European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Lithium-Niobate-Based Frequency-Agile Integrated Lasers

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Abstract *We demonstrate narrow-linewidth ultrafast tunable integrated lasers based on heterogeneously integrated thin-film lithium niobate on ultra-low loss silicon nitride integrated photonic circuits. Using self-injection locking of a hybrid microresonator, we achieve a tuning speed of > 10 peta-Hertz-per-second. We also perform FMCW LiDAR ranging experiments. © 2022 The Author(s)*

Introduction

Rapid progress in the domain of thin-film lithium niobate integrated photonics resulted in demonstration of CMOS-compatible electro-optic modulators [1, 2], electro-optic frequency combs generation [3] and microwave-optical quantum transduction [4]. Photonic circuitry based on lithium niobate can also find its application in the domain of integrated tuneable lasers [5].

Ultra-low noise lasers have been demonstrated based on self-injection locking of diode lasers to integrated [6] and whispering gallery mode [7] optical microresonators with ultra-low loss. It was recently demonstrated that by using an optical microresonator with piezo-electrical actuation and stress optical tuning, we can endow such a laser with MHz tuning bandwidth and GHz frequency excursion, ideal for coherent laser-based ranging [8].

However, high tuning linearity and efficiency were observed, the frequency bandwidth of laser wavelength modulation is inherently limited by the excitation of mechanical modes by the actuator. Thus, additional stringent phononic engineering is required to reach high modulation frequencies (up to 10 MHz [8]). In contrast, electro-optical actuation does not strongly excite mechanical modes of the chip and supports GHz bandwidths [1].

In this paper, we designed an electro-optically tuneable laser source based on the heterogeneously integrated lithium niobate on Damascene silicon nitride (LNOD) platform [9], endowing ultra-low-loss circuits [10] with electro-optic tunability and demonstrate its potential for applications such as frequency modulated continuous-wave (FMCW) LiDAR.

Results

A conceptual representation of the proposed tunable laser is given in Fig. 1(a). A distributed-feedback (DFB) indium phosphide laser is self-injection-locked to an external LNOD microring resonator mode, and the output frequency is changed by applying voltage to electrodes placed along the resonator circumference. The structure of the LNOD waveguide (see Fig. 1(b)) leads to a hybrid optical mode that partially penetrates the layer of lithium niobate making possible electro-optic modulation. A high-quality factor for the

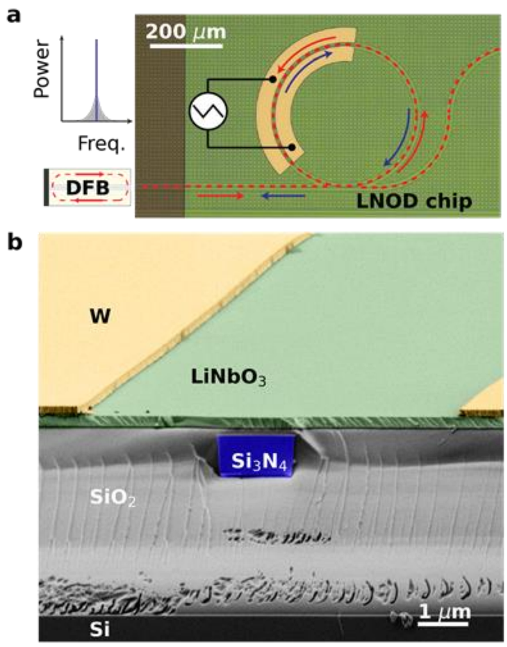

Fig. 1: (a) Schematic of the integrated tunable laser source. A DFB laser diode is self-injection locked to a high-Q optical mode of a LNOD microring resonator via butt-coupling. Rayleigh scattering from inhomogeneities in the microring provide the feedback to the DFB. The laser frequency is modulated by applying a voltage from an arbitrary waveform generator to integrated tungsten electrodes. (b) False-colored scanning electron microscope image of a LNOD waveguide cross-section.

LNOD mode is important for achieving wide locking bandwidth and pronounced linewidth narrowing [11]. Because of the low-loss Damascene silicon nitride circuits underneath, median intrinsic coupling rate (Fig. 2(a)) is 100 MHz. That is equivalent to a quality factor of 2×10^6. The self-injection-locked state of the laser is characterized by locking bandwidth of 1.1 GHz, 30 dB suppression of the phase noise spectrum and intrinsic frequency noise of 3.14 kHz (see Fig. 2(c)).

The frequency tuning potential of the laser can be inferred from Fig. 2(b), where the electro-optic response curve is measured by positioning a reference laser on the flank of a selected resonance and applying a voltage to the electrodes with a vector network analyser. The small-signal frequency response is flat, showing no degradation of modulation efficiency with the modulation frequency from 10 kHz to 100 MHz. For frequency-modulated continuous wave (FMCW) LiDAR [12], linear ramp wavelength tuning plays the central role. Thus, we characterize this tuning pattern by applying a triangular voltage waveform to the microresonator electrodes (see Fig. 3(a)). Using a 10 MHz of modulation frequency, we achieve a laser wavelength tuning rate of 12 PHz/s. The chirp nonlinearity at 100 kHz is <1%, and the tuning efficiency is 30 MHz/V.

As a proof-of-principle demonstration, we perform FMCW LiDAR measurements in laboratory environment. For scene elements, we selected a donut-like polystyrene shape and a plastic instrument box. The collected data, after processing, is presented as the point clouds in Fig. 3(b, c). The evaluated resolution of these experiments is 15 cm.

Conclusions

By increasing the quality factor of fabricated LNOD microresonators and the amount of back-reflection, it should be possible to increase the locking bandwidth and decrease the linewidth. Thus, a finer resolution in FMCW ranging experiments would be expected. The reflection could be increased, for instance, by introducing tapers on the lithium niobate layer to enable adiabatic transition of the mode of Damascene silicon nitride integrated waveguide into the one of a LNOD integrated waveguide. This would improve the coupling efficiency of light coming back to the laser. The tuning efficiency could also be improved by optimizing the hybrid LNOD waveguide geometry to achieve a higher confinement factor in the lithium niobate layer. Beyond FMCW LiDAR, the tunable laser source demonstrated here could be utilized for optical

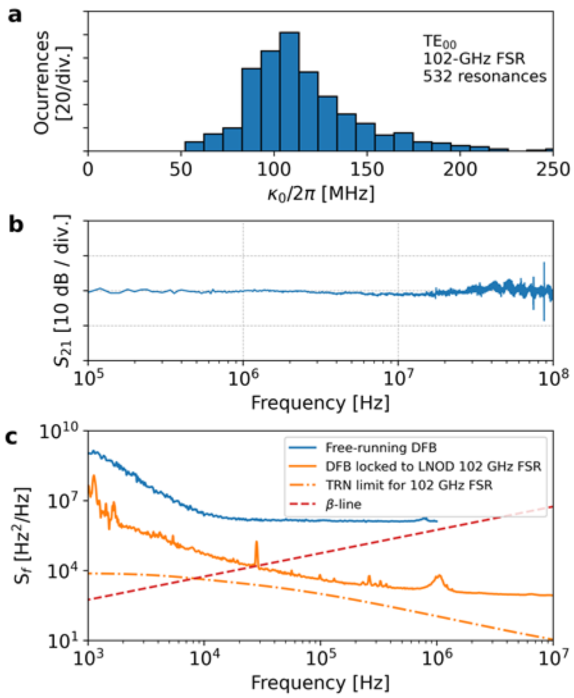

Fig. 2: (a) Histogram indicating intrinsic decay rate distribution of 532 resonances of a LNOD microring with a free spectral range (FSR) of 102 GHz. The median of the distribution is 100 MHz, which corresponds to a quality-factor of 2×10^6. (b) Frequency-dependent electro-optic modulation efficiency of the optical microresonator. (c) Laser frequency noise spectra of the free-running DFB laser (blue line), of the DFB locked to a LNOD microring with 102-GHz FSR (solid orange line), its simulated thermorefractive noise limit (dash-dotted line), and β-line (dashed red line) [15].

coherence tomography [13] and trace gas sensing [14].

Acknowledgements

The samples were fabricated at the EPFL Center of MicroNanoTechnology (CMi) and the Binnig and Rohrer Nanotechnology Center (BRNC) at IBM Research. We thank the cleanroom operations team of the BRNC, especially Diana Davila Pineda and Ronald Grundbacher, for their help and support. This work was supported by contract HR0011-20-2-0046 (NOVEL) from the Defence Advanced Research Projects Agency (DARPA), Microsystems Technology Office (MTO), by funding from the European Union Horizon 2020 Research and Innovation Programunder the Marie Sklodowska-Curie grant agreements No. 722923 (OMT) and No. 812818 (MICROCOMB) and under the FET-Proactive grant agreement No. 732894 (HOT), and by funding from the Swiss National Science

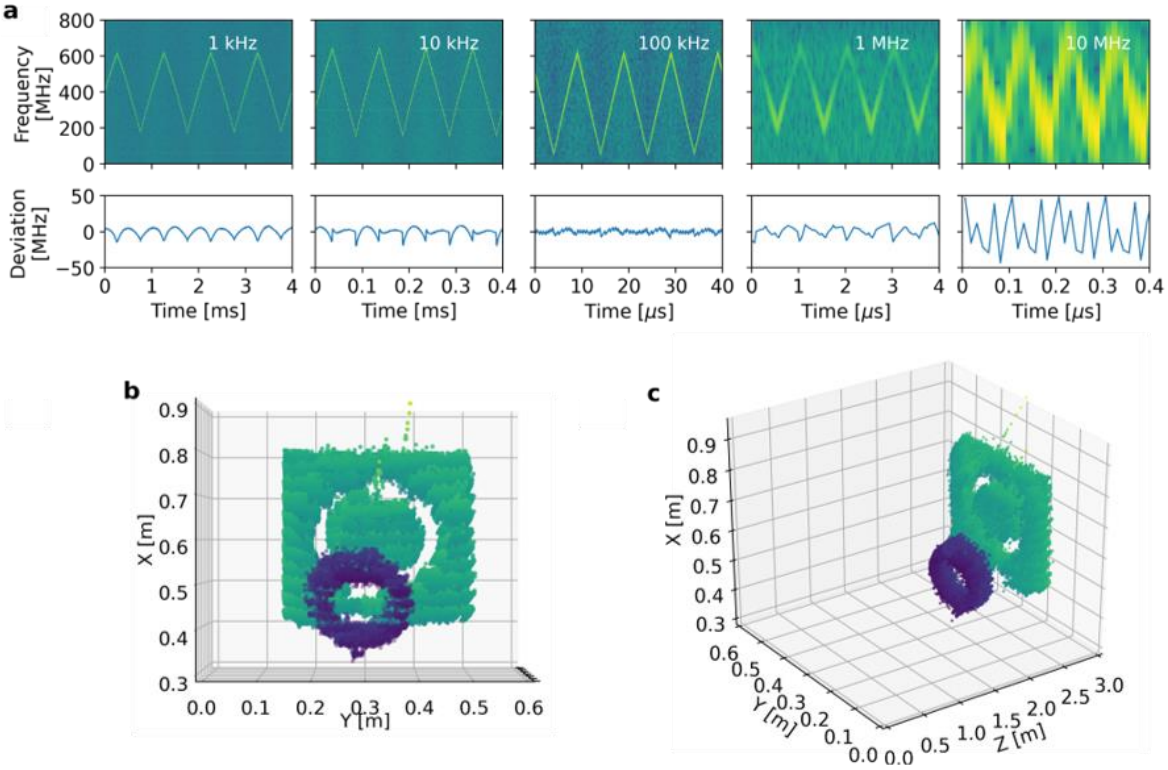

Fig. 3: (a) (Top row) Time-frequency analysis of triangular laser frequency chirps measured via the heterodyne beatnote between the tunable laser and a CW reference laser. (Bottom row) Deviation of measured laser frequency from ideal triangular chirp. (b, c) Point clouds, representing a scene composed of a polystyrene donut-like shape and a plastic plane behind, obtained in FMCW LiDAR experiments with the tunable laser source.

Foundation under grant agreements No. 176563 (BRIDGE)and No. 186364 (QuantEOM).

References

[1] Wang, C. et al. "Integrated lithium niobate electro-optic modulators operating at CMOS compatible voltages," *Nature* vol. 562, p. 101–104, 2018, DOI: http://dx.doi.org/10.1038/s41586-018-0551-y.

[2] M. He et al., "High-performance hybrid silicon and lithium niobate mach–zehnder modulators for 100 gbit s-1 and beyond," *Nature Photonics* vol. 13, p. 359–364, 2019, DOI: https://doi.org/10.1038/s41566-019-0378-6.

[3] Zhang, M. et al. "Broadband electro-optic frequency comb generation in a lithium niobate microring resonator", *Nature* vol. 568, p. 373–377, 2019, DOI: https://doi.org/10.1038/s41586-019-1008-7.

[4] Xu, M. et al. "High-performance coherent optical modulators based on thin-film lithium niobate platform," *Nature Communications* vol. 11, no. 3911, 2020, DOI: https://doi.org/10.1038/s41467-020-17806-0.

[5] Op de Beeck, C. et al. "III/V-on-lithium niobate amplifiers and lasers," *Optica* vol. 8, p. 1288–1289, 2021, DOI: http://opg.optica.org/optica/abstract.cfm?URI=optica-8-10-1288.

[6] Jin, W. et al. "Hertz-linewidth semiconductor lasers using cmos-ready ultra-high-q microresonators," *Nature Photonics* vol. 15, p. 346–353, 2021, DOI: https://doi.org/10.1038/s41566-021-00761-7.

[7] Soltani, M. et al. "Ultrahigh-q whispering gallery mode electro-optic resonators on a silicon photonic chip," *Optics Letters* vol. 41, p. 4375–4378, 2016, DOI: http://ol.osa.org/abstract.cfm?URI=ol-41-18-4375.

[8] Lihachev, G. et al. "Ultralow-noise frequency-agile photonic integrated lasers," arxiv:2104.02990, 2021, DOI: https://arxiv.org/abs/2104.02990

[9] Churaev, M. et al. "Heterogeneously integrated lithium niobate photonics," arXiv:2112.02018, 2021, DOI: https://arxiv.org/abs/2112.02018

[10] Liu, J. et al. "High-yield, wafer-scale fabrication of ultralow-loss, dispersion-engineered silicon nitride photonic circuits," *Nature Communications* vol. 12, no. 2236, 2021, DOI: https://doi.org/10.1038/s41467-021-21973-z.

[11] Kondratiev, N.M. et al. "Self-injection locking of a laser diode to a high-q wgm microresonator," *Optics Express* vol. 25, p. 28167–28178, 2017, DOI: http://www.osapublishing.org/oe/abstract.cfm?URI=oe-25-23-28167.

[12] Uttam, D. & Culshaw, B. "Precision time domain reflectometry in optical fiber systems using a frequency modulated continuous wave ranging technique," *Journal of Lightwave Technology* vol. 3, p. 971–977, 1985, DOI: https://doi.org/10.1109/JLT.1985.1074315.

[13] Ji, X. et al. "On-chip tunable photonic delay line," *APL Photonics* vol. 4, 090803, 2019, DOI: https://aip.scitation.org/doi/10.1063/1.5111164.

[14] Truong, G.-W. et al. "Frequency-agile, rapid scanning spectroscopy," *Nature Photonics* vol. 7, p. 532–534, 2013, DOI: https://doi.org/10.1038/nphoton.2013.98.

[15] Domenico, G. D., Schilt, S. & Thomann, P. "Simple approach to the relation between laser frequency noise and laser line shape," *Applied Optics* **49**, p. 4801–4807, 2010, DOI: http://www.osapublishing.org/ao/abstract.cfm?URI=ao-49-25-4801.