Photonic Integrated Circuits for Precision Spectroscopy

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Abstract: A dual-laser indium phosphide photonic integrated circuit for precision spectroscopy lidar was designed and fabricated. A stabilization experiment demonstrated a twentyfold improvement in the long-term frequency stability of the master laser.

1. Introduction

Laser sources that are precise and accurate are essential for metrology, coherent communications, and precision spectroscopy [1,2]. In an integrated path differential absorption (IPDA) lidar [3], a stable source enhances the accuracy and spectral resolution of atmospheric gas absorption-line measurements. Consequently, airborne measurements require reduced averaging times and offer greater spatial coverage.

Reduced system cost, size, weight, and power (C-SWaP) is desirable for such platforms. Here we have designed and fabricated an indium phosphide (InP) photonic integrated circuit (PIC) for precision spectroscopy. The architecture is based on a previous demonstration that utilized discrete fiber-coupled L-band telecom optical devices [4]. All required optical functions have been integrated onto the PIC except for a carbon dioxide (CO_2) gas cell reference. The PIC includes master and slave sampled grating distributed Bragg reflector lasers (SGDBRs), a phase modulator (PM), a high-speed photodiode (PD), a Mach-Zehnder modulator (MZM) for pulse generation, semiconductor optical amplifiers (SOA), and directional couplers. Following characterization of the integrated photonic components, a wavelength stabilization experiment was performed on the master laser using an external CO_2 reference. The long-term stability of a beat note frequency generated with the integrated PIC master laser and a stable bench-top external cavity laser (ECL) was measured with a frequency counter. Over a 1-hour period, the long-term frequency stability improved twentyfold for gate times of 1 second.

2. PIC Principle of Operation

A microscope image of the full lidar PIC is shown in Fig. 1. The design and fabrication details were reported in [5]. Using frequency modulation stabilization, similar to the Pound-Drever-Hall technique [6], the master laser was stabilized to a reference CO_2 absorption line at a wavelength of 1572.335 nm. The CO_2 is contained in a gas cell with an equivalent path length of 10 m and pressure of 40 mbar. Frequency modulation of the master laser is facilitated by the integrated PM. Modulated light is collected off chip with a lensed fiber, directed through the reference cell, and then photodetected. When phase sensitive detection of a beat note at the modulation frequency and a radio frequency (RF) reference occurs, a frequency discriminating error signal is generated. Servos then filter the error signal and correct the laser wavelength by tuning the PIC temperature and current into the phase section of the SGDBR master laser. In a separate optical phase locked loop (OPLL), a beat note between the master and slave lasers is detected by the high-speed PD, frequency divided, and phase locked to an RF reference. The slave laser therefore retains the master laser stability at a frequency offset provided by the beat note. Determined by the on-chip PD bandwidth, offset frequency locking up to ±15 GHz is possible. As the slave laser is stepped across the absorption line sampling points, an integrated pulse generator MZM (or SOA) generates 1 μs pulses.

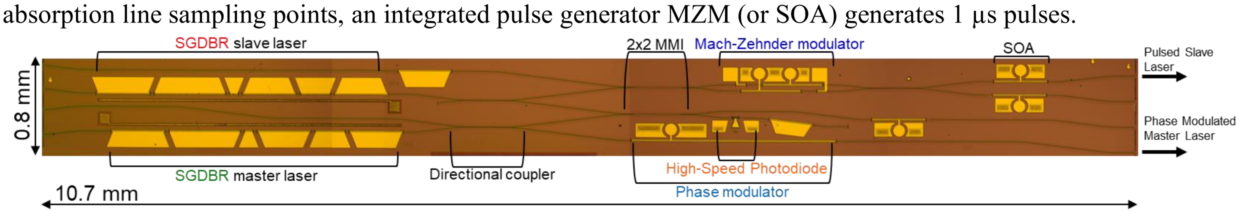

Fig. 1. PIC microscope image with master and slave lasers, high-speed PD, SOAs, PM, MZM, and couplers.

3. Test Setup and Measurements

A stabilization experiment was performed on the master laser using the gas cell reference, bench-top current sources and servo, and commercial-off-the-shelf fiber-coupled optical and connectorized electronic components. A schematic of the test setup is illustrated in Fig. 2 along with a close-up photograph of the PIC on carrier under test. Light from the PIC master laser was modulated with an external lithium niobate phase modulator. The modulation frequency, index, and phase shifter delay were selected to optimize the frequency discriminating error slope. The output power from the PIC, including fiber coupling losses, was measured to be -3 dBm. A frequency counter was used to characterize the long-term stability of a beat note generated between the on-chip master laser and an ECL.

Measurements of integrated test structures in Fig. 3(a)-(d) report, respectively, small signal SOA gain of 18 dB, normalized PD bandwidth of 15 GHz, SGDBR light-current-voltage (LIV) curves demonstrating a 50 mA threshold current, and an efficient PM requiring less than 0.5 Vpp to generate a π shift in the carrier phase. Figure 3(e) shows the frequency discriminating error slope and gas cell transmission as the laser wavelength is swept across the absorption line. Figure 3(f) reports the frequency stability of the beat note over a 1-hour period for 1-second gate times. The overall improvement in the long-term beat note frequency standard deviation was twentyfold from 101 MHz without feedback to 5.20 MHz with feedback applied to the master laser phase section only.

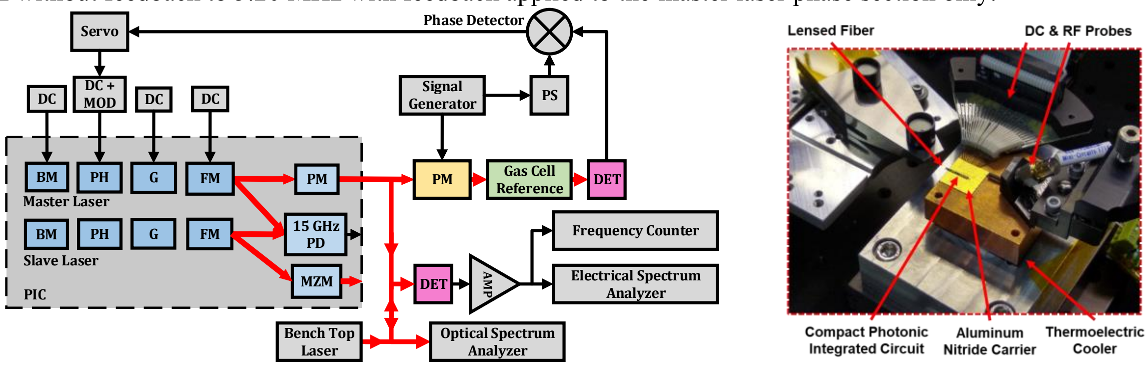

Fig. 2. PIC master laser stabilization test setup and PIC on carrier photograph.

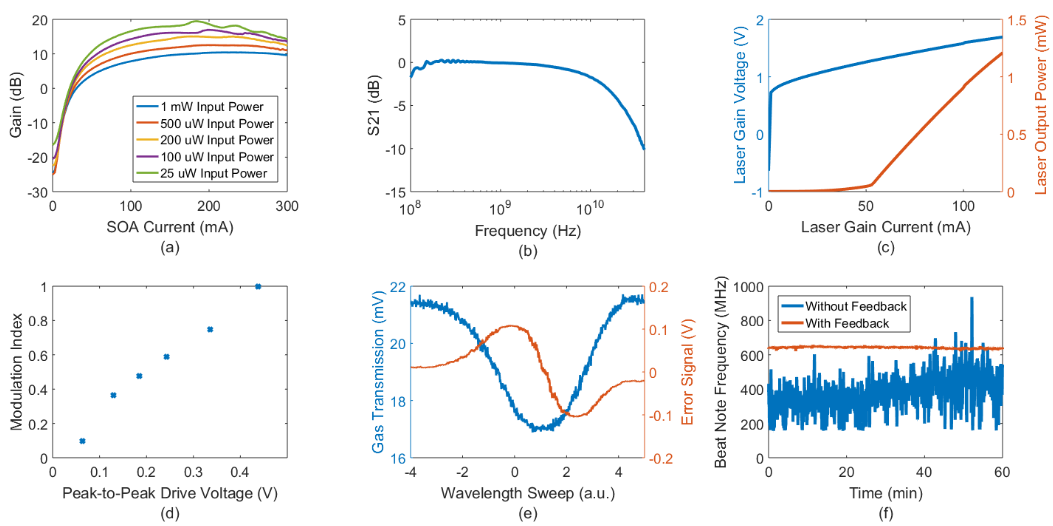

Fig. 3. (a) SOA gain; (b) normalized PD bandwidth; (c) laser LIV; (d) PM modulation efficiency at 25 mA forward bias; (e) gas transmission and error signal; (f) beat-note frequency stability.

4. Conclusions

We designed and fabricated a lidar PIC for precision spectroscopy in a monolithic InP platform. The PIC includes two SGDBR lasers, a PM, SOAs, an MZM, and a high-speed PD. Integrated components were characterized and the master laser was stabilized with a gas cell reference. Measurements showed a twentyfold improvement in the laser frequency long-term stability. It is worth noting that by engineering our platform and mirror responses, SGDBR lasers can be stabilized to any wavelength reference within their tuning range, which is typically greater than 40 nm. Gas sensing measurements using the lidar PIC will be carried out in future work.

5. References

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