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Photonic Crystal Fiber based Optical Sensor for Biomedical Applications: A review

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Abstract:

This paper describes the photonic crystal fiber based optical sensor for analyte sensing. For sensing the large dynamic range of analyte refractive index, we have studied the resonant properties of core guided modes and plasmon politron modes. 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 surface plasmon resonance sensors since its distinctive capability of guiding the evanescent field penetration. In plasmonic sensors, at the time, the phase matching condition is achieved, surface plasmon polaritons mode may be excited and results in extreme resonance condition. Unknown bio-analyte index of refraction can be computed by measuring the resonance wavelength. The sharp deep resonance curve results in the enhancement of signal to noise ratio and biosensing performance. By improving the width and depth of resonance curve, which are the two critical parameters, the PCF sensor biosensing performance can be enhanced. Moreover the effect of the thickness of the metallic layers on the biosensing performance is also studied by further structure optimization.

Keywords: PCF, Resonance, Analyte, Sensitivity

1. Introduction

In past few decades, a rapid rise in the development of special type of photonic based optical biosensors has been noticed which in turn enhances their applications in biomedical domain. This special type of photonic crystal fibre (PCF) consists an array of holes filled with air along the proliferation bearing has pulled in gigantic research enthusiasm over the globe [1]. By and large the mix of photonics and plasmonics is a developing exploration zone that will aid by upgrades in covering innovation and furthermore draw in developing enthusiasm for the PCF people group. There is a developing enthusiasm for investigating PCFs for use as cutting edge sensor gadgets by attacking the air gap with assortment of materials [2], for example, polymers fluid, and gas. The degree of freedom in the waveguide configuration is incredibly upgraded, contrasted and that for traditional fibres for explicit applications [3]. In addition SPR innovation has assumed as a significant function in current bio-sensing

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environment. Being horribly perceptive to the analyte index of refraction on dainty metal layer, the plasmonic technology has been executed in numerous sensors geometries for estimation of bio-chemical species [4]–[7].

Out of these sensors geometries, PCFs based SPR sensors geometries have demonstrated various exceptional points of interest in light of the fact that the unique structures are sufficiently capable in sensing the analyte location [8]–[15], a few or the entirety of the fibre openings are covered with thin metal films. There are numerous kinds of plasmonic metals for example Au, Ag, Al, Cu, Pt and Pd, which pulls the consideration of researchers and bio-analysisists. Gold (Au) metal is most broadly utilized for covering in PCF based optical sensor. Drude model describes the dielectric constant of gold [8], and provides a solid match in terms of results and few literatures is also reported in this context. The bioanalyte may be filled in these metalized openings or neighbourhood openings. Surface plasmon polaritons travels at the interface between metal film and the bioanalyte. The analyte refractive index change will influence the reverberation situation, and in this manner the qualities of the transmitted light. The transmitted light is observed with the help of spectrum analyzer and from the reflectance spectra bio-analyte refractive index can be recognized. In any case, in all these plasmonic sensors [8]-[15], bioanalyte is constantly filled into the fiber clad openings all over the fibre centre of photonic crystal fiber, to control the instrument of all out reflection, plasmonic biosensor can distinguish just the bio-analyte which has RI lower than the fibre canter. On account of the silica PCF, the most extreme location estimation of the RI is constrained to 1.42 [8]–[15].

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2. 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 [1-2].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, surose solution or any other gas.

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 ration. But larger D_{hole}/Λ ratio usually causes reduced effective area and increases nonlinearity and ultimately affects the biosensing performance. 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.

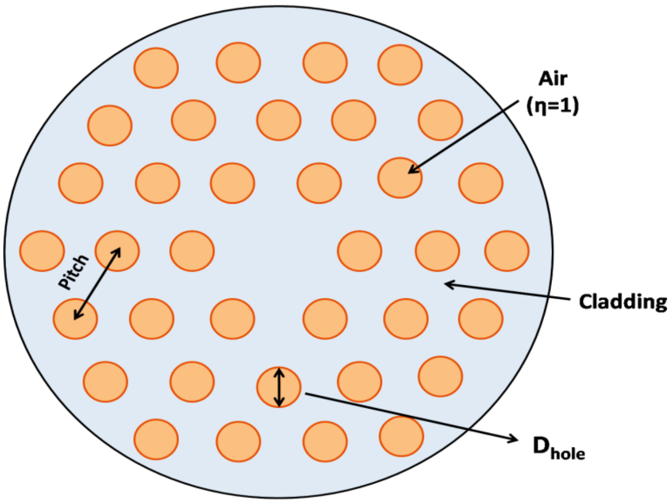

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Fig. 1 General schematic representing the PCF Design

As shown in Figure 1, D_{hole} represents the diameter of holes. The greek symbol Λ represents the lattice pitch between air-filled holes. Silica is used as a fiber material and its index of refraction is determined by well-known Sellmeier equation [16] as:

$$n(\lambda) = \sqrt{1 + \frac{D_1\lambda^2}{\lambda^2 - C_1} - \frac{D_2\lambda^2}{\lambda^2 - C_2} - \frac{D_3\lambda^2}{\lambda^2 - C_3}} \qquad (1)$$

In the above equation, D_1=0.696166300, D_2=0.407942600, D_3=0.897479400, C_1=4.67914826×$10^{-3}\mu m^2$, C_2=1.35120631×$10^{-2}\mu m^2$ and C_3=97.9340025μm^2 [16]. These represents the coefficients of well-known Sellmier equation, *n* represents the index of the silica and λ represents the wavelength [21]. The complete structural design of PCF can be modelled by finite-element method (FEM). To study the mode confinement nature, scattering boundary conditions are applied on the outermost layer. The dielectric constant of Au is expressed by Drude-Lorentz equation, as explained in Johnson and Christy [17].

$$\varepsilon_{gold} = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + j\gamma_{Decay})} - \frac{\Delta\varepsilon\Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L\omega} \qquad (2)$$

In the above equations, ε_{gold} represents permittivity of gold metal, ε_∞ represents permittivity at high frequency, ω_p represents plasma frequency, ω represents the angular frequency and is given as $\omega = 2\pi c/\lambda$ and Υ_{Decay} represents the decaying frequency. c represents light velocity in vacuum and Δε represents the weighting factor. The gold dielectric constant is responsible for observing the resonance behaviour in the sensing region of the above said sensor and it has to be carefully chosen at a particular wavelength.

3. 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. 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. So comparatively accuracy is more than other numerical methods available. It basically involves the following four steps:

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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.

4. Sensitivity Evaluation Techniques

As far as optical sensors are concerned then sensitivity is one of the important parameter that determines its sensing range for a specific bio-analyte. Sensitivity is usually expressed by the ratio of change or shift in resonant wavelength to the change in refractive index. Structural optimization is required to optimize the diameter of holes, lattice pitch and other sensor structure parameters. In SPR phenomenon, the evanescent magnetic field exists so for plasmonic phenomenon, effective excitation of evanescent waves is the most critical factor. The suitable wavelength of the input TM-polarized wave, which can produce the plasmons and resonance phenomenon is applied for simulating the sensor using the FEM based commercial package COMSOL Multiphysics 5.2 for analyzing the above said design.

4.1. Wavelength Interrogated Methodology

The main benefit of wavelength interrogated methodology is that it possesses enhanced sensitivity as well as enhanced detecting limit in comparison to the other detecting methodology available. The wavelength sensitivity may be computed as [18]:

$$\boldsymbol{Sensitivity_w = \frac{\Delta\lambda_{peak}}{\Delta n_{analyte}}} \qquad (3)$$

In the above equation, *Δλ* peak represents the difference of two resonance wavelength and $\Delta n_{analyte}$ represents the change in analyte RI. The diameter of air-filled holes has least impact on the sensitivity in wavelength interrogated method [19].

4.2. Amplitude Interrogation Methodology

Amplitude interrogation methodology is simplest and cost-effective because it does not involves any spectral manipulation. Sensitivity for this method can be computed from the equation as given below [20][21]:

$$\boldsymbol{S_{analyte}(\lambda) = -\frac{1}{\alpha_{loss}(\lambda, n_{analyte})}\frac{\delta\alpha_{loss}(\lambda, n_{analyte})}{\delta n_{analyte}} \quad [RIU]^{-1}} \qquad (4)$$

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In above equation, $\alpha_{loss}(\lambda, n_{analyte})$ represents the entire propagation loss at a distinct RI of bio-analyte and $\delta\alpha_{loss}(\lambda, n_{analyte})$ represents the difference among the loss spectrum before and after change in index of refraction [21].

The mode loss (dB/cm) of fiber core guided mode is computed with the general equation as given by [22]:

$$\alpha_{modal} = \frac{40\pi . I_m(n_{effec.})}{ln(10)\lambda} \cong 8.686 \times k_0 . I_m[n_{effec.}] \times \frac{10^4 dB}{cm} \qquad (5)$$

In the above equation, $k_0 = \frac{2\pi}{\lambda}$ represents the wave number in free space and λ represents the wavelength in μm.

5. Conclusions

We have presented the analysis of PCF based optical refractive index sensor. Photonic crystal fiber based optical sensors are most widely utilized for environmental, biological and biochemical sensing applications. The proposed sensor structure can be numerically simulated with the FEM method and 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 PCF based sensor may serve as potential candidate in detecting biological species. After structural optimization, the PCF based optical sensor can represent enhanced sensitivity, SNR and excellent accuracy for sensing the biological species in large dynamic range.

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