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Sensitivity analysis of steering-wheel gas sensor against diverse core air hole sizes and core materials in terahertz wave band

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Abstract. We design a photonic crystal fiber (PCF) based gas sensor, which works based on evanescent field, by introducing a steering-wheel shape of large noncircular air-hole structure in the cladding region. Further, using the full-vectorial finite element method (FEM), we compute the relative sensitivities of the proposed sensor as 83% and 91% when the operating frequencies are 1THz and 0.5THz, respectively. The proposed sensor is suitable for detecting any kind of chemical and biological gases.

1. Introduction

Photonic crystal fiber (PCF) is also termed as micro structured fiber (MOF) or holly fiber. It is well established that photonic crystal fiber has become unsung hero in sensing applications [1-2]. Despite the popularity of evanescent-field sensing modality for fiber optic sensors, it continues to face the challenge of insufficient mode field overlap with measurable gases[3]. Hence, it leads to reduced sensitivity and the uppermost relative sensitivity of traditional PCF reported currently is still very low [4]. Owing to the industrial revolutions, the emission of gas has become one of the threatening factors in the society. This gas emission is unavoidable, in general, in several industries such as medicine, paper, pesticide, chemical, cosmetics etc[5-6]. At this juncture, gas sensor has become the need of hour in order to examine the gas concentration and followed by re-treatment.

Recently, many researchers have proposed several gas sensors that work based on evanescent field for gas detection. To achieve high sensitivity and less loss, we choose appropriate core materials and structural parameters for designing the gas sensors[7]. In this paper, we propose such a gas sensor fulfilling the above mentioned traits.

2. Design of steering wheel- micro structured fiber

In this section, we dwell into the design of steering wheel micro-structured fiber sensor that works based on evanescent-field. The features of this steering wheel -MOF are large light intensity overlap due to noncircular holes, low nonlinear effects and ultra-low confinement loss[8-9]. The geometrical structure of the proposed gas sensor is shown in Fig. 1. The design parameters are as follows: pitch, Λ = 35 µm, air holes, r_1 = 22 µm, r_2 = 0.12 mm, R_1 =0.866 mm, R_2 =0.894 mm, R_3 = 0.954 mm and web thickness, d = 21 to 25 µm. It is to be noted that the proposed sensor could easily be fabricated when compared to the conventional PCF as the air hole sizes are relatively larger in the proposed design.

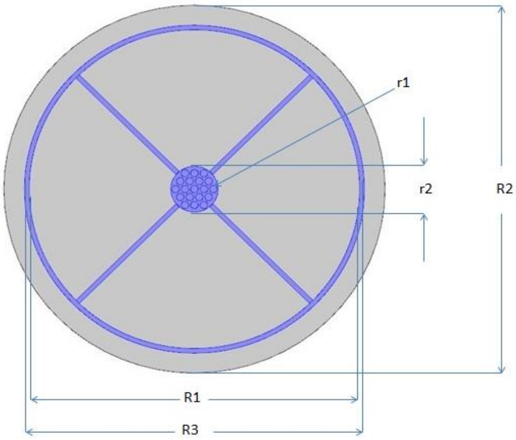

Figure 1. Geometrical structure of the steering-wheel PCF.

2.1 Mode Field Distribution

Figure 2 represents the mode field distribution of the proposed gas sensor. In the proposed steering structure, PTFE (Teflon) is used as core material and noncircular air hole contains the air medium. The sensitivity of this PCF purely depends on power ratio between the input light and evanescent wave[10]. The evanescent wave is absorbed by the noncircular large air holes.

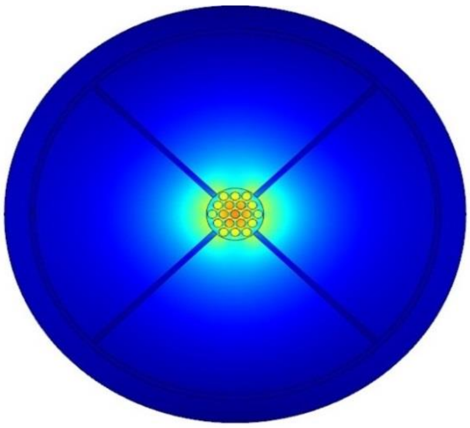

Figure 2. Mode-field distribution at 300 µm wavelength.

The proposed PCF gas sensor allows a directed mode to overlap with adjacent air holes more effectively because adequate surface area of the core is exposed to the evanescent field of this design. Therefore, the sensitivity of this model is greater and confinement loss is lower than that of traditional PCF. The novel PCF gas sensor is a total internal reflection-type PCF and only a very small part of the optical energy is distributed in the noncircular large air holes. The evanescent field in the air holes is absorbed by the gas species which can be obtained by the Beer-Lambert law[11],

$$I(\lambda) = I_0(\lambda)\exp[-r\alpha_m(\lambda)lC]. \tag{1}$$

Here I and I_0 refer to the output light intensity in the presence of gas and in the absence of gas, respectively. The parameter α_m refers to the absorption coefficient of the gas which is a function of the wavelength (λ), interaction length (l) and gas concentration (C) [12-13]. Sensitivity is a significant parameter in the evanescent wave based sensor. The sensitivity of the gas can be determined by numerical formula is given by [14]

$$r = \frac{n_r}{n_e} f\ . \tag{2}$$

Here, n_r is the refractive index of the filling substance in the cladding region, n_e is the guide-mode effective refractive index, and r is the relative sensitivity coefficient. For the new PCF gas sensor model, f is the ratio of the optical power within the noncircular large air holes to the total power and this can be expressed as[15-16],

$$f = \frac{\iint_{holes}(E_x H_y - E_y H_x)dxdy}{\iint_{total}(E_x H_y - E_y H_x)dxdy}\ . \tag{3}$$

Here E_x, E_y, H_x and H_y are the transverse and longitudinal electric and magnetic field model components, respectively.

3. Results and discussion

In this section, we compute the power proportion in non-circular air holes and relative sensitivity of the proposed gas sensor calculated for different d values of 18 µm, 20 µm and 22 µm. Besides, we study the above characteristics for various core materials such as poly Tetrafluoroethylene (PTFE or Teflon), polypropylene (PP), polyethylene-high density (HDPE) and polyethylene terephthalate (PET).

3.1 Power percentage in non-circular air holes

As it is clear from the simulation result as shown in the Fig.3 power percentage reduces in non-circular air holes as and when the frequency is increased. Further, it also increases when the radius of air holes in the core (r_c) is reduced. From Fig. 3, it is clear that the power percentage is 83% at 1 THz frequency for an air hole core radius of 22 µm.

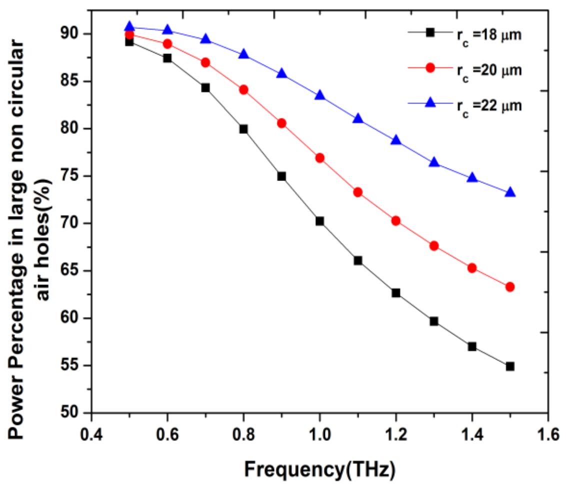

Figure 3. Power-percentage in noncircular large holes (%) proposed PCF with respect to frequency for various core radii.

From Fig. 4, power percentage decreases in non-circular air holes with increase in frequency [17-18]. However, it increases when the refractive index (PET -1.64, HDPE -1.54 , PP 1.49 and PTFE -1.38) of the core materials is decreased.

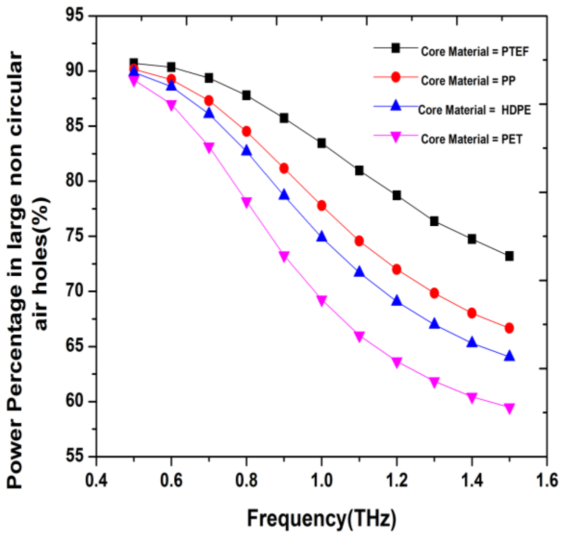

Figure 4. Power-percentage in noncircular large holes (%) proposed PCF with respect to frequency for various core materials.

3.2 Sensitivity Analysis

As seen from Fig. 5, relative sensitivity increases with reduction in frequency as evanescent field penetrates into the cladding, which eventually interacts with gas samples [19]. Thus, the sensitivity increases with increase in the wavelength. The maximum sensitivity is 83% at 1THz. Further, the sensitivity turns maximum for larger air hole radius.

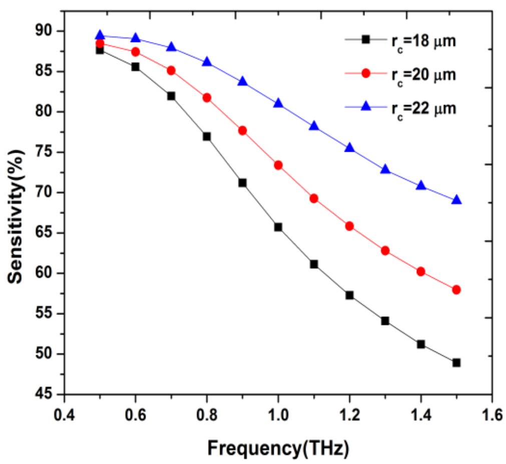

Figure 5. Relative sensitivity of proposed PCF with respect to frequency for various core air holes radii.

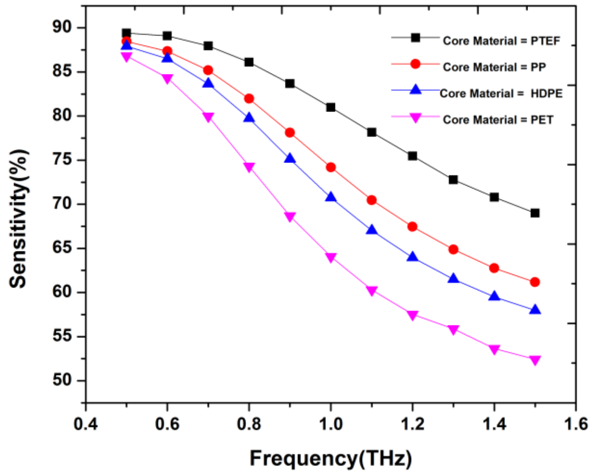

Figure 6. Relative sensitivity of proposed PCF with respect to frequency for various core materials.

As seen from Fig. 6, relative sensitivity increases with the decrease of frequency. We find that sensitivity of PET core material, HDPE core material ,PP core material, and Teflon core material are 64%, 72%, 75% and 83%, respectively, at 1 THz frequency.

4. Conclusion

We have proposed a PCF gas sensor based on evanescent wave using finite element method by varying the diameter of the air holes in the core and for different core materials. We have found that the power percentage in noncircular large air holes is 83% when the incident frequency is 1 THz. A better evanescent field distribution can be attained in the large non-circular cladding region by selecting an appropriate core air hole size (22 μm) and by choosing Teflon as a suitable background material. This results in an increased sensitivity and a reduced confinement loss at a critical frequency of 1THz. This proposed fiber would be highly useful for sensing the bio-chemicals with an increased sensing range.

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