Mid-Infrared Silicon Photonic Devices and Sensors

Swapnajit Chakravarty[1], Hai Yan[2], Yi Zou[2], Ray T. Chen[1,2]
[1]*Omega Optics Inc., 8500 Shoal Creek Blvd., Austin, TX, 78757, USA*
[2]*Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78758, USA*
Author e-mail address: swapnajit.chakravarty@omegaoptics.com, raychen@uts.cc.utexas.edu

Abstract: Mid infrared silicon photonic integrated components, namely grating couplers, strip and slot waveguides, slotted and un-slotted photonic crystal waveguides, photonic crystal microcavities are experimentally demonstrated in silicon-on-sapphire. Application in trace gas sensing is experimentally demonstrated. Progress towards monolithic integration of lasers and detectors are discussed.

Silicon has been the material of choice of the photonics industry over the last decade due to its easy integration with silicon electronics as well as its optical transparency in the near-infrared telecom wavelengths. In recent years, photonic devices on chips are increasingly being used for chemical and biological sensing. Chemicals are best recognized by their unique wavelength specific optical absorption signatures. Slow light in PC slot waveguides [1-3] has been used to reduce the optical absorption path length and achieve high detection sensitivity in on-chip optical absorption spectroscopy for the selective detection of volatile organic compounds [1, 2] and greenhouse gases [3] based on unique analyte absorption signatures in the near-infrared (near-IR). It is common knowledge that mid-infrared (mid-IR) wavelengths offer at least two orders of magnitude larger absorption cross-sections than the near-IR. Silicon is optically transparent from 1.1 μm to 8 μm with research from several groups in the mid-IR [4-6]. In this paper, we present our work in mid-IR integrated silicon photonics with applications in trace gas sensing. We also review progress towards monolithic integration with mid-IR lasers and difference frequency generated sources.

With any waveguide core, one must also consider the appropriate cladding, transparent in the wavelength range of interest. Two commonly used substrates for silicon photonics have been silicon-on-insulator (SOI) with cladding oxide transparency till $\lambda\sim3.7\mu m$ and silicon-on-sapphire (SoS) with cladding sapphire transparency till $\lambda\sim5\mu m$. Methods to increase the wavelength bandwidth of silicon have included demonstrations of free-standing membrane mid-IR silicon waveguides [7]. We have used the SoS platform in our mid-IR silicon photonics research.

Fig. 1(a) shows a typical measurement setup used in our experiments. For efficient optical characterization of mid-IR integrated photonic components, an essential element is a high efficiency coupler from an external light source into the integrated photonic component [8]. For this purpose, grating couplers were designed in our SoS platform to couple light into and out of the SoS device, via single-mode ZrF_4 mid-IR optical fibers, as shown schematically in Fig. 1(b). Initial device characterizations were performed at $\lambda=3.43\mu m$ using a commercially available interband cascade laser (ICL) from Thorlabs. On the output end, the transmitted light through the integrated mid-IR device is measured with a liquid nitrogen cooled InSb detector. In order to improve signal-to-noise ratio, a mechanical chopper (1 KHz) is used, and detected signals from InSb are demodulated by a lock-in amplifier.

Fig. 2 shows the electric-field intensity profile for coupling light into and out of SoS via grating couplers. The optimized coupling angle was 11^o for the transverse-electric (TE) coupled mode for which a coupling efficiency ~29% was measured experimentally, matching with simulation results. Strip waveguides and slot waveguides were characterized and propagation losses ~2.1dB/cm and ~11dB/cm were experimentally measured, as shown in Fig. 2. Efficient strip to slot mode converters were designed and fabricated showing a loss of about 0.13 dB per mode converter, corresponding to 97% conversion efficiency, which agreed well with the simulated result of 98% [8].

Fig. 3 (a-c) shows scanning electron micrograph images (SEMs) of various mid-IR photonic crystal waveguides (PCWs) experimentally investigated on the SoS platform [9, 10]. Characterization of PCWs is typically done with broadband or tunable laser sources that can scan a range of wavelengths to accurately identify the position of the PCW band edge. We overcame the logistical limitation by tuning the lattice constant of the PCW, and thus scanning the transmission band edge across our fixed wavelength ICL over several devices. Propagation loss measurements were done over different lengths of the respective devices in the guided wave region below the light line. Propagation loss ~12dB/cm and 13dB/cm were observed in conventional PCWs and holey slotted PCWs. No transmission was observed in the stop gap, and very high propagation losses >500dB/cm were observed above the light line in accordance with theory.

Fig. 4 shows measurement results of sensing triethylphosphate (TEP) with a 800μm long holey slotted PCW in Fig. 3(b). TEP has an absorption cross-section $\sim10^{-21}cm^2$/molecule at $\lambda=3.43\mu m$ and was experimentally detected at 10ppm concentrations with an estimated detection limit of 1ppm [10]. Waveguide coupled photonic crystal microcavities were also demonstrated in the mid-IR SoS platform [11], with potential applications in mid-IR biosensing. PC microcavities with Q~3500 were experimentally demonstrated.

However, in order to make a transition from the research lab to the field, integrated photonic devices need to be packaged into light-weight, low form factor systems integrated with lasers and detectors. Silicon, in particular, is not a light emitter. Methods have been investigated to heterogeneously couple light from III-V lasers into SoS with a vision for monolithic integration [12]. We will also review our recent work to generate mid-IR light from near-IR sources via difference frequency generation (DFG) in silicon nitride strained silicon waveguides.

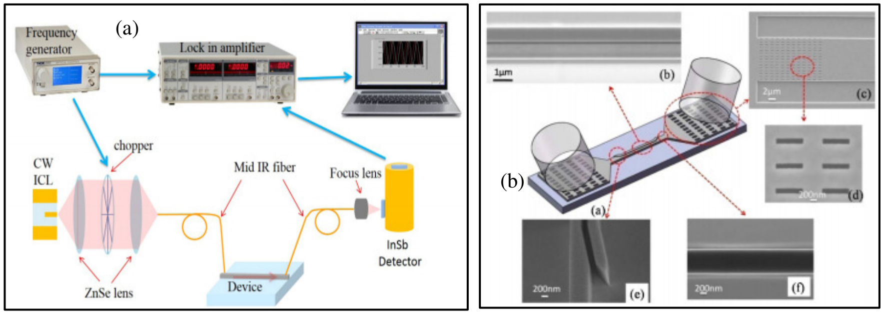

Fig. 1: (a) Schematic of the mid-IR experimental setup. (b) Schematic of the fabricated device, (c) SEM image of fabricated slot waveguide, (d) SEM image of SWG coupler, (e) magnified view of air holes, (f) close-up of strip waveguide to slot waveguide mode converter, and (g) SEM image of single mode strip waveguide with 1 μm width. [8-11]

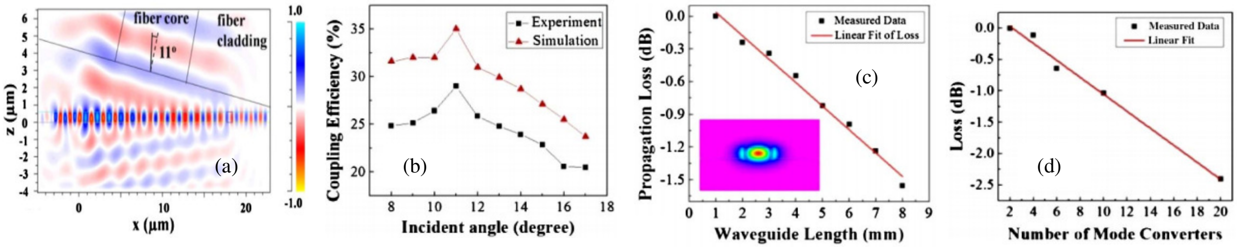

Fig. 2: (a) Simulated output optical field from grating coupler to fiber (b) Experimental measured and simulated coupling efficiency with different incident angles. (c) Measured loss of eight single mode waveguides in SOS. The waveguides are 0.6 μm in height and 1 μm in width. 2.1 dB/cm propagation loss is achieved by linear fitting. (d) Measured loss versus number of strip-to-slot waveguide mode converters in SoS. [8]

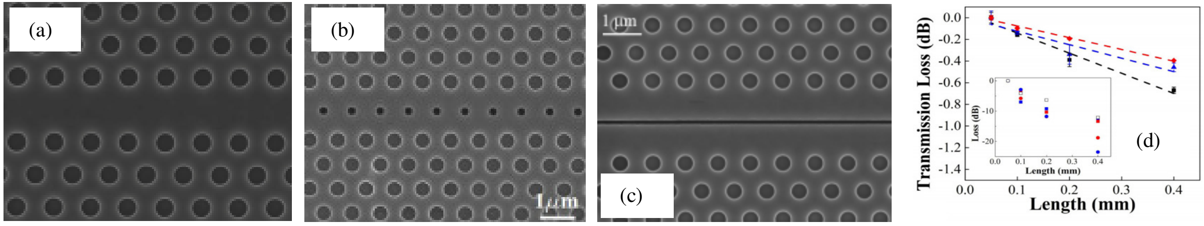

Fig. 3: SEM of (a) conventional photonic crystal waveguide (PCW) , (b) holey slotted PCW, and (c) rectangular slotted PCW in silicon-on-sapphire for operation at λ=3.43μm. (d) Propagation loss of the guided mode in the conventional PCW in (a).[9, 10]

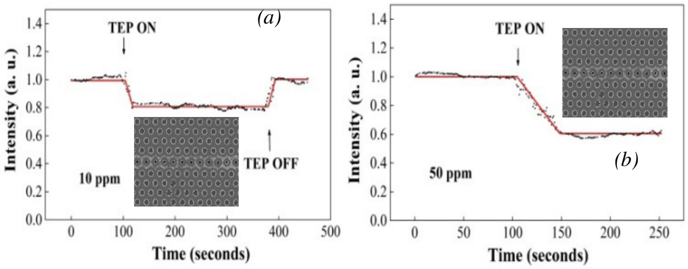

Fig. 4: Transmitted light intensity through an 800μm long HPCW in SoS as a function of TEP concentration (a) 10ppm and (b) 50ppm respectively. Sufficient signal in (a) indicates potential to sense down to 1ppm. [10]

In summary, silicon integrated photonics promises to have a significant impact in the mid-IR with widespread applications in chemical and biological sensing. This research has been supported by SBIR awards IIP-1127251 (NSF), Contract #W911-SR-12-C-0046 (Army). DFG research is supported by Grant# 70NANB16H183 (NIST).

References

[1] Appl. Phys. Lett. 98 (2), 023304 (2011)
[2] Optics Lett. 38 (19), 3799 (2013)
[3] Optics Lett. 36, 984 (2011)
[4] Nat. Photonics 4(8), 495 (2010)
[5] Opt. Express 19(6), 5579 (2011)
[6] Opt. Express 20(28), 29361 (2012)
[7] Opt. Lett. 39(19), 5661 (2014).
[8] Opt. Lett. 39, 3070 (2014)
[9] Optics Express 23, 6965 (2015)
[10] Sens. & Actuators B 221, 1094 (2015)
[11] Appl. Phys. Lett., 107, 081109 (2015)
[12] CLEO, Abstract ID: STu4I.2, San Jose, CA(2015)