Photonic Crystal Slot Waveguide Spectroscopy for the Detection of Chemical Warfare Simulants

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Abstract: A photonic crystal slot waveguide based infrared absorption spectroscopy device is demonstrated for the on-chip spectroscopic determination of chemical warfare simulant triethylphosphate.

OCIS codes: (300.0300) Spectroscopy; (300.6470) Spectroscopy, Semiconductors; (280.4991) Passive Remote Sensing

1. Introduction

The threat posed by nerve agents in chemical warfare to soldiers, the threat to civilians in the event of a terrorist attack as well as environmental pollution caused by industrialized societies highlight the fact that intentional and unintentional contamination of the environment by rogue elements and the civilized society respectively, can be equally harmful to the earth and its inhabitants. It is therefore necessary to develop a technology for rapid detection and identification of hazardous gases. Infrared (IR) spectroscopy is widely used as a simple and reliable technique for quality control and analysis due to unique spectral signatures. However, infrared spectroscopy requires bulky and expensive optical elements. In recent years, quantum cascade laser sources have resulted in lasers in mid-infrared wavelengths which probe fundamental molecular vibrations of most molecules. However, requirement of a gas cell still makes on-chip integration impossible and heterogeneous integration cumbersome.

In this paper, we demonstrate a novel lab-on-chip photonic crystal (PC) slot waveguide infrared spectrometer for diode laser absorption spectroscopy of chemical simulant triethylphosphate at 9.5μm. The device measures absorption signatures of the target gas using slow light enhanced absorption of light in a photonic crystal slot waveguide. The proposed photonic crystal slot waveguide is shown schematically in Figure 1 (a). It consists of a triangular lattice of photonic crystal air holes and a slot waveguide etched into a waveguide on gallium arsenide (GaAs) with a bottom aluminum oxide (Al_xO_y) cladding. The measurement principle is based on the Beer-Lambert-Bouguer absorption method. According to this technique, transmitted intensity I is given by

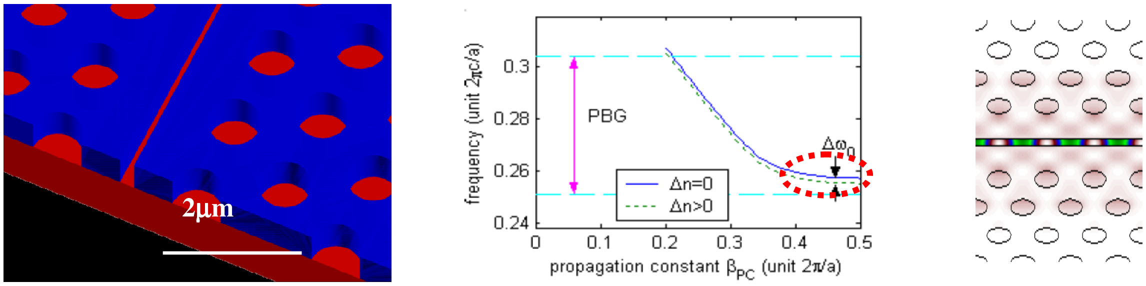
$$I = I_0 \exp(-\gamma\alpha L) \text{ ....(1)}$$

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 systems, L must be large to achieve a suitable sensitivity of the measured I/I_0. For lab-on-chip systems, L must be small, hence γ must be large. Mortensen et al showed [1] using perturbation theory that

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

where c is the velocity of light in free space, v_g is the group velocity in the medium of effective index n and f is the filling factor denoting the relative fraction of the 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 the analyte, greater the effective absorption by the medium.

Fig. 1(b) shows the dispersion relation of a guided mode in a photonic crystal waveguide. The slow light region in the photonic band gap with low group velocity $v_g = d\omega/d\beta$ is circled in red. It has been demonstrated that the group velocity of propagating light can be reduced by a **factor of 100** in the slow light region [2]. Slot waveguides have attracted considerable attention over the past few years due to their ability to confine light with high intensity in narrow low-index slots between high index ridges (Fig. 1(c)) [3]. This has the effect of increasing f as well as lowering n in Equation 2. Calculations show that electric field intensity $|E|^2$ is increased by a **factor of 10** in the slot compared to planar waveguide evanescent coupling. The combined effects of slow group velocity and high optical field intensity (Fig. 1(d)) in the slot can lead to **a factor of 1000 reduction in interaction length** required to sense analytes in photonic crystal slot waveguides. The miniaturization by significant reduction in interaction length compared to commercial spectrometers enables in-situ measurements and analysis.



(a) (b) (c)

Figure 1: (a) Schematic of a photonic crystal slot waveguide [**Legend:** **Gallium Arsenide (blue)**, **Aluminum Oxide (red)**] (b) Dispersion curve of guided mode in photonic crystal slot waveguide. The low group velocity region is circled in red. (c) Simulated electric field intensity in a photonic crystal slot waveguide combining the slow light effect of photonic crystal waveguide and high intensity in low-index slot.

The peak of triethylphosphate absorption line occurs at ~9.5µm; by measuring change in photonic crystal slot waveguide transmission spectra in presence of triethylphosphate at two wavelengths, one at the peak of the known absorption spectrum at 9.5µm and the second at the known zero at ~6.5µm, the presence of triethylphosphate will be determined. Slow light enhanced absorption will significantly reduce transmission at 9.5µm in the presence of triethylphosphate while no change in the transmission will be observed at the zero point wavelengths at ~6.5µm.

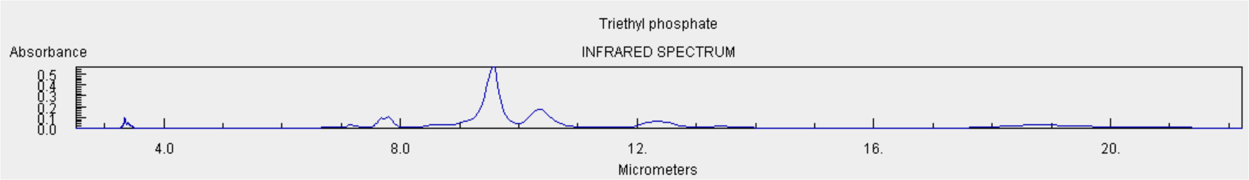


Fig. 2: Absorption spectrum of triethylphosphate.

2. Results

Photonic crystal slot waveguide spectroscopy has been employed to demonstrate the absorbance spectrum of methane gas in air [5] as well as xylene in water [6] as shown in Fig. 3(a) and (b) respectively. The same methods will be employed for the determination of triethylphosphate.

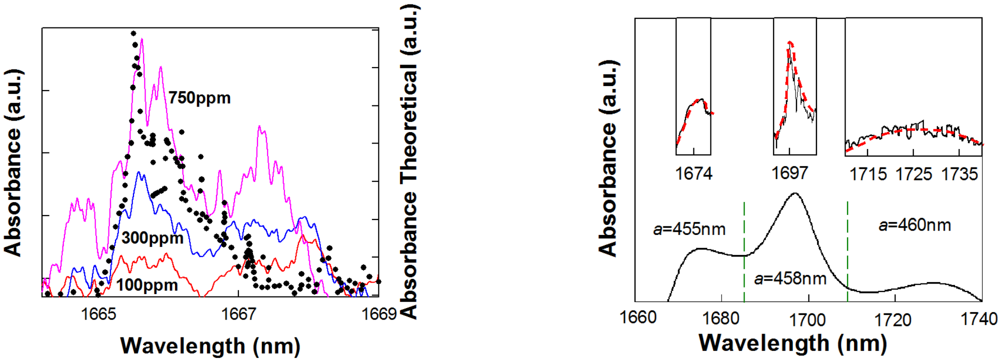


Fig. 3: Absorbance spectrum determined from photonic crystal slot waveguide spectroscopy (a) of methane at concentrations down to 100ppm [5] and (b) 100ppb xylene in water, both with a 300µm photonic crystal slot waveguide [6].

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3. References

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