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Numerical Analysis and Design of Photonic Crystal Fiber Based Surface Plasmon Resonance Biosensor

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Abstract

In this paper, a high sensitive photonic crystal fiber (PCF) based surface plasmon resonance (SPR) biosensor is numerically studied. In this structure, as a plasmonic material, gold (Au) is used because of its chemical activeness. And a layer of sensing medium is used outside of the fiber to make the structure effective. Any unknown biomolecular analyte can be detected by placing or flowing it on the metal surface. Guiding properties and results are investigated using Finite element method (FEM). Results show that maximum sensitivity is 4000 nm/RIU, as well as resolution, is 2.5×10^{-5} RIU of the proposed sensor.

Keywords

Biosensor, PCF, SPR, SPP Mode, Sensitivity

1. Introduction

The surface plasmon is referred as the plasma oscillation which is localized at the surface or interface. "Plasmon" means quasi-particle representation of plasma frequency [1]. Plasma oscillation represents the phenomena that free electrons of the metal oscillate cooperatively from their equilibrium position [2]-[7]. In SPR measurement the change of refractive index change in nanometer range can be detected easily. For this reason SPR is used in different bio-sensing application such as detection of label-free antigen-antibody reaction.

In the last couple of years, SPR biosensor has been created a remarkable place from the other biosensors because of its high sensitivity and reliable procedure [8]. Kretschmann configuration [8] is widely used in which a very thin layer of metal is directly deposited on the surface of coupling prism. It is bulky in size and difficult to optimize. Furthermore, it cannot be used in remote sensing application. For removing this barrier of remote sensing optical fiber is used. Its advantage is that its core diameter is small that is why it can be used in small areas along with the capability of remote sensing. In the last decade, PCF has been contributed to different applications owing to its several properties [9] and several types of sensor have been designed using PCF. The PCF SPR sensor is worked on evanescent field principle and it is produced because of propagation of light in the core-cladding region [10]. Owing to changing of analyte local refractive index (RI), the RI of the surface plasmon polaritons (SPP) will be changed and finally, resonant wavelength will be also changed [10].

R.C. Jorgenson has propounded in [11], the very first optical fiber SPR sensor in where the core was coated by the Au film to exhibit plasmonic response. In [12], Polymer selectively coated PCF structure has been put forth by J. N. Das and R. Jha. Moreover, in [13] J. N. Das and R. Jha used multiple graphene layers in birefringence control PCF structure for SPR sensor. Previously the multiple metal layers are exercised in PCF SPR sensor and liquid infiltration inside the air holes or core [14]. Recently PCF SPR biosensor is designed by keeping the metal as well as sensing absorbate outside the PCF structure [15] [16].

Comprehensively as plasmonic material, gold and silver have been used. Among them, silver is preferable due to its most conductive nature, sharp peak and high detection accuracy compared to gold [17]-[25] But silver can be easily oxidized and detection accuracy will be reduced. Silver oxidization can be prevented by using a thin layer of graphene on the silver layer [26] [27] [28]. But gold is chemically immutable and shows larger wavelength shift in resonant wavelength. As a result detection accuracy to detect unknown analyte is raised [28] [29] [30] [31] [32].

In this work, a regular hexagonal PCF SPR biosensor has been proposed where the metal (gold), as well as sensing absorbate, is placed outside the PCF structure. This reduces the fiber structure complexity and sensing process easier. The unknown analyte can be easily detected by flowing it or just placing it outside of the gold surface just in label-free detection mode. Our structure is easy to construct in terms of fabrication.

2. Design Methodology

At the outer circle, six circles are omitted so that evanescent field can be flown to excite the metal surface. The cross section of our numerically proposed sensor has been shown in **Figure 1**. A simple three-ring, hexagonal PCF is designed for the SPR sensor.

According to the standard fiber drawing “stack and draw” technique, the proposed fiber can be constructed. In our core guided mode, the air holes in the

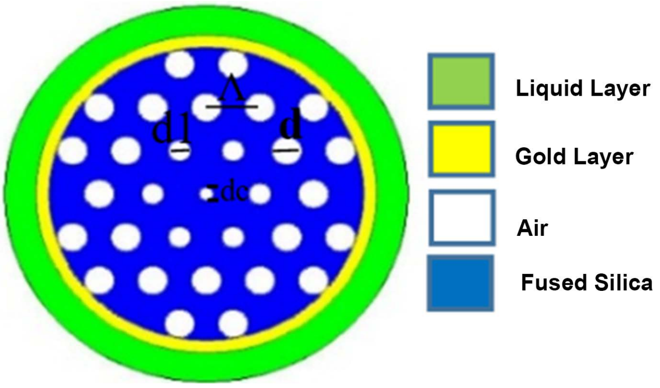

Figure 1. Cross Section view of propounded Sensor.

first ring act as low index cladding. It has been used to vacillate the phase matching with plasmonic mode by reducing the refractive index. Our sensor parameters are defined as pitch Λ = 1.7 μm, diameter of the first ring air hole (d1), the second air hole (d2) and the diameter of the centre air hole (dc) are 0.4 Λ, 0.55 Λ and 0.25 Λ respectively. Moreover, the thickness of the gold layer is defined to 40 nm and it is about the ideal case. The real part of the dielectric constant of the gold has been defined from the Drude-Lorentz model [16]. The RI of silica has been taken by using Sellmeir equation [16].

$$n^2(\lambda) = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} - \frac{B_2\lambda^2}{\lambda^2 - C_2} - \frac{B_3\lambda^2}{\lambda^2 - C_3} \tag{1}$$

where $B_1 = 0.69616300$, $B_2 = 0.407942600$, $B_3 = 0.897479400$, $C_1 = 4.67914826 \times 10^{-3}\ \mu m^2$, $C_2 = 1.35120631 \times 10^{-2}\ \mu m^2$, $C_3 = 97.9340025\ \mu m^2$ are the coefficients of Sellmier equation [16] and n is the RI of the silica and λ is the wavelength in μm. We use finite-element method (FEM) and also use scattering boundary condition (SBC) on the outest layer to determine mode confinement behavior.

3. Results and Discussion

The working fashion of the PCF based on SPR sensor is evanescent electromagnetics field. For plasmonic phenomenon efficient excitation is the key factor. At a definite frequency of the incident light which can excite the surface and produce resonance, The Finite Element Method (FEM) based software such as "*Comsol Multiphysics* 4.4" framework has been used to simulate and analyze our proposed structure. Although there exists both the horizontal and vertical polarization, we consider only horizontal polarization here because vertical polarization is lesser compared to the horizontal polarization.

Figure 2 shows, the horizontal polarization property of fundamental core mode and surface plasmon mode.

As the mode propagates through the core, plasmon mode at the metal sensing layer is excited by the core mode. Resonance occurs when the real part of the local RI of the core mode and the surface plasmon mode matches. At this specific point maximum modal loss is found. At maximum loss point imaginary value of

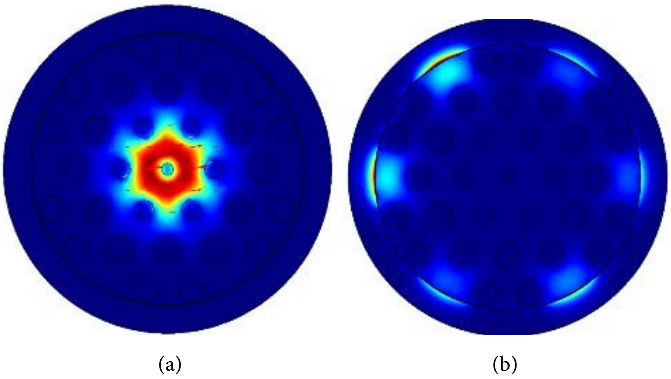

Figure 2. Field properties of (a) core guided mode for x-polarization and (b) Surface Plasmon Polarition mode.

RI of the core guided mode reaches to largest value. After this point, it has been noticed, modal loss is started decreasing again between core mode and plasmon mode. The modal loss of the fundamental core guided mode is extracted by using the equation below [19].

$$\alpha = 8.686 \times k_0 \cdot \mathrm{Im}\left[n_{eff}\right] \ \mathrm{dB/m} \tag{2}$$

where $k\_0 = 2\pi/\lambda$, λ are the wave number, wavelength in μm in free space.

Figure 3 shows that at 640 nm wavelength a very sharp peak is found. At that point real part of the core mode and SPP mode coincide. It defines that maximum power has transferred to fundamental core mode to SPP mode. Due to core cladding refractive index contrast sharp peak is found. Without influenced by other higher-order plasmonics one resonance is found for the fundamental mode. Sensing performance is indicated by the presence of resonance on the metal surface. At wavelength 640 nm phase matching phenomena is found where fundamental core mode, SPP mode and loss peak are well matched.

Our sensor is providing very sensitive results according to the analyte RI change. RI changing will change the phase matching phenomena between the core mode and SPP mode. RI change can be detected by measuring the loss spectra shift. By increasing the analyte RI loss spectra is shifted toward the higher wavelength. It is shown in Figure 4.

3.1. Wavelength Interrogation Technique

The advantage of Wavelength Interrogation technique is that it has higher sensitivity as well as higher detection range compared to the Amplitude detection technique [10]. In this method, RI variation is detected by measuring the resonance shift $\Delta\lambda_{\text{peak}}$. Sensitivity in this method is defined as [20].

$$S_\lambda\left[\frac{nm}{RIU}\right] = \Delta\lambda_{\text{peak}} / \Delta n_a \tag{3}$$

where n_a is the analyte refractive index. In this method, positive RI sensitivity is found 4000 nm/RU which is 4 times higher than the ref. [10] and 2 times than [16]. For the analyte RI, 1.34, 1.35, 1.36 and 1.37 resonant peak is found at 640,

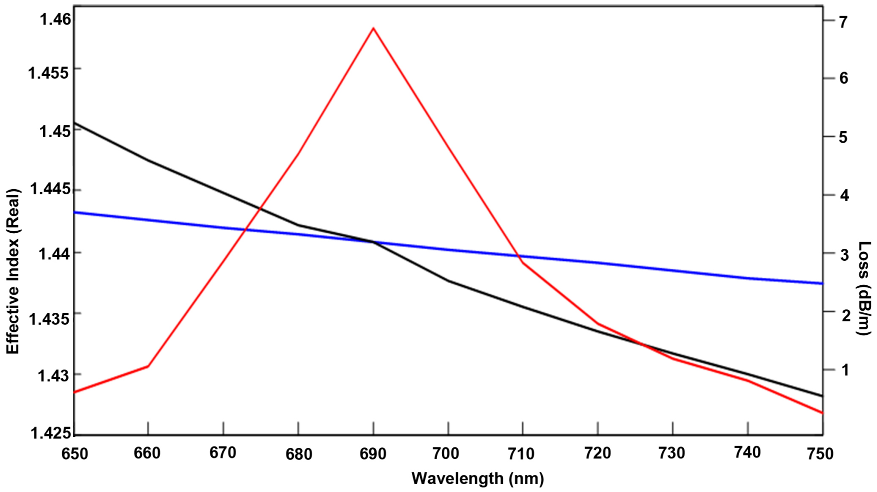

Figure 3. Relation of dispersion of core mode and surface plasmon polarition mode.

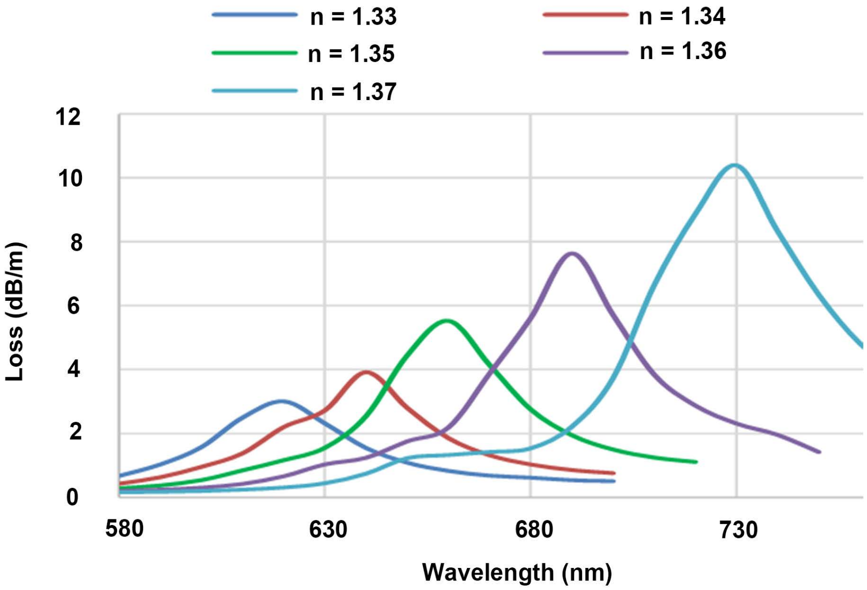

Figure 4. Loss spectrum profile of our proposed sensor by changing analyte RI from 1.33 to 1.3.

660, 690 and 730 nm and corresponding sensitivity is found as 2000, 2000, 3000 and 4000 nm/RIU respectively. Only higher sensitivity does not mean that the sensor can detect analyte accurately. By measuring sensor resolution it is possible to find that the sensor can detect analyte accurately or not. If we presume the proposed sensor can detect 0.1 spectral resolution then the sensor resolution is 2.5×10^{-5} RIU which is also better than in [10].

3.2. Amplitude Interrogation Technique

The advantage of this method is that this method is simple and cost effective because no spectral manipulation is needed here. Sensitivity in this method can be derived as in [10].

$$S_A(\lambda)\left[\mathrm{RIU}^{-1}\right] = -\frac{1}{\alpha(\lambda, n_a)}\frac{\delta\alpha(\lambda, n_a)}{\delta n_a} \tag{4}$$

Here, the overall propagation loss is denoted by $\alpha(\lambda, n_a)$ along the wavelength at a specific analyte RI as well as the difference between the loss spectra before and after the analyte RI change is denoted $\delta\alpha(\lambda, n_a)$. By using this method maximum 265 RIU^{-1} is found at 730 nm wavelength for the analyte RI of 1.37. Moreover, amplitude sensitivities are found 81, 89 and 153 RIU^{-1} are found for 1.34, 1.35 and 1.36 RI. If we assume, 1% change in transmitted intensity can be sensed accurately then the sensor resolution is found 3.7×10^{-5} RIU.

4. Conclusion

A numerically PCF based SPR biosensor has been proposed and studied. The FEM method has been adopted to model the computational domain of the proposed sensor and a circular perfectly matched layer has been used outside the structure to abolish radiation toward the surface. The proposed sensor shows wavelength sensitivity of 4000 nm/RIU with resolution of 2.5×10^{-5} RIU. Also, the sensor shows the amplitude sensitivity of 265 RIU^{-1} with resolution of 3.7×10^{-5} RIU. As the sensor is easy to fabricate by using draw and Stack method. Due to promising result and simple sensing scheme we believe that this sensor can be a good candidate for biological and biochemical analyte detection.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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