Mid-Infrared Trace Gas Sensing using Photonic Crystal Waveguides

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ABSTRACT: Photonic crystals offer an ideal platform for on-chip absorption spectroscopy through engineering and enhancing light matter interaction. Using photonic crystal waveguides, we experimentally demonstrate parts per million and parts per billion level detection of different gas species.

Applications of Mid-Infrared photonics span from thermal imaging and free-space communications to medical and bio-agent sensing and absorption spectroscopy. All commercial absorption spectroscopy systems including Fourier transform infrared spectroscopy (FTIR), tunable direct laser absorption spectroscopy (TDLAS), cavity ring-down spectroscopy (CRDS), and photo-acoustic spectroscopy (PAS) have bulky and expensive optical components [1]. On-chip absorption spectroscopy is an alternative that eliminates this requirement and offers a lightweight and alignment-free spectrometer that is suitable for low size, weight and power (SWaP) applications. Thanks to the slow light effect and enhanced modal overlap with the analyte, photonic crystal waveguide (PCW) offers an ideal platform for on-chip Mid-IR spectroscopy.

The principle of enhanced absorption relies on the phenomenon of slow light unique to PCW structures and enhanced optical field intensities in low index narrow slots that combine to increase the effective path length traversed by the guided wave through the sensed gas. According to the Beer-Lambert technique, transmitted intensity I is given by:

$$I = I_0 \exp(-\alpha\gamma L) \qquad (1)$$

Where I_0 is the incident intensity, α is the absorption coefficient of the medium, L is interaction length and γ is the medium-specific absorption factor determined by dispersion enhanced light-matter interaction. In conventional free-space systems, γ = 1; thus, L must be large to achieve a suitable sensitivity of measured I/I_0. Since L is very small for on-chip systems, γ must be large to compensate this reduction in length. Using perturbation theory, it is shown that [2]:

$$\gamma = f \times \frac{c/n}{v_g} \qquad (2)$$

where c is the velocity of light in free space, v_g is the group velocity in medium of effective index n and f is the filling factor denoting relative fraction of optical field residing in the analyte medium. Hence by tuning group velocity and filling factor we can enhance sensitivity of our device.

Fig. 1 (a) shows the schematic of a slotted PCW. Slotted PCW is a hexagonal lattice of air holes within a slab of the substrate with a single missing row of holes along the Γ – K direction. An optimized design will ensure a large modal overlap with the analyte along with a large bandwidth for propagating guided mode and a wide stop band. This optimization is achieved through tuning the ratio of small holes radius in the center to bulk holes radius. Fig. 1(b) and Fig. 1(c) show top view SEM images of the TE-polarization selective SWG coupler and slotted PCW fabricated on a SOI platform to operate at the center wavelength of λ=3.4μm designed for alcohol detection.

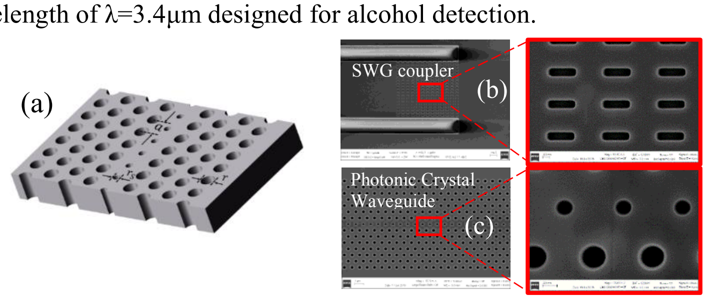

Figure 1: Top-view SEM images of the (a) SWG grating coupler (b) Photonic crystal waveguide, figures at the right-hand side are zoomed-in images of the indicated areas

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Fig. 2 illustrates a schematic of the measurement setup used for gas sensing. Light emitted from a single wavelength laser is collimated and coupled into a single mode fiber using a set of an aspheric lens and a biconvex lens. Transmitted light from fiber is coupled into and out of the chip using TE-polarization selective subwavelength grating couplers. Calibrated concentration of target gas diluted in an inert carrier gas is flowed from a vapor generator to the chip. Finally, output light is collected by another single mode fiber and measured by an InSb detector. A mechanical chopper is used to improve signal to noise ratio and output signal from InSb detector is demodulated by the lock-in amplifier.

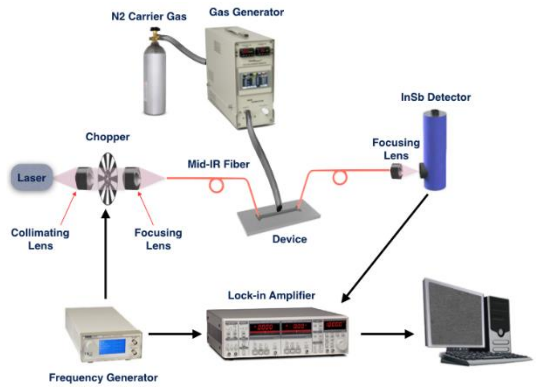

Figure 2: Schematic of the measurement setup for gas sensing

Using this setup, we have detected 3 parts per million (ppm) greenhouse gas carbon monoxide (CO) at λ =4.55μm with feasibility to detect down to sub-100 parts per billion (ppb) by nominal device modifications in a silicon-on-sapphire (SoS) platform. We also detected the chemical warfare simulant triethylphosphate (TEP) down to 10ppm at λ =3.4μm also in a SoS platform. Recently, we experimentally demonstrated the detection of ammonia at λ =6.15μm in an InGaAs-InP platform and alcohol at λ=3.4μm in a SOI platform, using enhanced analyte overlap integrals in nanophotonic structures. Fig. 3 shows typical gas sensing results obtained separately with photonic crystal waveguides in mid-IR in various material systems. More measurements using other nanophotonic waveguide structures like subwavelength waveguides is in progress and will be presented later.

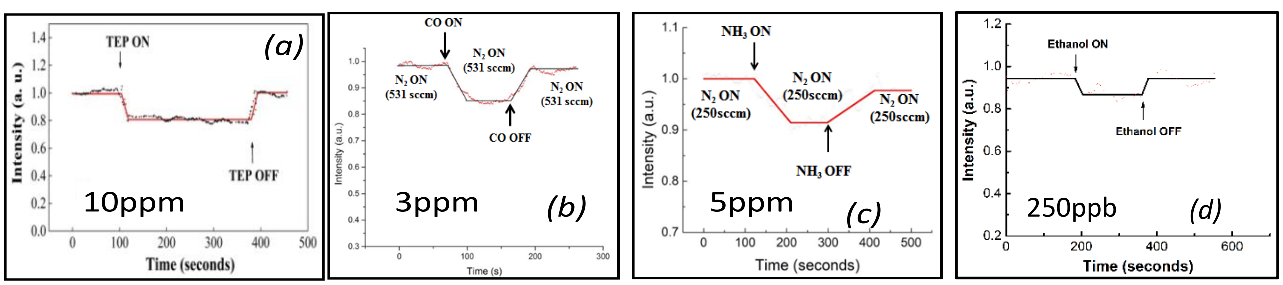

Figure 3: Experimentally detected gas concentrations for (a) TEP (b) CO (c) NH_3 and (d) Ethanol in mid-IR nanophotonic waveguides.

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