Integrated Phase-locked Multi-THz Comb for Broadband Offset Locking

John S. Parker, Abirami Sivananthan, Mingzhi Lu, Leif Johansson, Larry A. Coldren
Electrical and Computer Engineering Department, University of California at Santa Barbara, Santa Barbara, CA 93106-9560

Abstract: We demonstrate an integrated InGaAsP/InP 2.06 THz broadband comb for offset locking SG-DBR widely tunable lasers. The comb has 70 lasing lines and is generated using a hybrid mode-locked laser with intracavity gain flattening.

OCIS codes: 140.4050 Mode-locked lasers, 250.5300 Photonic integrated circuits, 280.3640 Lidar.

1. Introduction

Broadband combs have a multitude of applications including: injection locking laser arrays [1], sources for orthogonal frequency division multiplexing (OFDM) [2], and in metrology [3]. Emerging applications for broadband combs exists in offset locking devices. Such devices use the comb source as a reference for precise frequency positioning. Recently, offset locking of up to 15 GHz has been demonstrated with two monolithically integrated widely tunable SG-DBR lasers with an integrated optical phase-locked loop (OPLL) [4]. Additionally, offset locking to an external comb source has been used to phase-lock two DBR lasers at heterodyne frequencies <50 GHz [5].

When combined with comb sources, offset locked lasers can be positioned at any set frequency with Hz precision across the comb bandwidth. This enables higher spectral efficiency for dense wavelength division multiplexing systems (DWDM), allowing far greater channel density and frequency stability than with wavelength lockers. In another configuration, rather than keeping the offset frequency fixed, the tunable lasers can be swept across the comb lines for high-resolution light detection and ranging (LIDAR) functionality. To sweep between the multiple reference lines, the frequency of the SG-DBR OPLL is offset locked using an RF modulation signal from one comb line until it reaches the next. Upon reaching the adjacent comb line, the RF signal is reset and the OPLL locks to this new reference line allowing the sweep to continue until reaching the end of the comb span.

We have fabricated an integrated comb source with >2 THz bandwidth and <10 Hz frequency error between comb lines using an InGaAsP/InP quantum well (QW) based material platform. The comb is generated from a 30 GHz hybrid mode-locked laser with an intracavity gain flattening filter (GFF) based on an asymmetric Mach-Zehnder interferometer (MZI). The GFF provides the inverse spectral profile of the material gain, reducing gain competition between modes, and allowing more modes to lase simultaneously. This device is compatible with SG-DBR OPLLs, and provides the potential for single-chip integrated LIDAR systems with THz frequency sweeps. The resolution of a frequency modulator continuous-wave (FMCW) LIDAR system is roughly: c / (2 x bandwidth) ≈ 75 µm (e.g. the topography on the face of a penny), for a 2 THZ comb span.

2. Design and fabrication

A ring mode-locked laser architecture is chosen due to its ease of integration with other components, e.g. SG-DBR OPLLs, to realize highly versatile photonic integrated circuits (PICs). Such rings and their couplers are defined using low-cost and high throughput i-line photolithography, allowing ring MLLs to be placed anywhere on the PIC without the need for more complicated processing.

A ring MLL with a GFF is designed and fabricated on an InGaAsP/InP offset quantum well (OQW) platform that consists of seven compressively strained 6.5 nm QWs and eight tensile strained 8 nm barriers that are epitaxially grown above a 300 nm thick 1.3Q InGaAsP layer as part of the base epi. Passive areas are defined using a selective wet-etch and a single blanket regrowth is done to cover the device with 1.8 µm p+-doped InP cladding, a 150 nm p++-doped InGaAs contact layer, and a 400 nm 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 and current injection based phase shifters, as shown in Fig. 1. The material structure and the fabrication steps are compatible with SG-DBR OPLLs, allowing both to be integrated monolithically without changes to the processing or device architecture.

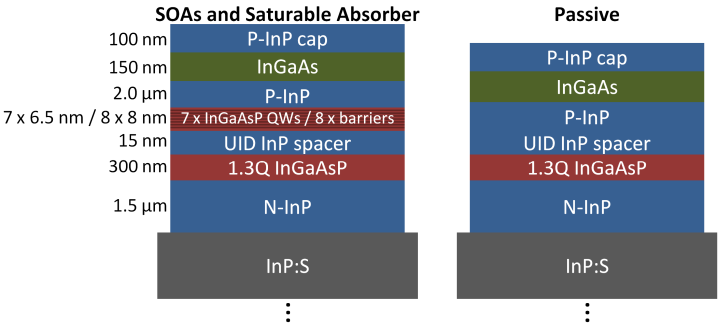

Fig. 1. Monolithic integration InGaAsP/InP platform that uses a 7 offset quantum well (OQW) material layer structure. Active sections (left) are used for the semiconductor optical amplifier (SOA) and the saturable absorber. The passive sections (right) are used for low-loss waveguides and phase tuning regions.

After regrowth, the waveguide is defined with photoresist on a Cr/SiO_2 bilayer hard mask. The Cr is etched using a low power Cl_2-based inductively coupled plasma (ICP), and the SiO_2 is etched using an SF_6/Ar based ICP. The resulting 600 nm SiO_2 mask acts as a hard-mask to define the InGaAsP/InP deeply etched waveguides using a Cl_2/H_2/Ar (9/18/2 sccm) ICP and a 200°C heated chuck at a chamber pressure of 1.5 mT. The resulting etched features are shown in Fig. 2(a)-(c). After removing the SiO2 mask, blanket deposition of a 350 nm isolation layer of silicon nitride is performed. Vias are opened for topside p-metal contacts. N-metal contacts are realized through backside deposition of Ti/Pt/Au onto the n-doped conducting InP substrate.

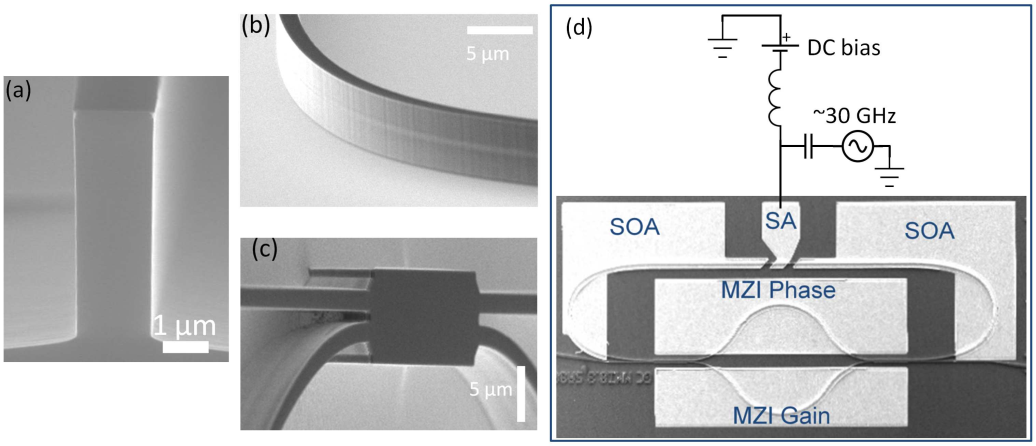

Fig. 2. Scanning electron microscope (SEM) images of the etched waveguide showing: (a) 5 µm deep etch with vertical sidewalls, (b) waveguide bends with smooth sidewalls, and (c) multimode interference (MMI) couplers. (d) A hybrid mode-locking schematic for the GFF MLL, showing an SEM image of the device with a DC biased and 30 GHz RF modulated saturable absorber (SA). The MZI gain arm allows tuning of the extinction ratio, while the phase arm allows placement of the filter zero.

The fully fabricated GFF MLL PIC, shown in Fig. 2(d), has a round-trip cavity length of 2600 µm, corresponding to lasing lines spaced by 29.5 GHz. The 600 µm asymmetric MZI filter uses 3 dB, i.e., 50-50, multi-mode interference (MMI) couplers to form two arms, which differ in length by 16 µm providing a free-spectral-range (FSR) of 40 nm. One of the arms of the MZI filter has an SOA that can be used to control the extinction ratio (ER) of the GFF, whereas the other arm has a phase shifter allowing adjustment of the filter zero.

3. Comb Generation

The device is biased at 210 mA drive current (~3x laser threshold), -2.6 V bias on the saturable absorber; the MZI filter is biased at 35 mA into the active filter arm to set the extinction ratio, and 17 mA into the passive phase tuning arm to set the filter zero. The RF beat tone under passive mode-locking is shown in Fig. 3(a) with a -20dB linewidth around 20 MHz and the peak at -75 dBm measured on the electrical spectrum analyzer (ESA) with a high-speed photodiode. A 15 dBm RF drive tone was applied to the saturable absorber, as shown in Fig. 2(d), to provide hybrid mode-locking (HML) and the resulting RF beat tone after HML is shown in Fig. 3(b). With HML, the RF linewidth FWHM is below the minimum resolution of the ESA (<10 Hz), and the noise pedestal at -75 dBm during passive mode-locking, has been decreased by 20 dB. The resulting RF tone is 35 dB above the background passively mode-locked pedestal and >50 dB above the background noise.

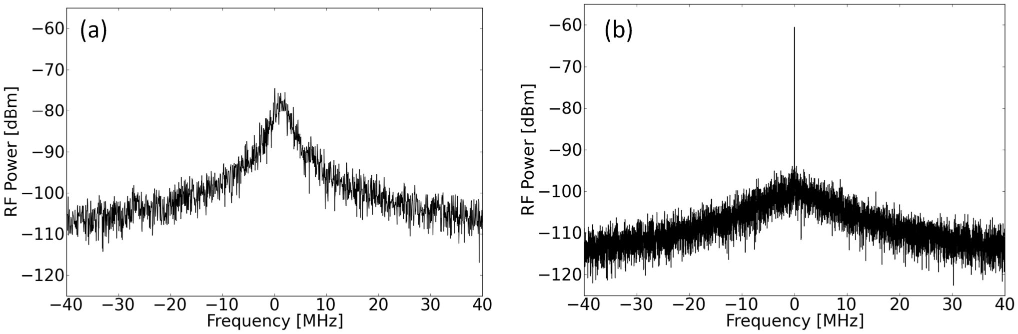

Figure 3: Normalized RF beat tones centered at 29.5 GHz from the GFF MLL under (a) passive mode-locking i.e. only a DC bias of -2.6V, and (b) under hybrid mode-locking with a 15 dBm RF signal applied. (RBW = 30 KHz).

The RF linewidth corresponds to the frequency error between adjacent lasing lines in the comb spectrum. By reducing the RF linewidth with HML, we are able to set the reference comb line spacing with a precise frequency and better than 10 Hz accuracy (as determined by the RF source). By using the HML configuration, the frequency error between comb lines is stabilized and immune to minor thermal or mechanical drift. The 2 THz comb span shown in Fig. 4 was taken after HML was achieved, indicating that HML does not limit broadband comb generation with this device. These results demonstrate that the frequency spacing between lasing lines can be stabilized on GFF MLLs, while maintaining >2 THz comb spans.

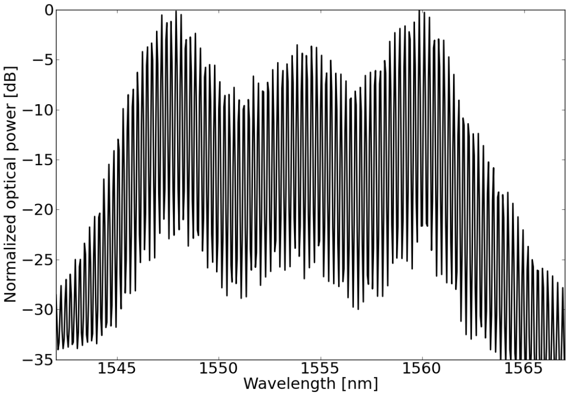

Figure 4: Optical spectrum from the GFF MLL under active mode-locking. The -10 dB span is 2.06 THz covering 70 lasing lines.

5. Conclusion

We have demonstrated a broadband 2 THz comb generator that can be integrated with SG-DBR OPLLs and enable single-chip high resolution LIDAR systems. The comb generated has <10 Hz error between comb lines and is a promising frequency reference to use in sweeping offset locked lasers.

Acknowledgements

This work was supported by the DARPA PICO program. A portion of the work was done in the UCSB nanofabrication facility, part of the NSF funded NNIN network.

References

[1] S. Bennett, B. Cai, E. Burr, O. Gough, A.J. Seeds, "1.8-THz bandwidth, zero-frequency error, tunable optical comb generator for DWDM applications," *IEEE Photonics Technology Letters,* vol. 11, no. 5, pp. 551-553, May 1999.

[2] N. Dupuis, C.R. Doerr, L. Zhang, L. Chen, N.J. Sauer, L.L. Buhl, D. Ahn, "InP-based comb generator for optical OFDM," *Optical Fiber Communication Conference and Exposition (OFC/NFOEC),* March 6-10, 2011, paper PDPC8.

[3] S.A. Diddams, D.J. Jones, J. Ye, S.T. Cundiff, J.L. Hall, J.K. Ranka, R.S. Windeler, "Direct RF to optical frequency measurements with a femtosecond laser comb," *IEEE Transactions on Instrumentation and Measurement,* vol. 50, no. 2, pp. 552-555, 2001.

[4] S. Ristic, A. Bhardwaj, M.J. Rodwell, L.A. Coldren, and L.A. Johansson, "An optical phase-locked loop photonic integrated circuit," *J. Lightwave Tech.,* vol. 28, no. 4, pp. 526-538, Feb. 15, 2010.

[5] L. Ponnampalam et al., "Monolithically Integrated Photonic Heterodyne System," *J. Lightwwave Technol.*, vol. 29, no. 15, pp. 2229-2234, Aug. 1, 2011.