Highly-Stable Integrated InGaAsP/InP Mode-Locked Laser and Optical Phase-Locked Loop

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***Abstract*— We demonstrate an integrated InGaAsP/InP mode-locked laser that is stabilized with an optical phase-locked loop (OPLL). Using the OPLL, a single comb line is locked to a reference oscillator (a 200 Hz linewidth Brillouin laser). The comb linewidth is reduced from 100 MHz (unlocked) to < 550 Hz (locked) using the OPLL. The rms phase error between the comb and reference laser is 20°. The linewidth of the adjacent comb lines is < 1 kHz, and the comb spans 430 GHz.**

***Index Terms*— Mode locked lasers, photonic integrated circuits, integrated optics, comb line generation, optical phase locked loop.**

I. Introduction

INTEGRATED mode-locked lasers (MLLs) are a common source for optical comb generation, whereas other comb sources include optical parametric oscillation (OPO) [1] and cavity-enhanced phase modulation [2]. InGaAsP/InP optical comb sources operating at $1.55\,\mu$m wavelength have applications in metrology [3], low-noise microwave and THz oscillators [4], sensing and imaging (e.g. frequency-resolved and frequency-modulated-continuous-wave (FMCW) LIDAR) [5], and wavelength-division-multiplexed (WDM) data communication [6]. Typically semiconductor combs have optical linewidth of >1 MHz and frequency drift in the MHz range arising from electrical, thermal, and mechanical fluctuations. Narrower optical linewidth and improved stability enables better resolution for sensing and imaging, as well as higher spectral efficiency, i.e., higher QAM, for telecommunications.

Stabilization of integrated comb sources can be achieved using optical injection locking and feedback circuits, such as phase-locked loops. Researchers have demonstrated injection-locked active, passive, and hybrid mode-locked lasers [7]–[10], with hold ranges for locking varying from ∼200 to 800 MHz. As injection locking typically suppresses all modes but a few near the injected tone [10], these demonstrations used either large RF drive power with active mode locking (20.5 dBm) [8] to create multiple reference lines inside the cavity, or achieved this externally using a Mach–Zehnder modulator and injected multiple phase-locked tones with passive mode locking [9]. A trade-off quickly becomes apparent between phase-noise reduction and comb suppression. Higher injected powers reduce more of the phase noise. However, they also suppress the adjacent modes leading to single-mode lasing at high injected power.

The optical phase-locked loop (OPLL) is a promising device to achieve stabilized broadband comb sources with high levels of phase-noise suppression. An OPLL allows the phase noise to be cloned from a reference laser to a slave laser, i.e., a current controlled oscillator, within the loop bandwidth. Only recently have integrated OPLLs been demonstrated [11], and heterodyne locking at a frequency offset from −9 to 7.5 GHz has been shown [12]. Through optical integration, the loop is less affected by environmental noise and the loop bandwidth has been increased to over 1.1 GHz [13]. When integrated, the OPLL requires a semiconductor laser, an optical mixer, an optical detector, and a loop filter which can be as simple as resistors and capacitors or as complex as a custom HBT, CMOS, or BJT circuit with amplifiers and mixers. The entire system can fit in the palm of your hand, can be smaller than a quarter, and can run on batteries.

In this demonstration, a monolithic mode-locked laser with an optical mixer and photodetectors is integrated with transimpedance amplifiers (TIAs) and an electronic loop filter. The monolithic photonic integrated circuit (PIC) enables a short OPLL loop delay and provides stable and robust coupling between the optical components to reduce noise. The integrated OPLL comb source has a footprint $< 10 \times 10$ mm^2, where most of this area is due to the electronics and associated wire bonding. To our knowledge, this is the first demonstration of a monolithic semiconductor mode-locked laser stabilized with an OPLL. Short loop delay, realized through photonic integration, is crucial to achieving this stable locking.

II. MLL Fabrication

A Fabry–Perot MLL, an optical coupler, an optical mixing element, and photodetectors are fabricated on an InGaAsP/ InP offset quantum well (OQW) platform that consists of seven 0.9% compressively strained 6.5 nm QWs and eight −0.2%

Manuscript received March 22, 2013; revised May 31, 2013; accepted July 31, 2013. Date of publication August 8, 2013; date of current version August 30, 2013. This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) Photonic Integrated for Coherent Optics program. A portion of this work was done at the UCSB nanofabrication facility, part of the National Science Foundation (NSF) funded NNIN network.

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Digital Object Identifier 10.1109/LPT.2013.2277865

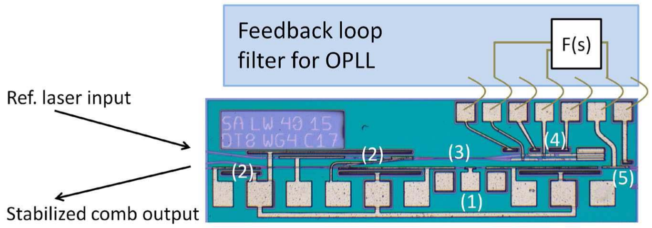

Fig. 1. Microscope image of the PIC and schematic of the loop filter with numbered components: (1) mode-locked laser, (2) optical coupler and SOA amplifiers for comb and reference laser, (3) optical mixer, (4) balanced photodetectors, and (5) current-injection based phase tuning pad.

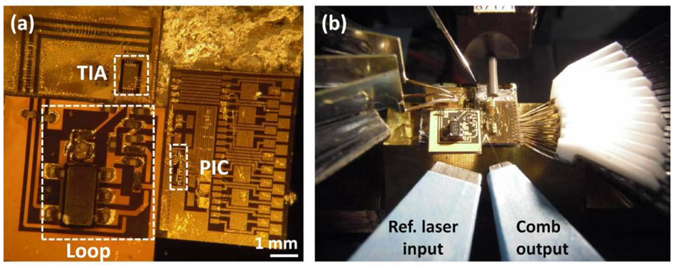

Fig. 2. Images of (a) the integrated PIC, TIA, and loop filter on AlN carriers, and (b) the OPLL system under testing. The input fiber for the reference laser is shown on the left side, the output fiber for the comb is shown on the right side. High-speed probes (left and back) and DC probes (right) are shown.

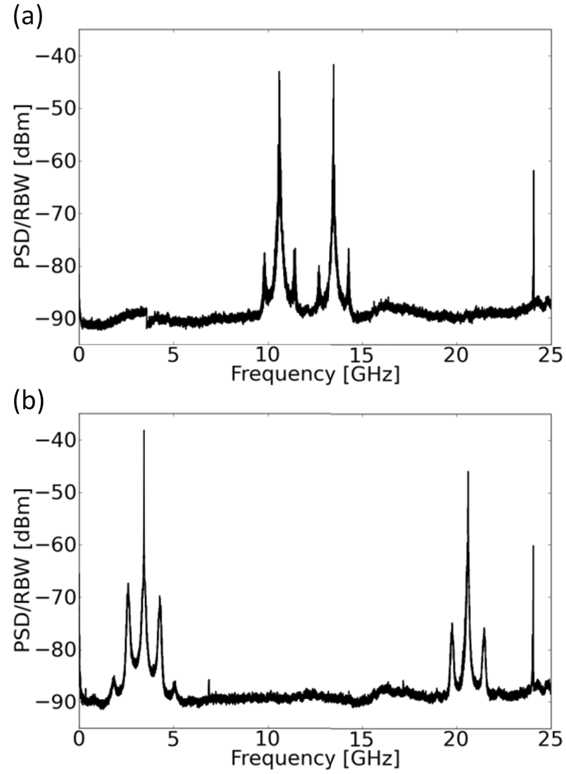

Fig. 3. Heterodyne beat spectrum of a DFB laser and the locked comb lines under passive mode locking (RBW 200 kHz). (a) Comb lines on the low-wavelength side of the comb are arbitrarily measured at 3 and 21 GHz. (b) Comb lines on the high-wavelength side of the comb are arbitrarily measured at 11 and 13 GHz. In both plots f_{rep} is shown at 24 GHz. Locking is achieved using a second DFB laser. The optical linewidths measured are 2–4 MHz.

tensile strained 8 nm barriers that are epitaxially grown above a 300 nm thick 1.3Q InGaAsP layer as part of the base epi.

The PIC fabrication uses i-line photolithography for photoresist definition and standard cleanroom processing techniques on all steps. Passive areas are defined using a selective wet-etch and a single blanket regrowth is done to cover the device with a p^{+}-doped InP cladding, a p^{++}-doped InGaAs contact layer, and an InP capping layer to protect the InGaAs contact layer during device fabrication. The active material is used to define the semiconductor optical amplifiers (SOAs) and the saturable absorber (SA), whereas the passive material is used to define the low-loss waveguides, optical couplers, and current injection based phase shifters. A microscope image of the completed device is shown in Fig. 1.

III. Opto-Electronic Integration

The fabricated laser bars are singulated into $500 \times 170\ \mu m^2$ PICs and mounted on gold coated AlN carriers with AuSn solder. The TIAs are InP based HBTs fabricated by Teledyne Scientific. The TIA chip also has limiting amplifiers with ~30 dB maximum gain for small signals. The loop filter for the OPLL is designed on a separate AlN carrier using a commercial Op-Amp with 0603 resistors and capacitors optimized for the correct transfer function, and simulated using Advanced Design Systems software by Agilent. The three OPLL systems (PIC, TIA, and loop) are soldered onto a thin gold coated AlN mount in close proximity to minimize loop delay and GSG signal pads are connected with short wire bonds. An image of the finished system is show in Fig. 2(a), and in Fig. 2(b) under test.

Nearly balanced photodetectors (BPDs) (with 20% power imbalance) are used on the PIC with current subtraction done with the Op-Amp. The BPDs reduce the influence of RIN since this noise is common to both detectors.

IV. Optical Locking Results

The OPLL system is first locked using a 1 MHz optical linewidth DFB laser as an optical reference. The OPLL comb is passively mode locked and 3 mW optical power is coupled into a lensed optical fiber at the left laser facet. The reference laser is optically mixed on-chip with the output of the MLL and measured on the integrated photodetectors. This error signal is fed through the TIAs, the loop filter, and finally back into a current-controlled phase pad on the MLL. The MLL with the phase pad operates as a current controlled oscillator (CCO) to clone the phase error of the reference within the loop bandwidth.

Once locked, the optical comb lines are measured using a heterodyne technique with a second DFB laser arbitrarily placed near the comb lines of interest. The spectrum of the low-and high-wavelength side of the comb is shown in Fig. 3(a) and Fig. 3(b), respectively; two comb lines and f_{rep} are visible. The RF beat tone linewidth at f_{rep} is 2 MHz under passive mode locking, where f_{rep} is the cavity repetition frequency of 24 GHz. The loop bandwidth is ~790 MHz, and resonance peaks at ±790 MHz are visible on both sides of all comb lines. The optical linewidth of the locked comb

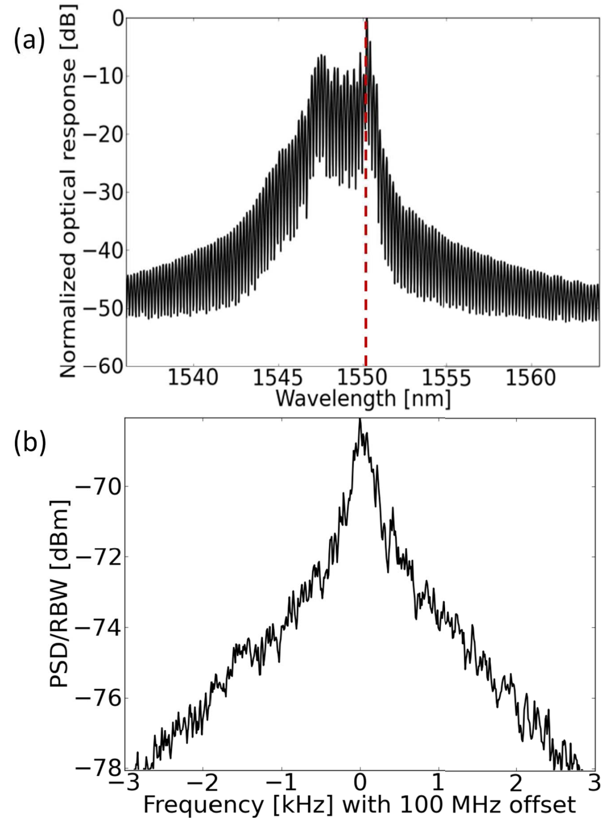

Fig. 4. (a) The optical comb spectrum measured on the OSA with the wavelength of the reference laser shown in the dashed vertical line (res. 60 pm), and (b) heterodyne beat-tone measurement on the ESA used to calculate optical linewidth (RBW 200 Hz). The beat-tone width is 550 Hz at −3 dB from the peak.

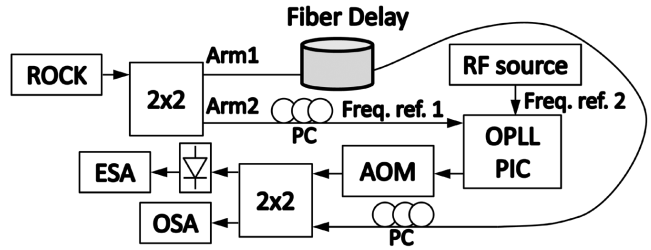

Fig. 5. Optical phase-locked loop measurement set-up using the 200 Hz linewidth Rock laser. The fiber delay in Arm1 is set to 150 km for linewidth measurement, and matched path length with Arm2 for residual phase-noise measurement. AOM: Acousto-optic modulator. PC: Polarization controller. ESA: Electrical spectrum analyzer. OSA: Optical spectrum analyzer.

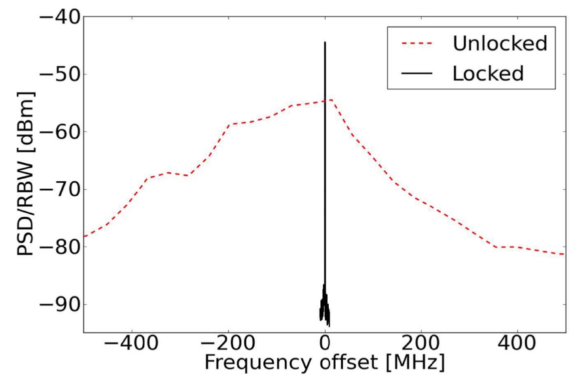

Fig. 6. Optical linewidth measurement with (solid black, RBW 200 Hz) and without (dashed red, RBW 2 MHz) the optical phase-locked loop. The optical linewidth is reduced from 100 MHz to <550 Hz.

line is 1 MHz. The measured linewidths of the adjacent comb lines are 2–4 MHz within a 10 dB bandwidth of the locked tone, thus nearly matching the RF beat tone linewidth. Without the OPLL locking to the reference laser, the comb linewidths are ∼100 MHz. This demonstrates that the phase errors between adjacent comb lines are partially correlated, within the f_{rep} linewidth, and therefore reducing the phase noise of a single comb line reduces the phase noise of all comb lines.

To improve the stabilized comb, the NP "The Rock" 200 Hz linewidth laser is used as the optical reference, and is positioned at 1550 nm. The MLL is also hybrid mode-locked using an RF power of +15 dBm, which increases the precision of the frequency spacing between the comb lines. The beat tone linewidth at f_{rep} is <10 Hz (limited by the ESA resolution), see Fig. 7(a). The laser drive current is 120 mA and the SA is biased at 0 V. The optical spectrum of the locked tone is shown in Fig. 4(a).

The linewidth of the locked comb line is measured using a delayed heterodyne technique, as shown in Fig. 5. The reference laser is put through 150 km of fiber and a 100 MHz acousto-optic modulator (AOM), and then mixed in a 2×2 fiber coupler with the output of the mode-locked laser. The output of the optical mixer is measured on an electrical spectrum analyzer (ESA) at 100 MHz.

The measured frequency width at −3 dB is 550 Hz, as shown in Fig. 4(b), which means the actual optical linewidth of the comb line is below this due to the self-heterodyne technique. The measured linewidth is the combined phase noises of the two lasers. However, 150 km of fiber provides only 734 μs of delay, which is shorter than the coherence time of the Rock laser (1.59 ms). The self-heterodyne measurement is hence operating near the limit $t_{delay} = t_{coherence}$ [14], which means that an upper bound of 550 Hz can be set on the linewidth, but the exact linewidth cannot be determined without additional fiber such that $t_{delay} \gg t_{coherence}$. The optical linewidth of the comb lines without the OPLL is 100 ± 30 MHz, as shown in Fig. 6, more than 10^5 times larger than the locked linewidth.

Stable locking is achieved for the duration of testing, > 3 hrs without any adjustment. The duration of locking is limited by the fiber coupling from the reference laser into the PIC, which drifts over time. To verify the OPLL locking, the loop filter is turned off and the measured 100 MHz AOM tone is no longer observed. The unwanted reference laser power that reflects from integrated PIC components and reaches the laser cavity is measured to be < −30 dBm, and no injection locking is observed.

The optical linewidths of the adjacent comb lines are measured at $f_{rep} \pm f_{AOM}$ on the ESA, as shown in Fig.7. These linewidths are <1 kHz measured with a 75 km fiber delay, which are greater than the locked tone linewidth due to added phase noise induced by amplitude noise in the MLL OPLL system.

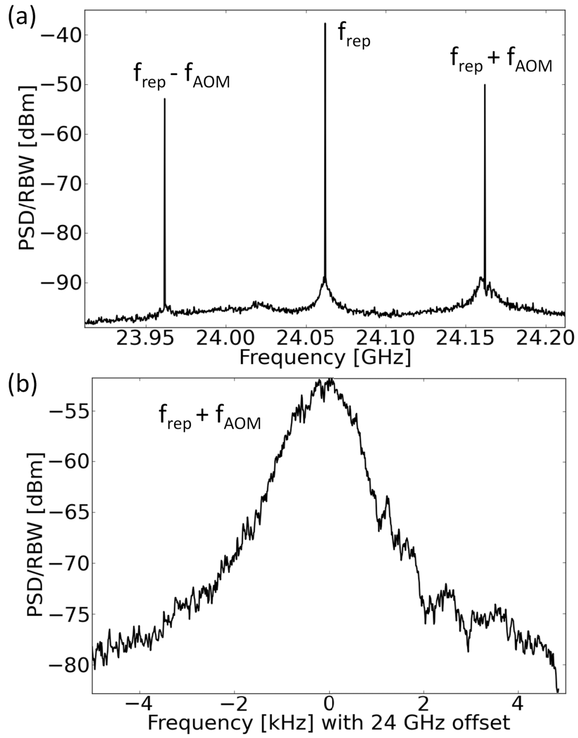

Fig. 7. (a) Linewidth of the adjacent comb lines measured at $f_{rep} \pm f_{AOM}$ on the ESA after 75 km of delay (RBW 10 kHz), and (b) zoomed in at $f_{rep}+f_{AOM}$ (RBW 100 Hz).

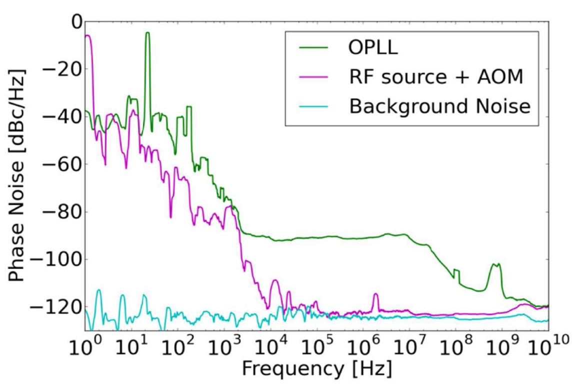

Fig. 8. Residual phase noise of the locked comb line measured on the ESA (green). The low frequency phase noise is dominated by the acousto-optic modulator (AOM) and the RF driver used in this measurement (purple).

The measured residual phase noise of the locked comb line compared to the reference laser is shown in Fig. 8. This is measured by matching the paths lengths of Arm1 and Arm2 by adjusting the fiber delay shown in Fig. 5. The phase noise has a pedestal from 1 kHz to 10 MHz, which arises due to the laser RIN. The phase-noise below 1 kHz is dominated by the acousto-optic modulator and the RF source operating at 100 MHz used in the set-up. Thus, the measured phase noise is most accurate above 1 kHz. The phase-noise variance is 0.12 rad^2 from 1 kHz to 10 GHz, corresponding to 20° standard deviation from the locking point.

V. Conclusion

Close integration of OPLLs and PICs enables low phase-noise, stable, and highly compact optical frequency comb generators. A 430 GHz span comb is demonstrated with $<$550 Hz optical linewidth at the locked tone and $<$1 kHz on adjacent tones. The OPLL achieves a 20° standard deviation from the locking point. Using a suitable CMOS TIA, amplifier, and loop filter could reduce the dimensions to $< 2 \times 2$ mm^2, and further reduction to noise can be achieved through the use of well-balanced detectors.

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