Gas Sensor Based on Large Hollow-Core Photonic Bandgap Fiber

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ABSTRACT— **One concern in using photonic band-gap fiber (PBGF) as a gas sensor is the response time. In this type of the gas sensors, response time is the time required for gas to diffuse into the hollow-core. So considering a large hollow-core PBGF (HC-PBGF), the response time can be significantly reduced. But in the large HC-PBGF, the fundamental issue is the presence of higher order modes (HOMs). Sometimes the leakage loss of the HOMs is comparable to those of the fundamental mode. So in order to suppression of the HOMs, six small-cores with reasonable radius were incorporated in the cladding of the proposed fiber. In other words, due to resonant-coupling mechanism of HOMs in central core with fundamental mode of outer cores, the leakage loss of the HOMs can be enhanced. Considering optimum parameters such as hollow-core radius, air filling factor, and the distance between the center-to-center of two adjacent air holes, the small-cores are surface-mode-free and proposed structure can be considered effectively single mode. So at the wavelength of 1550nm the relative sensitivity of the gas sensor was improved to 97%. The results proved the ability of proposed design as a sensitive gas sensor with low response time.**

KEYWORDS: Fiber optics sensors; Gas sensor; hollow-core PCF; Response time.

I. INTRODUCTION

Monitoring and detection of hazardous gases are important considerations in many industrial and environmental applications. One of the devices due to its high sensitivity, low response time, and compactness more attention has been devoted is photonic crystal fiber [1]. So far many studies on the use of photonic crystal fibers for gas sensing have been reported [2]-[8]. Compared to other types of the photonic crystal fibers, hollow-core photonic bandgap fibers (HC-PBGFs) have individual properties that make them suitable for gas sensing [9]-[12]. In the HC-PBGF based gas sensors, almost all of the optical power is confined in the core filled with gas samples, interaction of guided light and gas samples is enhanced, so this type of gas sensors are sensitive and accurate devices [13]-[15].

Obviously, one of the important considerations in gas sensors is the response time. On the other hand the large core of a HC-PBGF can be filled with gas in a short time. So in this paper a high sensitive gas sensor based on large HC-PBGF is designed. Two major limitations occurred when the light is guided through the hollow-core of PBGF; the presence of surface modes and higher order modes (HOMs). Especially in the particular case of large hollow-core, HOMs exhibit leakage losses which are sometimes comparable to those of the fundamental mode [16]. In the proposed structure by incorporating six small-cores in the cladding of the fiber, we show that suppression of HOMs in large HC-PBGF can improve the relative sensitivity of the gas sensor.

II. PRINCIPLES OF OPERATION

A setup for gas sensing is schematically shown in Fig. 1 [17]. This diagram can be interpreted as follows; light with a particular wavelength through a single-mode fiber (SMF) was launched into HC-PBGF. We have focused on the middle part of this setup. In fact a hollow-core photonic bandgap fiber was designed for gas sensing. Due to the absorption of light by the gas samples, some of the guided light is attenuated. According to the Beer-Lambert law [18], gas within the HC-PBGF is monitored by the measuring the attenuation of the guided light.

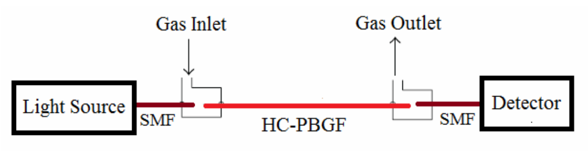

Fig. 1 The setup of the HC-PBGF based gas sensor [17].

According to Beer-Lambert law, the relationship between gas concentration and optical intensity in a waveguide can be defined as:

$$I(\lambda) = I_0(\lambda)\exp\left[-r\alpha_m(\lambda)LC\right] \tag{1}$$

where, I and I_0 are the output light intensities with and without the presence of gas being detected, respectively, $\alpha_m(\lambda)$ is the absorption coefficient of gas, L is the waveguide length, C is the gas concentration, and r is the relative sensitivity coefficient defined as:

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

where, n_r is almost equal to unit and refers to the index of the gas sample. 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 that in the HC-PBGF can be calculated by:

$$f = \frac{\int_{\text{hol.-core}}\left[E_x H_y - E_y H_x\right]dxdy}{\int_{\text{tot.}}\left[E_x H_y - E_y H_x\right]dxdy} \tag{3}$$

where, E_x, E_y, and H_x, H_y are the transverse electric and magnetic fields of the fundamental mode, respectively. In fact, the sensitivity of the structure is calculated by integrating the optical power inside the air-core and dividing it by the total power carried by the mode.

The photonic bandgap fiber guides light via photonic bandgap mechanism; in other words, only certain wavelengths of light can be propagated in the fiber. So, the absorption wavelength of the gas sample must be within the bandgap. A bandgap region with central wavelength around 1.55μm is desirable and covers the absorption lines of a number of important gases such as acetylene (C_2H_2), carbon dioxide (CO_2), carbon monoxide (CO) and ammonia (NH_3) [19]. For example acetylene absorption wave is approximately $\lambda_{\text{absorb}} = 1.53\mu\text{m}$ [20]; so, according to the bandgap, the operation wavelength is considered as $\lambda_{\text{operation}} = 1.55\mu\text{m}$, which is very close to the minimum loss wavelength. According to the absorption spectrum, the maximum absorption wavelength of acetylene is 1.53μm [20].

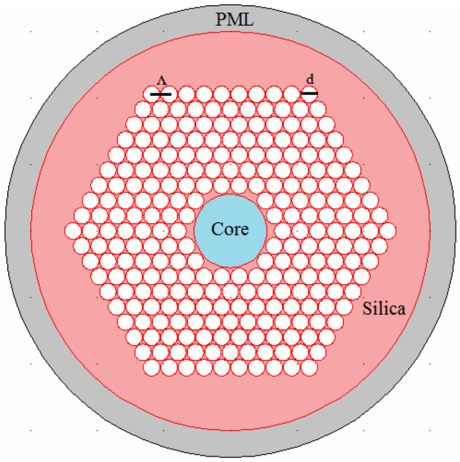

Fig. 2 The cross section of large hollow-core PBGF.

Figure 2 shows the cross section of the large hollow-core PBGF. The HC-PBGF comprises of a triangular lattice of air holes and a large hollow-core which is obtained by removing three rows of air holes from its center. In this design, the proposed fiber with following structural parameters is considered; $\Lambda = 2.63\mu\text{m}$ and $d/\Lambda = 0.95$, where Λ is the distance between the center-to-center of two adjacent air holes and *d* is the diameter of air holes, as shown in Fig. 2.

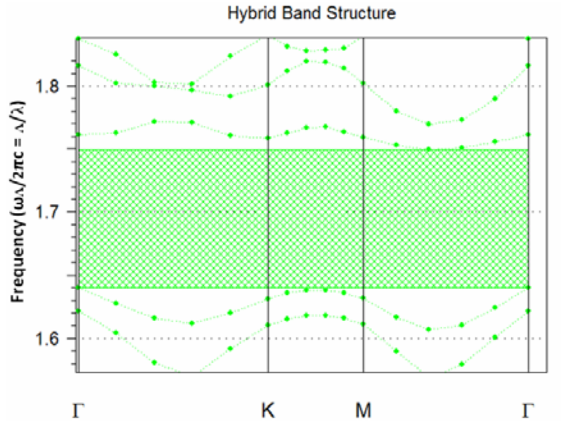

Fig. 3 The band diagram of the proposed fiber with structural parameters as $\Lambda = 2.63\mu\text{m}$ and $d/\Lambda = 0.95$.

Figure 3 shows the bandgap diagram by considering the silica refractive index as $n = 1.45$, lattice constant of $\Lambda = 2.63\mu\text{m}$, and air-filling factor of $d/\Lambda = 0.95$. The bandgap is shown as the shaded area. With normalized propagation constant of $k_z\Lambda/2\pi \approx 1.7$ and considering $\Lambda = 2.63\mu\text{m}$, a bandgap exists with central wavelength equal to $\lambda_{\text{op.}} = 1.55\mu\text{m}$. So, the operation wavelength is located in the bandgap region. As shown in vertical axis of the Fig. 3, $1.64 < \dfrac{\Lambda}{\lambda} < 1.75$. On the other hands, the lower and higher normalized wavelengths are 1.64 and 1.75, respectively. Otherwise considering $\Lambda = 2.63\mu\text{m}$, the bandgap is determined with a range of $1.5\mu\text{m} < \lambda < 1.6\mu\text{m}$.

III. SUPPRESSION OF HOMS

When the large HC-PBGF is used as a gas sensor, one of the important limitations is HOM. In order to enhance the suppression of the HOMs in large HC-PBGF, an index-matching mechanism between the HOMs in the central air-core and cladding modes, within a range of wavelengths has been introduced [21]. But in the proposed structure by incorporating six small air-cores in the cladding of the fiber [16], the suppression of the HOMs was achieved through the resonant-coupling mechanism of central air-core modes with outer small air-core modes. The proposed structure in basis of the structure presented by Saitoh *et al.* [16], was shown in Fig. 4.

As shown in Fig. 4, six small cores were incorporated in the cladding of the fiber with sixfold symmetry. In order to obtain a strong coupling between HOMs in the central core and fundamental modes of outer cores in this design, there is only one air hole between central core and each of the outer small-core. Each of the small-cores was obtained by removing seven air holes in the cladding. Considering a particular radius ($R_{\text{small-core}} = 1.13\Lambda$), each of the small-cores are surface-mode-free [22]. Introducing six small-cores close to the central core, would increase the leakage loss of the HOMs in the central core in comparison to those of the fundamental mode [21]. First the large hollow core was considered and the relative sensitivity was calculated. Considering $R_{\text{hol.-core}} = 2.1\Lambda$, the relative sensitivity was equal to 86.7%. In the next step, the relative sensitivity was calculated by considering six small cores. According to Eq. 2, the relative sensitivity is proportional to the optical power that confined in the central hollow-core (*f*). So the sensitivity was calculated by integrating the optical power in the central core and dividing it by total power carried by the optical mode. In this step, the gas sensor sensitivity was improved to 97%. Since suppression of the HOMs in the central core, the fiber can be considered effectively single-mode.

Surface modes are created when photonic crystal is abruptly terminated. On the other hand, when the surface of the air-core intersects one of the dielectric corners of the photonic crystal, surface modes are created. So in order to suppression of the surface mode, the portions of the air-core must cut through the cladding air holes [23]. It is known that the thickness of silica ring surrounding the air-core plays an important role in the suppression of the surface modes [24]. If the glass-boundary between the air-core and cladding is assumed as a polygonal ring, the effect of surface modes was significantly reduced. Since the shape of the air-core is circular, by incorporating six small air holes around the air-core with diameter of $d_h = 0.68\Lambda$, we have changed the shape of the air-core to hexagonal. This design can lead to a better confinement of optical modes in the central large core. Small air holes are shown in Fig. 5 with a different color. As shown in Fig. 5, more portions of the central air-core cut through air region of the cladding which in turn the impact of surface mode was reduced.

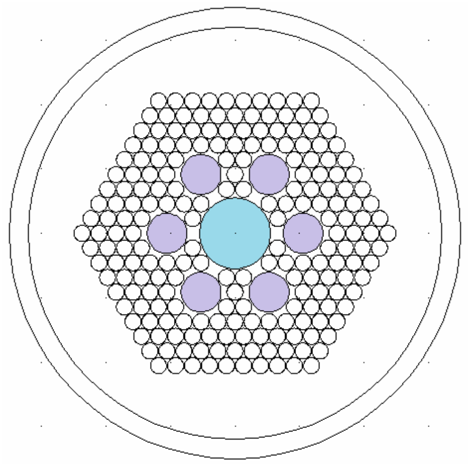

Fig. 4 The cross section of the fiber with six additional small-core ($R_{\text{small-core}} = 1.13\Lambda$).

IV. RESULTS AND DISCUSSION

To investigate the structural parameters and optical properties of the proposed photonic bandgap fiber, finite element method (FEM) was applied due to high accuracy and reliability in the analysis of photonic crystal fibers [25]. Figure 6 shows the optical mode distribution of the prior structure which the large hollow-core is considered (without six small-cores). As can be seen from Fig. 6, at the edge of the large core, some of the surface modes interfere with the fundamental mode. Furthermore, because of the HOMs in the large core and due to leakage losses of the modes, the relative sensitivity is not significant. In the next step, the proposed structure with six outer small cores and additional air holes around the central hollow-core was considered and the corresponding sensitivity was calculated. The relative sensitivity was improved to 97%.

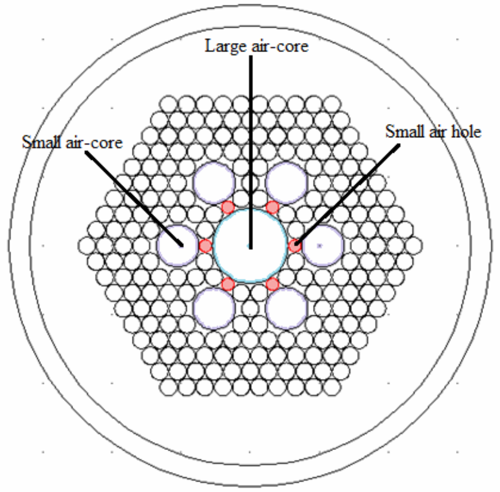

Fig. 5 Cross section of the fiber that small air holes are distinguished ($d_h = 0.68\Lambda$).

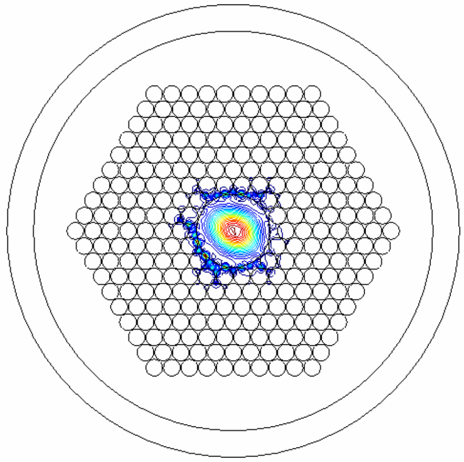

Fig. 6 The optical mode distribution of the primary structure.

The presence of small-cores in the cladding would increase the leakage loss of the HOMs in comparison to those of the fundamental mode of the large central core. So it can be assumed that the fiber is single-mode. The results are summarized in Fig. 7. As can be seen, the proposed structure is effectively single-mode. The impact of changes in the central core radius on the relative sensitivity was investigated as shown in Fig. 8. As shown in Fig. 8, the relative sensitivity corresponding to the biggest radius is significant. In the next step, the relative sensitivity was calculated as a function of wavelength, the results of which are shown in Fig. 9. As can be observed in this figure, at $\lambda = 1.55\mu\text{m}$, the sensitivity was maximum.

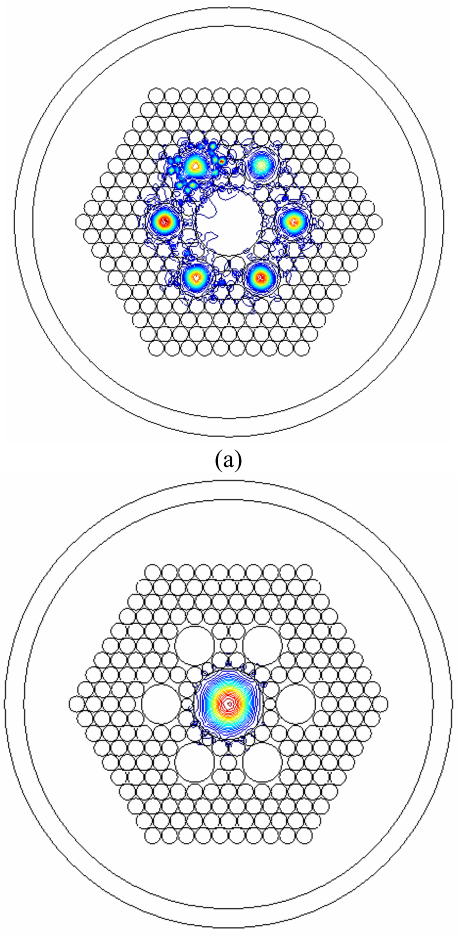

Fig. 7 (a): Fundamental mode of the outer small-cores, (b): the proposed structure that is effectively single-mode.

In Fig. 10, the confinement loss of the proposed structure as a function of wavelength is plotted. The confinement loss for fundamental mode at the operation wavelength ($\lambda = 1.55\mu\text{m}$), is about 23×10^{-2}dB/m that is acceptable.

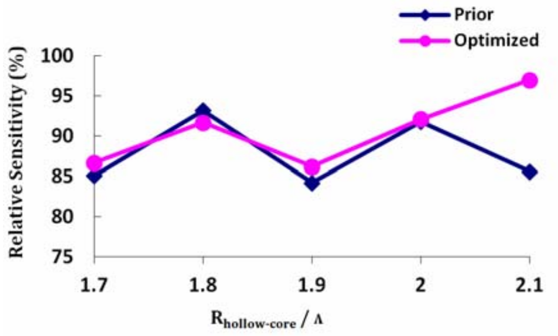

Fig. 8 Relative sensitivity versus central hollow-core radius.

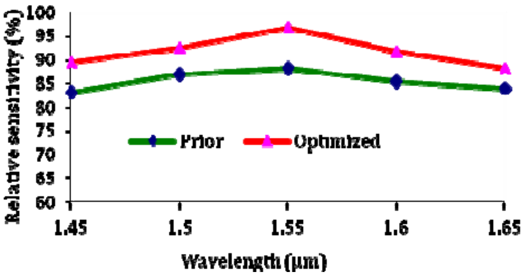

Fig. 9 The relative sensitivity versus wavelength.

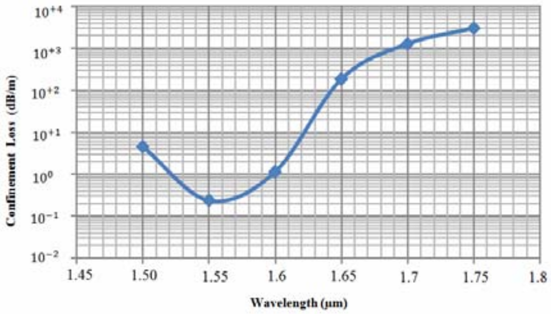

Fig. 10 The confinement loss with respect to the wavelength for proposed structure.

V. CONCLUSION

In this paper a gas sensor based on HC-PBGF has been proposed. The large core of a HC-PBGF can be filled with gas in a short time. So the response time of the sensor can be reduced. One of the major limitations when the light is guided through hollow-core of PBGF is the presence of HOMs. In the proposed structure by incorporating six small-cores in the cladding of the fiber, in order to suppression of HOMs in large HC-PBGF, the relative sensitivity of the gas sensor was improved to 97% and the confinement loss was equal to $23\times10^{-2}\text{dB/m}$. Furthermore, by introducing six small air holes around the central core, the effect of the surface modes was considerably reduced. The proposed structure can be considered effectively single mode fiber that can be used as a sensitive gas sensor.

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