Carbon Dioxide Sensing with a Photonic Integrated Differential Absorption LiDAR Transmitter

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We have designed and characterized a differential absorption LiDAR transmitter based on an Indium Phosphide Photonic Integrated Circuit that has been fabricated through an open access generic integration platform using standard building blocks. We demonstrate its suitability for carbon dioxide sensing.

Keywords: *differential absorption LiDAR, carbon dioxide sensing, random-modulation continuous wave LiDAR, photonic integrated circuits, semiconductor lasers*

INTRODUCTION

Remote sensing of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O), is essential to control climate change. Differential Absorption LiDAR (DIAL) is the most implemented active technique for atmospheric greenhouse gases measurements. This technique consists in launching at least two laser signals tuned at different wavelength, one close to the center of a targeted gas absorption line and the other set away from the same line in a region of low absorption. In this way, the gas concentration along the light path can be obtained by measuring the different absorption that both signals have suffered.

DIAL systems are mainly based on solid state pulsed laser sources that can provide extremely high peak powers. However, Intensity-Modulated Continuous-Wave (IM-CW) techniques have gain interest due to their low peak power requirements which allow the use of semiconductor lasers [1]. Among these techniques, Random-Modulation Continuous-Wave (RM-CW) technique [2] has already been implemented using discrete semiconductor lasers [3]. It consists in modulating the intensity of both signals with a pseudorandom sequence or M-sequence, with a delay between them. These signals are launched, and after traveling and interacting with the gas, are backscattered by a hard target and detected at the receiver. Due to the M-sequence correlation properties, performing the cross correlation of the received signals with the original M-sequence allows to determine the absorption that each wavelength has suffered and, in consequence, the gas concentration and the distance to the target. These relatively complex DIAL systems can benefit from the advantages shown by Photonic Integrated Circuits (PICs) in terms of multiple device integration, power efficiency, small footprint and weight, low cost and radiation hardness. Recently, a dual laser Indium Phosphide (InP) PIC operated in pulsed regime has been proposed for carbon dioxide sensing [4].

In this contribution, we demonstrate an InP PIC as the transmitter of a RM-CW DIAL system by measuring a carbon dioxide gas cell in a fiber setup. The PIC has been fabricated through an open access generic integration platform using standard building blocks. We discuss its design and the performance of the different integrated devices as well as the PIC as a whole.

DESIGN AND FABRICATION

Fig.1 shows a photograph of the fabricated device as well as its schematic. The PIC consists of three identical 4-section DBR lasers. All lasers are designed to emit close to 1572 nm and include an internal photodiode (PD) (not indicated) to monitor their output power. Lasers 1 and 2 are used to perform the DIAL measurement and are tuned to λ_1 and λ_2, respectively. Laser REF is used together with fast PDs, PD1 and PD2, to tune and stabilize the emission wavelength of lasers 1 and 2 by measuring their beating notes while keeping the Laser REF wavelength tuned to the CO_2 absorption line through an electro-optical loop in the same way as in [3]. Therefore, the PIC contains not only the transmitter for the DIAL system but also the optical part of the stabilization unit. The pseudorandom modulation of each signal is implemented with electro-absorption modulators EAM1 and EAM2, respectively. Five Semiconductor Optical Amplifiers (SOAs) are integrated to provide gain to the outputs of the PIC and to control the output power of the different lasers. The chip has two optical outputs, one for the DIAL signals and the other for the reference signal, denoted as OUTPUT and OUTPUT REF, respectively. On the electrical side, the PIC has twenty DC electrical pads for providing current and voltage to the different blocks and measuring the internal PDs. In the lower part of the PIC, four RF ground-signal-ground pads are used for modulating the EAMs and getting the beating note signals from the fast PDs. The backside of the chip is the common ground for all DC blocks.

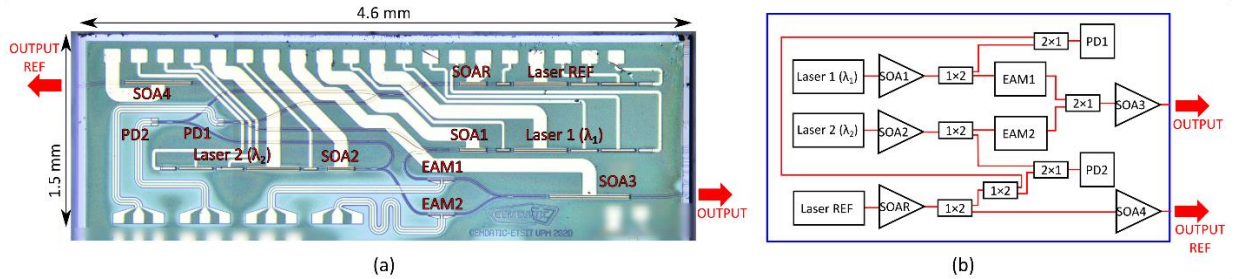

Fig. 1. (a) Photograph of the developed PIC transmitter for RM-CW DIAL with a size of 4.6×1.5 mm. (a) Schematic of the PIC.

The PIC has been fabricated by SMART Photonics through the open access platform JePPIX (Joint European Platform for Photonic Integration of Components and Circuits). The initial design and simulations were performed using VPIphotonics Design Suite while the final design and layout was created with Nazca Design.

EXPERIMENTAL RESULTS

We have experimentally characterized the different blocks and devices that are integrated in the PIC. The DBR lasers are single-mode and show some degree of tunability by adjusting the current through the DBR, phase and active sections. The full PIC is also tuned by controlling its temperature. Fig. 2 (a) shows the power-current (P-I) and voltage-current (V-I) curves and their corresponding optical spectra map obtained using a 6 GHz resolution Optical Spectrum Analyzer (OSA). In the upper part of Fig. 2 (a) we can observe the behavior of Laser 1 when its current is swept. Its threshold is around 25 mA and some discontinuities and kinks are shown around 40 and 70 mA that correspond to modal jumps. In spite of this, Laser 1 shows single mode operation in almost the complete lasing range with a Side-Mode Suppression-Ratio (SMSR) of 40 dB. All DBR lasers behave similarly when operated individually. When this measurement is repeated with Laser 2 switched-on, both P-I curve and spectra change considerably as shown in the lower part of Fig. 2 (a). The Laser 1 threshold is maintained but the modal jumps sequence has changed. We attribute this to the low isolation of the DBR lasers, due to the small reflectivity of the front DBR sections, together with the amplified spontaneous emission from outer SOAs and residual reflectivity at the integrated couplers. However, a detailed exploration of the different parameters unveils regions where the whole system is stable and robust.

Fig. 2 (b) illustrates the performance of the EAMs by showing the optical spectra recorded with a high resolution (10 MHz) Brillouin Optical Spectrum Analyzer (BOSA). The wavelength difference between both lasers is 0.13 nm (15.8 GHz). We have noticed a linewidth increase in Laser 1 due to the current injection in the mirror sections that have applied to tune Laser 1 respect to Laser 2. The estimated linewidth of Laser 1 is around 700 MHz, while for Laser 2 is around 100 MHz. The extinction ratio induced by the EAMs is around 15 dB in both signals and no changes in the wavelengths are observed.

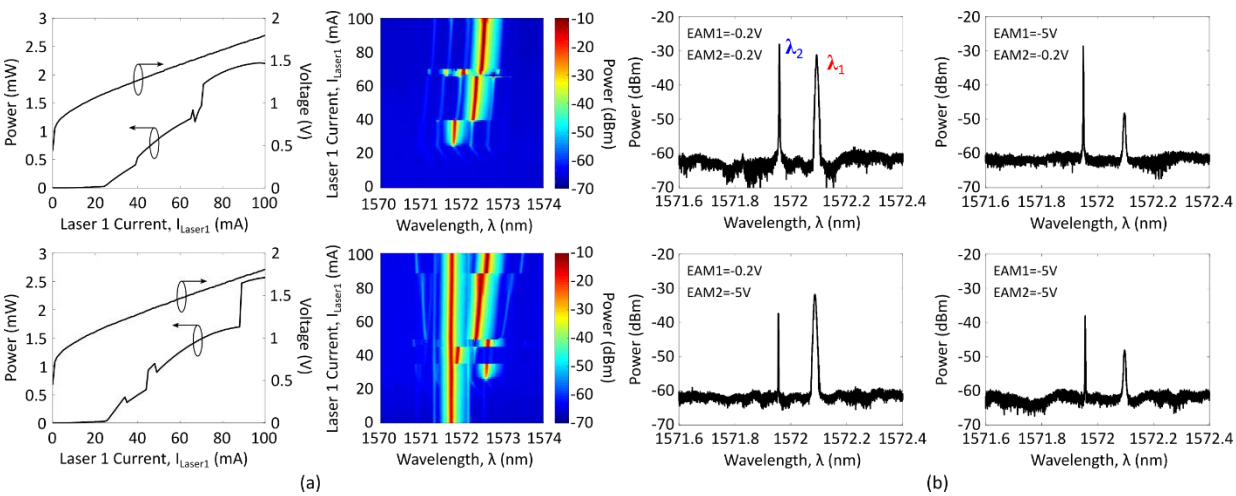

Fig. 2. (a) DBR lasers performance. Left: Power-current and voltage-current curves. Right: Their corresponding optical spectra map. Upper: Only Laser 1 switched-on and sweeping its current. Lower: Laser 2 switched-on and sweeping Laser 1 current. (b) EAMs performance. Optical spectra measured for different EAM voltages.

Fig. 3 (a) shows the experimental setup used to demonstrate the fabricated PIC for carbon dioxide sensing. The output signals from the OUTPUT port are gathered using a lensed fiber, then the light is divided in two paths, one goes directly to the receiver and the other is directed using a circulator to a path which includes the carbon dioxide gas cell and a fiber spool ended with a fiber reflector. After being reflected, the light follows the path back to the circulator which directs it to the receiver. The receiver is a PIN PD with a 200 MHz bandwidth transimpedance amplifier. The M-sequences are generated using a System-on-Chip Field Programmable Gate Array (SoC FPGA) that have fast ADC and DAC converters (100 MSa/s). It also digitizes the received signals and sends the data to a PC that performs the cross-correlation. Fig. 2 (b) shows the correlation results using a 12.5 Mbit/s 8-bit M-sequence. For this measurement, λ_2 is tuned to the peak of the chosen carbon dioxide absorption line (1572.02 nm) while λ_1 is tuned off the line (1572.2 nm). The first two peaks in the cross-correlation, E_1 and E_2, correspond to the signals that have travelled the short path, while the two peaks, R_1 and R_2, correspond to the signals that have travelled the path with the gas cell. From the correlation, the Differential Absorption Optical Depth (DAOD) [3], i.e. the absorption due to the gas, the Signal-to-Noise ratio (SNR) for the lowest intensity signal, the path optical losses difference (α) and the path length difference (L) can be obtained. In this case, DAOD = -0.51 dB, SNR = 13.2 dB, α = 7.6 dB and L = 1044 m, that are in agreement with the values obtained by tunable laser absorption spectroscopy performed with the BOSA and an optical time domain reflectometer.

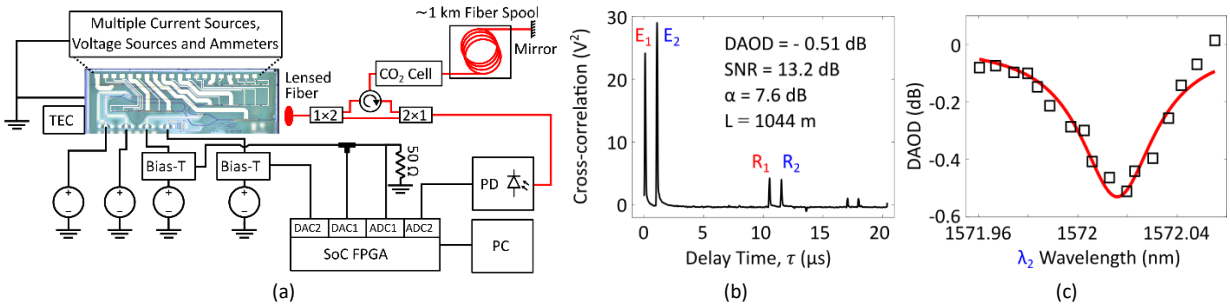

Fig. 3. (a) Experimental setup for the carbon dioxide gas cell measurement that emulates a LiDAR configuration. (b) Cross-correlation obtained averaging 50 single-sequence cross-correlations from the received signals. (c) Carbon dioxide absorption line at 1572.18 nm measured with the PIC while changing its temperature and consequently the tuning of the pair of signals.

CONCLUSIONS AND OUTLOOK

We have designed and characterized a RM-CW DIAL transmitter based on an InP PIC that has been fabricated through an open access generic integration platform using standard building blocks. We have characterized the individual integrated blocks and devices as well as the performance of the PIC as a whole. Carbon dioxide sensing with our PIC has been demonstrated by measuring a gas cell in a fiber setup. Next steps include implementing the wavelength stabilization unit and performing a real scenario measurement of atmospheric carbon dioxide.

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References

[1] J.F. Campbell, et al., *Field evaluation of column CO_2 retrievals from intensity-modulated continuous-wave differential absorption lidar measurements during the ACT-America campaign*, Earth and Space Science, vol. 7, e2019EA000847, 2020.
[2] N. Takeuchi, N. Sugimoto, H. Baba, and K. Sakurai, *Random modulation cw lidar*, Applied Optics, vol. 22, no. 9, pp. 1382--1386, 1983.
[3] M. Quatrevalet, et al., *Atmospheric CO_2 sensing with a random modulation continuous wave integrated path differential absorption lidar*, IEEE Journal of Selected Topics in Quantum Electronics, vol. 23, no. 2, pp. 157--167, 2017.
[4] J. Fridlander, et al., *Dual laser indium phosphide photonic integrated circuit for integrated path differential absorption lidar*, IEEE Journal of Selected Topics in Quantum Electronics, vol. 28, no. 1, 6100208, 2022.