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Optimizing of rod-type photonic crystal waveguide methane gas sensor

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ABSTRACT

The applicability of rod-type photonic crystal waveguides to enhance the absorption sensitivity of methane gas has been investigated. It has been shown numerically that a suitably optimized rod-type photonic crystal waveguide has potential to form the miniaturized absorption spectrometer. The key advantage of this sensing architecture is the enhancement of the absorption sensitivity of the methane gas due to the slow-light effect.

1. Introduction

Detecting of gas species and measurement of their concentrations is very important in process control and environmental monitoring. Therefore, development of gas sensors in order to identify and quantify small traces of compounds in gas species is highly demanded [1,2]. The infrared (IR) spectral region typically is used for absorption spectroscopy of most gases [1–3]. This is because most gases like methane have the strongest molecular absorption lines in the infrared and near-infrared spectral regions, where the optical components are often expensive [1]. In near-infrared spectral region, absorption lines are very weak, limiting the detection sensitivity. Commercial absorption spectroscopy devices such as White or Herriot absorption cells can enhance the detection sensitivity but these cells are bulky and require relatively large gas cells [4,5].

It has been shown that slow-light effects offer an attractive alternative solution to achieve high performance in nonlinear optics process such as third harmonic generation and four-wave mixing as well as sensing applications [6–12]. The slow-light can be achieved by modifying the dispersion of the medium or by designing the periodic dielectric guiding structures such as a photonic crystal waveguides (PhCWs) [13–15]. The slow-light effect can be used to enhance the absorption sensitivity by a factor as large as the group index via prolonging the interaction time between the probe light and gas molecules [16,17].

In addition to PhCs structures as gas cells, fiber-based systems like the photonic crystal fiber (PCF) and hollow-core photonic crystal fiber (HC-PCF) have been used as the miniaturized absorption gas cells in gas detection [18–21].

In this paper, we investigate the applicability of rod-type PhCWs to enhance the absorption sensitivity of the methane gas.

The paper is organized as follows. The physical structure of the proposed gas sensor is presented in Section 2. A brief theory of absorption detection in slow-light region is given in Section 3. Section 4 presents the numerical results of the regular sensor structure for absorption detection of the methane gas. Section 5 presents optimization of sensor structure for enhancement of absorption detection. Section 6 is conclusion.

2. Photonic gas sensor structure

In conventional absorption-based gas sensor, gas cell is realized by standard cuvette e.g., a glass tube located between the light source and the detector. A schematic of detection system with a cuvette-based gas cell of with a light–matter interaction path length of L is shown in Fig. 1. In miniaturized gas detection system, gas cell is replaced by a PhC structure instead of standard cuvette [9].

In this paper, a rod type PhCW is considered as an absorption measurement-based methane gas sensor structure. This gas sensor structure originally has been reported in ref [22]. The structure consists of a triangular lattice of the silicon rods with refraction index

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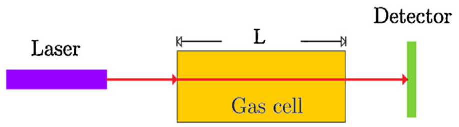

Fig. 1. Schematic of a cuvette-based cell of gas detection system.

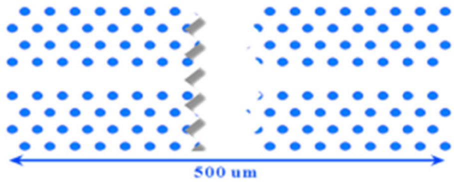

Fig. 2. Schematic representation of the proposed PhCW methane gas sensor.

of 3.52 in air background. The radius of rods is $r = 0.2a$, with a being the lattice periodicity. The waveguide is formed by removing the central row of rods along the propagation direction Γ–K. The 2D schematic of this design is displayed in Fig. 2.

To achieve the optimum results in our calculations, a length of $L = 500\ \mu$m is assumed for the waveguide. We limit our calculations to TM polarization (magnetic field parallel to the plane).

Fig. 3 shows the TM-polarization dispersion diagram of the PhCW calculated by the plane-wave method (PWE) [23]. The fundamental guided mode dispersion of waveguide exhibits a nearly zero slope at $0.46 < kz < 0.5$ (slow-light region). For sensing application of the PhCW, It is important to have a propagating mode inside the band gap that exhibits high transmission and low group velocity. Thus, it is desired that the propagating mode inside the band gap in the slow group velocity region to be as much as away from the upper air band in order to avoid coupling of the modes. Hence, we would define the spectral range as the spectral distance between propagating mode-gap and the upper air band in slow group velocity region. In Fig. 3, the spectral range between the propagating mode-gap and the upper air band in slow group velocity region is illustrated by an arrow.

In following sections, it will be verified that the spectral range is effective factor to enhancement of optical absorption by analysing the absorption profiles of methane gas.

3. Absorption gas detection in the slow-light regime

The interaction of light and gas molecules can be described by the Beer–Lambert law according to which, when the light passes through the gas sample, the intensity of transmitted light is given by [3]:

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

where α is the absorption coefficient of gas related to gas concentration, (C_{gas}), L is the interaction path length of sample cell and I_0 denotes the intensity of the incoming radiation. The optical absorption loss coefficient due to the gas sample can be expressed as [24]:

$$\alpha = C_{\text{gas}}\, \Gamma\, \alpha_0 \qquad (2)$$

where Γ is the optical field confinement factor in medium which is describing the overlapping field with the absorbing material and α_0 is the absorption coefficient of gas in bulky medium. In a structural slow-light medium like PhCW the modal absorption coefficient of gas α_{mod} linearly scales with the group index [17,25]:

$$\alpha_{\text{mod}} \approx \Gamma\, n_g \alpha_0 \qquad (3)$$

where n_g is the group index of propagating mode. The group index n_g of propagating mode in waveguide is inversely proportional to the group velocity v_g. In a PhCW, wherever the dispersion curves are flat a low v_g or a high n_g can be achieved. Eq. (3) shows that the slow-light effect (low v_g) can significantly enhance the modal absorption.

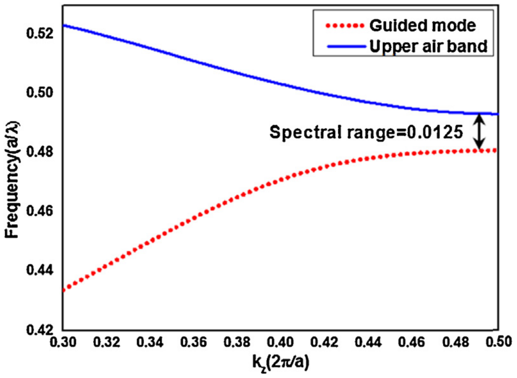

Fig. 3. TM-polarization band structure of a rod-type PhCW, the red dotted curve indicates the fundamental guided mode.

4. Results of regular sensor structure for detection of methane gas

In the Infrared region of the spectrum, the methane gas has two fingerprints: the ν_3 band, centered at 3.3 μm and the ν_4 band centered at 7.6 μm. Previous experimental reports show that the absorption peak at 7.6 μm provides a better signal-to-noise ratio [26]. Therefore, in our calculations, the absorption wavelength of $\lambda = 7.625\ \mu$m is considered.

We assumed that the methane gas with the extinction coefficient, k, filled the waveguide, where k is the imaginary part of refractive index. In bulk systems the absorption coefficient α_0 is related to the imaginary part of refractive k as [27]:

$$\alpha_0 = \frac{4\pi k}{\lambda} \qquad (4)$$

In order to simulate the optical attenuation caused by the absorption lines of the methane gas based on the designed PhCW gas sensor, the molecular absorption cross section σ and knowledge about the shape of the absorption lines of methane gas are required. The required parameters are obtained from previous experimental data. The absorption cross-section of methane at 7.625 μm is 4.375×10^{-15} mm^2, obtained from HITRAN (high resolution transmission) database [28]. The fit-function of measurement absorption line at wavelength 7.625 μm and the absorption cross-section are used to calculate an expression for the extinction coefficient k of the methane gas as a function of wavelength [22].

$$k(\lambda) = \frac{7.625\ \mu\text{m}}{4\pi^2 . k_a} \cdot \frac{b}{b^2 + (\lambda - 7.625\ \mu\text{m})^2} \qquad (5)$$

where b and k_a are 3.5055×10^{-10} and 1.1506×10^7, respectively.

In our calculation, we have used this function as the imaginary part of the refractive index of the methane gas with 700 ppm to numerically simulate the absorbance loss caused by methane. The complex refractive index $n(\lambda) = 1 + ik(\lambda)$ of the methane is used in Finite element method (FEM) calculations to describe the material property of the methane gas. The FEM calculations method is based on solving of the Helmholtz electromagnetic wave equation in the frequency domain.

The absorption spectrum of the methane gas is determined by the difference in transmission spectra of the PhCW structure at the