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Theoretical Research of Gas Sensing Method Based on Photonic Crystal Cavity and Fiber Loop Ring-Down Technique

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Abstract

A high-sensitive <u>gas sensing method</u> is proposed, in which <u>miniaturized</u> photonic crystal (PC) cavity is utilized <u>as the sensing element</u>, and cryptophane E molecular is infiltrated in defected holes of PC cavity as the sensitive material to methane gas. Particularly, slow light in <u>side-coupled</u> PC waveguide is optimized to enhance refractive index sensitivity of <u>the</u> PC cavity <u>and</u> fiber loop ring-down technology is used to demodulate output <u>resonant spectrum</u> of the sensing system. Simulation results demonstrate that a refractive index sensitivity of 450 nm/RIU and a quality factor of 1105 can be obtained in the slow light engineered PC cavity. For measurement of methane concentration, the theoretical sensitivity can be up to 4.21 $\mu s/\%$ and the minimum detectable concentration can be as accurate as 2.37 ppm.

Keywords: Photonic crystal cavity; slow light; fiber loop ring-down; gas concentration

1. Introduction

Gas concentration measurement has always played an important role in many industrial, biomedical and environmental applications [1]. Many methods have been proposed to measure gas concentration and among them optical gas sensor is the most popular apparatus, since they provide high sensitivity, fast response, remote monitoring, immunity to electromagnetic interference, freedom from combustion and explosion [2]. Recently, there is a growing interest in developing high-sensitive and miniaturized optical gas sensor, for implementing high-precision, low-power and portable detection of low concentration gas with fast analysis time and reduced reagent consumption [3].

In recent years, photonic crystal (PC), which possesses the unique property of guiding and manipulating light at micro-nano dimension, has become a prominent candidate for realizing miniaturized optical sensors [4]. In particular, PC cavity exhibits strong field confinement and has long photon lifetime [5]. These characteristics give rise to an optical mode with a resonant wavelength that is highly sensitive to local changes of its surrounding mediums, and make PC cavity a promising building block of high-sensitive sensors [6-11].

For gas sensor based on PC cavity, the present measurement principle is mainly based on that the resonant wavelength of PC cavity will shift with intrinsic refractive index variation of measured gas that infiltrated in the air holes of PC cavity [10, 11]. Comparing with traditional optical gas sensor, the size of PC cavity based gas sensor can be drastically reduced. However, the corresponding refractive index variation due to concentration change is usually very low, so the designed sensor can only be used to measure the refractive index of different gases. And to enhance the measurement sensitivity, the precision fabrication of a cavity with complex and exact designed resonant structure is needed [10, 11]. Besides, as any other gases and external environment parameters can all result in comparable refractive index variation of air hole, they will bring many unpredictable and undesirable errors to the sensing system, and even cause the sensor unable to work. What's more, to demodulate the

wavelength shift signal, an expensive optical spectrum analyzer (OSA) must be used, and the requirement of measuring condition is very strict.

Fiber loop ring-down (FLRD) technology has been widely used to demodulate the output signals of fiber Bragg grating [12, 13], long period fiber grating [14], and photonic crystal fiber interferometer [15]. In 2014, we demonstrated for the first time that the FLRD technology can also be used for high-sensitive and high-precision demodulation of the output resonant spectrum of PC cavity, which was then used for refractive index sensing [9]. Besides, we have demonstrated the feasibility of localized infiltrating different fluids into specific air holes of PC. However, to enhance the refractive index sensitivity and quality factor of PC cavity, it is needed to carefully optimize and finely tune the sizes, positions or shapes of local air holes on the order of nanometer, which will add the fabrication difficulty of the PC cavity. Besides, these optimized PC cavities based on structural adjustments are very sensitive to slight changes of structural parameters. Therefore, the nanometer-scale precision required to realize sophisticated and optimized structures eventually becomes a limiting factor in achieving desirable PC cavity [16].

Recently, it has been demonstrated that slow light in side-coupled waveguide of PC cavity can be used to enhance the refractive index sensitivity of PC cavity [17]. And the higher the group index of slow light, the higher the sensitivity of refractive index sensor is. Therefore, in this paper, to decrease the fabrication difficulty of PC cavity and its sensitivity to fabrication errors, the shapes and sizes of all air holes in PC cavity are kept the same and central positions of all air holes are periodical arranged. Then, to optimize the resonant properties of PC cavity, slow light technology is introduced in the PC cavity by infiltrating fluid into the first two rows of air holes adjacent to the side-coupled waveguide, without any structural variations. This post-fabrication technology can be used to modify effective refractive index of air holes after the fabrication of PC cavity, so the resonant properties can be optimized at any time, and the fabrication difficulty of PC cavity can be greatly relaxed as compared to previous optimization methods based on pure structural variations. Besides, in Ref. [9], we have demonstrated that the influences of fabrication errors on

the proposed PC cavity can be calibrated.

In this paper, by using the good selectivity and high sensitivity of cryptophane E molecular to methane gas [18], a cryptophane E infiltrated PC cavity is designed to measure the concentration of methane gas. Then, to improve the system sensitivity, high group index slow light is obtained in this side-coupled PC waveguide by infiltrating fluid into the first two rows of air holes adjacent to the waveguide, without any structural variations. Finally, a fiber loop ring-down (FLRD) technology is utilized for wavelength demodulation.

2. System Design and Sensing Principle

Fig. 1 shows the schematic diagram of FLRD methane gas sensing system. Optical pulse was generated by modulating the output of a light source with an intensity modulator, which in turn was controlled by a signal generator. Here, the light source was a tunable laser source, with operating wavelength tuned from 1528 nm to 1564 nm, and an output power of 20 mW. Besides, an isolator was used to prevent unwanted feedback into the modulator and the light source. Then, the modulated optical pulse would be coupled into a fiber loop via a 1% arm of coupler 1. In this fiber loop, the gas cell, as shown in the inset (a) of Fig. 1, is composed of a cryptophane E infiltrated PC cavity. The used optical fiber is conventional single mode fiber (Model: Corning SMF-28e+), with core diameter of 8.2 μm, cladding diameter of 125 μm, core refractive index of 1.4682 RIU and cladding refractive index of 1.4628 RIU. As a result, the diameter of the loop is about 50 cm. It should be mentioned that the variation of methane gas concentration will change the refractive index of cryptophane E, and then induce transmittance variation of PC cavity at given operating wavelength. After the intensity of transmitted light changed due to different methane gas concentrations, the transmitted light would be coupled out via a 1% arm of coupler 2, such that most of light intensity of the optical pulse would be kept inside the fiber loop and continued to travel around the fiber loop. In these continuous circulating processes, the output periodic trains of the optical pulse, which like the

patterns shown in the inset (b) of Fig. 1, would be intercepted by a photodetector and converted into electrical signals. An oscilloscope was then used to view the ring-down signals. Finally, the ring-down data would be processed and displayed by a computer.

Cryptophane has been demonstrated to be the only functional molecule that has direct photosensitive property to methane. In 2005, M. Benounis et al. demonstrated that the cryptophane E molecular possesses good adsorption and desorption properties only to alkane [18]. By using this property, they further proposed an evanescent wave methane sensor, which behaved good reversibility, repeatability and stability. However, the detection limit is still as high as 2% v/v. Then in 2009, S. Wu et al. fabricated a mode-filtered methane sensor, whose detection limit could be down to 0.06%. However, the response time was as long as 5 min [19]. In this work, the cryptophane E molecule, which is generated by using vanillin as raw material, will be infiltrated into the defected holes of PC cavity. The stereochemical architecture and specific molecular structure of cryptophane E are shown in Fig. 2.

When methane interacts with the intra-cavity of cryptophane molecule, the corresponding dipole moment of cryptophane will be changed, along with its RI variation [18]. The relationship between refractive index n of cryptophane E and concentration C of methane gas can be given as:

$$n=1.448-0.46C \tag{1}$$

Due to that the refractive index of cryptophane is related to the concentration C of methane gas, the resonant wavelength of PC cavity will shift with the variation of C (in v/v). In another point of view, the transmittance T (in %) of PC cavity at given operating wavelength is a function of C, which can be expressed as [9]:

$$\Delta T = \frac{3\sqrt{3}Q \cdot S_n}{4\lambda} \cdot \Delta n = \frac{-0.345\sqrt{3}Q \cdot S_n}{\lambda} \cdot \Delta C \tag{2}$$

where λ is the resonant wavelength of PC cavity, Q is the quality factor of PC cavity, $S_n = \Delta\lambda/\Delta n$ is the sensitivity coefficient of resonant wavelength to the refractive index n of cryptophane E, and S_n can be considered as a constant in a small range of Δn.

Since the light energy will be decreased when it transmits through the PC cavity, the transmission of optical pulse with certain wavelength will also be changed once it

is sent into the fiber loop. As a result, the optical pulse will travel some round trips in the fiber loop, whose transmittance can be expressed as:

$$I(t)=I_0 \exp\left(-\frac{t}{\tau}\right) \tag{3}$$

where I_0 and $I(t)$ denote input and output intensities of the optical pulse, respectively; t is the transmission time of the optical pulse; τ represents the ring-down time, which is referred as the time taken for the light intensity decreasing to 1/e of the initial input light intensity and can also be expressed as [20]:

$$\tau=-\frac{4.34t_r}{\alpha}=-\frac{4.34n_{\text{eff}}s/c}{A+B} \tag{4}$$

where $t_r=n_{\text{eff}}s/c$ is the time that the optical pulse taken to complete one ring-down trip; s is the total length of fiber loop, which is set as 1 km; $c=3.0\times10^8$ m/s is the light velocity in vacuum; n_{eff} is the effective refractive index of fiber, which equals to 1.4682 RIU; $\alpha=A+B$ is the transmission variation (in dB) of total system for each round trip, where A is the intrinsic loss of sensing system and $B=-10\lg T$ is the transmission variation of PC cavity at certain working wavelength.

FLRD technology is used to measure the ring-down time τ of an optical pulse in fiber loop. So the sensitivity of the whole gas sensing system can be given as:

$$S=\frac{\Delta\tau}{\Delta C}=\frac{\Delta\tau}{\Delta\alpha}\cdot\frac{\Delta\alpha}{\Delta T}\cdot\frac{\Delta T}{\Delta C}=\frac{-9.982t_r}{\lambda T\alpha^2}\cdot QS_n \tag{5}$$

Therefore, when considering the sensing scheme of PC cavity in this design, both high S_n and high Q are desired in designing the PC cavity and PC waveguide to achieve a high sensitivity and good resolution measurement method of methane concentration. Besides, there are two advantages of this FLRD technology: one is that the output τ is independent of light intensity, resulting in a low sensitivity to loss induced by external disturbances, which can further enhance the measurement sensitivity and precision; the other one is that it needs not expensive optical spectrum analyzer and the measurement of τ for many pulses leads to a higher throughput.

3. Modeling and Optimization

The basic structure of our proposed PC cavity is shown in Fig. 3, in which the air

holes are hole-typed and triangular arranged, with lattice constant *a* of 320 nm, hole radius *r* of 99.2 nm and slab thickness *h* of 220 nm. The reasons of selecting this structure are as follows: Firstly, it is theoretically demonstrated that the width of maximum photonic band gap in a triangular lattice PC slab is larger than that of square lattice one. Also, the absolute gap of the triangular lattice PC slab is less sensitive to the variations of geometrical parameters [21]. Secondly, hole-typed PC is easy to be fabricated and its air-bridge structure is more favorable to reduce the vertical leakage of light from the substrate than pillar-typed PC in practical applications [22]. Thirdly, due to the large refractive index difference between Si and air, light confinement within the slab is expected to be strong. Particularly, the air-bridge silicon-on-insulator (SOI) slab composed of a Si membrane surrounded by air both above and below is one of the most popular and promising platform to implement various PC devices [6]. Considering the existing technology of SOI, the usual thickness of SOI is selected around 220 nm, to ensure the single mode transmission of PC device. Finally, due to the scaling property of PC, the relationship between operating wavelength λ and lattice constant *a* can be expressed as: $a=U\cdot\lambda$, where *U* is the normalized operating frequency. Therefore, the properties of PC remain unchanged, provided that one enlarges or reduces the structural parameters proportionally [23]. However, by considering the tradeoff between fabrication difficult and obtained width of the photonic band gap, the radius of the circular air hole is usually set between 0.3*a*~0.32*a*. Then, the corresponding normalized operating frequency U (=a/λ) is usually located between 0.2~0.3. Therefore, the lattice constant *a* is always set around 350 nm to make the PC device operate around the wavelength of 1550 nm with low absorption loss. Besides, the cavity length and width are selected by considering the current fabrication level. To maintain the consistency and the repeatability of all air holes in PC, the number of air holes should be 50~100. Therefore, the length and width of the proposed PC cavity in this paper are set as 32 μm (100 holes) and 16 μm (50 holes), respectively.

As for the proposed PC cavity, it is formed by the following procedures: Firstly, arranging air holes of triangular lattice on a silicon slab (n_{si}=3.48) of SOI substrate to

form a perfect PC slab. Secondly, removing the central row of air holes from the perfect PC along the x direction to form a W1-typed line defected waveguide. Thirdly, inserting one pair of two air holes (defected holes) into this waveguide (considered as two reflectors), in which a point defect is introduced to form a cavity. Finally, infiltrating cryptophane E, which is the sensitive material to methane, into the four defected holes of PC cavity to build the sensing region; then, infiltrating fluid with suitable refractive index into the first two rows of air holes adjacent to the waveguide to generate slow light effect. Specially, the refractive index of the first two rows of holes is defined as n_f, and the refractive index of the four defected holes is defined as n.

In the following simulations, the finite difference time domain (FDTD) method is used to analyze the field distribution and resonant properties of PC cavity, while the plane wave expansion (PWE) method is used to analyze the slow light properties of PC waveguide. Fig. 4 shows the relationship between the resonant wavelength λ of PC cavity and the refractive index n of defected holes. As shown in the inset (a) of Fig. 4, the transmission spectrum of PC cavity when n=1.38 behaves a narrow Lorentzian curve, whose resonant wavelength is 1451.5 nm and quality factor is 725. The corresponding steady-state electric field distribution is shown in the inset (b) of Fig. 4, which demonstrates that there is a large part of light energy that confined in the point defect region. Therefore, the resonant spectrum would be sensitive to the refractive index variation of defected holes in PC cavity due to large degree of light-matter interaction inside them.

When n changes from 1.33 to 1.45 with an interval of 0.02, the resonant wavelength of PC cavity will shift to longer wavelength (red shift) with the corresponding refractive index sensitivity of S_n=70 nm/RIU. Combined with the above analyses, this property can be well used for the measurement of refractive index as well as the methane concentration. Then, to further enhance the measurement sensitivity, slow light in PC waveguide is optimized by infiltrating fluid with suitable refractive index n_f into the first two rows of air holes. The refractive indices of fluids that are available for infiltration span most of window, namely, from 1.33 for water

based solutions to 1.5 for silica oil matching liquids and to 2.31 for Cargille liquids [24]. Considering the sensing property of PC cavity based sensor, the higher the group index of slow light, the higher the refractive index sensitivity of slow light engineered PC cavity is. Besides, the wider the bandwidth of slow light, the wider the measurement range of PC cavity based sensor. Therefore, it is needed to obtain slow light with high group index and wide bandwidth. When the refractive index n_f of infiltrating fluid is changed from 1.86 to 1.90, the corresponding slow light properties of PC waveguide are shown in Fig. 5.

To see the simulation results clearly, the calculated group index n_g and corresponding bandwidth $\Delta\lambda$ are summarized in Table I. It is shown that the group index is decreased and the corresponding bandwidth is increased with the increasing of infiltrating refractive index. By considering the group index and bandwidth together, the fluid with refractive index of 1.88 is chose, which can be obtained from the standard H series (n_f=1.81-2.00) of Cargille Liquids. Certainly, the slow light properties of PC waveguide can be further improved by other infiltration methods, such as infiltrating more holes and infiltrating different fluids.

Fig. 6 shows the corresponding group index and group velocity dispersion (GVD) curves of PC waveguide when fluid is infiltrated (n_f=1.88) or not (n_f =1.0). It is demonstrated that slow light with nearly constant group index of 15.5 and low GVD value on the order of 10^6 ps^2/km can be realized over a bandwidth of 40.5 nm. In this case, the variation of resonant wavelength λ of the slow light engineered PC cavity along with the refractive index n is analyzed, as shown in Fig. 7. The transmission spectrum and corresponding steady-state electric field distribution of the slow light engineered PC cavity are shown in the inset (a) and inset (b) of Fig. 7, respectively. In comparison to the case of conventional PC cavity (as shown in Fig. 4), the light energy is much strongly confined in the point defect region, which illustrates that slow light can enhance the interaction strength between light and sample that infiltrated in defected holes. In addition, the refractive index sensitivity S_n can be increased to 450 nm/RIU, and the quality factor Q is increased to 1105. According to

Eq. (5), the measurement sensitivity of PC cavity based methane sensor can be enhanced by 9.8 times after the slow light was introduced.

4. Sensing Results and Discussion

According to the theoretical analyses above, the normalized transmission spectra of the slow light engineered PC cavity for different methane concentrations were calculated, as shown in Fig. 8. As seen, the resonant wavelength shifts towards shorter wavelength as the methane concentration is increased from 0 to 1% with an interval of 0.2%. In another point of view, if the operating wavelength of optical pulse is set to be 1563.2 nm, where the six resonant curves are all in quasi-linear regions, the corresponding normalized intensities (marked with circle dots on the dashed line in Fig. 8) will decrease with increasing methane concentration.

To model this relationship, the transmission loss B of PC cavity at 1563.2 nm as a function of the methane concentration C is displayed in Fig. 9. As seen, B is linearly proportional to C with sensitivity of 6.4 dB/%. According to [25] and [26], the total system loss for each round trip is about 2.51 dB. Therefore, combined with Eq. (4), the relationship between ring-down time τ and methane concentration C is also shown in Fig. 9, from which we can get that the measurement sensitivity of methane concentration can be up to 4.21 μs/%.

As the minimum detectability of a current oscilloscope can be 1 ns, the theoretical minimum detectable methane concentration can be down to 2.37 ppm. Namely, the proposed sensing system based on PC cavity can realize the high-sensitive and high-precision measurement of gas concentration. Compared to other gas sensors based on optical technology [2], the head size of sensor (in micro scale) is greatly decreased. Besides, compared to other gas sensors based on PC cavity [10, 11], which can only identify the gas species and cannot distinguish the quantity of gas concentration, the practicability of our proposed sensor is greatly improved. Finally, compared to our published gas sensors based on slow light in PC waveguides [27, 28],

whose detection limit are respectively 3.15 ppm and 1.56 ppm, the sensing properties are equivalent. However, the used PC elements are both slotted photonic crystal waveguide, which is formed by opening a slot along the line defect of PC waveguide. However, the width and position of the introduced slot are difficult to control. Specially, in Ref. [27], the first and second rows of air holes are needed to be changed to optimize the slow light properties of PC waveguide. The above problems will all increase the fabrication difficulty of PC element. On the contrary, for the proposed PC cavity of this paper, only one kind of air hole is needed and the central positions of all air holes are periodical arranged, whose fabrication difficulty and costs can be effectively decreased.

The above analyses consider only the case that the methane concentration is changed from 0 to 1%. However, the linear measurement regions and the corresponding measurement sensitivities of the sensor can be confirmed once the configuration of sensing system is fixed. Therefore, for other concentration regions, our proposed system can also work as a linear gas sensor by a premeditated calibration procedure: after the original methane concentration is calibrated, the sensor knows the original operating wavelength and sensitivity; then, the relative concentration is measured and accumulated according to the change of light intensity; finally, the operating wavelength and sensitivity are altered once the concentration shifts into another region.

However, when considering the practical applications of the proposed measurement method, we should consider several uncertainties: Firstly, in actual implementations, the robustness of the sensor against fabrication errors of PC is a significant factor, as the resonant property of PC cavity and the slow light property of PC waveguide are all sensitive to the structural variations of PC [29, 30]. Fortunately, for this proposed PC cavity structure, we have demonstrated that the fabrication errors will only influence the initial resonant wavelength and will not change the refractive index sensitivity [9]. Meanwhile, by using the post-fabrication technology of fluid infiltration, the slow light property of PC waveguide allows itself to be adapted depending on actual PC structure, while the refractive index aspect offers the potential

for achieving desirable slow light properties by freely choosing appropriate infiltrating fluids, which relaxes the constraint on the fabrication accuracy of PC waveguide [31]. Secondly, for the optimized structure of PC cavity with fluid infiltration, it is challenging to precisely infiltrate fluid into planned air hole whose diameter is below 200 nm. If the refractive index of the infiltrating fluid is changed, the corresponding slow light properties of PC waveguide as well as the corresponding resonant properties of PC cavity will be changed, which will then introduce measurement error into the sensing system. However, with the development of optofluidic technology in recent years, various selective infiltration techniques for PC devices have been demonstrated by some research groups [32]-[35]. It has been demonstrated in experiment that the infiltration method with using a computer controlled micropipette actuated in three dimensions enables nearly single hole resolution [34]. Besides, in the infiltration process, it is needed to timely inspect the properties of PC cavity via transmission and spectrum measurements, which can not only provide a reliable guide for the infiltration process, but also calculate the resonant properties of PC cavity that will be used in practical situations. Therefore, the infiltration errors can be neglected for our proposed PC cavity. Thirdly, the capability to efficiently couple light from conventional fiber into the PC cavity. It remains indeed challenging because the typical waveguide cross-section (<1 µm width and <500 nm thickness) results in serious impedance mismatch phenomenon. But now many experiments have demonstrated that the coupling efficiency can be greatly improved by using suitable tapering structure [36]. Therefore, the coupling loss can now be considered as a resolved issue. Fourthly, some external parameters, such as temperature, moisture, overpressure inside the cell, will all induce the shift in the absolute resonant wavelength of PC cavity (namely, the cross sensitivity problem between these parameters), and thus influence the sensing properties of the proposed system. To avoid the temperature influence, the sample should be mounted on a temperature controlled stage inside an airtight gas cell, which allows measurements in vacuum and in different methane environments. Then, to decrease the water vapour in the gas cell, the measured gas should be dehydrated by using a freeze-dryer before

entering the gas cell. <u>Likewise,</u> to maintain a constant gas pressure in the gas cell, the gas should be injected into the gas cell with a constant rate that just sufficient to entirely <u>fill the gas cell</u>, which can be determined <u>by monitoring</u> the shift of the resonant wavelength with increasing methane volume. When a new increase of the <u>methane volume</u> does not induce further shift of the resonant wavelength, the <u>gas cell</u> <u>can be</u> considered to be completely filled with the methane, whose pressure is constant. Nevertheless, <u>the influences of these external parameters</u> mentioned above <u>can all be</u> counteracted by using an identical reference system, and thus improving the measurement accuracy. <u>However, what should be mentioned is that</u> although many methods have demonstrated the technically feasible to resolve the above <u>four</u> <u>uncertainties,</u> <u>they still will increase difficulties at the sensor fabrication.</u> Therefore, it will take a long time to build the experimental setup and the requirement of working environment is very strict. Besides, the main work of this paper is to demonstrate the possibility of slow light in increasing the refractive index sensitivity of <u>PC cavity</u> and fiber loop ring-down technology in enhancing the demodulation precision of resonant spectrum of <u>PC cavity</u>. <u>All in all</u>, the proposed technology <u>opens the way</u> for exploring miniaturized, high-sensitive and high-precision gas sensing architecture, which will offer the beneficial <u>guidance</u> and reference for further study. The ongoing study will focus on the experiment study of the proposed <u>sensing method</u>, and the experimental results will be published in the near future.

5. Conclusion

In summary, <u>a gas sensing method based on photonic crystal cavity and fiber loop</u> <u>ring-down technique was theoretically researched.</u> Combining the excellent resonant properties of PC cavity, the slow light enhanced light-matter interaction in PC waveguide, the good sensitivity of cryptophane E to methane gas, and the high demodulation precision and low cost of FLRD, <u>a miniaturized, high-sensitive and</u> <u>high-precision gas sensing architecture was proposed, which has the potential to be</u> <u>used for measurements of gas concentration in some harsh environments and special</u>

<u>conditions.</u>

Acknowledgments

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Biography:

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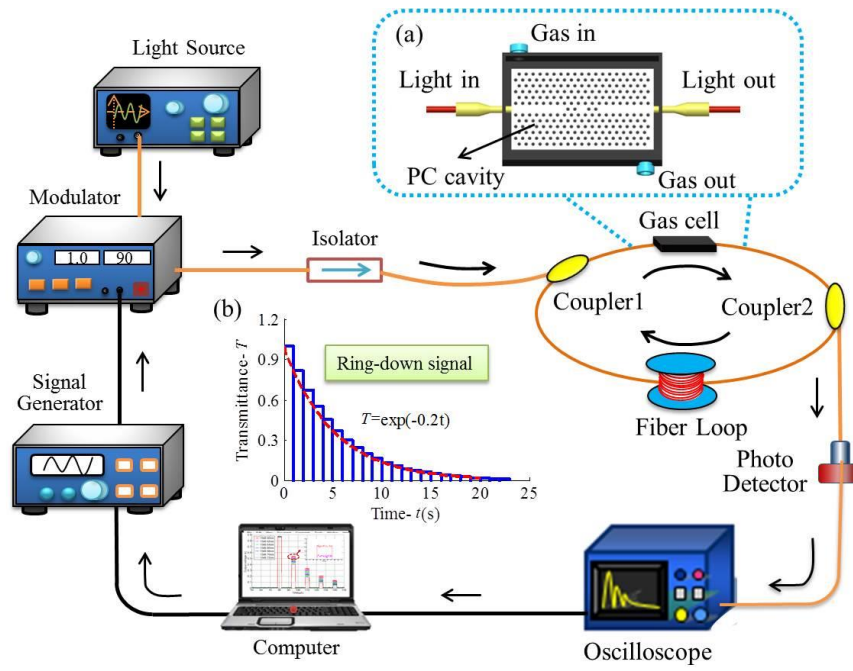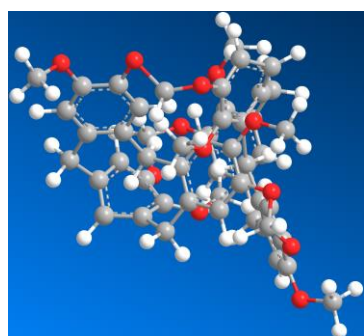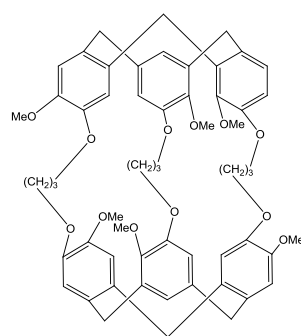
Fig. 1. Schematic diagram of FLRD methane gas sensing system, in which the inset (a) shows the specific structure of gas cell, which is composed of a cryptophane E infiltrated PC cavity, and inset (b) shows an example of ring-down signal generated by FLRD system.

(a)   (b)

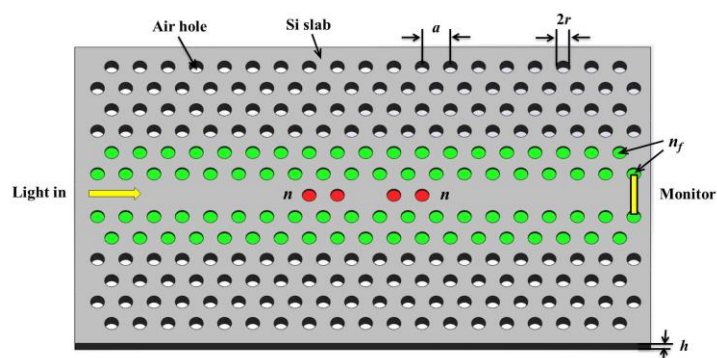Fig. 2. Stereochemical architecture (a) and specific molecular structure (b) of cryptophane E

Fig. 3. Basic structure of slow light engineered PC cavity, in which the central four holes are infiltrated with cryptophane E, and the first two rows of air holes are infiltrated with suitable fluid for slow light optimization.

Fig. 4. Variation of resonant wavelength along with the refractive index n that infiltrated in defected holes of conventional PC cavity (n_f=1.0), while the inset (a) and (b) show the transmission spectrum and corresponding steady-state electric field distribution when n=1.38.

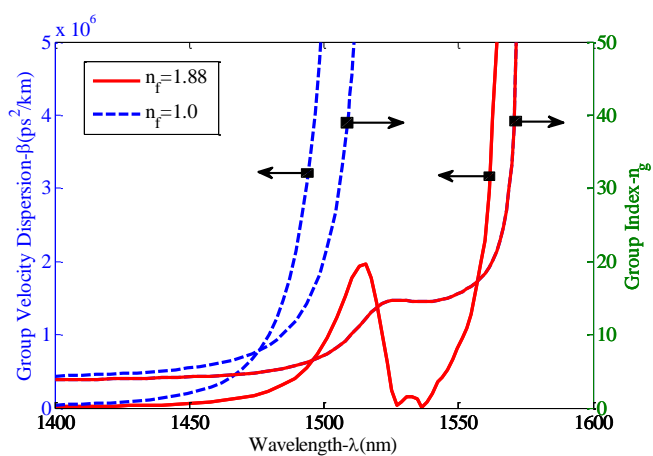Fig. 5. Group index curves of PC waveguides with different infiltrating refractive index n_f.

Fig. 6. Group index and GVD curves of PC waveguide when fluid is infiltrated (n_f=1.88) or not (n_f =1.0).
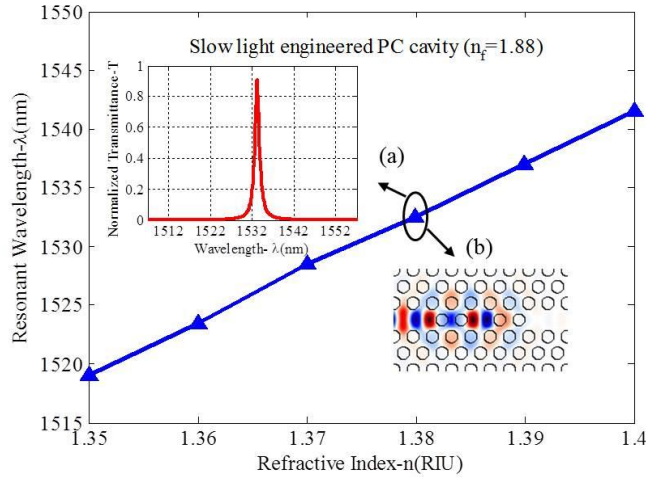
Fig. 7. Variation of resonant wavelength along with the refractive index *n* that infiltrated in defected holes of slow light engineered PC cavity (n_f=1.88), while the inset (a) and (b) show the transmission spectrum and corresponding steady-state electric field distribution when *n*=1.38.
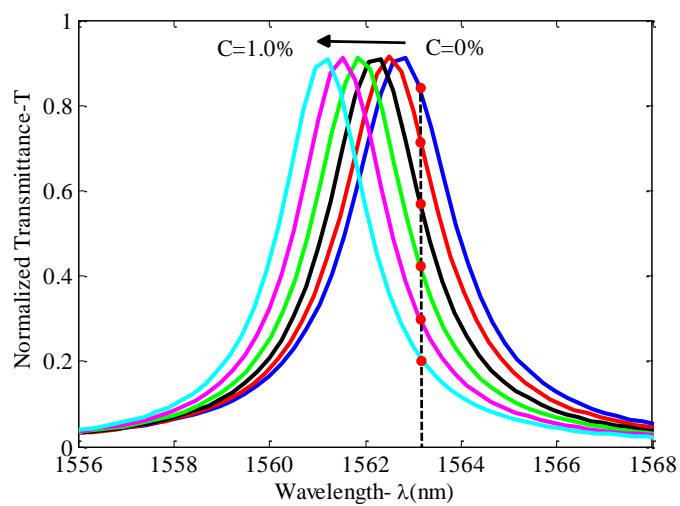
Fig. 8. Normalized transmission spectra of the slow light engineered PC cavity for different methane concentrations.
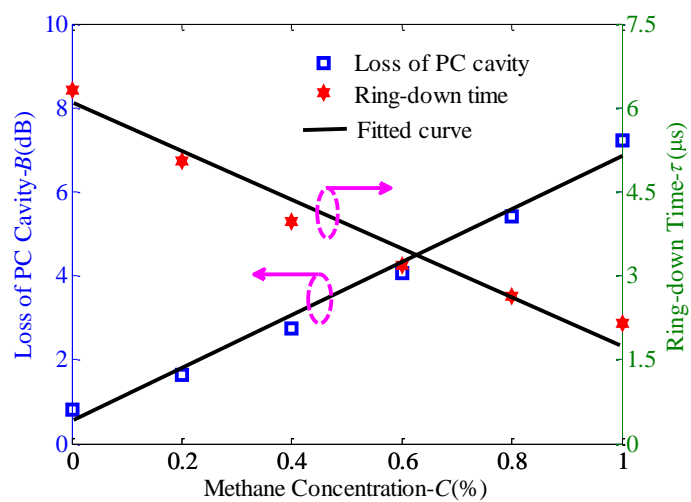
Fig. 9. Relationships of the loss of PC cavity and the corresponding ring-down time of sensing system to methane concentration.

Table I Comparison of slow light properties of PC waveguide with different infiltrating refractive index

Refractive index n_f	1.86	1.87	1.88	1.89	1.90
Group index n_g	22	18	15.5	12.5	11
Bandwidth $\Delta\lambda$ (nm)	19	27	40.5	48	55