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RESEARCH ARTICLE

Improved gas sensor with air-core photonic bandgap fiber

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Abstract The propagation loss of a fiber can be increased by coupling core mode and surface mode which will deteriorate the performance of photonic bandgap fiber (PBGF). In this paper, we presented an air-core PBGF for gas sensing applications. By designing $\Lambda = 2.63\ \mu\text{m}$, $d = 0.95\ \Lambda$, and $R_{\text{core}} = 1.13\ \Lambda$, where Λ is the distance between the adjacent air holes, the fiber was single-mode, no surface mode was supported with fiber, and more than 90% of the optical power was confined in the core. Furthermore, with optimizing the fiber structural parameters, at wavelength of $\lambda = 1.55\ \mu\text{m}$ that is in acetylene gas absorption line, significant relative sensitivity of 92.5%, and acceptable confinement loss of 0.09 dB/m, were simultaneously achieved.

Keywords gas sensor, photonic bandgap fiber (PBGF), sensitivity, surface modes, air core radius, confinement loss

1 Introduction

Fiber optic gas sensors offer many advantages, such as immunity to electromagnetics interference, small size, low cost, resistance to high temperature, large bandwidth, and the possibility to perform safe remote and distributed measurement [1–5]. Some of fiber optic gas sensors are implemented based on photonic crystal fibers due to small dimension and high accuracy [6]. These fibers with air holes in the silica cladding region have solid or hollow core. Recently, a new class of optical waveguides called air-core photonic bandgap fiber (PBGF) has emerged, and PBGFs can offer promising alternatives for a range of sensing applications due to their large overlap between hollow-core and mode field [7,8].

Air-core PBGFs have unique merits described as above, so that they are able to replace conventional optical fibers in telecommunications. For example, PBGF based references may be applied in the calibration of optical measurement instruments and in monitoring channel wavelength in wavelength division multiplexing (WDM) systems [9]. We are interested in PBGF with the wavelength from 0.8 to 2 μm. This range is within the low loss window of silica fiber and covers the absorption lines of many important gases such as acetylene (C_2H_2) and methane (CH_4) [10]. The interaction of light and gas sample causes attenuation of light through the photonic crystal fiber. The gas is monitored by measuring the attenuation of light caused by evanescent wave absorption [11]. One of the solid-core fibers is index guiding fiber. In this type of fibers, very low percent of optical power is exposed to the sensing region and its sensitivity is low. But in the air-core PBGF, more than 90% of optical power is confined in the core filled with the gas sample, the interaction of light and sample is enhanced, so the sensitivity in PBGFs is significantly improved [12–14]. For this purpose, we study a PBGF with a cladding region consisting of a triangular lattice, which is composed of circular air holes in silica. PBGFs have potential to provide low-loss transmission with delivery of high power, though due to the finite number of air hole rings, the modes in the air-core PBGFs are leaky. The air-filling factor, which is defined as the ratio of the hole diameter to the pitch (d/Λ), and Λ is the distance between the adjacent air holes. Research on silica fiber shows that air-core PBGFs has a larger air-filling factor and better mode confinement, which leads to wider bandgap and lower confinement loss [15].

However, the gas sensors based on PBGF have two limitations, multi-mode air-core and surface modes. Surface modes will deteriorate the performance of air-core PBGF. The number of optical mode, supported by a PBGF is determined by the dimension of the core and its boundary, which is composed of very thin layer of silica.

In infrared optical communications, C-band refers to the wavelength range of 1530–1565 nm. Since the absorption wavelength of acetylene is in C-band, the signal of proposed sensor can be transmitted to further place.

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Optimization of the air-core radius plays an important role in reducing optical transmission loss.

In this paper, we designed an air-core PBGF for acetylene gas sensing. We found exact size of the air-core radius is effective to improve the relative sensitivity of optical gas sensor. In addition, we showed maximum relative sensitivity and minimum confinement loss were obtained simultaneously by choosing a certain air-core radius. This sensor node can be used in the optical network protection system of pipelines carrying oil, gas, and other important resources.

2 Principles of operation

Air-core of PBGF acts as a waveguide and a sensing region. In this waveguide, light and gas sample interact each other. And according to Beer-Lambert law [16], the intensity of light is attenuated by the absorption of evanescent wave:

$$I(\lambda) = I_0(\lambda)\exp[-r\alpha_{\mathrm{m}}(\lambda)LC], \tag{1}$$

where I and I_0 are the output light intensities with and without gas respectively, $\alpha_{\mathrm{m}}(\lambda)$ is the absorption coefficient of gas, L is the length of waveguide, C is the concentration of gas, and r is the relative sensitivity coefficient defined as

$$r = \left[\frac{n_r}{n_{\mathrm{eff}}}\right]f, \tag{2}$$

where n_r refers to the index of the gas sample. The effective index of the guided mode is represented by n_{eff}, and f is the fraction of the total power located in the air-core.

Since, in PBGF, more than 90% of the optical power is enclosed inside its air-core, the sensitivity of this sensor is typically high as it acts as sensing region. Meanwhile, PBGF as a waveguide only can make certain wavelengths of light propagate in the fiber. So the absorption wavelength of the gas sample must be within bandgap. The absorption wavelength of acetylene ($\lambda_{\mathrm{absorb}}$) is approximately 1.53 μm, according to the bandgap, we consider the operation wavelength ($\lambda_{\mathrm{operation}}$) of 1.55 μm, which is very close to the minimum loss wavelength [17].

3 Results and discussion

To investigate properties of the proposed PBGF, finite element method (FEM) was applied due to its proven reliability and high accuracy for analyzing the photonic crystal fibers. Perfect match layer (PML) is so far the most efficient absorption boundary condition for this purpose. In all analyses, the silica refractive index and the air hole index were considered to be equal to 1.45 and 1, respectively. Figure 1 shows the cross section of the proposed structure. Air-core PBGF comprises of triangular lattice of air holes, and a core, which is obtained by removing seven air holes from its center. In this design, the proposed structure with the following characteristics is considered: $\Lambda = 2.63$ μm, $d = 0.95\ \Lambda$ and $1.10\ \Lambda < R_{\mathrm{core}} < 1.22\ \Lambda$, where Λ is the distance between two adjacent air holes, d is the diameter of the air hole and, R_{core} is the air-core radius. In the cross section of fiber, a range of air-core radius, where the proposed fiber is single mode, is shown. Figure 1 also illustrates the fiber is single-mode and the effect of the surface modes is very low. In other words, in this range, the fiber will have the best performance. As shown in Fig. 1, 1.10 Λ and 1.22 Λ are the boundary values.

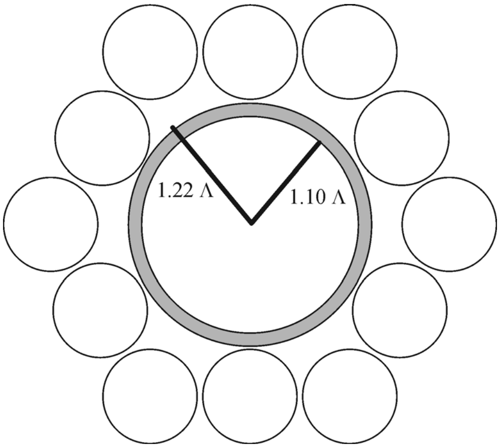

Fig. 1 Cross section of the proposed fiber

Figure 2 shows the bandgap diagram of proposed fiber when we set a refractive index of 1.45, an air-filling factor of 0.95 and a lattice constant of 2.63 μm. the shaded area in Fig. 2 shows the bandgap. Although there is a wider bandgap at lower wavelength, but we chose higher bandgap because the operation wavelength is located in this region. As shown in Fig. 2, with normalized propagation constant equal to $k_z\Lambda/(2\pi) = 1.68$, a bandgap occurs considering $\Lambda = 2.63$ μm, the operation wavelength ($\lambda_{\mathrm{operation}}$) is 1.55 μm.

First, we consider the air-core radius equal to 1.22 Λ, and its effect on the sensitivity was studied. Figure 3(a) shows the optical field distribution, although the light is confined in the air-core, but at the edge of the air-core, some of the surface modes interfere with the fundamental mode. We assumed this interference reduces the sensitivity of the structure. We calculated the sensitivity of the structure by integrating the optical power inside the air-core, and dividing it by the total power carried by the mode. With this air-core radius, the sensitivity was equal to 84.6%. According to Fig. 1, $R_{\mathrm{core}} = 1.22\ \Lambda$ is the largest air-core radius that we can consider and $R_{\mathrm{core}} = 1.10\ \Lambda$ is the minimum air-core radius. In the next step, the air-core

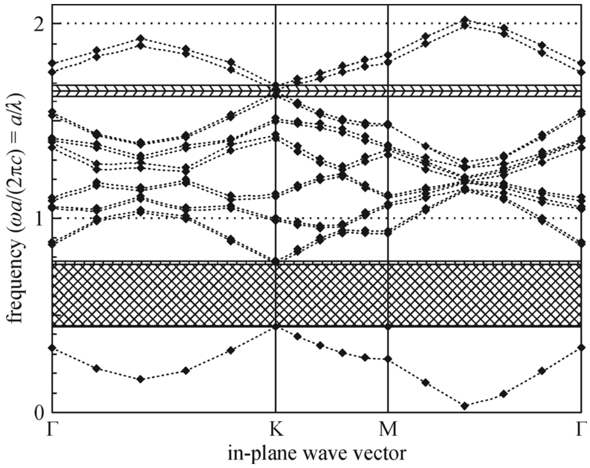

Fig. 2 Band diagram of proposed fiber

radius of 1.10 Λ was assumed, and previous calculations were repeated. As shown in Fig. 3(b), smaller radius of the air-core leads to an increase in thickness of silica layer surrounding the air-core. It was taken for granted that the sensitivity of this proposed structure increases with the increasing radius of air-core because the greater amount of the light is confined in the air-core. But in contrast to the assumed, due to multi-mode air-core, the sensitivity did not change considerably.

In fact, the less light is confined in the core due to smaller air-core radius, but the sensitivity does not change considerably due to lower confinement loss, it was equal to 84.2%.

As shown in Fig. 3(a), a large amount of light is confined in the air-core, but due to multi-mode air-core, the sensitivity is limited. But in Fig. 3(b), coupling of core mode to surface mode can give rise to propagation loss and reduces the sensitivity. It is known that, if the boundary thickness is about $0.5(\Lambda-d)$, no surface mode was observed. According to this, the optimum radius of air-core must be considered as R_{core} = 1.13 Λ. Figure 3(c) indicates the optical field distribution for optimum case. As shown in Fig. 3(c), the proposed fiber is single-mode and supported no surface mode. Our calculations results indicate that considering this radius, the sensitivity was improved to 92.5% (see Fig. 4).

The sensitivity with respect to the radius in the range from 1.10 Λ to 1.22 Λ is shown in Fig. 4. As shown, the sensitivity is maximized for R_{core} = 1.13 Λ.

By comparing Figs. 3(a)–3(c), it is found that in the proposed structure of fiber shown in Fig. 3(c), greater amount of light was confined in the air-core and the propagation loss was lower compared to the one shown in Fig. 3(a), although the air-core radius of the former was smaller than that of the later. Low propagation loss results from eliminating the surface mode. As well as with this radius (R_{core} = 1.13 Λ), modal unification can be achieved. In other hands considering R_{core} = 1.13 Λ, fiber is single mode.

The confinement loss, L_C, in decibel per meter, is given by

$$L_C = \frac{17.37\pi}{\lambda}\mathrm{Im}[n_{\text{eff}}], \tag{3}$$

where Im[n_{eff}] and λ are the imaginary part of effective index and wavelength respectively. We calculated confinement loss, L_C, as a function of air-filling factor with ten air-hole rings. The result is shown in Fig. 5. Although we could say larger value of air-filling factor is necessary for reducing the confinement loss in an air-core PBGF with a finite number of air holes in the cladding region [18,19], but as shown in Fig. 5, the minimum loss occurs at air-filling factor (d/Λ) = 0.95. In other hand, with specific wavelength, one must optimize air-filling factor to obtain the minimum loss. So, optimized air-filling factor is considered to 0.95.

In the next step, to optimize air-core radius due to minimum loss, we calculated confinement loss as a

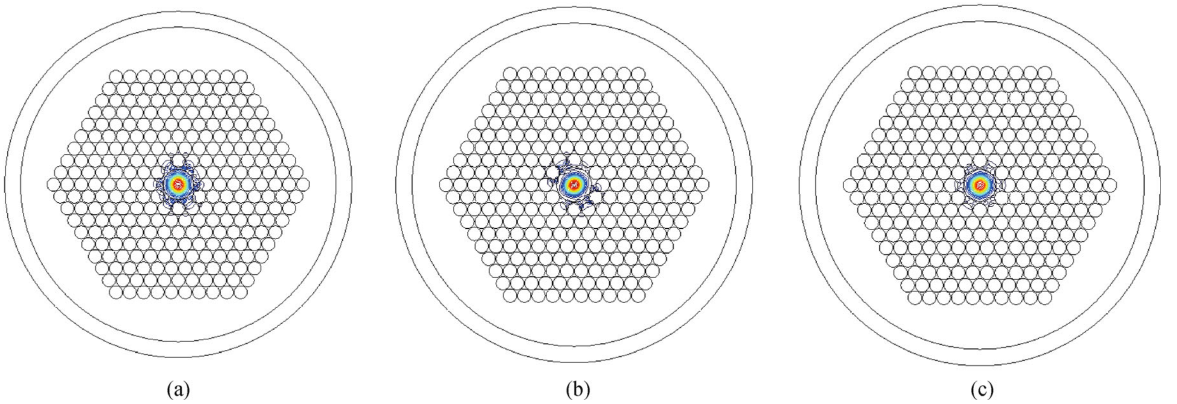
(a) (b) (c)

Fig. 3 Optical field distribution in PBGF for the core radius of (a) R_{core} = 1.22 Λ, (b) R_{core} = 1.10 Λ, and (c) R_{core} = 1.13 Λ (the optimum case)

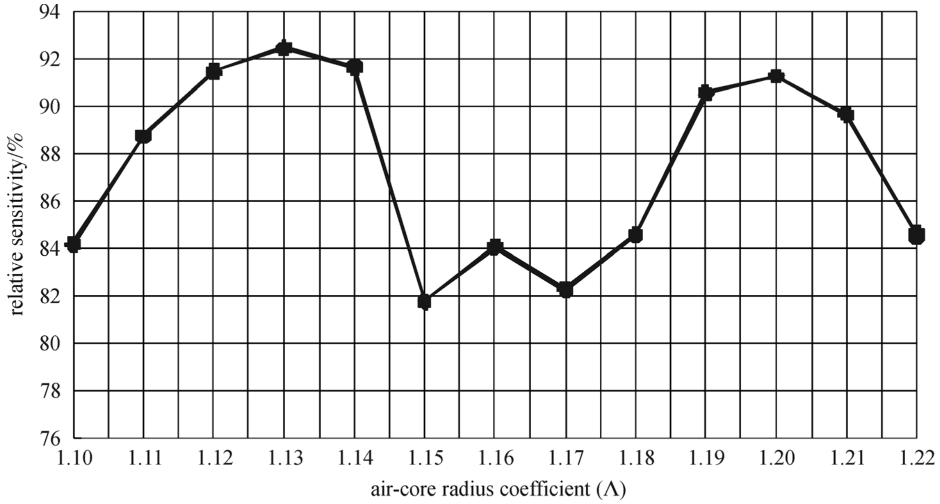

Fig. 4 Relative sensitivity versus air-core radius

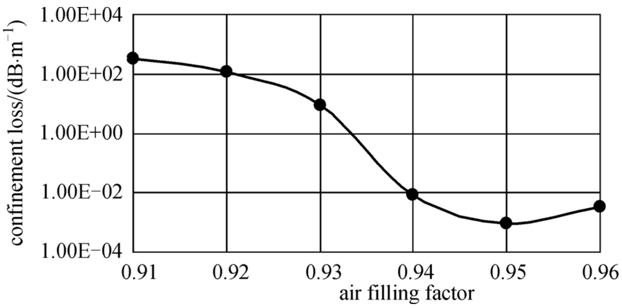

Fig. 5 Confinement loss versus air-filling factor

function of air-core radius with ten air-hole rings. The result shown in Fig. 6 indicates that the minimum loss occurs at air-core radius $R_{\text{core}} = 1.13\ \Lambda$.

With the same air-filling factor, we investigated the impact of changes in the air-core radius on the modal unification, relative sensitivity and confinement loss. By comparing Figs. 4 and 6, it can be found that higher relative sensitivity and lower confinement loss simultaneously can be achieved in the same air-core radius, $R_{\text{core}} = 1.13\ \Lambda$.

4 Conclusions

A novel optical fiber gas sensor based on PBGF was proposed. The dependency of sensing properties, such as relative sensitivity and confinement loss on the fiber structural parameters, has been investigated. We have shown that careful design of the air-core radius is very effective in reducing the number of air-guided modes and surface modes. It can also lead to increase of the relative sensitivity and reduction of confinement losses. To achieve higher sensitivity and lower confinement loss and reduced surface modes, simultaneously, we proposed a fiber with

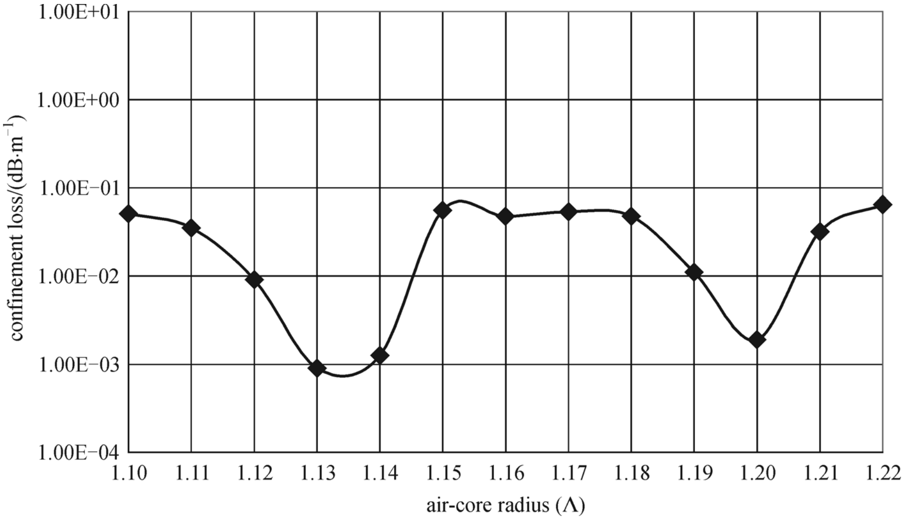

Fig. 6 Confinement loss with respect to the air-core radius

optimized structural parameters. In the proposed fiber at wavelength of $\lambda = 1.55\,\mu\text{m}$ that is in acetylene gas absorption line, a significant relative sensitivity of 92.5% and acceptable confinement loss of 0.09 dB/m were simultaneously obtained as air-core radius was equal to 1.13 Λ.

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