium niobate electro-optic modulators operating at CMOS-compatible voltages," Nature **562**, 101-104 (2018).
5. W. Jiang, et al., "Lithium Niobate Piezo-optomechanical Crystals," arXiv preprint, arXiv:1903.00957 (2019).
6. L. Shao, et al., "Microwave-to-optical conversion using lithium niobate thin-film acoustic resonators," Optica **6**, 1498-1505 (2019).
7. Y. Yang, et al., "1.7 GHz Y-Cut Lithium Niobate MEMS Resonators with FoM of 336 and fQ of 9.15×10^12," in *2018 IEEE/MTT-S International Microwave Symposium - IMS*(2018), pp. 563-566.
8. L. Shao, et al., "Phononic Band Structure Engineering for High-Q Gigahertz Surface Acoustic Wave Resonators on Lithium Niobate," Physical Review Applied **12**, 014022 (2019).
9. J. Capmany, et al., "A tutorial on microwave photonic filters," J. Lightwave Technol. **24**, 201-229 (2006).