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Ultrafast frequency-agile narrow-linewidth lasers using lithium niobate integrated photonics

(Student paper)

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We present a narrow-linewidth frequency-agile integrated laser based on heterogeneously integrated thin-film lithium niobate on ultra-low-loss Damascene silicon nitride integrated photonic circuits. The platform features tapers with a transition loss of only 0.1 dB from a silicon nitride to a hybrid lithium niobate mode. Utilizing self-injection locking, we realize a tuneable laser with a tuning speed of 12 PHz/s. We also make a system-level demonstration by performing coherent frequency-modulated continuous-wave LiDAR ranging experiments.

Keywords: *thin-film lithium niobate, Damascene silicon nitride, heterogeneous integration, frequency-agile lasers, FMCW LiDAR*

INTRODUCTION

Recent progress in the field of thin-film lithium niobate integrated photonic circuits manifested itself in demonstrations of low-V_π electro-optic modulators [1, 2], generation of electro-optic frequency combs [3] and microwave-optical transduction [4]. Lithium-niobate-based circuitry can also be applied in the domain of integrated frequency-agile laser sources [5]. Ultra-low-noise lasers have been shown via self-injection locking of diode lasers to integrated [6] and whispering gallery modes [7] optical microresonators with high quality factors.

It has been recently shown that by using an optical microresonator with piezo-electrical actuation, one can endow such a laser with a MHz-wide tuning bandwidth and a GHz-wide frequency excursion range, as needed for coherent laser-based ranging [8]. Although both highly linear frequency modulation and high tuning efficiency were observed, the bandwidth of laser wavelength modulation is fundamentally limited by excitation of mechanical modes of the substrate by the actuator. Thus, phononic engineering is necessary to achieve high modulation frequencies (up to 10 MHz [8]). In contrast, electro-optic modulation does not excite mechanical modes of the chip, while supporting GHz bandwidths of modulation [1]. Therefore, we assembled an electro-optically tuneable laser comprising a heterogeneously integrated lithium-niobate-on-Damascene-silicon-nitride (LNOD) microresonator [9], combining the advantages of passive ultra-low-loss photonic circuits [10] with the electro-optic tunability. We demonstrate the potential for applications by performing frequency-modulated continuous-wave (FMCW) LiDAR experiments. The platform, *inter alia*, features a low-loss-taper transition of the silicon nitride integrated waveguide mode into a lithium niobate mode (see Fig. 1). It exhibits 0.1 dB loss per transition (versus 2 dB for the straight transition), and < 0.8 dB loss for ten cascaded transitions (see Fig. 1(d, f)). The taper is employed to enhance the back-reflection to the laser diode, thus, facilitating better locking conditions.

RESULTS

A conceptual representation of the tunable laser is given in Fig. 2(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. 2(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 LNOD mode is important for achieving a wide locking bandwidth and pronounced linewidth narrowing [11]. Because of the low-loss Damascene silicon nitride circuits underneath, the median intrinsic loss rate (see Fig. 2(c)) is $\kappa_0/(2\pi) = 100$ MHz, equivalent to a quality factor of 2×10^6. The self-injection-locked state of the laser is characterized by a locking bandwidth of 1.1 GHz, 30 dB suppression of the phase noise spectrum, and intrinsic frequency noise of 3 kHz (see Fig. 2(e)).

The frequency tuning potential of the laser can be inferred from Fig. 2(d), 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 analyzer. 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], wavelength tuning with a linear ramp plays the central role. Thus, we characterize the tuning by applying a triangular voltage waveform to the microresonator electrodes (see Fig. 2(f)). Using a 10 MHz 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. The tuning efficiency can be further improved by reducing the thickness of the silicon nitride waveguides and of the silicon oxide interlayer, thus, increasing the participation ratio of the optical mode in lithium niobate. Following this approach, efficiencies up to 300 MHz/V can be reached in a push-pull configuration, what has been experimentally verified.

As a proof-of-principle demonstration, we perform FMCW LiDAR measurements in a laboratory environment. For scene elements, we use a donut shape made of polystyrene and a plastic instrument box. The collected data, after processing, is presented as point clouds in Fig. 2(g) and (h). The evaluated resolution of these experiments is 15 cm.

DISCUSSION

By further increasing the quality factor of fabricated LNOD microresonators, it should be possible to increase the locking bandwidth and decrease the linewidth of the laser in the self-injection locked state. Thus, a finer resolution in FMCW ranging experiments would be expected. Also, introduction of loop-mirrors as a new circuitry element and use of racetrack resonators instead of microrings would further enhance back-reflection and tuning efficiency what eventually could lead to a coherent LiDAR engine at CMOS-compatible voltage levels.

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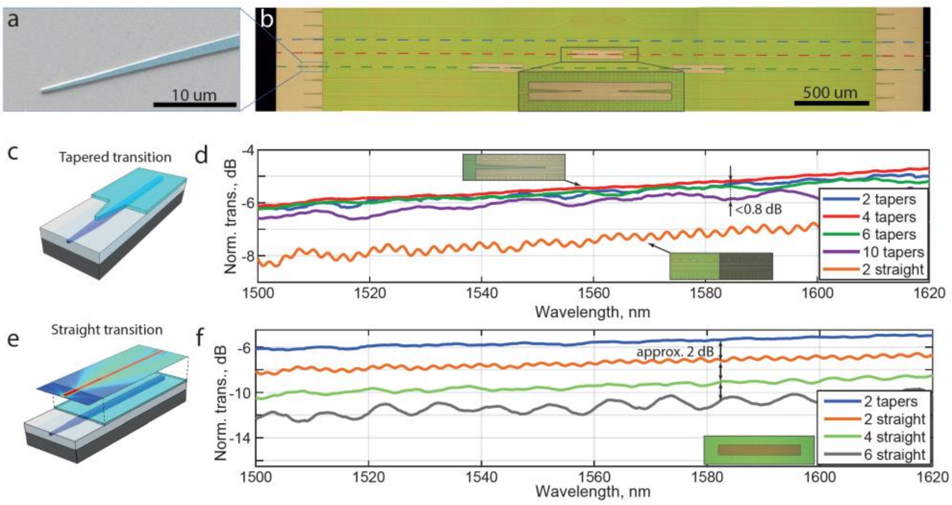

Fig. 1. ***Adiabatic mode transitions.*** *(a) False-colored SEM image of an LNOD taper. (b) Micrograph of a chip with tapers. (c) Illustration of a tapered transition. (d) Transmission spectra of breakout LNOD waveguides shown in (b) along with data for a straight transition as reference. (e) Illustration of a straight transition. (f) Transmission spectra of LNOD waveguides with straight transition breakouts.*

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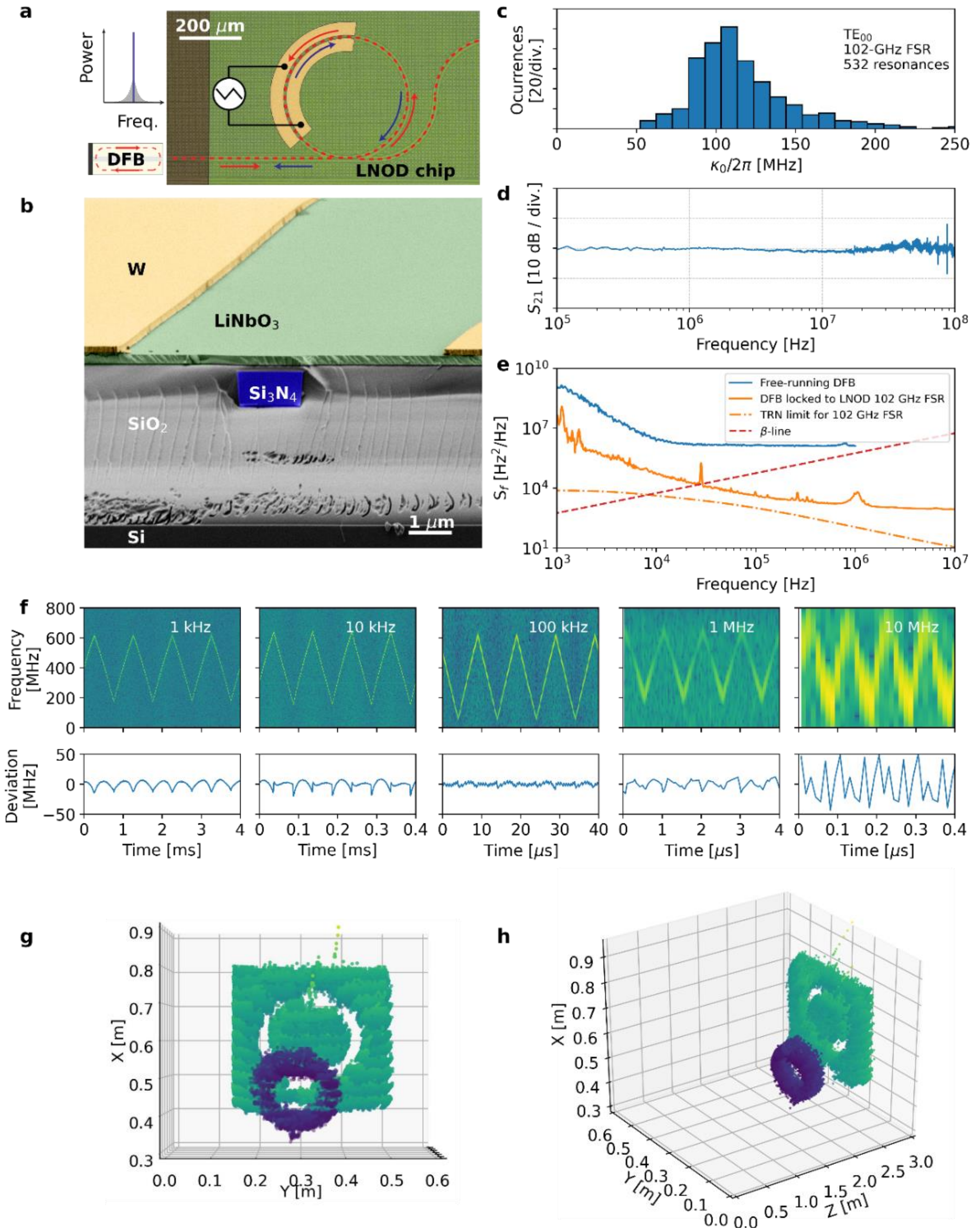

*Fig. 2. **SIL LNOD tunable laser.** (a) Schematic of the integrated tunable laser source. A DFB laser diode is self-injection locked to a high-Q optical mode of an LNOD microring resonator via butt coupling. Rayleigh scattering from inhomogeneities in the microring provide the feedback to the DFB. The 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. (c) 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, corresponding to a quality factor of* 2×10^6*. (d) Frequency-dependent electro-optic modulation efficiency of the optical microresonator. (e) Laser frequency noise sprectra 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). (f) (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 an ideal triangular chirp. (g-h) Point clouds, representing a scene composed of a polystyrene donut shape and a plastic plane behind, obtained in FMCW LiDAR experiments with the tunable laser source.*