Study of Photonic Crystal Fiber Modeling using COMSOL for Sensor Design: A review

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Abstract: This paper describes the study of photonic crystal fiber structure modeling for optical fiber sensor design using COMSOL Multiphysics simulation software. The use of photonic crystal fiber enhances the phase matching between optical fiber core guided modes and plasmon modes. PCF bring new strength to the fabrication of optical sensors since its distinctive capability of guiding the evanescent field penetration. There are certain number of air-holes in the PCF fiber which runs along the length of the fiber. For enhancing the sensitivity of the fiber, some parameters of the air-holes needs to be changed and then the structure is simulated with multiphysics software. By improving the width and depth of resonant curve, which are the two critical parameters, the PCF sensor biosensing performance can be enhanced.

Keywords: PCF, Dispersion, Modal, Analyte

1. Introduction

Nowadays photonic crystal fibers (PCF) [1] is of much attention all around the world.PCF which is also known as holey fibers are special type micro structured fibers. It consist of central defect region contained by many air-holes, lying along whole length of the fiber. The major difference between the photonic crystal fiber and conventional fiber is due the RI profile of core and cladd region of the fiber.PCF can offer more flexibility [2] than conventional fibers in design of optical properties such as birefringence, dispersion and confinement loss. PCF with low and flattened dispersion are useful for improving optical fiber communication capabilities. It has achieved increased attention because of its novel optical characteristics [3]. PCF guide optical waves through one of the two methods: effective-index guidance and photonic band gap guidance. PCF has two parameters to define its geometrical structure, they are diameter of air hole(D) and pitch length(Λ).By varying this two parameter PCF with different properties can be obtained [4]. The main advantages which PCF offers are like getting good birefringence properties, minimum dispersion, good nonlinearity. Typically, there are many PCF structures for PCF like first one is Hexagonal photonic crystal fiber, in which vertex of an equilateral triangle [5] has air holes. This type of PCF is known as Hexagonal photonic crystal fiber [6]. Apart from the HPCF structure there are other structures available like square lattice PCF, cob web PCF, honeycomb PCF, octagonal PCF and decagonal PCF [7], which has gained utmost importance in nowadays PCF sensor design [7].

2. Finite Element Method

Finite element method is a typical and authentic approach for the engineering recommendations as optical sensors. This is the most suitable tool for simulating the sensor structure and it has different modules like wave optics and RF module. Maxwell's equations are also solved with the help of finite element method [6].The total sensor structure is divided into different domains. Each domain is then appropriately meshed with suitable number of elements because the wave propagation will takes place only if all the domains are properly meshed. FEM method of simulation provides accurate results for difficult sensor structure and other designs [7]. So comparatively accuracy is more than other numerical methods available. It basically involves the following four steps:

i) Discretion the solution zones in fixed number of sub-zones.

ii) Formulating the guiding Maxwell's equations for mode propagation.

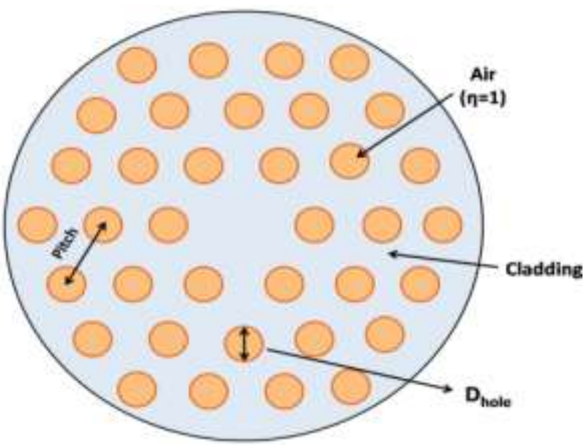
iii) Compilation of different elements in solution zone.

iv) Finally, analysing the design system of equations.

3. Theory and Design

Photonic crystal fibers (PCFs) guide light through a solid or hollow core by employing various inherent optical properties of artificially created crystal like cladding, generally, which is a periodic arrangement of air holes in silica glass [8].The cross section of the photonic crystal fiber for sensing applications is depicted in Fig 1. As shown in Figure the sensor proposed structure is exhibited in a simple and straightforward design which consisting of air-filled holes having circular shape, gold (*Au*) metal layer and biosensing layer. The biosensing layer is that layer which consists of analyte RI which is to be examined. Several examples of analytes are blood, tear, sucrose solution or any other gas [8].

The various properties are required to be discussed for photonic crystal fiber. One important property regarding PCF is confinement loss. We usually require large number of holes in the structural design, in order to obtain least confinement loss. But this could result in enhanced complexity in the design fabrication of the sensor structure. Therefore, an optimum number of air-filled holes is to be calculated with the allowable balance on confinement loss. Another critical factor that determines the confinement loss is the D_{hole}/Λ ratio, where d represents the diameter of hole and Λ represents the lattice pitch. Confinement loss is inversely proportional to the D_{hole}/Λ relation [8]. But larger D_{hole}/Λ ratio usually causes reduced effective area and increases nonlinearity and ultimately affects the biosensing performance [8].



(a)

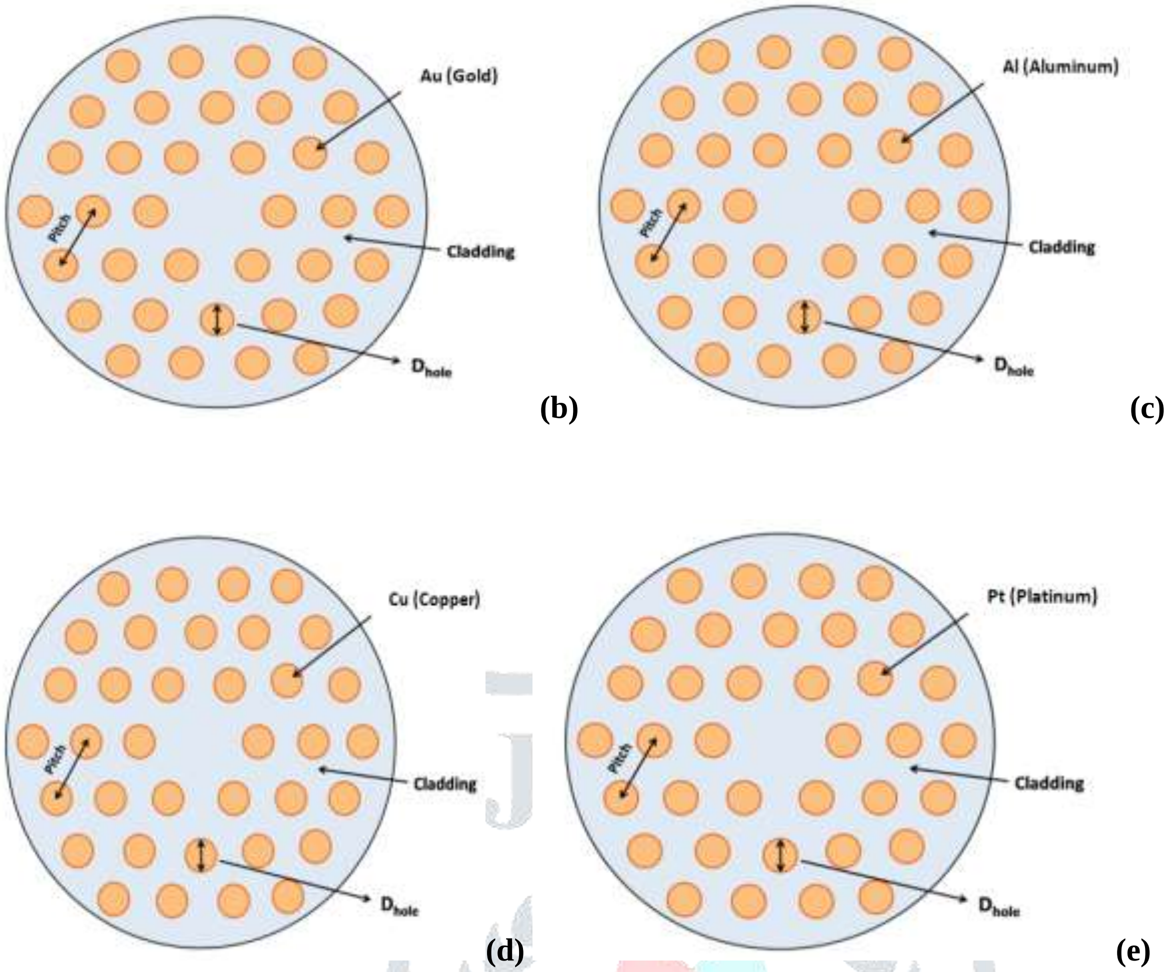


Fig. 1: General schematic representing the PCF Design with three layers (a)Air-holes rings (b) Gold-holes (c) Aluminium-holes (d) Copper-holes (e) Platinum-holes

Therefore, larger values of D_{hole}/Λ ratio are applicable only to extremely nonlinear optical fibers. Therefore, it is necessary that for allowable confinement loss during the structural optimization of ratio D_{hole}/Λ, necessary care should be there in order to make sure the mode propagation requirement over larger value of spectral width. Figure 1 shows the photonic crystal fiber model which has been modelled in COMSOL simulation software. In Fig.(a) we can see the three layers of air-holes rings. The diameter of the holes is chosen as 8micrometer. The spacing between two holes is known as pitch. Similarly Fig.1(b, c, d, e) shows the three layers of holes and nobel metals Au-Gold, Al-Aluminium, Cu-copper, Pt- Platinum respectively is used. We have modeled these structure in COMSOL with optimized parameters and we have got the electric field variation as shown in Fig. (2) for all these nobel metals, at a frequency of 3E14 and 2.3077E14.

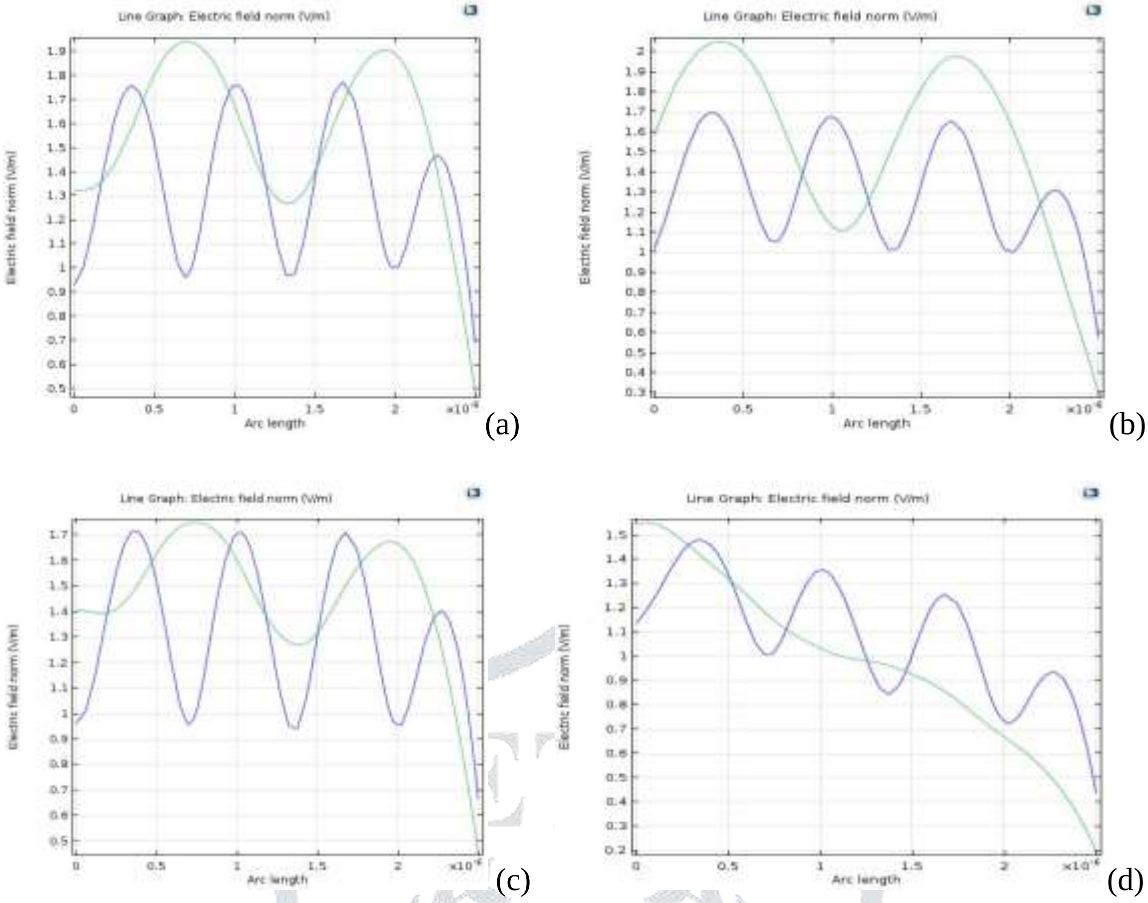


Fig. 2: Electric Field variation with arc length for three layers of holes with four different nobel metals for (a)Au-holes rings (b)Al-holes (c) Cu-holes (d)Pt-holes

4. Important Parameters concerning PCF

Now we will study some important properties of PCF like chromatic dispersion, confinement loss, effective area and non-linearity. Chromatic dispersion arises in Photonic crystal fiber because different colors or wavelengths arriving at the reception side slightly at different times. This causes a delay of certain amount in the reception of the optical signal. But such types of Photonic sensor utilizes air-holes having equal diameter and are placed in a cladd of the optical fiber. This special design of PCF sensor helps in reducing the chromatic deispersion. We usually vary the different characteristics of the air-holes to achieve better performance of the sensor. Chromatic dispersion can be calculated easily from n_{eff} versus the wavelength value as given by the below equation [8]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 R_e(n_{eff})}{d\lambda^2} \quad ps/(nm.km) \qquad (1)$$

In this equation, $R_e(n_{eff})$ represents effective index real part, λ represents the operating wavelength and c represents the light velocity in vacuum.

Another important properties of PCF is the confinement loss. This loss depends on number of air holes, their diameter and spacing between holes. Confinement loss, which is a fraction of leaky modes [1] is calculated from the imaginary part of n_{eff} by using equation as given below [8]:

$$Confinement_{loss} = 8.686 k_0 I_m (n_{eff}) \frac{dB}{km} \quad (2)$$

In this equation, I_m represents the imaginary part of effective mode index , and k_0 is the free space wave number, which is equal to 2π/λ. Now we will calculate the effective fundamental mode confined area during its mode propagation. The desired equation for calculating this is given as below [8]:

$$A_{eff} = \frac{\left(\iint |E|^2 dx\, dy\right)^2}{\iint |E|^4 dx\, dy} \mu m^2 \quad (3)$$

In this equation, E represents the E-field in the medium which is attained by retrieving the solution from Maxwell equations. Another important point regarding PCF is that when the light power density is too much then certain non-linear effects starts appearing. The equation which describes the relationship between nonlinearity and effective area is given as below [8]:

$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}} \quad \left({}^{1}/_{W.Km}\right) \quad (4)$$

In this equation λ represents the wavelength, and n_2 represents the nonlinear RI of the fiber core. It is clearly seen that effective area and non-linearity factor are both inversely proportional to each other.

5. Conclusions

We have presented the analysis of modeling of PCF based structure for optical sensor design. From COMSOL modeling analysis we can say that it is easy to see E-field penetration inside the circular air-holes of PCF structure. We have also shown the E-field penetration for different structure using different nobel metal inside circular holes. From the desirable properties of PCF, we conclude that Photonic crystal fiber based optical sensors are most widely utilized for environmental, biological and biochemical sensing applications. With the proposed sensor structure modeling we can easily analyze the PCF based optical sensor and further we can optimize the sensor structure with the help of COMSOL finite element simulation software. Further the use of use of perfectly matched layer, in circular shape outside the structure, eradicates the radiations directed toward the surface. Owing to satisfactory results and simplest sensing strategy, we expect that COMSOL modeling of PCF based sensor may serve as potential candidate for sensing analysis of PCF based sensor.

References:

[1] J.C. Knight, T.A. Birks, P. St. J. Russell, and D.M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," Opt. Lett., Vol. 21, pp.1547-1549, Oct. 1996.

[2] Jensen J.B., Riishede J., Broengx J., Laegsgaard J., Tanggaard Larsen T., Sorensen T., Hougaard K., Knudsen E., Libori, S.B., Bjarklev A., " Photonic crystal fibers; fundamental properties and applications within sensors," Sensors, 2003. Proceedings of IEEE , vol.1, no., pp. 269- 278 Vol.1, 22-24 Oct. 2003.

[3] Russell P., Dettmer R., "A neat idea of photonic crystal fibre," IEE Review , vol.47, no.5, pp.19-23, Sep 20014.

[4] Bjarklev A., Riishede J., Barkou Libori S.E., Broen J.,,"Photonic crystal fibres- novel fibres, new applications," Transparent Optical Networks, 2002. Proceedings of the 2002

4th International Conference on , vol.2, no., pp. 172- 178 vol.2, 2002.

[5] Jianguo Liu, Lifang Xue, Zhi Wang, Kai G., Liu Y., Weigang Zhang, Xiaoyi Dong, "Large anomalous dispersion at short wavelength and modal properties of a photonic crystal fiber with large air holes," Quantum Electronics, IEEE Journal of , vol.42, no.9, pp.961-968, Sept. 2006.

[6] Jianhua Li, Rong Wang, Jingyuan Wang, Zhiyong Xu, Yang Su, "Novel large negative dispersion photonic crystal fiber for dispersion compensation," Mechanic Automation and Control Engineering (MACE), 2011 Second International Conference on , vol., no., pp.1443-1446, 15-17 July 2011.

[7]Heike Ebendorff-Heidepriem, P. Petropoulos, S.Asimakis, V. Finazzi, R.C. Moore, K. Frampton, F.Koizumi, D.H. Richardson, and T. M. Monro, "Bismuth glass holey fibers with high nonlinearity," Opt. Express, Vol.12, pp5082-5087, Oct.2004.

[8] Amir.A, S. Revathi, Srinivasa Rao Inbathini & Abhijith Chandran, "Modeling of Circular Photonic Crystal Fiber Structure for High Non-linearity," International Journal of Advanced Electrical and Electronics Engineering, (IJAEEE)," 2278-8948, Volume-2, Issue-3, 2013.