# Sub-Parts-Per-Million Level Detection of Ethanol using Mid-Infrared Photonic Crystal Waveguide in Silicon-on-Insulator

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**Abstract:** We experimentally demonstrate an Ethanol sensor based on a slotted photonic crystal waveguide fabricated on a silicon on insulator platform to perform at a center wavelength of 3.4µm. Utilizing a 9mm long PCW, concentrations of down to 500 parts per billion (ppb) of Ethyl alcohol is detected.

Mid-infrared absorption spectroscopy has attracted considerable attention owing to the rovibrational signatures of compounds of interest in the solid, liquid or gas phase in the spectral region of 2-20µm - also called the molecular fingerprint region - and their large absorption cross-section in this regime [1]. One such compound, Ethanol gas, has an absorption cross-section of $2\times10^{-19}$cm$^2$/molecule with a peak absorbance at $\lambda = 3.4\mu m$ . For precise and real-time detection of trace amounts of this gas we need a compact, highly sensitive and selective sensor. On-chip spectrometers are promising devices that unlike their off-chip commercially available counterparts offer sensing in portable applications. Thanks to the slow light effect and enhanced modal overlap with the analyte, photonic crystal waveguide (PCW) has become an ideal platform for the on-chip Mid-IR spectroscopy. In this paper, we design and fabricate an on-chip ethyl alcohol sensor and use it to detect sub-parts-per-million levels of ethanol.

Our PCW-based gas sensors use the absorption spectroscopy scheme which is described by the Beer-Lambert law. According to this law, transmitted intensity at the output of the waveguide is given by:

$$I = I_0 \exp(-\gamma\, \alpha_{abs} \mathrm{L} - \alpha_{prop} \mathrm{L}) \qquad (1)$$

where $I_0$ is the incident intensity, L is the interaction length, $\alpha_{prop}$ is the propagation loss, $\alpha_{abs} = \varepsilon C$ is the absorption parameter with ε as the molar absorption and C as the concentration, and finally $\gamma$ is the medium-specific absorption factor and is determined by dispersion enhanced light-matter interaction and is given by: $\gamma = f \times \frac{c/n}{v_g}$. 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 the relative fraction of optical field residing in the analyte medium. A photonic crystal waveguide can enhance light matter interaction through engineering both the group index and the filling factor.

The photonic crystal waveguides comprise hexagonal lattices of air holes within a slab of silicon with a single missing row of holes along the $\Gamma-$ K direction. Using plane-wave expansion method, the structure was optimized and designed to ensure a relatively large bandwidth and a wide stop gap, simultaneously. Fig. 1(a) shows simulation results for the guided mode bandwidth below the oxide light line as well as the stop gap region width in terms of normalized frequency $(\alpha/\lambda)$ versus the radius of the small air holes. In the optimized device, for a lattice constant of $\alpha$, there is a single row of smaller holes in the center of PCW with radius $r_s = 0.7r$, where $r = 0.22\alpha$ is the radius of the holes in the bulk lattice. Fig. 1(b) plots the dispersion diagram for this structure and Fig. 1(c) illustrates the 3D electric field intensity profile of the propagating light in the waveguide. The enhanced peak electric field in the central small holes can be observed.

The devices are fabricated on an SOI wafer with a 500nm thick silicon layer on top of a 3µm thick buried oxide (BOX). The pattern of the passive waveguide is transferred to the silicon device layer using electron beam lithography and inductively coupled plasma etching. Fig. 1(d) shows top view SEM image of the photonic crystal waveguide. As in previous research [2,3], a photonic crystal index taper is inserted at both interfaces of the PCW and strip waveguides. Input and output grating couplers are also designed and implemented to couple the light into and out of the waveguides.

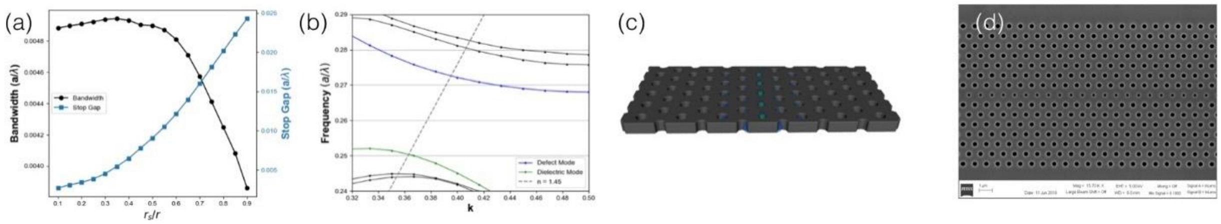

Fig. 1. (a) Variations of the bandwidth and stop gap as a function of $r_s$ (b) Dispersion diagram of the photonic crystal simulated by 3D plane-wave expansion (c) 3D electric field intensity profile of the propagating light in the waveguide (d) Top view SEM image of the photonic crystal waveguide

Fig. 2(a) illustrates a schematic of the measurement setup used for gas sensing. Light emitted from a single wavelength interband cascade laser is collimated and coupled into a single-mode fiber with aspheric and biconvex lenses, respectively. Input light coupled in from the fiber via the grating couplers propagates through the photonic crystal waveguides and the transmitted light is coupled out of the waveguide through output gratings. A Calibrated concentration of ethanol diluted in nitrogen is flowed from the vapor generator to the chip. Finally, output light is collected by a multimode mode fiber and measured by an InSb detector.

Our devices are characterized using a single wavelength external source with a center wavelength of $\lambda = 3.4\mu m$. So, in order to demarcate the stop gap and light line boundaries similar devices with different lattice constants were fabricated and measured. Fig. 2 (b) plots the normalized transmitted intensity through the PCW devices with varying lattice constants. As observed, photonic crystals waveguides with a lattice constant larger than 850nm are above the stop gap band edge. Fig. 2(c) illustrates our gas sensing measurement results. The normalized transmitted light intensity through a 9mm long slotted photonic crystal waveguide when exposed to 500ppb of ethanol gas is plotted as a function of time. Ethanol was flowed from a calibrated Kintek vapor generator in a nitrogen carrier gas. The carrier gas is always ON. A 11.7% drop in the transmitted signal through the photonic crystal waveguide is observed when ethanol flow is turned ON. When etahnol flow is turned OFF, the signal goes back to original levels in nitrogen flow.

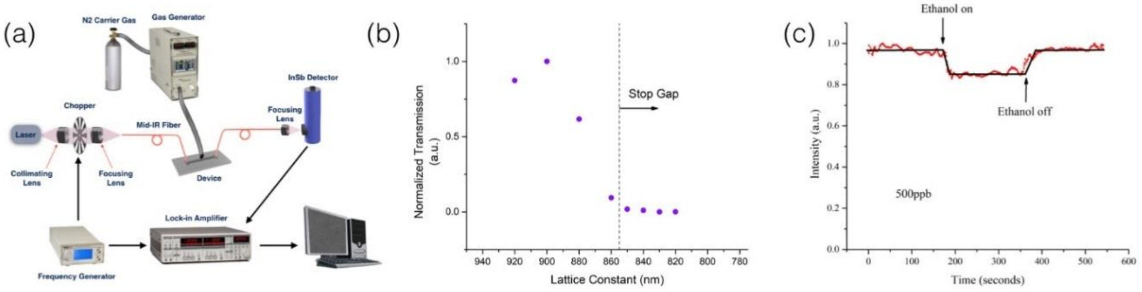

Fig. 2. (a) Schematic of the experimental setup for gas sensing (b) Normalized transmitted intensity through the PCW devices with different lattice constants (c) Transmitted light intensity through a 9mm long PCW with a lattice constant of 920nm exposed to 500ppb of Ethanol gas

In summary, we designed and fabricated slotted PCW on SOI platform to detect sub parts per million level concentration of Ethanol. We experimentally demonstrated detection of 500 parts per billion ethanol at 3.4μm wavelength on the silicon on insulator platform. The research was funded by the NIH Grant # 1 R43 AA026122-01. The authors also acknowledge the use of Texas Nanofabrication Facilities supported by the NSF NNCI Award #1542159.

## 3. References

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