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Theory and method for enhancing sensitivity of multi-gas sensing based on slow light photonic crystal waveguide

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ABSTRACT

A novel harmonic detection theory and method for multi-component gas sensing based on photonic crystal waveguide (PCW) slow light is proposed. The PCW is used as gas chamber, and harmonic detection method was adopted for signal processing. This system could real-time and remote monitoring multi-component gases simultaneously with sensitivities increased by 10,278, 8650 and 6282 times respectively compared with system PCW not used. The proposed theory and method possesses powerful practicability and favorable application prospects. It could be also applied to other fluid concentration detection system, thus providing a new idea for expanding applications of slow light in sensing fields.

1. Introduction

The detection of gas concentration and composition has always been an important frontier area in the development field of sensor technology. In practical application, especially for the remote monitoring of those trace amount of toxic gases with high sensitivity and high precision has always been the subject of intense research [1].

In recent years, with the increasing investigation about the theory and technology of slow light, the mechanism of generation of slow light, become clear gradually. In 2005 [2], the IBM researchers reduced the speed of light to 1/300 of the original at room temperature by using photonic crystal waveguide (PCW) as a medium for slow light, which took a crucial step for the application of photonic crystal slow light waveguide in the sensor fields. In 2006, Xiao et al. [3] theoretical analysis that the mobile content of transmission spectrum could reflect the refractive index of the liquid, whose sensitivity could up to 900 nm/RIU. In 2010, Jaime et al. [4] designed a high sensitivity system for antibody detection using the slow light regime of PCW. In the same year, Askari et al. [5] presented a compact and high sensitivity refractive index sensor using slow light in PCW.

Researchers from Denmark [6,7] and Germany [8,9] recently found that the slow light could greatly enhanced light-matter interaction, which could increase the absorption coefficient. According to the Lambert–Beer law, the attenuation of the traveling intensity follows:

$$I = I_0 \ \exp(-\alpha \cdot C \cdot L) \tag{1}$$

Where, I_0 is the intensity of input light; I is the intensity of output light; C is the gas concentration; α is the absorption coefficient; L is the optical path length (so is the length of the gas chamber).

Under the same sensitivity, the volume of sensor would be reduced if α increased. Many scholars have reoriented their research work in this area during the following years. In 2007, A. Lambrecht et al. [8] exploited an ultracompact optical gas sensor for the measurement of CO_2 due to slow light inside a two-dimensional photonic crystal gas cell. In 2008, Jensen et al. [7] designed a microsystem for O_2 detection by using one-dimensional photonic crystal, the required optical path length can be greatly reduced as slow light enhanced light–gas interaction. Surely the exploitation of slow light increased absorption coefficient of gas has potential applications for high sensitivity gas sensing.

In this work, combining photonic crystal slow light waveguide technology and the harmonic detection signal processing method, we demonstrated a new method of multi-component gases sensing. Owing to the introduction of slow light technology, the sensor's sensitivity was significantly increased. Thus it provides potential applications for real-time detecting those trace and toxic gases in remote distance. For the measurement of fire indicator gases (CO_2, CO and HCN) with this method, the whole detecting

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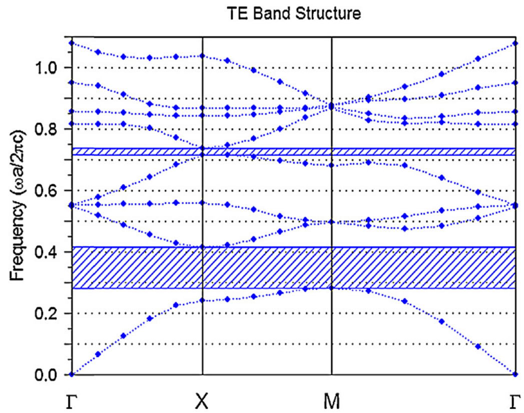

Fig. 1. The band structure of photonic crystal.

cycle only takes 0.3 s, and their sensitivity increase 10,278, 8650 and 6282 times respectively.

2. Theory

2.1. Slow light in photonic crystal waveguide

In 1987, Yablonovitch [10] and John [11] firstly and independently proposed the concept of photonic crystal, referring to semiconductor crystal and the concept of its electronic band gap. Photonic crystal is a kind of crystal designed and made artificially, which possess of periodical dielectric structure in optical scale. Its basic property is the photonic band gap, and the transmission of electromagnetic wave is prohibited when it falls into the band gap, as shown in Fig. 1.

The PWE method is a powerful analysis tools that can be used to simulate the structures of photonic crystal. When certain defects are introduced into photonic crystal, it could generate guided modes, namely, defect modes shown in Fig. 2, thus forming the PCW. The group velocity of input light whose frequency is in the defect modes can be calculated by:

$$v_g = \frac{dw}{dk} = \frac{c}{n + w(dn/dw)} = \frac{c}{n_g} \tag{2}$$

Where, k is wave vector, w is the light frequency.

In this process, because of the large dispersion characteristic of photonic crystal, $(dn/d\omega) \gg 1$, the slow light emerges. Fig. 3 shows the group velocity of PCW, which can even be reduced to 0 in theory [12]. As the dispersion property of photonic crystal is closely related to its structure parameters, one may obtain the required dispersion relations by adjusting the difference between the background refraction and the dielectric column refraction or the arrangement or the filling factor of the dielectric column.

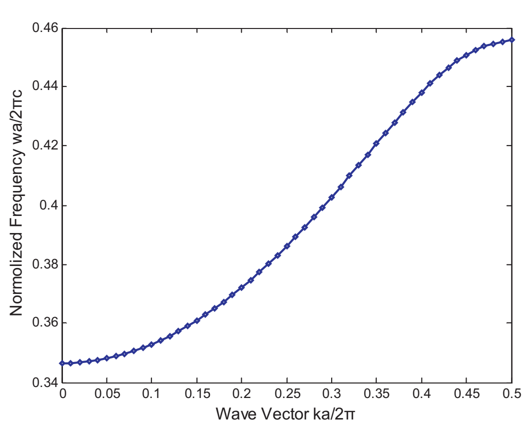

Fig. 2. Curve of photonic crystal waveguide guided mode.

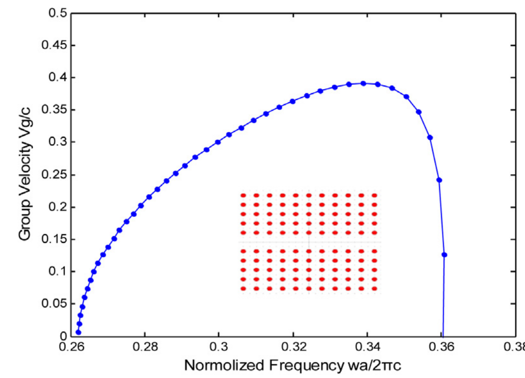

Fig. 3. The group velocity of photonic crystal.

From above, we know that if photonic crystal is chosen as the transfer medium which has the large dispersion characteristic of $(dn/d\omega) \gg 1$, v_g would be smaller. That is to say, slow light generated. Fig. 2 shows the group velocity of light guided by PCW, which can even be reduced to 0 in theory [8]. As the dispersion property of photonic crystal is closely related to its structure parameters, the required dispersion property can be obtained by adjusting the constituents of the photonic crystal and the geometry of the lattice.

2.2. Slow light enhanced gas absorption

The propagation of light in a PCW can be explained by the well-known Maxwell's equation:

$$\nabla \times \nabla \times |E\rangle = \epsilon \frac{w^2}{c^2} |E\rangle \tag{3}$$

Where $\epsilon = \varepsilon + i\delta\varepsilon$, ϵ is the dielectric constant, E is the intensity of electric field, c is the speed of light in vacuum, w is the radian frequency of the light.

Applying first-order electromagnetic perturbation theory we have:

$$\delta w = -\frac{w}{2} \frac{\langle E|\delta\varepsilon|E\rangle}{\langle E|\varepsilon|E\rangle} \tag{4}$$

According to the molecular absorption theory, the absorption coefficient of gas is given by:

$$\alpha = \frac{2w\ \Delta n}{c} \tag{5}$$

Where $w = (c/n)k$, k is the wave vector, and $v_g = (\partial w)/(\partial w)$, n is the refractive index. Substituting $w/c = (\Delta k)/(\Delta n)$ into Eq. (5), we get the following equation for the absorption coefficient of gas in PCW:

$$\alpha = 2\ \Delta k = \frac{2\,\Delta w}{v_g} \tag{6}$$

Combining Eqs. (4) and (6), the result is:

$$\alpha = \frac{2}{v_g} \cdot \frac{w}{2} \cdot \frac{\langle E|\delta\varepsilon|E\rangle}{\langle E|\varepsilon|E\rangle} = f \frac{Kc}{v_g} \cdot \frac{\delta\varepsilon}{\varepsilon} \tag{7}$$

Where, K is the wave vector in free space given by $K = (w/c)$, f is the filling factor of gas in PCW, and $0 < f < 1$ is easily understood.

At the same condition, when considering a homogeneous gas, the absorption of gas from Eq. (6) now can be expressed as:

$$\alpha_g = 2\ \Delta k = 2k \frac{\Delta n_{g1}}{n_{g1}} = 2K\ \Delta n_{g1} = K \frac{\delta\varepsilon}{n_{g1}} \tag{8}$$

Where, n_{g1} is the refractive index of gas, which is about 1.0 for all common gases, so we consider $n_{g1} \approx 1$.