INTEGRATED PHOTONICS TECHNOLOGY FOR SPACE-BASED REMOTE-SENSING

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ABSTRACT

We review integrated photonics technology and the applications for space-based remote-sensing. We cover the state of the technology and its advantages in a variety of sensing applications, discussing some active programs implementing integrated photonic solutions and showing the potential for improved systems performance.

Index Terms— Photonic integrated circuits, Remote-sensing, Space, Satellite sensing

1. INTRODUCTION

Photonic integrated circuits (PICs*) are the optical analog to electronic integrated circuits (EICs). In the same way that EICs replaced vacuum tubes and other bulk electrical components, PICs are revolutionizing the creation, manipulation and detection of light (photons), replacing free-space and fiber-based optics and parts with chip-based optical waveguides and components. The same revolution that occurred with integrated electronics is currently under way in photonics and it is advancing more rapidly because the highly-developed tool-set from the electronics industry can be applied to photonics fabrication.

PICs incorporate multiple photonic components on a single chip. This facilitates a drastic reduction in photonic system cost, size, weight and power (CSWaP). Photonic systems for communications and sensing are traditionally constructed with discretely packaged devices that are connected electrically and optically with wires and fibers, respectively. This approach takes advantage of mature commercial off-the-shelf (COTS) components, however, it requires cumbersome assembly processes and introduces many interfaces, which are potential failure points. In addition to reducing CSWaP, integrated photonics can increase yield, reliability, and robustness and reduce cost. This technology aims to minimize external interconnections and the use of bulk optics. Instead of connecting photonic components with chip-to-fiber, fiber-to-fiber, and freespace optical coupling interfaces, integrated waveguides are leveraged to yield seamless interconnections.

Space communications and sensing systems have long leveraged mature photonic components developed for the higher volume telecommunications industry. Because of the ever-growing demand for bandwidth by consumers and enterprises, significant investments have been made in integrated photonics technology to enable growth in fiber optic telecommunications, data center communications, and access networks. As a result, a highly functional set of photonic components exist which can be used in a much wider set of applications like automotive sensors, medical devices, defense and science instrumentation. As was done previously, space applications can and should leverage the technology being developed for these markets. Also, given the new directions to deploy vast swarms of small satellites for communications, imaging, mapping, and sensing, by both the government and private sector, the economies of scale further motivate the use of integrated photonics for space applications to ensure rapid deployment and low cost. NASA's desire for small, lightweight, rugged, efficient and highly functional optical sensors makes PIC technology crucial for the next generation of flight hardware. The significant reduction in CSWaP, enables deployment on smaller space platforms, reducing mission costs and improving performance. NASA is working with several partners on developing integrated photonics technology for future space missions [1].

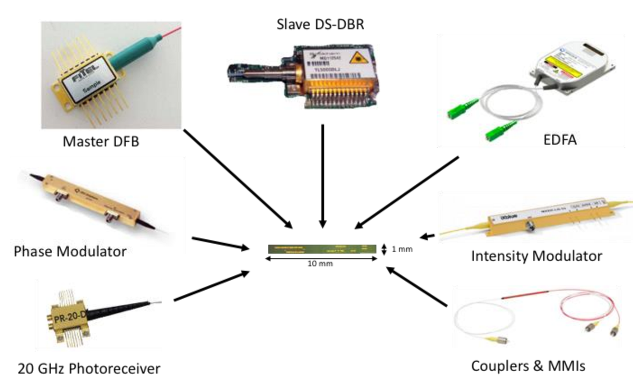

Figure 1 – Illustration of single-chip implementation of PIC technology. A NASA-funded PIC being developed for space

* PICs are alternately referred to as integrated photonics, photonic circuits, lightwave circuits, integrated optical circuits, microphotonics, nanophotonics and variants.

sensing with ~15 photonic components on a 1-mm x 10-mm chip (image presents primary required photonic functions).

2. TECHNOLOGY PLATFORMS

As for transistor ICs that come in a variety of technologies (ex. silicon CMOS, BiCMOS, HEMT, etc.), PICs can also be constructed in various forms from a number of different material platforms.

The infrastructure for photonics wafer processing falls under three primary categories: large commercial production foundries, smaller commercial foundries and R&D or academic-based foundries. As in the electronics industry, it is possible to make relatively low-cost photonics products through automated large-scale production. This model however is not cost effective for low-volume or developmental products and largely makes the large commercial production foundries impractical for R&D. However, also following the electronics industry model, PIC multi-project wafer (MPW) offerings exist, where each user utilizes a fraction of the mask reticle, enabling cost-sharing of a wafer production run among a large number of developers. This enables cost-effective development of experimental designs.

The state of the art is difficult to quantify in integrated photonics because it is a disparate field and it is moving quickly. Many commercial entities with advanced technology do not publish their results due to their proprietary nature. In addition, different material systems and wavelength regions are at different levels of development. However, some generalizations can be made. The highest functionality systems are in the 1550 nm wavelength range. Two of the more popular PIC platforms are indium phosphide (InP) and silicon photonics (SiPh). SiPh has the most highly developed manufacturing capability and has the largest wafer size (up to 30 cm diameter) and highest resolution lithography capability. It also has highly developed photonic component sets including modulators, photodetectors, filters, splitters/ couplers, attenuators and mode converters. However, silicon (Si) is not a good material for making lasers so lasers are predominantly grown on indium phosphide and then coupled externally in a variety of ways. InP is also a highly functional system which has the same components as Si but the material processing is not as well-controlled. InP is a compound semiconductor material that has been used widely to build diode lasers, particularly for the telecommunications industry. Using various integration techniques (*e.g.*, butt joint growth (BJG), selective area growth (SAG), *etc.*), InP can be used to integrate not only lasers on a chip, but also other photonic components such as modulators, photodetectors, filters [2]. The InP photonics industry has remained mostly vertically integrated, meaning various companies maintain their own technologies and perform most steps of their supply chain internally. Those steps include wafer growth, design, fabrication, backend processing, test, assembly, and packaging. Because of this, InP has mostly been inaccessible. The motivation for developing SiPh, on the other hand, was to not only leverage large-volume IC manufacturing to enable high yield and scalability, but to also provide access to a photonics technology platform; Si-based ICs have become a mainstay in part because researchers and engineers can access this technology for development through shared-cost MPW runs offered through services such as MOSIS and Europractice.

Just as for ICs, each PIC material platform comes in a variety of flavors. BJG and SAG were mentioned for InP, but there are several others as well. For SiPh, use of 220-nm thick silicon on insulator (SOI) has become somewhat standard, but variants exist that leverage thinner and thicker SOI. Other PIC platforms include gallium arsenide (GaAs), gallium antimonide (GaSb), silicon nitride (SiN), silica planar lightwave circuit (PLC), and lithium niobate (LN). Each of these platforms carries its own optical and electrical characteristics, which influence the types of photonic functions that can be realized as well as their associated performance. Also importantly, the transparency window or wavelength region supported by each platform is different. InP, for example, has been leveraged primarily for lasers and PICs operating in the 1300-1550nm wavelength region to support fiber optic and free space communications. InP can also extend to longer wavelengths for mid-infrared (mid-IR) applications, and to slightly shorter wavelengths approaching 1000 nm. SiN technology can support a wide spectrum from ~400 nm in the visible to ~2XXX nm. Hybrid approaches to closely couple light from one chip to another (InP to Si, *e.g.*) is also an active research area.

The current state of the art is over a thousand photonic components on a single chip. [3]. Communications speeds of several TBPS have been achieved. On-chip spectrometers have been developed with wide spectral range and fine resolution.

The commercial foundries that cater to this kind of business have a set of pre-designed photonic components that are made available to the designer. These components can be arranged by the designer into a system to achieve desired functions. The software design interface for this set of pre-designed components is called the process design kit (PDK) and in general is designed to interface with other higher level software tools. In Fig. 2, the blocks in orange are in general taken care of by the foundry. Each foundry has strengths and weaknesses in terms of capability, cost, component performance, material, schedule, *etc.* (In rough terms, MPW runs at a given foundry occur ~3 times per year taking ~6 months for chip fabrication.) Correct choice of foundry for a given design is an important consideration.

Academic-based foundries, (in general,) have less developed PDKs, but not necessarily less overall capability. This means using university facilities requires/allows more customization and immersion into the detailed design process with more integration of the designer into the design rule checks (DRC) and the PDK development. In many cases, these facilities are available on a fee-for-service basis allowing non-academic personnel to use the foundry. Many universities across the U.S. have large recent investments into these facilities. There are also a couple options for consultants/designers to act as a go-between between customer and foundry.

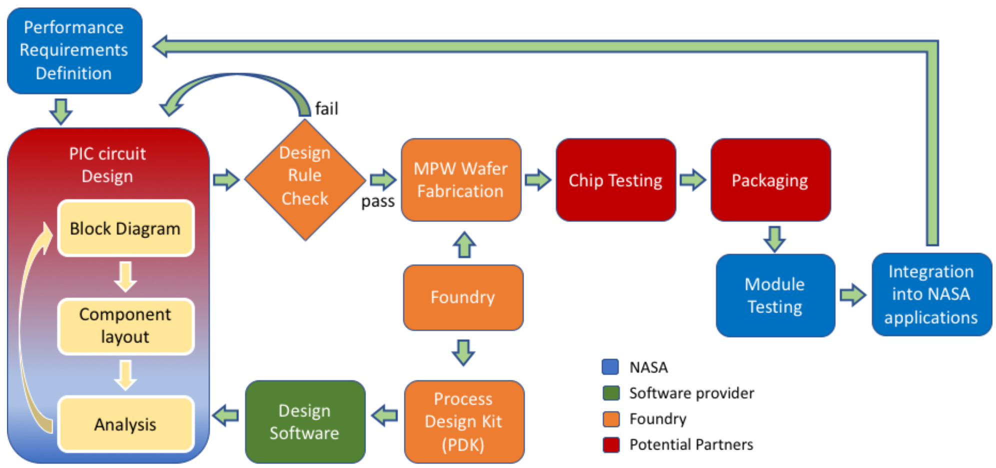

Figure 2 – Flow Chart of the Ecosystem for PIC development

3. REMOTE-SENSING APPLICATIONS

Space-based remote-sensing applications can benefit from this new technology. For many applications, the development cost for a novel photonic chip could be significant. Traditionally, IC development is paid for with high volume production, spreading the cost of development across many products. For some future space applications (*e.g.*, optical communications infrastructure), there is potential for high-volume production, but many space sensing applications will remain low-volume. However, the reduction in SWaP is so significant, that the saving in launch costs can easily cover the technology development costs.

Space-based remote-sensing applications that can benefit from PIC technology include lidars, microwave and mm-wave heterodyne spectrometers, optical spectrometers, radiometers, and many more. These instruments are enabled by complex optical functionality. NASA has been funding a number of universities and small businesses to develop prototypes to demonstrate these technologies.

NASA – Goddard and UCSB are currently collaborating on a number of programs including lidar mapping and spectroscopy measurements that can benefit from integrated photonics. We are developing a narrowly-tunable laser that sweeps through the 1572.3-nm carbon dioxide (CO_2) absorption feature [4]. This enables precise wavelength control and tuning from a single photonic chip. To make an atmospheric measurement from space, this PIC seed laser would be followed by optical amplifiers. Short-range measurements or atmospheric limb measurements could be accomplished with less power. This architecture could also be used for other spectroscopic targets like methane, water vapor or other gases of interest.

Figure 3 shows a sampled grating diffraction Bragg reflector (SGDBR) laser with integrated semiconductor optical amplifiers (SOAs) and Mach-Zehnder modulator (MZM). The SGDBR enables wide wavelength tunability and the MZM enables high-speed amplitude modulation. The SOAs increase optical power and compensate for other losses in the system.

Figure 4 shows a more complex PIC designed for high-fidelity lidar spectroscopy. It includes two different types of lasers. One is a master wavelength-locked distributed feedback (DFB) laser that is referenced to the CO_2 absorption. The SGDBR is an offset-locked laser that tunes around the master. The two laser signals are mixed together on the high-speed photo-detector to measure the wavelength difference using the beat-note in a heterodyne configuration. The wavelength-scanned slave laser signal is then amplitude-modulated with an MZM and then amplified with an SOA. In earlier configurations, all these functions required independent components and significant systems integration with far more interfaces. This single-chip design demonstrates the power of PIC technology, decreasing size, weight, and power, improving reliability and ruggedness and enabling complexity and functionality.

We are also investigating a GaAs-based integrated photonic seed laser at 1030-nm for mapping applications. This is a wavelength-scanned laser enabling compact, efficient, non-mechanical beam-steering. Again, for planetary measurements from orbit, optical amplification is needed. Shorter-range measurements for 3D imaging (*e.g.*, mapping lidar for a rover) are possible with much less transmitted power.

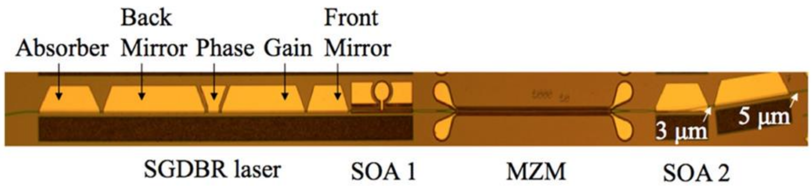

Figure 3 - Microscope image of fabricated InP PIC transmitter comprising a sampled grating DBR (SGDBR) laser, a high-speed semiconductor optical amplifier (SOA), a Mach-Zehnder modulator (MZM), and a high-power SOA.

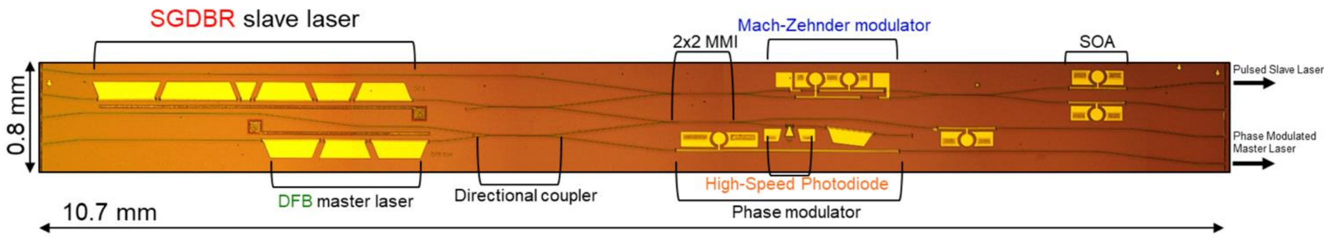

Figure 4 - Microscope image of dual-laser PIC for spectroscopic Lidar. PIC includes distributed feedback (DFB) master laser, SGDBR slave laser, high-speed photodetector, phase modulator for phase-locked loop (PLL), intensity modulator for pulse encoding, various SOAs for power boosting.

Another application that is being developed is radio frequency (RF)-photonics. At its core, an RF signal modulates an optical wave so the RF information is encoded onto the optical carrier. Then the signal can be processed using the well-developed photonics tools. This encompasses a wide range of RF bands from microwave to THz. High-frequency RF signals like THz signals can be difficult to process due to lossy waveguides and components. Encoding the information onto an optical carrier enables the manipulation, processing and detection of wide-band RF signals. On-chip tunable optical filters, arrayed waveguide gratings and high-fidelity laser wavelength references enable signal processing that traditional RF methods would find complex, physically large and power-hungry. Also, due to the comparatively very-low-loss photonic waveguides, transmitting high frequency RF signals this way can also be advantageous. As a result, for many applications, the initial loss upconverting the RF signal to an optical carrier is a good systems trade.

4. CONCLUSIONS

Integrated photonic technology has many advantages for space-based remote-sensing. We have touched on a few of the applications for which we have active development but the technology is enabling for many more measurements than have been discussed here. PIC technology can significantly decreases CSWaP which enables more functionality due to the potential for higher system complexity. The cost savings more than justifies the technology investment to develop the photonic systems. In addition to the cost savings, PIC systems increase reliability due to the reduction of interfaces and added components and ease of packaging. The highly developed set of photonic components enables a wide range of applications. This highly versatile technology can greatly enhance the next generation of satellite sensing measurements.

5. REFERENCES

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