DESIGN AND CHARACTERIZATION OF PHOTONIC CRYSTAL FIBER FOR SENSING APPLICATIONS

Monir Morshed
Md. Faizul Huq Arif
Sayed Asaduzzaman
Kawsar Ahmed
Department of Information and Communication Technology,
MawlanaBhashani Science and Technology University,
Santosh, Tangail, Bangladesh

Abstract

A simple structure of Photonic Crystal Fiber (PCF) for gas sensing and chemical sensing has been proposed in this paper. Index guiding properties of proposed PCF have been numerically investigated by using finite element method (FEM). From the numerical result, it is shown that the relative sensitivity and confinement loss depend on geomatrical parameters and wavelength. The relative sensitivity is increased by a increase of the diameters of central hollow core and innermost ring holes and confinement loss is decreased with a increase of the diameters of outermost cladding holes. By optimize the parmeters, the relative sensitivity is improved to the value of 20.10%. In this case, the confinement loss of the fiber is 1.09×10^{-3} dB/m.

Keywords: Confinement loss, Evanescent field, Gas sensor, Photonic crystal fiber, and Relative sensitivity

Introduction

A new era for faster communication in the modern world has started with the invention of PCFs. Now-a-days, PCF attracts the reasearchers due to its flexible properties comparing to the conventional optical fiber to design the sensors. PCF has been used for many sensing applications, such as gas sensing (Yu et al. 2008; Olyaee et al. 2013; Olyaee et al. 2014; Dash et al. 2014; Akowuah et al. 2012), chemical sensing (Monro et al. 2010), bio sensing (Sharan et al. 2014), cancer cell detection (Hossain et al. 2013), medical science (Olyaee et al. 2012) and temperature sensing (Wua et al. 2014).

Although, many papers have been reported on PCF based gas sensors, a great challenge takes place to the researchers for the enhancement of the sensitivity and reduction of confinement loss of PCF based gas sensors (Yu et al. 2008). X. Yu et al. at 2008 experimentally investigated a evanescent field absorption sensor where a Pure-Silica Defected-Core Photonic Crystal Fiber was used. They obtained the relative sensitivity of 4.79% and in this case confinement loss was 32.4dB/m. But, the sensitivity and confinement loss of this fiber was not significant. In 2011, Park et al. introduced a hollow high index ring defect of [X. Yu et al.,2008] that consists of the central air hole surrounded by a high index GeO_2 doped SiO_2 glass ring to improve sensing capability. The paper shown that the sensitivity increases 10% amend proportionally by some attributes like decrease the distance between center of two central cores, the increase of central core diameter and increase of diameters of air holes of two outer most layers and decreases the confinement loss 6×10^{-4} dB/m linearly. In 2013, D. Liangcheng et al. reported that the relative sensitivity of a gas sensor increases with respect to the increase of the diameters of the hollow core. In 2014, Olayee et al proposed a modified structure of [J. Park et al., 2011] to get the better relative sensitivity and confinement loss and also proposed a new structure with hexagonal holes in the inner ring instead of circular ring to significantly increase the sensitivity.

On the other hand, J. S. Chiang and T. L. Wu (2006) observed the propagation characteristics of an octagonal photonic crystal fiber. They showed that the confinement loss of O-PCF is lower than the H-PCF. Comparing to conventional PCFs, Octagonal PCFs provided some major attractive feature like bluer confinement loss, petty effective area and wideband single mode operation (X. Yu et al. ,2008).

According to the overall discussion, to get the higher relative sensitivity and lower confinement loss, a simple modified index guided hollow core PCF for gas sensing and chemical sensing has been proposed which consist three rings of air holes with three different formations. The inner most air holes ring of the cladding are kept hexagonal, the middle air holes ring and the outer most ring are made octagonal and decagonal, respectively. Here, complexity of the structure is reduced by remove the doping in the core and by decrease the number of air holes in the cladding compare to prior PCFs (S. Olyaee, 2014; J. Park, 2011).

Geometries of the Proposed PCF:

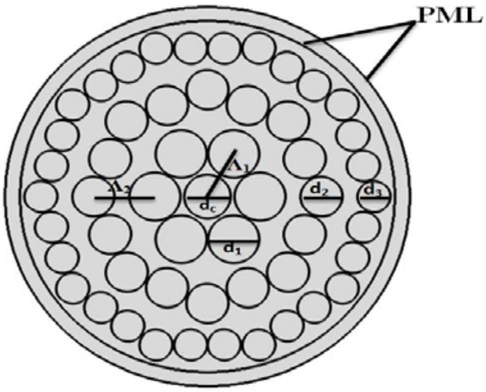

Fig 1. Cross-sectional view of proposed structure

Fig. 1 shows the cross sectional view of the proposed M-PCF (modified photonic crystal fiber). It consist of circular air holes which has been arranged in three rings on the silica background. The inner most ring of the air holes is hexagonal ,containing 6 air holes with the diameter d_1. The second ring is octagonal, containing 16 air holes with the diameter d_2. The third ring is decagonal, which comprises of 30 air holes with the diameter d_3. There is a central hollow core which has also been filled with air, and diameter is d_c. The air holes are arranged with two pitch values which have been denoted as Λ_1 and Λ_2 in the Fig.1.

Numerical Method Analysis

Finite-element method [FEM] with perfectly matched boundary layers (PML) was utilized to solve the Maxwell's equations because of its reliability (Saitoh et al.2002) and also investigated the optical properties of the PCF and measured confinement loss and sensitivity, as the goal of finding low confinement loss with high sensitivity.

Confinement loss: A small portion of power leakage can not avoid due to finite number of air holes in the cladding when light energy passes through a photonic crystal fiber. Confinement loss is the leaking of light from core to exterior matrix material. Confinement loss can be varied according to the number of layers, number of air holes, air hole diameter and the pitch. The confinement loss (dB/m) L_c has been defined by equation 1. (K. Kaneshima et al.,2006):

$$L_c=8.68k_0\mathrm{Im}[n_{eff}] \quad (1)$$

where, $k_0=2\pi/\lambda$; λ is the light wave length and $\mathrm{Im}[n_{eff}]$is imaginary part of the refractive index.

Sensitivity: From the Lambert Beers Law the relationship between gas concentration and optical intensity can be expressed in equation (2)

$$I_T(\omega)=I_0(\omega)\exp[-r\alpha(\omega)LC] \quad (2)$$

where $I_T(\omega)$ and $I_0(\omega)$ are the intensity of light before the absorbed energy and after the absorbed energy from light, L is the path length, C is the gas concentration and r is a relative sensitivity respectively.

The relative sensitivity can be calculated using equation (3)

$$r = \frac{n_r}{Re[n_{eff}]} f \quad (3)$$

where, $Re[n_{eff}]$= real part of the effective refractive index of the guided mode; n_r = refractive index of absorbing material and f is called the ratio of the air hole power and the total power where f is also calculated as optical power distribution function.

$$f = \frac{\int_{sample} Re(E_x H_y - E_y H_x)\, dx\, dy}{\int_{total} Re(E_x H_y - E_y H_x)\, dx\, dy} \quad (4)$$

where, E_x , E_y and H_x , H_y are the transverse electric fields and magnetic fields of the mode respectively. Increment the value of f will show the better sensitivity of the PCF. The mode field pattern E_x , E_y and H_x , H_y can be generated by the COMSOL Multiphysics 4.2 utilizing finite-element method (FEM) (Hoo et al.2003).

Result and Discussion

In this section, the dependance of the relative sensitivity and confinement loss on wavelength, hollow core, diameter of holes in first ring, diameter of holes in outer ring have been analyzed.

The variation of different hollow core diameters of d_c=3 μm, d_c=3.10 μm and d_c=3.20 causes linearly decrement of refractive index with the wavelength which have been shown in Fig. 2(b) .

a) (b)

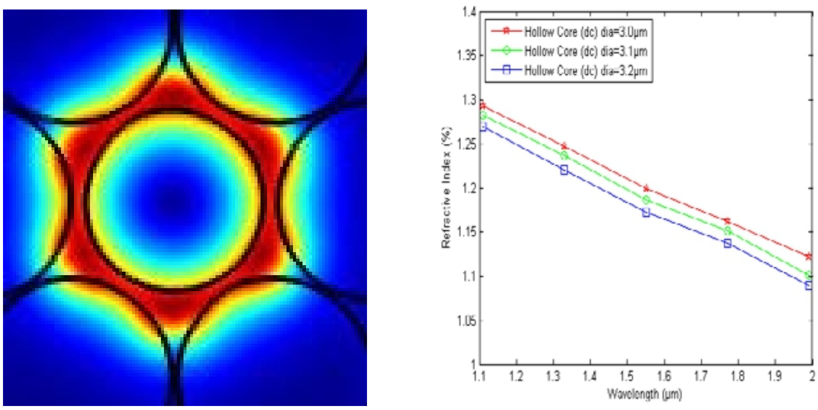

Fig 2. (a) The two dimensional end-face electric field distribution of the fundamental mode (b) Comparison between refractive Index and wavelength for hollow core diameter d_c=3 μm, d_c=3.10 μm and d_c=3.20 μm.

Fig. 3(a) shows the impact of changing of hollow core diameter on relative sensitivity. The relative sensitivity increases as a function of wavelength according to the increasing of the core diameter which has been shown in the figure when d_c=3.00 μm, d_c=3.10 μm and d_c=3.20 μm. Fig. 3 (b) illustrates the impact of changing of hollow core diameter on confinement loss. The behavior of changing of confinement loss is not proper. From the Fig. 3(b) it is clear that confinement loss increases according to the increasing of the core diameter. For d_c=3.00 μm the confinement loss is higher than the other diameters and for d_c=3.10 μm the confinement loss is lower.

(a) **(b)**

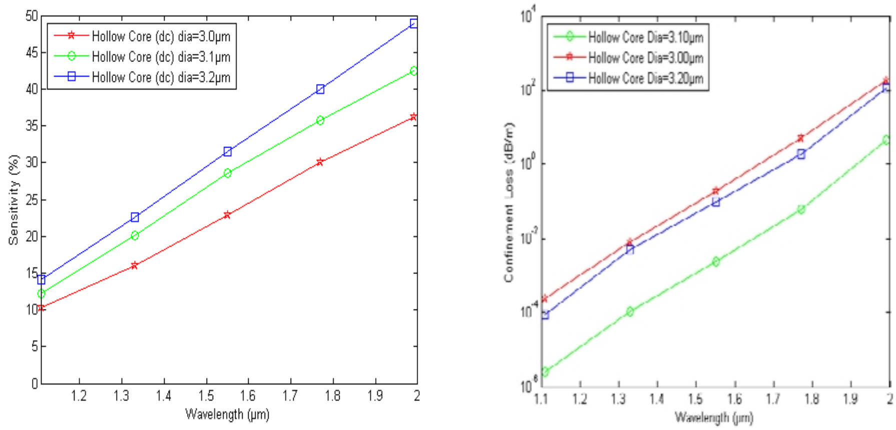

Fig 3. (a) Relative sensitivity versus wavelength (b)Confinement loss versus wavelength for different hollow core diameter dc=3 μm, dc=3.10 μm and dc=3.20 μm

(a) **(b)**

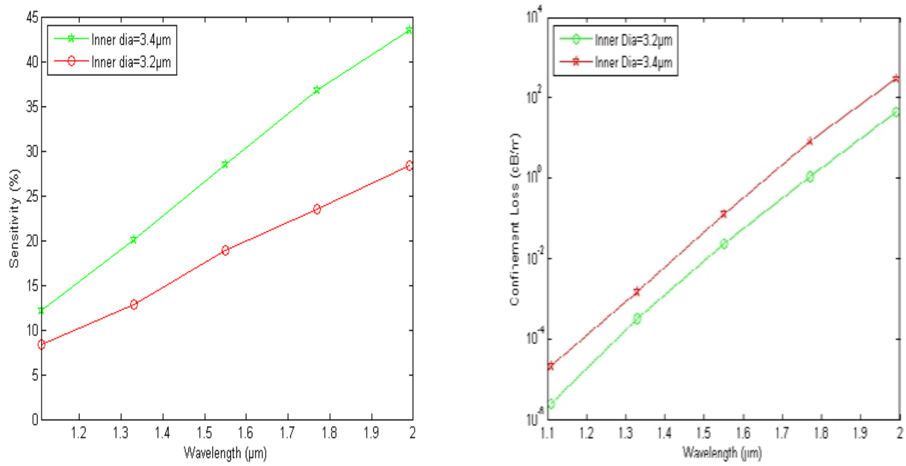

Fig 4. (a) Relative sensitivity versus wavelength (b) Confinement loss versus wavelengthfor different Inner Ring diameter d1=3.4 μm, and d1=3.2 μm.

Fig. 4(a) shows the effect of changing the diameter of holes in inner ring on relative sensitivity. The relative sensitivity increases according to the increment of the diameter of air holes in inner ring which has been shown in the figure when d_1=3.4 µm, d_1=3.2 µm. The relative sensitivity increases linearly with the wavelength and for d_1=3.4 µm the relative sensitivity is higher. From the figure Fig.4(b) it is clear that Confinement loss increases with respect to wavelength. For d_1=3.2 µm confinement loss is lower than d_1=3.4 µm. For d_1=3.4 µm the increasing of confinement loss is sharp for the wavelength from 1.1 µm to 1.8 µm.

(a) **(b)**

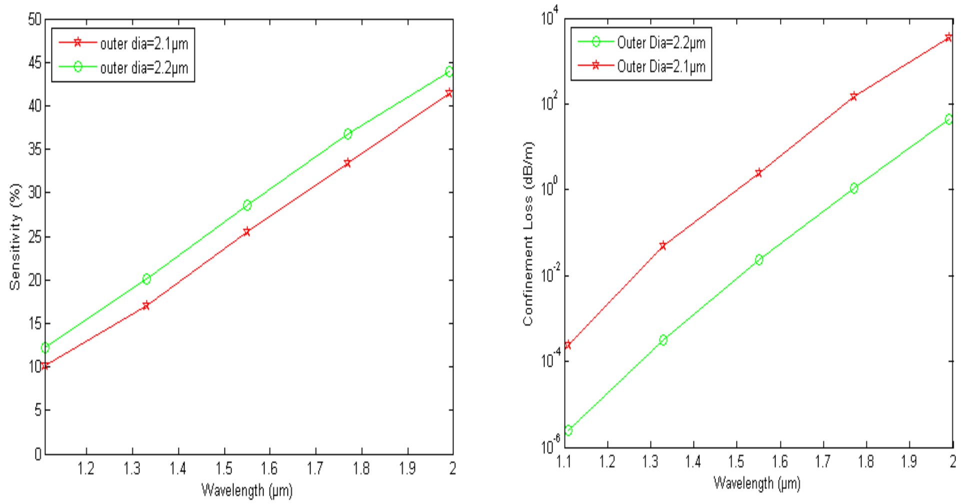

Fig 5. (a) Relative sensitivity versus wavelength (b) Confinement loss versus wavelength for different outer Ring diameter d_3=2.2 µm, and d_3=2.1 µm.

Fig.5(a) illustrates the influence of changing of the diameter of holes in outer ring on relative sensitivity with respect to wavelength. The relative sensitivity increases according to the increment of the diameter of holes which has been shown in the figure. The relative sensitivity increases linearly with the wavelength. And from Fig. 5(b) it is clear that the confinement loss increases gradually with the different outer ring diameters. For the diameter of holes in outer ring air d_3=2.2 µm, confinement loss is lower and almost sharply increases with the wavelength.

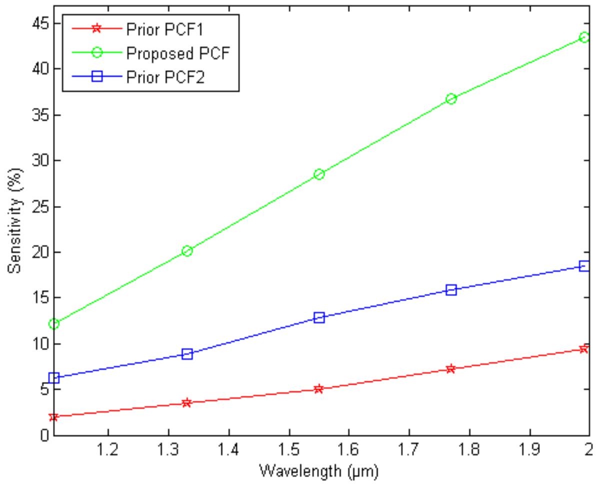

Fig 6. Comparison of Relative Sensitivity among proposed PCF and Prior PCFs.

The comparison of relative sensitivity among the proposed PCF and the prior PCFs (S. Olyaee, 2014; J. Park, 2011) have been shown in Fig. 6 which represents that the proposed M-PCF shows higher sensitivity than the prior PCFs from wavelength 1.1 μm to 2 μm.

Conclusion

The proposed simple M-PCF has been investigated by two guiding properties (the relative sensitivity and the confinement loss). It improves the relative sensitivity comparing with the prior structure. It shows that the relative sensitivity increases to the value of 20.10% at the wavelength of 1.33 μm and the confinement loss of this fiber is 1.09×10^{-3} dB/m which is much better than the early proposed structures. In this structure, there has not been used any doping. As it's structural simplicity, it would be easy to fabricate. Therefore, we could warrant that it can be used for both the gas and the chemical sensing applications.

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