Photonic Integrated Circuits at MWIR and Green Wavelengths for Biomedical Applications

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Abstract: Light at mid-wave infrared- as well as visible-wavelengths are widely used in biophotonic applications with the promise of much improved healthcare. This talk will review on recent progress made at OSU towards developing photonic integrated circuit technologies at these wavelengths.

The mid-wave infrared (MWIR) spectral region, spanning 3-30 µm, is significant in biomedical research because many biomolecules exhibit strong resonances in this region, yielding characteristic absorption lines. The absorption can be used as a tool to detect and recognize the presence of a particular gas or liquid in a considered ambience. Recent advances in MWIR light sources have found biomedical applications in tissue imaging, reconstruction, excision, and ablation. Despite the current use of bulk and expensive lasers including CO_2 lasers, free electron lasers, optical parametric oscillators, and fiber lasers in these applications, semiconductor diode lasers offer low size, weight, power, and cost (SWaP-C) potential and the prospects for future low-cost sensors. MWIR sensing systems based on evanescent wave field detection comprise MWIR illumination sources, appropriate waveguide structures propagating the lightwaves, and detectors [1]. Photonic integrated circuits (PICs) can be used to implement evanescent wave sensors, where the on-chip integration of three components such as light sources, an interaction volume in which the radiation interacts with the sample, and a detector is required either via a monolithic- or hybrid -integration.

From the material perspective, although low-bandgap compound semiconductor GaSb materials and its alloys are relatively less mature, they comprise the optimal material system for integrating MWIR lasers and detectors on PICs. At present there are no GaSb-based PICs with monolithically-integrated active and passive components that operate in the MWIR regime. In the field of optical sensing, MWIR devices such as type-I diode lasers and interband cascade lasers (ICLs) consume nearly an order of magnitude less power than quantum cascade lasers and can result in unprecedented sensitivity and selectivity by exploiting the molecular fingerprint region. Our work focuses specifically on developing a high-performance PIC technology for the 2.2-3.4 µm wavelength region using diode lasers, with many of the same advances later applicable to ICLs operating at 3-6 µm. The primary objective is to develop a complete PIC in which widely tunable lasers and passive components [2] will be monolithically integrated on a GaSb platform. Such integration within a PIC architecture, as shown in **Fig. 1**, is anticipated to reduce electrical power consumption ×30, size ×40, and cost ×5 or higher. Hence, our on-chip, low-cost, compact, robust, and energy-efficient PICs operating at MWIR wavelengths could enable the aforementioned biomedical applications.

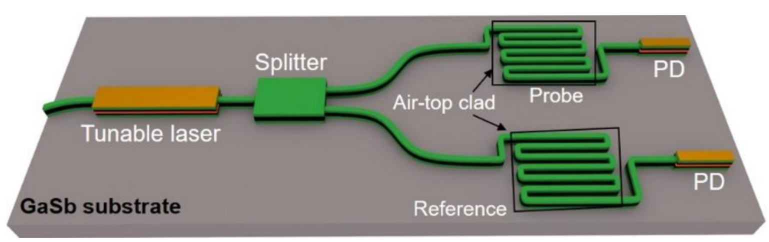

Fig. 1: Schematic of monolithic GaSb PICs for the wavelengths above 2 µm, being useful to develop an on-chip MWIR absorption spectroscopy sensor.

The evolution of wearable technologies has facilitated the adoption of non-invasive health monitoring devices that operate based on the direct detection of back-scattered light. These devices commonly utilize light-emitting diodes (LEDs) to gather essential photoplethysmography (PPG) data, such as heart rate and sleep patterns, etc. Current wearable devices utilize LEDs spanning a range of wavelengths, primarily at visible, near-infrared and extended short-wave infrared range of the electromagnetic spectrum. However, the LEDs face challenges in power efficiency, signal strength, and biomolecule detection. These issues could be substantially mitigated through the adaptation of PICs [3] which are equipped with on-chip lasers and sensors, among other components, thereby elevating spectral resolution, integration density, and power efficiency. For plethysmographic measurements, among various wavelengths, the green light proves effective for some non-invasive health monitoring applications due to its enhanced absorption by hemoglobin and deeper tissue penetration capabilities. [4]. Direct generation of green-yellow coherent light with high-indium-containing InGaN alloys is difficult due to low crystal quality. This material limitation can be tackled by using materials like lithium niobate (LN) with large nonlinear coefficients resulting in high up-conversion efficiency in PIC waveguides which can be further improved by utilizing resonant cavities. Most green light with second harmonic generation (SHG) in the market relies on quasi-phase matching (QPM) requiring a complex periodic polling process, making modal phase matching (MPM) more suitable for photonic integrated circuit applications. While MPM has been employed for up-converting telecom signals [5], its effectiveness in generating green light is yet to be demonstrated. Fig. 2 shows the schematic of the proposed MPM-based SHG of green light with an on-chip laser, SHG elements, and an add-drop filter.

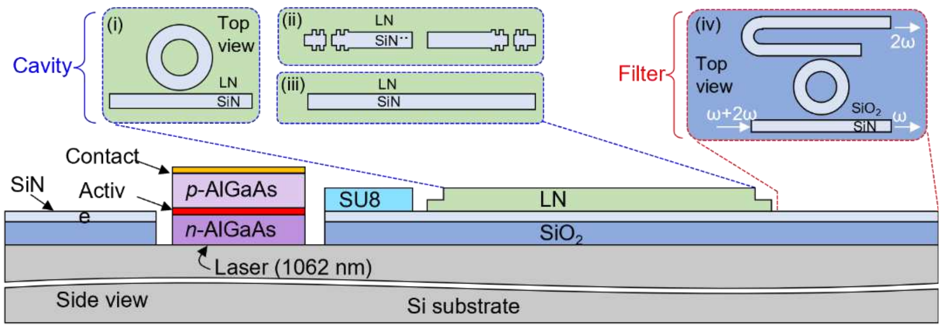

Fig. 2: Schematic of silicon photonic PICs for generating green light using a non-linear process. Insets: (i) microring resonator for SHG enhancement, (ii) Fabry-Pérot microcavities for SHG enhancement, (iii) single pass SHG process in a straight waveguide, and (iv) an add-drop microring filter to separate the pump and second harmonic signal.

We are currently working on demonstrating an MPM-based SHG approach that employs a single-pass waveguide to produce green light as shown in inset (iii) of **Fig. 2**. This process utilizes an on-chip infrared laser as the source of the fundamental wavelength (1062 nm), as shown in **Fig. 2**. To further enhance SHG efficiency, our next step involves incorporating cavities such as ring resonators and Fabry-Pérot microcavities, as illustrated in insets (i) and (ii) of **Fig. 2**. To directly harness the transverse electric (TE) mode generated from the laser, our approach employs a lower nonlinear coefficient d_{eff} to maintain mode compatibility throughout the ring resonator cavity. This strategy capitalizes on the high Q-factor attainable with micro ring resonators. Additionally, our research pioneers a technique for producing on-chip green light through SHG in Fabry-Pérot microcavities. Unlike the ring cavity, this method uses the maximum d_{eff} in x-cut y-propagating SiN-LN hybrid waveguides by exploiting a bend-free cavity structure. Following the generation of the second harmonic, or green light at 531 nm, it is crucial to isolate the pump's fundamental signal from the newly generated second harmonic signal. To achieve this, we have integrated an add-drop ring resonator, as shown in inset (iv) of **Fig. 2**. Employing a monolithic Fabry-Pérot microcavity, our study has theoretically achieved an SHG efficiency enhancement of up to 30,000 times. Moreover, our approach significantly enhances manufacturing flexibility by etching silicon nitride (SiN) rather than LN, overcoming the etching challenges posed by LN's physical and chemical properties. Moreover, our technique pioneers the innovative application of transferring LN onto patterned SiN via transfer printing, opening new avenues in the field of integrated optics and promising more versatile and efficient photonic devices.

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