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Integrated phase-locked lasers and photonic integrated circuits for remote gas sensing

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Abstract – An indium phosphide photonic integrated circuit for integrated path differential absorption lidar remote gas sensing was developed. Phase locking of the two integrated lasers and measurement of a carbon dioxide absorption line centered at 1572.335 nm was demonstrated.

I. Introduction

Photonic integrated circuit (PIC) technology enables a significant reduction in the cost, size, weight and power (CSWaP) of systems for free space communication and sensing applications [1-6]. This also enables the possibility to deploy photonic systems on small space platforms including CubeSats [5]. The indium phosphide (InP) PIC platform is able to monolithically integrate lasers, modulators, photodiodes, semiconductor optical amplifiers (SOAs) and passive components [1-6]. In this work, an InP PIC was developed for integrated path differential absorption (IPDA) lidar for remote sensing of carbon dioxide (CO_2) [6-8]. The PIC lidar is designed to scan over 40 GHz range around the center of a CO_2 absorption line at 1572.335 nm. This method requires accurate and fast wavelength tuning. A two-laser PIC comprising of a leader laser and follower laser was developed [7], The leader laser is stabilized with an absolute reference, a CO_2 cell. The follower laser is offset locked to the leader laser through an optical phase lock loop (OPLL) to ensure accuracy of the output wavelength. A SOA following the follower laser is used to encode frequency stepped optical pulses for scanning the 1572.335 nm absorption line. This work represents a significant step toward reducing system CSWaP for IPDA lidar systems for space applications.

II. Photonic Integrated Circuit

The PIC footprint is 0.8 mm × 8.3 mm as shown in Fig. 1. The PIC comprises of two lasers, couplers, a high speed photodiode for beat note detection, a phase modulator for the OPLL, and a SOA for encoding pulses. Both the leader and follower lasers share the same sampled grating distributed Bragg reflector (SGDBR) laser design with a center emission wavelength near 1572 nm. The laser gain medium comprises of seven quantum wells. The SGDBR gain section is 550 μm long, the phase section is 75 μm, and the backside SOA, used for monitoring, is 500 μm long. Both the front and back SGDBR mirrors use a grating period of 244 nm corresponding to a Bragg wavelength at 1573.6 nm. The front mirror consists of 5 grating bursts, while the back mirror consists of 12 grating bursts. Two different directional couplers were used for power splitting. Coupler A has a length of 180 μm and is designed for a splitting ratio of 80/20. This coupler design is used to routes most of the leader laser output to the phase modulator for the stabilization, and most of the follower laser output to the SOA pulse encoder. Coupler B, with a length of 320 μm, is designed for a splitting ratio of 50/50. This coupler mixes the two lasers' outputs and then splits for on-chip photodiode beat note detection and off-chip detection or monitoring. The 2500 μm long phase modulator is modulated at 125 MHz to generate a phase signal, which is used to stabilize the leader laser using the absolute CO_2 reference cell. The integrated photodiode demonstrates a bandwidth 15 GHz [6], enabling beat note detection for the OPLL offsetting locking and subsequent sweeping of the follower laser around the center of the absorption line. The 1000 μm long SOA on the follower laser side of the PIC provides greater than 40 dB DC extinction. This is used to generate high extinction pulses for the follower laser output.

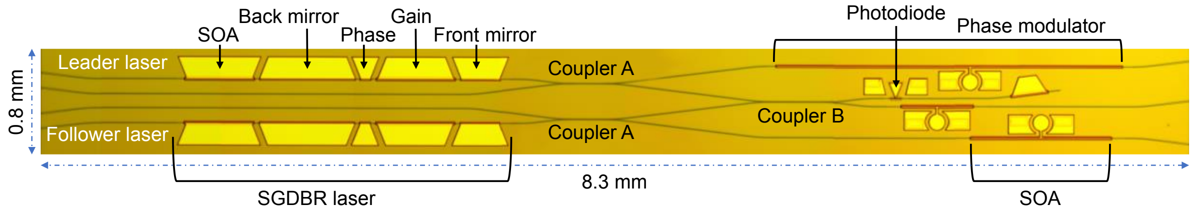
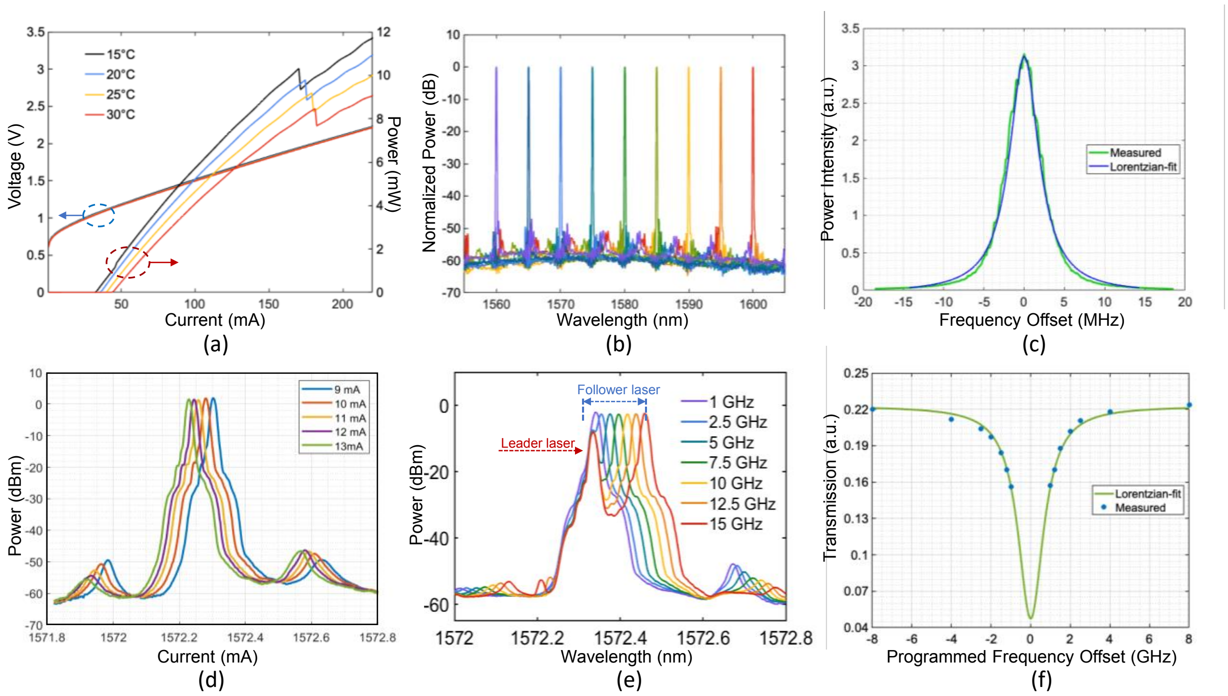


Figure 1: Microscope image of fabricated PIC for IPDA lidar remote gas sensing.

III. Measurement Results

The SGDBR lasers used for the leader and follower were characterized and Fig. 2(a) shows exemplary light-current-voltage (LIV) characteristics at various stage temperatures. The laser threshold current is approximately 33 mA at a temperature of 15 °C and the laser outputs greater than 10 mW at a drive current of 200 mA. The lasers tune over a range of more than 40 nm, between 1560 nm to 1600 nm, with more than 45 dB side mode suppression ratio (SMSR) as shown in Fig. 2(b). The lasers also demonstrate a 3-dB linewidth of 4.4 MHz as shown in Fig 2(c). While the lasers can be coarsely tuned using the front and back SGDBR mirrors, the phase section can be used for fine and continuous tuning. As shown in Fig. 2(d), by adjusting the phase section current between 9 and 13 mA, the laser wavelength is tuned passed 1572.335 nm.

In addition to characterizing the lasers, PIC operation was also demonstrated. We successfully demonstrated offset locking between the lasers at 1572.335 nm as shown in Fig.2(e). Here, the leader laser was stabilized with the CO_2 reference cell, and the follower laser was offset locked to the leader while tuning to offsets between 1 and 15 GHz. Using a separate CO_2 cell for the follower laser output, the CO_2 absorption line was measured. As shown in Fig. 2(f), 14 points were sampled around the CO_2 absorption line centered at 1572.335 nm. Using these sampled points, the overall absorption spectrum was estimated using a Lorentzian fit. These measurements demonstrate the overall operation of the IPDA lidar PIC for CO_2 sensing in a laboratory environment.



(a) (b) (c)

(d) (e) (f)

Figure 2. (a) LIV characteristics of SGDBR laser at varying stage temperatures. (b) Laser spectra showing tuning from 1560 nm to 1600 nm. (c) Delayed self-heterodyne linewidth measurement with Lorentzian fit. (d) Laser spectra with continuous tuning around 1572.335 nm using the laser phase section. (e) Spectra of the leader and follower laser as the leader laser is offset locked from 1 GHz to 15 GHz. (f) Measured absorption of a separate CO_2 test cell at 14 wavelength points where each point is an average of 1000 measurements taken over 100 µs.

IV. Conclusion

We have developed an InP PIC for IPDA lidar remote sensing of CO_2. This PIC enables the stabilization of a leader laser with an absolute CO_2 gas reference cell, and the subsequent offset locking and sweeping of a follower laser to measure the CO_2 absorption line centered at 1572.335 nm. This work represents a major step toward miniaturizing lidar systems for sensing applications and deployment on small space platforms.

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