Project Report
LSP-207

Photonic Integrated Navigation-Grade Gyroscope (PING): FY17 Line-Supported Advanced Devices Program

S. Bramhavar
J.J. Plant

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Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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ABSTRACT

Interferometric fiber optic gyroscopes (IFOGs) have established themselves as one of the most sensitive methods for measuring angular rotation, and have gained wide commercial adoption for a variety of inertial guidance, beam pointing, and stabilization applications. The optoelectronic components used in these gyroscopes typically consist of discrete parts (source, modulator, detector, etc.) linked together using optical fiber. This collection of discrete parts adds to the size, weight, power, and cost (SWaP-C) for the overall IFOG system and decreases its ease of manufacturability. The Photonic Integrated Navigation-Grade Gyroscope (PING) program seeks to integrate these IFOG components onto a chip-scale platform and to use the added functionality afforded by photonic integration to improve upon the performance of the entire system.

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1. PROGRAM OVERVIEW

This PING program was proposed as a multi-year effort with three primary thrusts. The first thrust was focused on producing high power, broadband optical sources with low-noise. This device will be based on an InP platform and utilize the slab-coupled optical waveguide (SCOW) technology developed at Lincoln Laboratory. The overall objective of this thrust is to demonstrate an optical source with a bandwidth greater than 50 nm, optical power greater than 100 mW, and relative intensity noise lower than -135 dB/Hz. These combined specs would demonstrate a clear improvement over current semiconductor or erbium broadband sources used in IFOGs today. One key feature of the proposed source is that the optical spectra will be tunable, allowing for increased scale factor stability in IFOG systems.

The second thrust (FY17) of the program focused on developing two separate photonic circuits. The first circuit is intended to provide the spectral measurement and feedback system needed to maintain wavelength stability of the tunable optical source. This circuit utilized a silicon nitride photonic circuit platform. A second circuit includes the integrated phase modulators and photodetectors used to control the IFOG and measure the optical signal. This chip will be based on an InP platform and will replace two discrete detectors and a packaged lithium niobate modulator currently found in almost all IFOG systems.

The third thrust will focus on integration of all of the components into a full three-axis gyroscope system (shown in Figure 1). The fiber coil, optoelectronic components, and required digital circuitry for full operation will be implemented in this phase of the program.

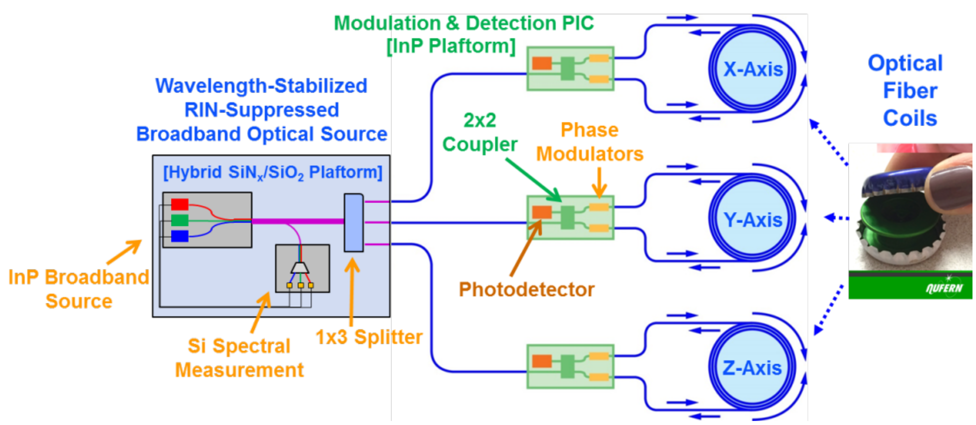

Figure 1. Illustration of 3-axis fiber optic gyroscope system with photonic integrated circuits.

2. TECHNICAL APPROACH AND EXPERIMENTAL RESULTS

2.1 FY2017 ACTIVITY

The goals of the FY2017 PING program activity were two-fold: the first goal was to design, fabricate, and test a spectral measurement chip in a silicon nitride material system. The second goal involved demonstrating an InP based photonic circuit for modulation and photodetection. The following sub-sections will outline the progress realized for each task.

2.1.1 Silicon Nitride Spectral Measurement Circuit

In order to provide feedback to the tunable optical source and reduce drift of the center wavelength over time and temperature, a spectral measurement system is required. The system envisioned for this application requires a silicon nitride photonic circuit platform in combination with a fiber-coupled Acetylene gas cell, as shown in Figure 2(a). Light from individual InP sources, each with slightly different spectral emission characteristics is first combined into a single silicon nitride waveguide. A portion of this light is picked off and sent through an optical ring resonator, which acts as a periodic filter for the broadband light (shown in red in Figure 2(b)). The light from this periodic filter is then sent into an Acetylene cell, which has a very well known and stable set of absorption lines (shown in green in Figure 2(b)). The ring resonator can be designed and thermally tuned such that only one of its many resonant frequencies aligns with one of the Acetylene absorption lines. By tuning the ring resonator filter to one individual absorption peak, the measured photodiode signal can then be indicative of how much power lies within a specific, stable, spectral band. This signal can then be monitored to ensure that the amount of power in this band remains constant over time and temperature.

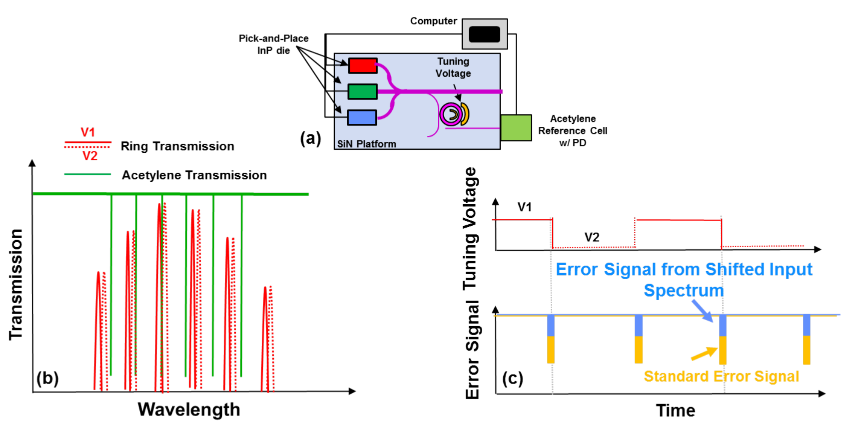

Figure 2. (a) Depiction of optical source and spectral measurement PIC. (b) Plot showing overlap of ring resonator and Acetylene. (c) Illustration showing error signal created through thermal tuning of ring resonator.

In FY17, this spectral measurement circuit was designed and completed fabrication. Individual devices are currently under test. An example picture of a fabricated chip is included in Figure 3.

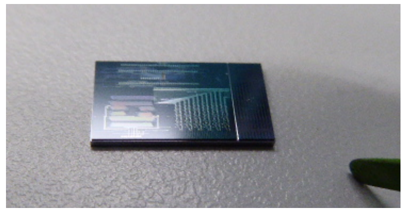

Figure 3. Picture of completed silicon nitride test chip.

2.1.2 InP Photodetector and Modulator Photonic Circuit

Another key element required in a complete IFOG is an integrated phase modulator and photodetection circuit. This circuit is to be implemented in an InP material platform, and takes a similar form to that shown in Figure 4. The key fabrication technique required for this type of photonic circuit to operate properly is to epitaxially regrow a selective area on the wafer such that the modulator region and photodetector regions have different epitaxial structures. An attempt was made in FY17 to fabricate such a structure, and subsequent test reveal very little light propagating through the waveguides. A debug was undertaken to attempt to assess the possible failure mechanisms, and the current likely failure mode is assumed to be the regrowth technique used during fabrication.

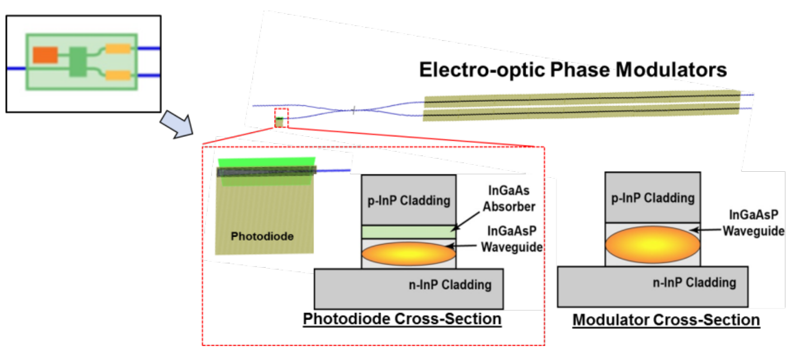

Figure 4. Illustration of InP phase modulator and photodetector photonic circuit.

2.1.3 Tunable InP/SiN Optical Source

Quantum-well intermixing (QWI) is a process which allows for the creation of gain regions with differing band gaps using the same starting quantum-well material. The process uses high-energy

Phosphorus atoms to create impurities, vacancies, or damage to the crystal. Following the implant step, a high-temperature anneal of the crystals allows these implant effects to diffuse into the sample and cause disordering of the quantum wells beneath the implanted regions, shifting the absorption band edge to higher energy (shorter wavelength) and thereby reducing the absorption loss of the quantum wells at longer wavelengths. Because these effects are localized to the implanted regions, masking can be used to define areas where the intermixing occurs, leaving the remaining areas of the material with minimal change.

Quantum-well intermixing was used for the PING program in an attempt to combine multiple gain regions on a single chip to broaden the overall spectral bandwidth of the optical source, and to utilize the independent control of each gain region to tune the optical spectrum over time to account for drifts. In FY16, a quantum-well intermixed source with tunable gain spectrum was demonstrated, but the optical power emitted from the source was quite small. In FY17, an alternative approach was attempted, in which individual InP gain chips were flip-chip bonded onto a silicon nitride platform. In this approach, separate InP chips with different gain spectra can be individually bonded onto a single silicon nitride platform and their output powers can be individually controlled to tune the overall output spectral characteristics. In order to understand the risk of this approach, it was critical to first realize an individual InP gain chip capable of outputting >20 mW of output power. This required a small re-design of the traditional SCOWA architecture, such that the mode confinement was increased in order to improve the overall ASE output power. It was also important to measure the output spectrum of such a broadband source. The results from one such device are shown in Figure 5(a). The output power from the device was greater than 50 mW, and the 3 dB spectral bandwidth was close to 20 nm. These characteristics make the desired approach, where multiple gain chips with different spectral peaks are bonded to a single silicon nitride circuit, an attractive solution to realize broadband, tunable, high power optical sources.

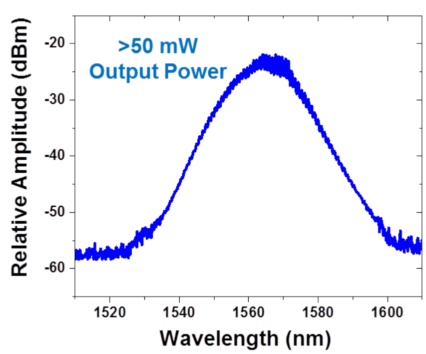

Figure 5. Plot showing output spectrum of individual InP gain chip.

A final technical component necessary to realize such a source involves being able to flip-chip bond separate InP gain chips onto a single silicon nitride circuit in order to combine their outputs. In FY17, a parallel effort (PROTO-PIC program) demonstrated that InP gain chips could be successfully bonded to silicon nitride waveguides. This represents a promising path forward for use in the creation of an optical source for IFOGs.

3. SUMMARY AND ONGOING WORK

The PING program seeks to develop a compact IFOG with navigation-grade performance, utilizing photonic integration to reduce the SWaP-C of existing IFOG optoelectronic components without sacrificing performance. For the optical source, slab coupled optical waveguide (SCOW) technology developed at the Laboratory was identified as a promising technology platform due to its high output power and noise-suppression capabilities.

The initial program activity was directed at re-engineering the SCOW mode to better match the needs of IFOG systems. To this end, a new SCOW amplifier architecture was designed, fabricated, and tested, demonstrating increased efficiency and reduced power consumption while achieving similar noise-suppression capabilities as previous devices. After this demonstration, a second fabrication run was completed in an attempt to incorporate quantum-well intermixing technology into the fabrication process to enable a broader optical bandwidth and the ability to actively tune the bandwidth to account for wavelength drifts over time. This fabrication run resulted in a demonstration of the predicted improved spectral output and tuning capabilities, but suffered from very low output power and efficiency.

As a result of the low power output from quantum-well intermixed photonic devices, a new path was outlined to fabricate individual InP gain elements with different gain bandwidths and to integrate multiple chips onto a single silicon nitride waveguide platform using pick-and-place tools. This technique allows for the efficiency and power output of the standard InP photonic circuit process to be maintained, while achieving broad spectral bandwidths and active tuning by combining the multiple gain elements on a single chip-scale platform. The individual gain chips required to achieve such a device were demonstrated in FY17, as was the ability to then bond these chips onto a common silicon nitride platform. A spectral measurement circuit was also designed and completed fabrication in FY17. This circuit is undergoing testing currently.

Through discussions with numerous external IFOG vendors, it has become clear that one of the primary points of interest and likely landing spot for MIT Lincoln Laboratory technologies would be the optical source. As a result, FY18 program activity will be directed towards developing a fully-packaged optical source that can be delivered to an external partner and tested in their test beds. Discussions with Honeywell, Northrop Grumman, and Draper have all resulted in significant interest in testing an optical source with >40 mW output power and <10 ppm wavelength stability. The focus of the FY18 activity will center around using our hybrid integration platform to combine the optical source and spectral measurement circuit and deliver such a source to these external partners.