Dual Laser Indium Phosphide Photonic Integrated Circuits for Remote Active Carbon Dioxide Sensing

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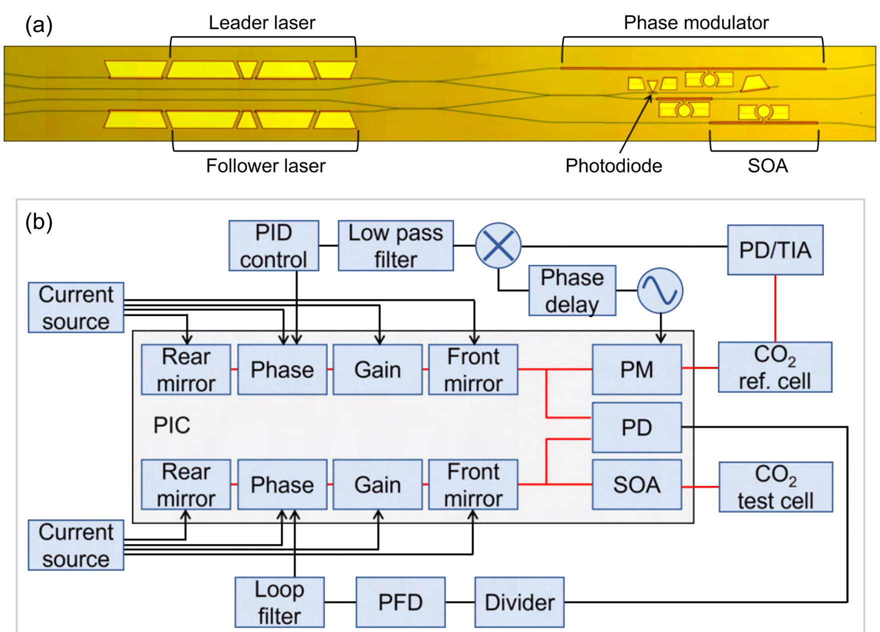
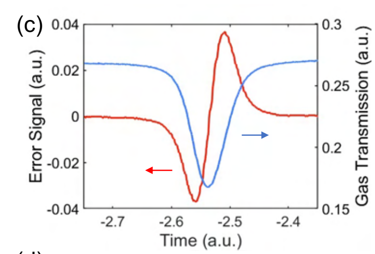
Abstract: Two generations of indium phosphide photonic integrated circuits were fabricated, characterized, and their performance compared. Successful sampling of carbon dioxide was performed in a laboratory setting under continuous wave sampling.

1. Introduction

In recent years, there has been increasing interest in photonic integrated circuits (PICs) for remote sensing and free space communication applications because of their low size, weight, and power (SWaP) [1-5]. Remote carbon dioxide (CO_2) sensing is one such application. Currently, remote spectrometers rely on reflected sunlight to passively measure CO_2 concentrations in the atmosphere. Engineers at NASA Goddard Space Flight Center (GSFC) have developed an active CO_2 sensor with an on-board infrared laser source to realize approximately 1 ppm precision [6,7]. The integrated path differential absorption lidar system includes a leader laser locked to the center of the CO_2 absorption line at 1572.335 nm and a follower laser offset locked to the leader laser. The follower laser is scanned ±15 GHz around 1572.335 nm to measure the CO_2 concentration from the shape of the absorption line. In this work, we present progress toward a low SWaP PIC-based module leveraging the architecture of the NASA GSFC system, which was built from discrete commercial off the shelf components.





(d)

	Generation 1	Generation 2
Couplers	Directional couplers only	Directional and MMI couplers
Phase modulator length (mm)	2.5	1.2
SOA length (mm)	1	1
PIC dimensions (mm)	8.2 x 0.8	9.5 x 0.8
On-chip photodiode	Insufficient performance	Suitable performance
Locked leader laser SMSR (dB)	54	47
Leader laser frequency std. dev. (MHz) (30 mins)	0.332	0.466
Follower laser frequency std. dev. (kHz) (30 mins)	33.126	3.614
Maximum follower laser power (mW)	12	16.5

Fig. 1. (a) Microscope image of fabricated first generation PIC. (b) Test setup used to characterize PIC. PID = proportional-integral-derivative. PD/TIA = photodiode/transimpedance amplifier. PM = phase modulator. PFD = phase frequency detector. (c) Absorption and error signal at the reference gas cell detector. (d) Table comparing the layout and performance of first and second generations.

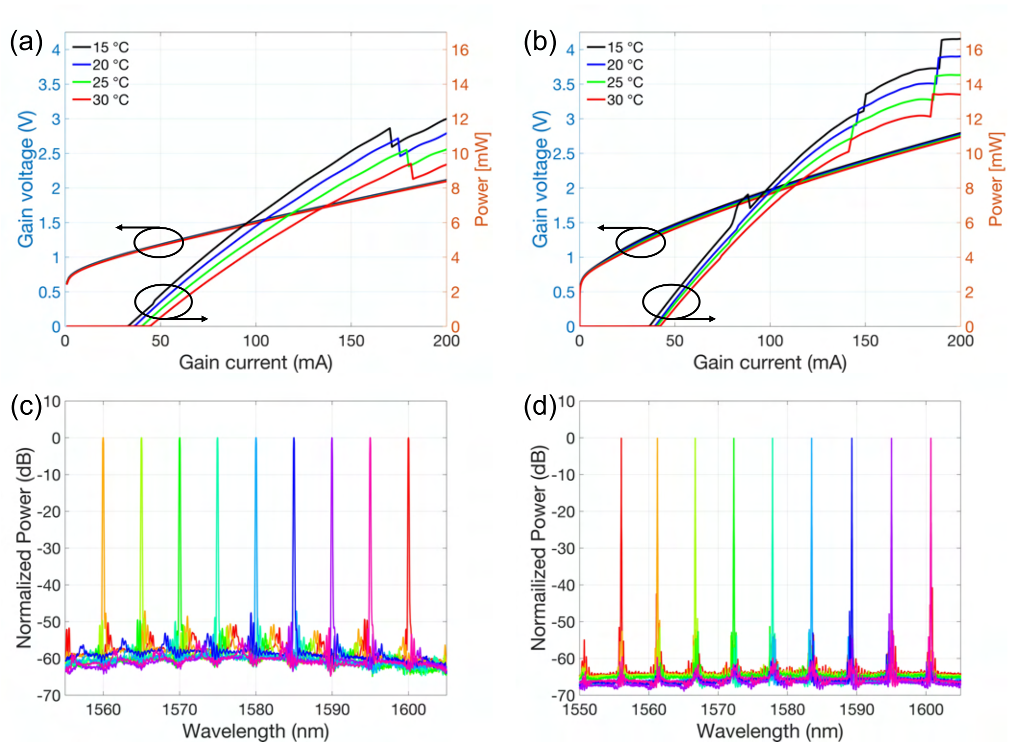


Fig. 2. (a) First generation light-current-voltage curve measured at the SOA. (b) Second generation light-current-voltage curve measured at the SOA. (c) First generation laser tuning. (d) Second generation laser tuning.

2. PIC Layout and Characterization

Two generations of InP PICs are designed and fabricated. One of the fabricated PICs is shown in Fig. 1(a), and the testing system is shown in Fig. 1(b). The overall system mainly consists of two parts, leader laser stabilization and follower laser offset locking. The overall gas sensing is achieved by performing both systems together.

The leader laser stabilization is achieved using a frequency modulation technique [6-8], where the leader laser is locked to a CO_2 reference cell by modulating the phase of the laser output signal at 125 MHz. The CO_2 reference cell works as a frequency discriminator; it generates a phase dependent error signal as shown in Fig. 1(c). The signal is extracted using a mixer, further filtered with a low pass filter, and processed using PID controls. The processed error signal is sent back into the phase section of the leader laser to achieve locking and stabilization.

The follower laser offset locking is accomplished using the optical phase lock loop technique [6,7]. An integrated photodiode detects the beat note signal from the leader and follower laser. The beat note signal is sent into PLL electronics, and is divided into a lower frequency signal through a multi-stage divider. Then, a phase frequency detector is used to detect the frequency difference between the divided signal and target frequency to generate a feedback signal. A loop filter was designed carefully to provide the best in-band phase noise and bandwidth for the feedback signal. The filtered feedback signal is sent back into the phase section of the follower laser to accomplish offset locking.

The two generations are compared here, where the first generation was reported to have accomplished gas sensing with continuous wave (CW) sampling using an external photodiode due to insufficient performance of the integrated photodiode [3-5,9]. Fig. 1(d) lists the major differences between the first and second generation PICs and corresponding performance, where the key difference is that the second generation used an integrated photodiode instead of an external photodiode. Fig. 2 shows a comparison of the device level characterization between the two generations. The second generation achieved a 45 nm tuning range and 12.7 mW output power with 150 mA current injection at 20 degrees Celsius, whereas the first generation has a 40 nm tuning range and 9.36 mW output power for the same conditions. However, the side mode suppression ratio (SMSR) of the second generation laser is slightly worse at some frequencies compared to the first generation laser. Since the two generations used the same laser design, this difference is mainly caused by fabrication variations, especially the depth of the etched grating.

Finally, system level characterization is compared in Fig. 3. Both generations successfully performed the gas sensing measurement using CW sampling, yielding an absorption spectrum with a fitted full-width half maximum of 1600 MHz. The leader laser stabilization performance is comparable between the two generations because a similar

PIC design and measurement setup were used for both generations. Leader laser stabilization over 30 minutes gave a standard deviation of 0.33 MHz and 0.46 MHz for the first and second generations, respectively. But, since the second generation used an integrated photodiode for the follower laser locking, the follower laser stabilization performance for the second generation achieved an order of magnitude improvement compared with the first generation. Over 30 minutes, the standard deviation of the follower laser frequency stability was 33.12 kHz for the first generation and 3.61 kHz for the second generation.

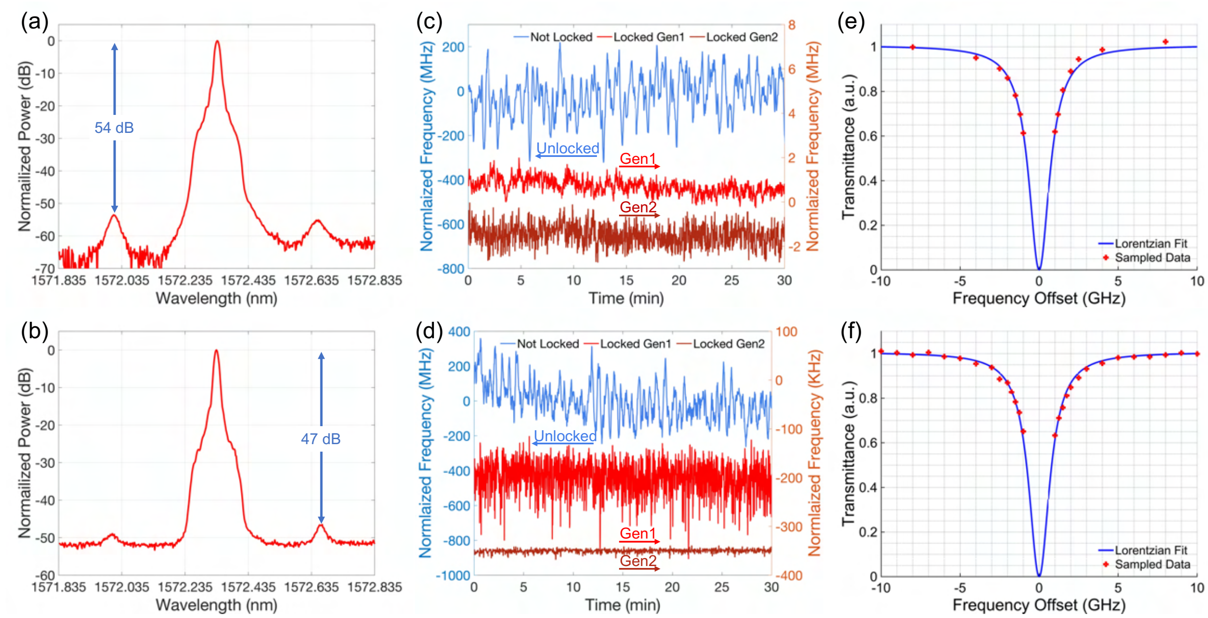


Fig. 3. (a) First generation locked leader laser spectrum. (b) Second generation locked leader laser spectrum. (c) Comparison of leader laser stabilization. (d) Comparison of follower laser stabilization. (e) First generation CW sampling of CO_2 with Lorentzian fit. (f) Second generation CW sampling of CO_2 with Lorentzian fit.

3. Conclusion

Successful laboratory CO_2 sensing was performed with compact PIC technology. The performance between the first and second generation PICs was compared for CW gas sampling. Improved stabilization was achieved for the second generation because an integrated photodiode was used instead of an external photodiode. Future work will focus on pulsed gas sampling and further SWaP reduction using close integration with control electronics in a compact package.

4. Acknowledgements

The authors acknowledge funding from NASA's Earth Science Technology Office (ESTO) Advanced Component Technology (ACT) program. A portion of this work was performed in the UCSB Nanofabrication Facility.

5. References

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