

# Photonic Crystal Chemical Absorption Spectroscopy for Multiplexed Detection of Xylene and TCE in Water

Wei-Cheng Lai<sup>1\*</sup>, Swapnajit Chakravarty<sup>2\*</sup>, and Ray T. Chen<sup>1</sup>

<sup>1</sup>Dept. Electrical and Computer Engineering, The University of Texas at Austin, 10100 Burnet Rd, PRC/MER 160, Austin, TX 78758, USA.

<sup>2</sup>Omega Optics, Inc., 10306 Sausalito Dr, Austin, TX 78759, USA.

wlai@utexas.edu, swapnajit.chakravarty@omegaoptics.com, raychen@uts.cc.utexas.edu, Fax: +1-512-471-8575

**Abstract:** We experimentally demonstrate simultaneous selective detection of xylene and trichloroethylene using photonic crystal waveguide. Sensitivity is improved by slow light effect of PC to 1ppb (v/v) for xylene and 10ppb (v/v) for TCE in water.

**OCIS Codes:** (280.0280) Remote sensing and sensors (050.5298) Photonic crystals

Techniques to detect and identify chemical and biological analytes based on photonic crystal (PC) platform have been investigated extensively in recent years. Many applications are working on the detection of volatile organic compounds (VOCs) by using different methods, such as optical planar Bragg grating [1], Fabry-Perot cavity sensor [2], and two dimension micro-gas chromatography [3]. In our previous work, PC slot waveguide structures successfully detected and identified VOCs in liquid and gaseous phases for xylene in water and methane in nitrogen respectively. [4-5] Results showed the enhancement due to slow light effect of photonic crystal waveguide (PCW) greatly reduces the total interaction length with chemical analytes. The length of PC slot waveguide for sensing xylene in water is only 300 $\mu$ m, which showed that the miniature PCW structure is an ideal platform for chip integrated optical absorption spectroscopy. Miniaturization enables the potential for multiplexed detection for the simultaneous identification and quantification of multiple organic compounds of interest. In this paper, we demonstrate multiplexed detection and identification of xylene and trichloroethylene (TCE) with a single measurement in a silicon based chip integrated optical absorption sensor.

The principle of our device is based on infrared absorption spectroscopy. According to the Beer-Lambert law, the transmitted intensity  $I$  is

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

where  $I_0$  is the incident intensity,  $\gamma$  is the absorption coefficient of the medium,  $L$  is the interaction length, and  $\alpha$  is the medium-specific absorption factor determined by dispersion enhanced light-matter interaction. For various applications,  $L$  must be large to achieve high sensitivity since  $\alpha = 1$ .

From perturbation theory,

$$\gamma \propto \frac{c/n}{v_g}$$

where  $c$  is the velocity of light in free space,  $v_g$  is the group velocity in the medium, and  $n$  is the refractive index of the medium. In this equation, the slower the group velocity, the higher is the absorption coefficient. This explains that the slow light effect of photonic crystal greatly enhances the absorption of light by chemical analytes.

In Fig. 1, the structure we design is based on W1 line defect waveguide with lattice constant  $a$ , where W1 denotes the width of PCW is  $\sqrt{3}a$ . The air hole diameter is  $d=0.53a$  and silicon slab thickness is  $h=0.63a$ . Multiplexed detection is achieved by parallel integration of two PCW structures using multimode interference (MMI) power splitter at the input and Y-junction power combiner at the output. Two compounds are measured, xylene and TCE. The absorption peak of TCE is at 1644nm and the absorption peak of xylene is 1674nm. There is no overlap between the absorption spectra of xylene and TCE at 1644nm or 1674nm. The PCWs are designed so that the slow light guidance bandwidth of each PCW overlaps with the absorbance peaks at 1644nm and 1674nm respectively. In our structure, the device which detects xylene has lattice constant  $a=405$ nm and the other device that is used for the detection of TCE has  $a=397$ nm.

We fabricated PCWs on silicon-on-insulator (SOI) devices with a 250nm top silicon layer, a 3 $\mu$ m buried oxide layer and a 2  $\mu$ m thick SU8 polymer is spun on top of device. Similar to previous demonstration, SU8 is hydrophobic, hence the absorption spectrum of VOCs can be obtained independent of any interference from the strong absorbance signatures of water. In contrast to our previous method using PDMS as the VOC absorbing layer [4], we found that

SU8 has low optical absorption loss in the wavelength range of interest between 1620-1700nm resulting in high signal-to-noise ratio. Light is coupled in and out through grating coupler and PCW to detect the chemical analytes. The transmission of the device designed for xylene and TCE are shown in Fig. 2(a) and (c) respectively. It shows the band edge is located at 1676nm for device with  $a=405\text{nm}$  for xylene detection as in Fig. 2(a) and the band edge of device with  $a=397\text{nm}$  for TCE detection is located at 1654nm in Fig. 2(c). Both transmission spectra show that the slow light region near the transmission band edge overlaps with the absorbance peaks of xylene and TCE. Figs. 2(b) and 2(d) show the absorbances measured at 1674nm and 1644 nm for xylene and TCE respectively as a function of the increasing concentration of the analytes. From the absorbance, the detection limit for device for xylene is  $10^{-7}\%$  (v/v) in water ( $\sim 1\text{ppb}$ ) and the detection limit for device for TCE is  $10^{-6}\%$  (v/v) in water ( $\sim 10\text{ppb}$ ).

For multiplexed detection of xylene and TCE, the two devices were connected by MMI optical power splitter and Y combiner as in Fig. 1(b) and Fig. 1(c). A single optical fiber is connected to the input grating coupler and a single fiber collects the transmitted light from the output grating coupler. In Fig. 3(a) and (b), the transmission spectrum of device for xylene and TCE are plotted respectively. In order to further test the performance of selectivity of our device,  $10^{-5}\%$  xylene in water is added on these two devices. After waiting for ten minutes, we measure the transmission and calculate the absorbance of each device to see the performance of devices for xylene and TCE. In Fig. 3(c), the device shows a flat absorbance and almost zero absorbance is detected for this device in this region of spectrum, but significant absorbance is observed at 1674nm in Fig. 3(d). Theoretically, the absorbance peak of xylene is around 1674nm. As we see the comparison of absorbance in Fig. 3(c) and (d), the selectivity of our device for specific chemical analyte is proved.

In summary, we demonstrated multiplexed detection of TCE and xylene in water using PC based chip-integrated optical absorption spectroscopy. High sensitivity due to slow light effect of photonic crystal waveguide and high selectivity for chemical analytes are shown. Future measurements will show simultaneous detection of xylene and TCE in a mixture and also in field water samples. The authors acknowledge the National Science Foundation (IIP-1127251) for supporting this work.

\*Joint first author

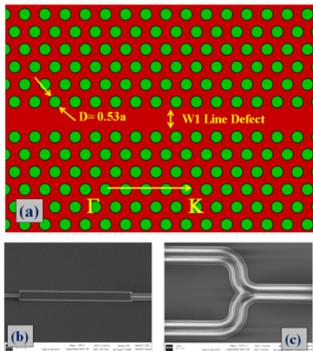


Fig. 1:  
(a) Photonic crystal structure (b)  $1 \times 2$ MMI optical power splitter (c) Optical Y combiner

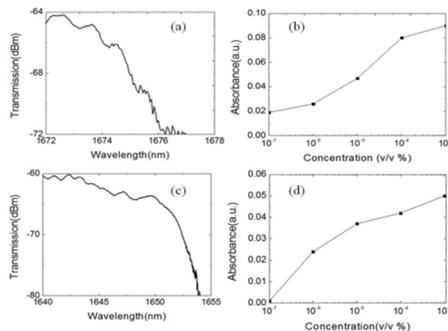


Fig. 2:  
(a) Transmission of device for xylene (b) Absorbance of xylene (c) Transmission of device for TCE (d) Absorbance of TCE

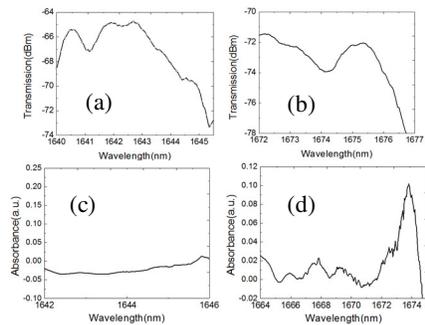


Fig. 3:  
(a) Transmission of device for TCE in a double device structure (b) Transmission of device for xylene (c) Absorbance around 1644nm (d) Absorbance around 1674nm

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