Low-noise frequency-agile photonic integrated lasers for coherent ranging

(Student paper)

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We demonstrate a hybrid photonic integrated laser that exhibit intrinsic linewidth of 25 Hz, while offering megahertz actuation bandwidth with the tuning range larger than 1 GHz, attained by a DFB laser self-injection locking to a high-Q Si_3N_4 microresonator with high confinement waveguides and AlN piezoelectrical actuator, allowing both single line operation and microcomb generation. We develop a compact FMCW LiDAR laser with triangular chirp optical signals at a rate up to 1 MHz and perform optical ranging in lab environment without requiring any linearisation.

Keywords: *FMCW LiDAR, hybrid integrated lasers, silicon nitride, self-injection-locking*

INTRODUCTION

Low-noise lasers are of central importance in a wide variety of applications, including high-spectral-efficiency coherent communication protocols, long-distance coherent light detection and ranging (LiDAR) and distributed fibre sensing. In addition to low phase noise, the ability to achieve high bandwidth actuation of the laser frequency is imperative for carrier recovery in coherent communications and triangular chirping for frequency-modulated continuous-wave (FMCW) based ranging. While there has been major progress in the development of heterogeneously integrated silicon based lasers – now commercially employed in data centres – that leverage CMOS wafer scale manufacturing, integrated lasers with lowest phase noises are based on optical feedback from components that do not possess fast frequency tunability, thus resulting in the lack of frequency agility. Applying the technique of self-injection locking to ultra low loss Si_3N_4 photonic integrated circuits has enabled hybrid integrated lasers with Hz-level Lorentzian linewidth, that have showed steady improvements. A particularly interesting application for integrated photonics based low noise lasers is coherent FMCW LiDAR. Recently, autonomous driving and areal mapping has increased the interest in such sources and a fully hybrid integrated low-noise, high and frequencyagile source could hence unlock further applications of coherent FMCW LiDAR. Laser phase noise limits the maximum operating distance and ranging precision in FMCW LiDAR. However, a key requirement for FMCW at long range is in addition to low phase noise, frequency agility, i.e to achieve fast, linear and hysteresisfree tuning.

RESULTS

The hybrid laser system comprises a laser chip with a distributed feedback (DFB) structure and a Si_3N_4 photonic chip in which a microring resonator and an AlN piezoelectrical actuator are integrated (Fig. 1(a-c)). The Si_3N_4 microresonator and the bus waveguide are fabricated with the photonic Damascene reflow process [1], showing an intrinsic quality factor of Q_0>20 millions. Made from polycrystalline AlN (Fig 1 (d)) as the main piezoelectric material, the piezoelectric actuator has molybdenum (Mo) and aluminium (Al) as the bottom electrode (ground) and the top electrode, respectively [2]. The DFB laser diode that is directly butt-coupled to the photonic chip is operating at central wavelength of 1556 nm with output power of 40 mW in free running regime. The gap between the laser chip and the microresonator is adjusted for optimal feedback phase [3], yielding the maximum locking range and the highest noise suppression rate of more than 35 dB. Figure 1(e) shows the frequency noise spectra of the laser in free-running regime and self-injection-locking to resonators with distinct FSRs of 190, 10 and 2 GHz, respectively. At frequencies above 1 MHz, the laser frequency noises reaches under 8 Hz^2/Hz, and the optical cross-correlation-based characterisation allows us to confirm the laser intrinsic linewidth is below 25 Hz.

The frequency noise power spectral density was found to be in good quantitative agreement with fundamental thermo-refractive noise (TRN) limit of the microresonator at mid range offsets from 5 to 100 kHz. Thus, we demonstrate using high confinement Si_3N_4 platform the laser performance limited by thermorefractive noise, which has only been shown in Si_3N_4 low confinment waveguides. We note that this intrinsic linewidth can be further reduced by using microresonators with even larger optical mode volume and therefore reduced TRN.

By tuning the voltage applied to the AlN actuator we tune the cavity resonance. By maintaining diode current at fixed value corresponding to the center of the self-injection locking range, we sweep the laser frequency. With the AlN actuators engineered based on novel contour mode cancellation and differential drive schemes, the microresonator resonance can be frequency-modulated via the stress-optical effect with a flattened bandwidth up to 1 MHz. We demonstrate optical carrier that is triangularly chirped with frequency excursion 1.2 GHz at rates up to 800 kHz with a deviation from a linear chirp less than 1 % (Fig.1 (f)). The versatility permitted by the outstanding optical and mechanical properties of the system allows us to demonstrate low-cost FMCW LiDAR engine with 12.5 cm resolution and 100 kpixel/s rate and perform an optical ranging experiment in the lab.

We investigate the reduction of tuning voltage requirement by introducing an integrated piezoelectric actuator based on lead zirconium titanate (PZT).

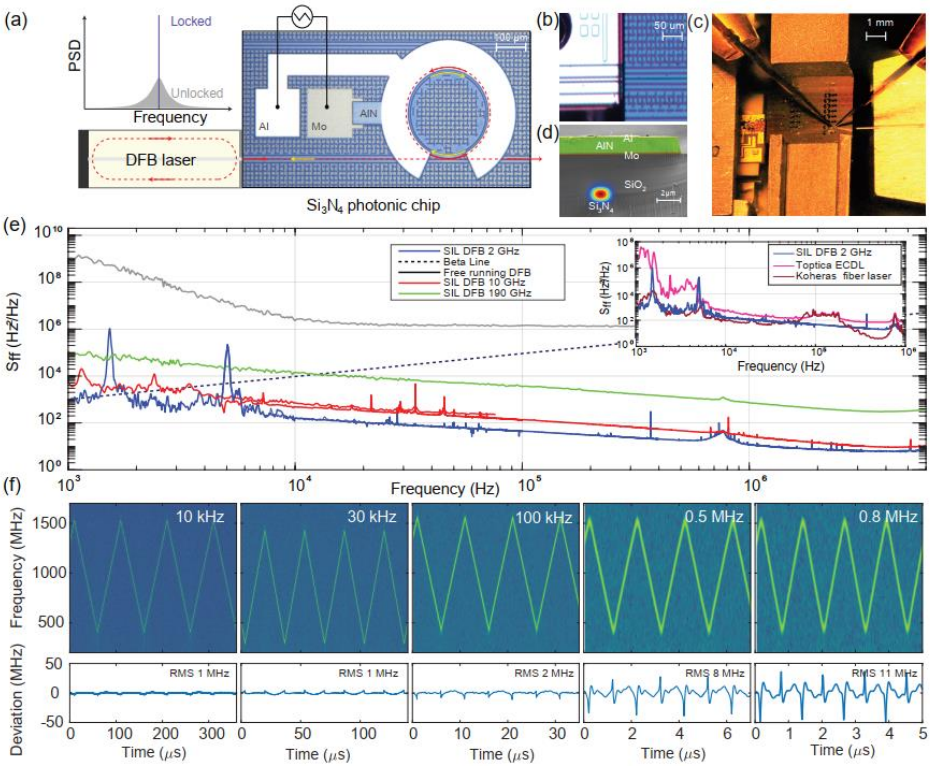

Fig. 1. (a) Principle of laser linewidth narrowing via laser self-injection locking. The laser frequency tuning is realised by applying a sweeping electrical signal on the AlN actuator that is monolithically integrated on the Si_3N_4 microresonator. (b) Optical micrograph showing the DFB laser butt-coupled to the Si_3N_4 photonic chip. (c) Material stack of the device. (c) Photo of the hybrid laser. (d) Material stack of the device. (e) Frequency noise spectra of the hybrid integrated laser system using microresonators with different FSRs. Inset: comparison to commercial ECDL and fiber lasers. (f) Time-frequency spectrograms of the heterodyne beatnotes for different chirp frequency. Bottom row: Residual of least squares fitting of the experimental time-frequency traces with a lineartriangular chirp pattern.

As an actual demonstration of the potential of the hybrid integrated laser, we perform optical FMCW LiDAR mapping in the laboratory environment. Importantly, we can - due to the excellent linearity, low hysteresis, and narrow linewidth – perform ranging without any adaptive clock sampling and without pre-distortion linearization.

DISCUSSION

The approach is based on foundry-ready processes that include photonic integrated circuits based on Si_3N_4 as well as AlN and PZT MEMS processing, and is therefore amenable to large-volume manufacturing. The combination of narrow linewidth (kHz level) along with the fast and flat actuation response, makes the

source ideally suited for medium to long-range coherent LiDAR, as required for autonomous driving, drone navigation, or industrial and terrain mapping. The combination of low noise and fast on chip tuning, alleviates the need for external components such as AOMs or single sideband modulators for fast frequency actuation, and may also find use in other areas such as locking of lasers to reference cavities, or atomic transitions - where a tight lock is required, and can be achieved with a high actuation bandwidth as demonstrated here. In addition, while our lasers were demonstrated at 1556 nm, the center wavelength can be readily extended to other ranges, including the near IR and mid-infrared, due to the transparency of Si_3N_4.

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