

Multiplexed Selective Detection and Identification of TCE and Xylene in Water by On-Chip Absorption Spectroscopy

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ABSTRACT

We demonstrate a device which can do multiplexed detection of two different chemicals on one chip by using infrared absorption spectroscopy. The signature of Trichloroethylene(TCE) and xylene in water enable multiplexed detection on one chip. We use the slow light effect in the photonic crystal design which enhances the absorption of the analytes by a factor of 30 as demonstrated by our previous works. In order to match the absorption peaks of these two analytes, photonic crystal slow light regions are designed at 1644nm and 1674nm with a SU8 cladding on top. Multiplexed detection is enabled by using a multimode interference (MMI) optical power splitter at the input, which divides optical power into two arms, and Y combiner at the output. Consequently, the absorption of these two chemicals can be enhanced by the slow light effect. The MMI structure and Y combiner also enable the multiplexed detection of two analytes on one chip.

Keywords: photonic crystal waveguide, slow light effect, chemical sensor

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1. INTRODUCTION

Technique to detect and identify chemical and biological analytes based on photonic crystal platform has been investigated more 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]. Other than the methods described above, in our previous work, photonic crystal slot waveguide structures are successfully used for detecting and identifying Volatile Organic Compounds (VOCs) in liquid and gaseous phases to detect xylene in water and methane in nitrogen. [4-5] Results shows the enhancement due to slow light effect of photonic crystal waveguide greatly reduces the total interaction length with chemical analytes. Thus, the length of photonic crystal slot waveguide for xylene in water sensing is reduced to 300 μ m, which shows photonic crystal waveguide structure is an ideal platform for the application on multiplexed sensing. In order to further integrate two photonic crystal waveguides on one chip, an optical splitter and combiner are needed. For optical splitting, multimode interference (MMI) power splitter is a significant method to divide input light in various applications for biological sensing, where the cascaded one by four MMI is successfully used. [6] In another group, a 1x16 wide angle Y-junction optical power splitter on silicon-on-insulator (SOI) are developed. [7] Therefore, in this paper, we integrate the photonic crystal waveguide structure with multimode interference (MMI) optical splitter at the input and Y-junction optical power splitter as a combiner at the output. The MMI and Y-junction combiner provide an easier and more convenient method for us to use only one fiber at input and output end of waveguide. In addition, two photonic crystal waveguides are in parallel on the chip, which eases the difficulty when we do the measurement.

2. PRINCIPLE OF OPERATION

The principle of infrared absorption spectroscopy is based on the Beer-Lambert law. According to this law, transmitted intensity I is given by:

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

where I_0 is the incident intensity, α is the absorption coefficient of the medium, L is the interaction length and γ is the medium-specific absorption factor determined by dispersion enhanced light-matter interaction. In conventional free-space systems, $\gamma = 1$; thus L must be large to achieve a suitable sensitivity of measured I/I_0 .

For lab-on-chip systems, L must be small, hence γ must be large. Mortensen et al showed [4] using perturbation theory that

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

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. Equation 2 shows that slow light propagation (small v_g) significantly enhances absorption. Furthermore, greater the electric field overlap with analyte, greater the effective absorption by the medium. Both conditions of small v_g and high f are fulfilled in a photonic crystal slot waveguide.

Photonic crystal (PC) waveguides have demonstrated group velocity slow-down factors ~ 100 [8]. Slot waveguides have also demonstrated significant increase in the electric field intensity in a narrow low index slot in a high index ridge waveguide, by at least a factor of 10 [9]. Slow light in PC waveguides coupled with electric field intensity enhancement in a slot in the PC waveguide, can therefore reduce v_g and enhance f , thereby theoretically shrinking the required absorption path length by a factor of 1000, an order of magnitude greater than ring resonator devices [10].

During the past two decades, PC devices have attracted significant interest due to their unique dispersive properties that allow control and manipulation of light-matter interactions on length scales of the wavelength of light [11]. Various miniature applications have been demonstrated with PC microcavities and PC slot waveguides for light emission [12], cavity quantum electrodynamics [13] and electro-optical modulation [14]. PC devices have shown significant promise in sensing applications due to high sensitivity to refractive index changes of the ambient [15]. Change in refractive index of a medium caused by an analyte is however not sufficiently analyte-specific and is therefore not a unique signature of the analyte. In contrast, absorption spectrum of an analyte is based on analyte-specific molecular vibrations, and thus identifies the analyte uniquely. In this paper, we demonstrate a PC slot waveguide that enables near-infrared spectroscopy of xylene in water, xylene being chosen as a representative volatile organic compound (VOC) contaminant in water with environmental and human health significance.

3. DEVICE DESIGN

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 $a=405\text{nm}$ and the other device that is used for the detection of TCE has $a=397\text{nm}$.

We fabricated PCWs on silicon-on-insulator (SOI) devices with a 250nm top silicon layer, a 3 μ m buried oxide layer and a 2 μ 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.

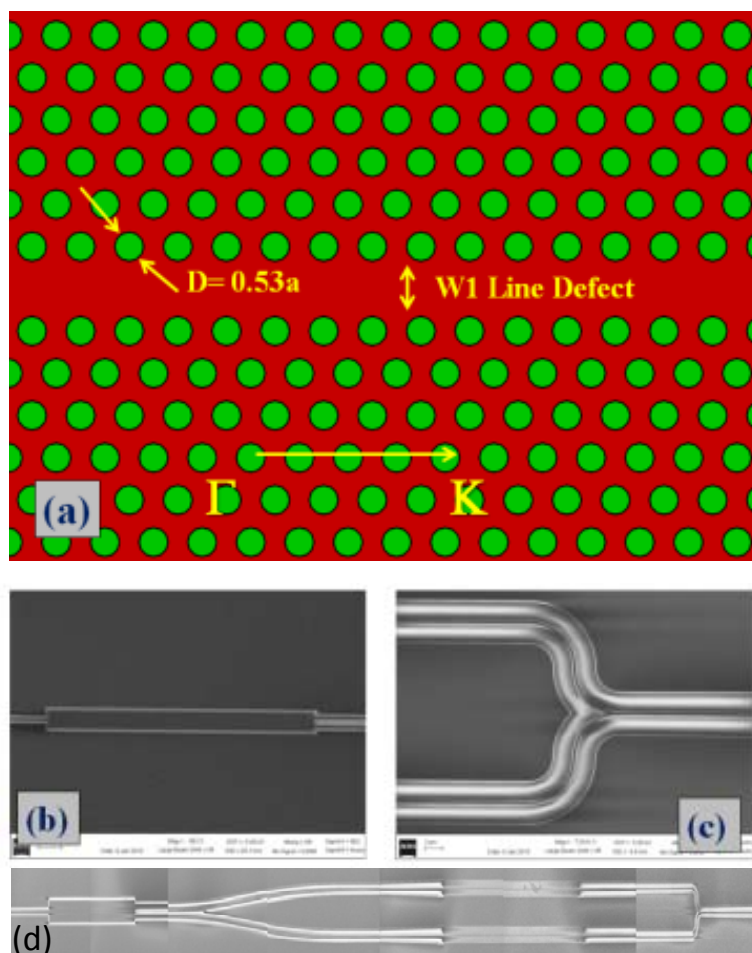


Fig. 1 (a) Photonic crystal structure (b) 1x2MMI optical power splitter (c) Optical Y combiner (d) The stitched SEMs of the whole device structure with MMI, Y combiner and Photonic crystal

4. EXPERIMENTAL RESULTS

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 $a=405$ nm for xylene detection as in Fig. 2(a) and the band edge of device with $a=397$ 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 1ppb) and the detection limit for device for TCE is 10^{-6} % (v/v) in water (\sim 10ppb).

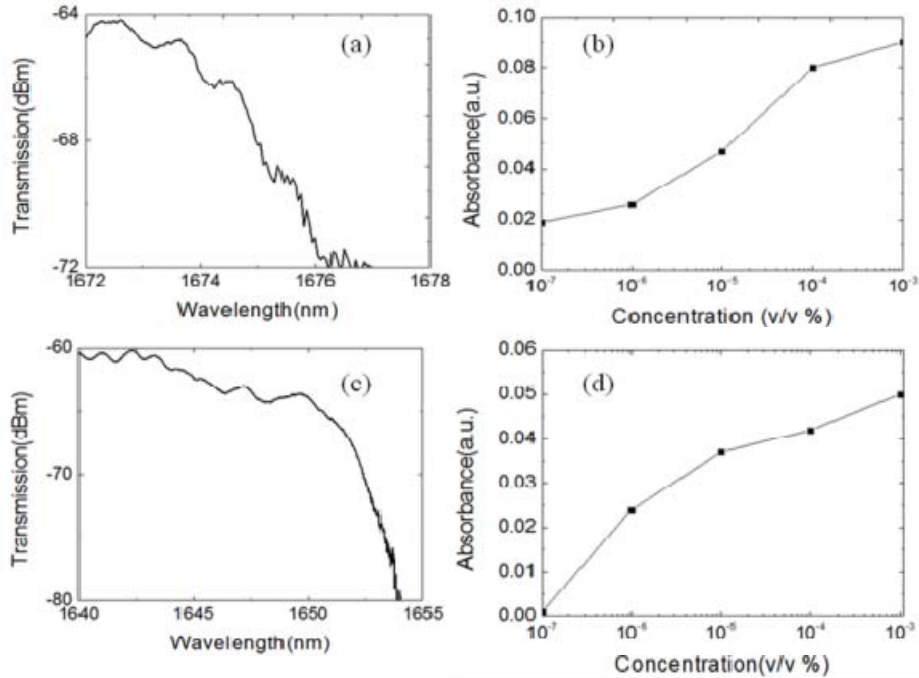


Fig. 2 (a) Transmission of device for xylene (b) Absorbance of xylene (c) Transmission of device for TCE (d) Absorbance of TCE

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.

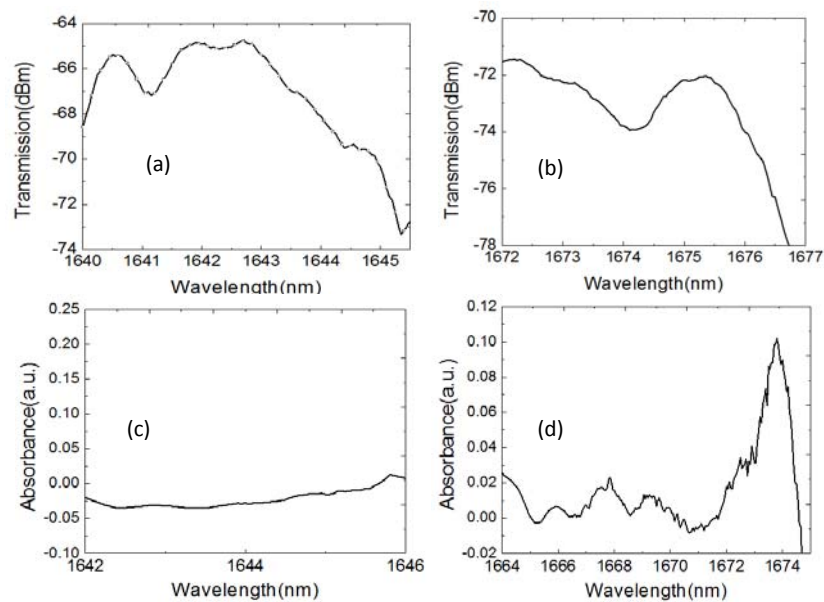


Fig. 3 (a) Transmission of device for TCE in a double device structure (b) Transmission of device for xylene (c) Absorbance around 1644nm (d) Absorbance around 1674nm

5. SUMMARY

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.

6. ACKNOWLEDGMENT

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7. REFERENCES

- [1] Girschikofsky, M., Rosenberger, M., Belle, S., Brutschy, M., Waldvogel, S.R., and Hellmann, R., "Optical planar Bragg grating sensor for real-time detection of benzene, toluene and xylene in solvent vapour," *Sensors and Actuators B: Chemical* 171-172, 338–342 (2012).
- [2] Deng, M., Tang, C.-P., Zhu, T., Rao, Y.-J., Xu, L.-C., and Han, M., "Refractive index measurement using photonic crystal fiber-based Fabry-Perot interferometer.," *Applied optics* 49(9), 1593–8 (2010).
- [3] Reddy, K., Guo, Y., Liu, J., Lee, W., Oo, M.K.K., and Fan, X., "Rapid, sensitive, and multiplexed on-chip optical sensors for micro-gas chromatography.," *Lab on a chip* 12(5), 901–5 (2012).
- [4] Lai, W.-C., Chakravarty, S., Wang, X., Lin, C., and Chen, R.T., "Photonic crystal slot waveguide absorption spectrometer for on-chip near-infrared spectroscopy of xylene in water," *Applied Physics Letters* 98(2), 023304 (2011).

- [5] Lai, W.-C., Chakravarty, S., Wang, X., Lin, C., and Chen, R.T., "On-chip methane sensing by near-IR absorption signatures in a photonic crystal slot waveguide," *Optics letters* 36(6), 984–6 (2011).
- [6] Zou, Y., Chakravarty, S., Lai, W.-C., Lin, C.-Y., and Chen, R.T., "Methods to array photonic crystal microcavities for high throughput high sensitivity biosensing on a silicon-chip based platform," *Lab on a Chip* (2012).
- [7] Tao, S.H., Fang, Q., Song, J.F., Yu, M.B., Lo, G.Q., and Kwong, D.L., "Cascaded wide-range Y-junction 1x16 optical power splitter based on silicon wire waveguides on silicon-on-insulator," *Optics Express* 16(26), (2008).
- [8] Mortensen, N.A., and Xiao, S.S., "Slow-light enhancement of Beer-Lambert-Bouguer absorption," *Appl. Phys. Lett* 90(14), 141108 (2007).
- [9] Notomi, M. "Extremely large group-velocity dispersion of line-defect waveguides in photonic crystal slabs," *Physical Review Letters* 87, 253902 (2001).
- [10] Robinson, J.T., Chen, L., and Lipson, M., "On-chip gas detection in silicon optical microcavities," *Optics Express* 16 (6), 4296 (2008).
- [11] Yablonovitch, E., "Inhibited Spontaneous Emission in Solid-State Physics and Electronics," *Phys. Rev. Lett.* 58, 1059 (1987); John, S., "Strong localization of photons in certain disordered dielectric superlattices," *Phys. Rev. Lett.* 58, 2486 (1987).
- [12] Chakravarty, S., Bhattacharya, P., and Mi, Z., "Electrically injected quantum-dot photonic crystal microcavity light emitting arrays with air-bridge contacts," *IEEE Photon. Tech. Lett.* 18, 2665 (2006).
- [13] Vuckovic, J., and Yamamoto, Y., "Photonic crystal microcavities for cavity quantum electrodynamics with a single dot", *Appl. Phys. Lett.* 82 (15), 2374 (2003).
- [14] Lin, C-Y., Wang, X., Chakravarty, S., Lee, B-S., Lai, W-C., Luo, J., Jen, A-K-Y., and Chen, R.T., "Electro-optic polymer infiltrated silicon photonic crystal slot waveguide modulator with 23dB slow light enhancement," *Appl. Phys. Lett.* 97, 093304 (2010).
- [15] Chakravarty, S., Topol'ančik, J., Bhattacharya, P., Chakrabarti, S., Kang, Y., and Meyerhoff, M.E., "Ion detection with photonic crystal microcavities," *Opt. Lett.* 30, 2578 (2005).