Lithium-niobate-based narrow-linewidth frequency agile integrated lasers with petahertz frequency tuning rate

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Abstract: We demonstrate an electro-optically tunable hybrid integrated laser self-injection locked to a mode of a heterogeneously integrated lithium-niobate-on-Damascene-silicon-nitride microresonator. An intrinsic linewidth of 3 kHz and a frequency tuning rate of 12×10^{15} Hz/s were observed. Proof-of-principle coherent LiDAR experiments were performed.

Thin-film lithium niobate photonic integrated circuits have found application as electro-optic modulators [1, 2], as a means for generating electro-optic frequency combs [3], and as microwave-optical quantum transducers [4]. Photonic circuits based on lithium niobate could also enable low-phase-noise electro-optically tunable lasers by taking advantage of self-injection locking and the associated frequency pulling effect [5]. Specifically, a laser oscillator can be locked to an optical mode of an external high-quality-factor cavity and the output frequency of the laser modulated via tuning of the cavity mode (e.g. by means of the Pockels effect).

This concept was previously realized for a distributed-feedback indium phosphide diode laser butt coupled to a Damascene silicon nitride microring resonator integrated with an aluminium nitride piezoelectric actuator providing stress-optic modulation of the microresonator mode [6]. Although low nonlinearity and high tuning efficiency were reported [6], the modulation speed was fundamentally limited by the mechanical resonances of the chip on which the devices were integrated, and additional phononic engineering is required. In this regard, electro-optic modulation could offer a more effective solution for modulation of the lasing wavelength. To this end, we employed heterogeneous integration of lithium niobate on Damascene silicon nitride (LNOD), combining the electro-optic tuning capability of the former with the ultra-low propagation loss of the latter [7].

A schematic of the device is shown in Fig. 1(a) and a characteristic cross-section of an LNOD structure in Fig. 1(b). Silicon nitride waveguides are buried in silicon dioxide and covered with a thin lithium niobate layer with tungsten electrodes on top. The ultra-low loss of the Damascene silicon nitride structures [8] leads to a median intrinsic decay rate of 100 MHz for the LNOD microresonator (Fig. 1(c)). The corresponding high quality factor of $Q \approx 2 \times 10^6$ enables a locking bandwidth of ~ 1.1 GHz and 20 dB suppression of the frequency noise power spectral density. The measured intrinsic linewidth of the locked laser is 3 kHz.

The potential of the platform for fast laser wavelength tuning is evident from Fig. 1(d), where we show the electro-optic tuning response of the microresonator. We measure it by setting the laser frequency to the flank of the resonance and applying the modulation voltage from a vector network analyser to the device electrodes. The small-signal frequency response is flat up to 100 MHz, well above the value achieved previously for stress-optic actuation. The highest tuning frequency measured for a triangular ramp waveform was 10 MHz with a frequency excursion of 600 MHz, corresponding to a tuning speed of 12×10^{15} Hz/s. A tuning nonlinearity of $< 1\%$ (with respect to frequency excursion) was observed at a modulation frequency of 100 kHz (Fig. 1(e)). These results pave the way to use of this tunable laser source for frequency-modulated continuous-wave (FMCW) LiDAR [9]. In a proof-of-principle experiment, we demonstrated reconstruction of a simple scene comprising a polystyrene donut-like shape and a wall of an instrument box, serving as background, with resolution of 20 cm (Fig. 1(f)).

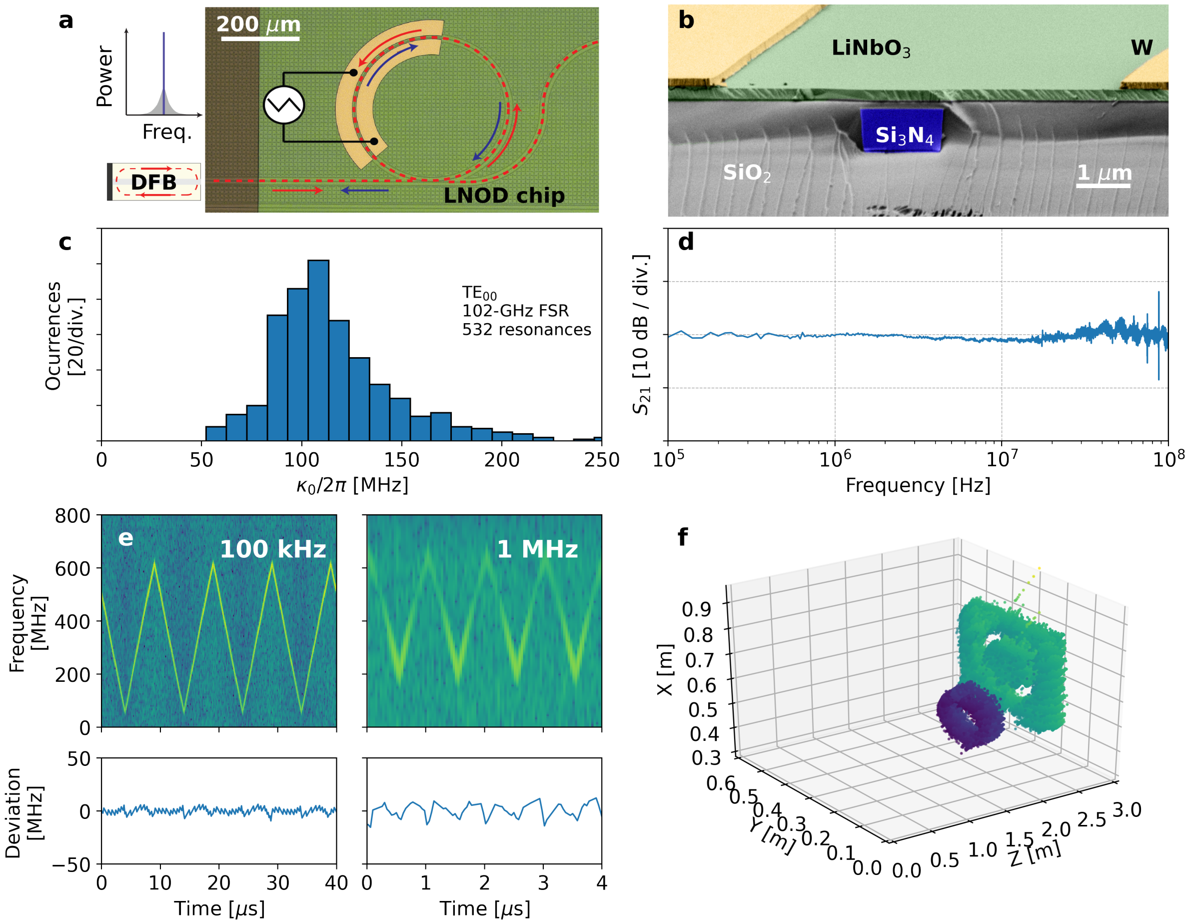

Fig. 1. **(a)** Schematic of the self-injection locking principle. Laser wavelength tuning is achieved by applying a voltage signal (e.g., a linear ramp) on the tungsten electrodes. **(b)** False-colored scanning electron microscopy image showing a cross-section of an LNOD device. **(c)** Histogram showing the distribution of the intrinsic decay rates $\kappa_0/2\pi$ for an LNOD microring resonator with a free-spectral range (FSR) of 102 GHz. The median value of the distribution is 100 MHz, which is equivalent to a quality factor $Q \sim 2 \times 10^6$. **(d)** Electro-optic modulation response of an LNOD microresonator with FSR of 102 GHz. **(e)** Time-frequency map of the heterodyne beat note between the integrated laser source and a reference external cavity diode laser (ECDL) when a triangular voltage ramp is applied to the electrodes of the LNOD microresonator for modulation frequencies of 100 kHz and 1 MHz. **(f)** Point cloud showing the reconstruction of a scene comprised of a polystyrene donut-like shape and a plastic wall of an instrument box behind, after processing the data collected in a proof-of-principle FMCW LiDAR experiment.

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