Exp. Theo. NANOTECHNOLOGY 5 (2021) 57 – 64

Experimental and Theoretical NANOTECHNOLOGY
http://etn.siats.co.uk/

Simulation design of silver nanoparticle coated photonic crystal fiber sensor based on surface plasmon resonance

Aseel I. Mahmood[*], *Shehab A. Kadhim, Nadia F. Mohammed, Intisar A. Naseef*

Materials Research Directorate, Ministry of Science and Technology (MOST), Baghdad, Iraq
*E-mail: aseelibrahim208@gmail.com

Received: 15/4/2020 / *Accepted:* 25/7/2020 / *Published:* 1/1/2021

Surface Plasmon Resonance (SPR) is the charge density excitation oscillation (surface Plasmon's, (SP)) caused by the polarized light along with the metal-dielectric interface by agreeing to phase-matching condition between polarized light and SPR. SPR method has unusual advantages like label-free, real-time and high resolutions with less than 10^{-7} RIU which is not consenting with other sensing methods. Photonic Crystal Fiber (PCF) presents unique features like design elasticity, geometric flexible and extraordinary guiding mechanism which head for better performance contrast conventional optical fibre, Additionally, the presence of air holes gives the possibility to insert multi able materials, that can recognize the interaction of travelling light and materials operatively. Adding the advantages of PCF to the properties of SPR, lead to design very strong and unique devices in different applications. In this paper, the PCF sensor based on SPR technique had been presented. The inner holes of PCF were coated with silver and then filled with air and ethanol. This was achieved theoretically by Finite Element Method (FEM). When the phase-matching condition was achieved at a fixed wavelength, the energy of the core-guided mode is shifted to the plasmon area and a resonant loss peak is observed at this wavelength. The simulated results show that a blue shifting is obtained when the outer air holes of PCF is filling with ethanol while the inner ring is filled with silver nano-particles. The maximum resolution and sensitivity are $5.66*10^{-4}$ RIU, 132.3 nm/RIU respectively in the sensing range of air refractive index to ethanol refractive index are obtained. The submitted design could be very useful in many fields like refractive index and temperature sensing applications.

Keywords: Temperature and Refractive index optical fibre sensors, Silver nanoparticles, Surface Plasmon Resonance, Finite Element Method.

1. INTRODUCTION

Now a day, the invention of the novel Photonic Crystal Fiber (PCF) leads to improving photonic technology in an unbelievable way in the sensor field. The use of PCF becomes very important in the sensor field because of their flexible structure which has ether bandgap or modified total internal reflection as a propagation phenomenon that is not available in the conventional fibre. The advantage of the microstructure holey fibre over conventional optical fibre which is an important factor that supports unparalleled sensing properties such as (i) single silica material is the background of PCF material. (ii) Several array designs of air holes. (iii) adding liquids and gases inside the PCF air holes gave them high advantages in the field of optical fibre sensors [1]. Very wide applications of PCF sensor in multiple fields like medical applications include biosensing, bioimaging, and drug detection, in addition in the field of food safety and gas and liquid sensors [2]. The amazing features of PCF make them very important in the field of sensing applications due to their high sensitivity, good performance, flexible and hand able design due to ability of infiltrated them with sensing agent (liquid or gas). Surface Plasmon Resonance based sensors get high attention in optical fibre sensor scientific committee Due to their very good properties like they could detect and analyze the required agent and high sensitivity and resolution, so this makes them applied in a wide field of applications. Like medical and biological sensors with real-time monitoring like detection of chemical and biological agents, glucose monitoring, disease detection. Also in the field of environmental monitoring like water quality testing, maintain food [3-6]. Also in the field of terahertz sensors [7], and SPR sensors [8-10]. Plasmonic optical fibre sensors are the results of SPR phenomenon. This Phenomenon happened when we have dielectric (silica fiber) – metal (gold for example) interface with a micro or nano- layer metal when the guided propagation modes couples with Surface Plasmon Polariton (SPP) mode under the conditions of phase-matching. When this condition is achieved to excite the plasmonic a resonance is occurred and the surface plasmon wave on the meatal will adsorbs most of the energy of the guided modes, thus gate a high loss spectrum at the resonance wavelength. This condition is very effected by the variable refractive index of the material closed to the metal layer. This variation could be due to the changing in solution concentration, the refractive index of the analyte, applied strain or stress which is lead to changing in resonance wavelength dip. This could be very good signs to improve sensor characteristics [11].

The SPR based sensors depend on the evanescent field of propagated modes in optical fibers, these leakage modes coupled with the SPP modes and when the condition of phase –matching achieved; the resonance will have occurred. There were many parameters affected the process like the meatal layer thickness which had to be in the nanometer range. Also the type of the material, gold is preferring due to not oxidization of them [12,13]. The advantages of both PCF and SPR lead to amazing sensing schemes reported in many articles. The dual-core PCF with gold layer thickness equal to 40 nm, the device was fully immersed in the liquids and obtained a sensitivity of about 725.89 RIU-1 [14]. Santos et. al presented D-type PCF-RI sensor based on SPR with a planar structure, where the conventional metal film is replaced by a metamaterial [15]. Peng et al. proposed a temperature sensor based on SPR the sensitivity was 720 pm/°C [16] and Mahmood et al submitted a PCF sensor based on SPR technique for environmental monitoring purpose.

In this paper, the PCF sensor based on SPR technique had been presented. The inner holes of PCF were coated with silver and then filled with air and ethanol. This was achieved theoretically by Finite Element Method (FEM). The submitted sensor could be a reference to develop and manufacturing chemical, biological and temperature sensor with high sensitivity.

Besides, the ability of remote and real-time sensing with compact structure and increase the sensing dynamic range.

2. EXPERIMENTAL

The designed simulation model was a Large Mode Area PCF (LMA-PCF) had a hexagonal six air hole rings centered around the solid core as clear in Fig. 1. The propagated modes will be speared in the cladding air holes area. The dimension of the model was as following; hole to hole spacing (Λ) equal to 0.75 µm, the air hole diameter (d) 0.3 µm, normalized air hole size (d /Λ) equal to 0.4, and core diameter (r) around 4 µm. The thickness of the metallic silver layer (t) is about 0.3 µm. The refractive index of the fibre background material which is silica was 1.45. In this work, the air holes of the designed models are filled with ethanol to detect the wavelength resonance.

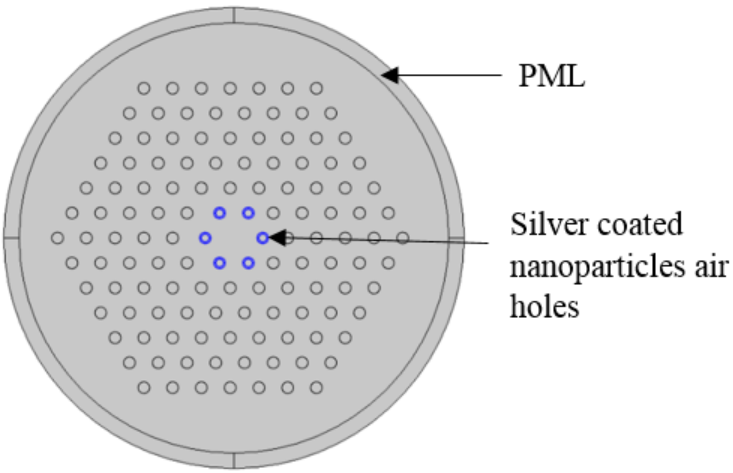

Figure 1 Schematic illustration of the proposed SPR-PCF sensor.

The Finite Element Method had been chosen to simulate the model through the simulation program COMSOL Multiphysics (version 4.4). here we chose a Perfectly Matched Layer (PML) as a boundary condition. The FEM had allowed the success an investigation of the experiment with the definition of mode and calculating the plasmonic mode through finding the complex propagation constant. In FEM sampling of the field at the nodes of an irregular mesh based on the construction of sub-elements within the structure will be considered. For the submitted model, the calculations of the field equations are represented discreetly in a system of algebraic equations and are solved by an eigenvalue method. The necessity of analyzing the field with different resolutions in different regions of the simulation domain force us to use the FEM, and thus provides a compromise between accuracy, resolution and consumption of computer memory resources. Here we chose extra finer mesh to get high resolution. the total number of mesh elements is 95562. The simulation for modal analysis is done in XY plane while light propagation is along the Z direction.

The propagation of light in a nonmagnetic optical medium is governed by the Maxwell equations [8]:

$$\nabla \times E(r,t) = -\partial_t B(r,t)\ \nabla \times B(r,t)$$

$$= \mu_0\ \partial_t\ D(r,t) \quad (1)$$

where $E(r,t)$ is the electric field, $D(r,t)$ is the electric displacement, $B(r,t)$ is the magnetic induction and μ_0 is the magnetic vacuum permeability. Combining these two equations, using continuous harmonic waves of the form $E(r,t) = E(r,w)\exp(iwt)$ and the constitutive relation $D(r,w) = \epsilon_0 n^2(r,w)E(r,w)$ yields the wave equation [8]:

$$\nabla \times \nabla \times E(r,w) - k_0^2 n^2(r,w)E(r,w) = 0 \quad (2)$$

With r=(x,y,z) and where $\mu_0\epsilon_0 w^2 = k_0^2, w$ is the angular frequency, ϵ_0 the permittivity of vacuum and n(r,w) is the index of refraction, this parameter is a complex one consists of real and imaginary part and it could be calculated as following [8]:

$$n(r,w) = n_r(r,w) + in_i(r,w) \quad (3)$$

The details of solving the above equations found in [8]. For the requirements of FEM, the cross-section of the designed sensor had been divided into triangular elements through selecting appropriate meshing. These triangles different in their shapes, sizes, and refractive indices according to sensor area. To get high resolution an extremely finer mesh had been selected. The material of the designed sensor model was pure silica. The presence of air holes of the cladding structures leading to from a especial type of losses called the confinement losses or leakage losses L_c ; L_c in dB/m is given by [8]:

$$L_c = -20\log_{10} e^{-k_0 Im[n_{eff}]} = 8.686 k_0 Im[n_{eff}] \quad (4)$$

Where (k_0) free space propagation constant, and $Im[n_{eff}]$ is the imaginary part of the complex effective refractive index (n_{eff}). The resolution (R) and the sensitivity (S) were obtained from the equations (5) and (6) respectively [8]:

$$R(\lambda) = \frac{1}{S(\lambda)}\Delta\lambda_{min} = \frac{\Delta\lambda_{min}\Delta n}{\Delta\lambda_{peak}} \quad (5)$$

$$S(\lambda) = \frac{\Delta n}{\Delta\lambda} \quad (6)$$

where λ_{min} is the minimum wavelength value between two spectral lines that can be detected, and λ_{peak} is the wavelength shift of the resonance peak obtained for the different external refractive indices values (n).

In the submitted work, the Gaussian –lime modes were used. This is considered as the best way which is suited for the excitation by standard Gaussian laser sources. Theoretically, phase

matching requires equating the propagation constants of the core guided mode and the plasmon mode, implying that the effective refractive index of the two modes has to be close which is achieved very well at our model.

3. RESULTS AND DISCUSSION

To perform the characteristics of the proposed sensor; the air holes of the LMA-PCF sensor based on SPR were infiltrated with air and ethanol, to detect the optical wavelength resonance of wavelength range (0.5-0.85) µm. The electromagnetic solver had been chosen to numerically simulate and investigate the PCF-SPR sensor, the core-guided modes and Surface Plasmon Polariton (SPP) mode were recorded. The single-mode Gaussian distribution output for the selected wavelength shown in Fig. 2. The fundamental Eigen mode at wavelength ranges (0.5-0.85) µm was assumed to be the input field. depending on the refractive index of analyte in this case (air and ethanol) the Eigenvalues which are effective refractive index were calculated through Maxwell equations for core and SPP modes for the corresponding wavelength ranges for air and ethanol as shown in Figs. 3 and 4 respectively. Then the resonant curves for air and ethanol had been studied by investigation the resonant properties of the submitted PCF-SPR based sensor through the calculation of confinement loss for air and ethanol using equation 4.

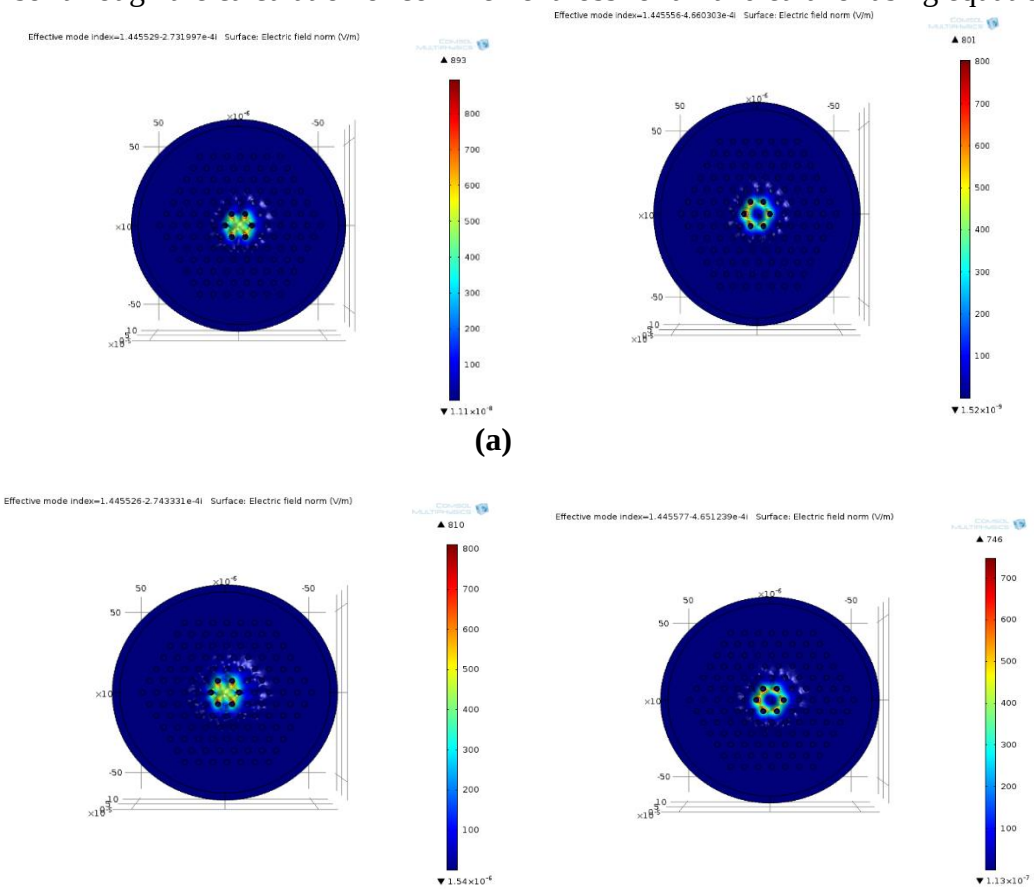

Figure 2 Electric field distribution of fundamental mode right pictures for core mode while left for SPP mode for selective wavelength 0.8 µm, (a) air-filled PCF, (b) ethanol filled PCF.

The main idea of the proposed SPR- sensor is to detect infiltrated liquid by FEM and creates plasmon to detect the variation of absorption of light by expected materials, which is ethanol. Figure 2 shows the 2D views of mode field profiles in case of empty PCF and infiltrated PCF.

The operating wavelength ranges (0.5-0.85) µm. Here we select an example of these modes which is 0.8 µm. It can be observed that the fundamental mode is more strongly bonded in the core region of the presented sensor due to high confinements this represents the core modes (right side figures). while there is a significant effect of the formation of cladding air holes and infiltrated one on-field profile due to SPR resonance (right side figures) which is clearly have high losses due to the resonance process.

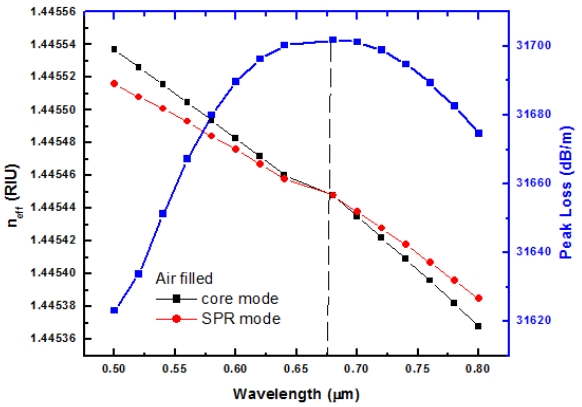

Figure 3 The dispersion relation of PCF-SPR, blue spectrum presents the confinement loss for PCF sensor filled with air.

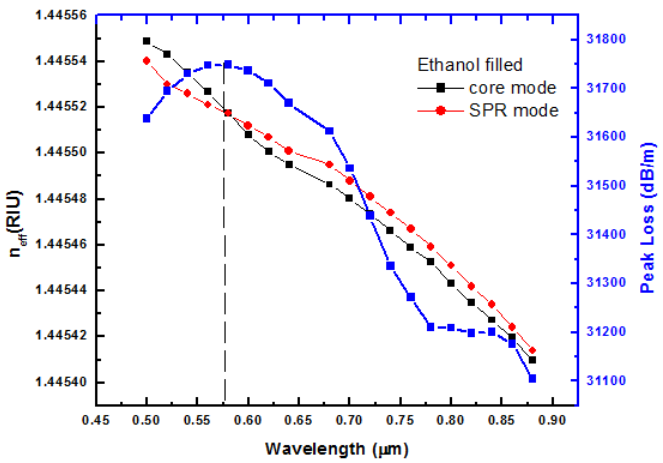

Figure 4 The dispersion relation of PCF-SPR, blue spectrum presents the confinement loss for PCF sensor filled with ethanol.

From Fig's. 3 and 4 when the real part of the obtained effective refractive index of belongs to core and SPP mode intercept in specific optical wavelength, this means the phase match condition is achieved. Also, this is mean a very strong mode leakage on the metal layer (silver nanoparticle layer) has occurred so we get a high confinement loss (blue line in Fig. 3 and 4). Depending on the small change of analyte refractive indices (air and ethanol), the real part of the effective refractive index of SPP mode changing, which causes the variation in the phase-matching wavelength between the core guided mode and the SPP mode. The resonant wavelengths for the submitted samples were shown in Fig. 5. The designed sensor has resonant countenance through the depending on the resonant wavelength on the refractive index of the infiltrated liquid, the maximum resolution and sensitivity are $5.66*10^{-4}$ RIU, 132.3 nm/ RIU respectively in the range of air and ethanol sample which was calculated through equations 5 and 6 respectively.

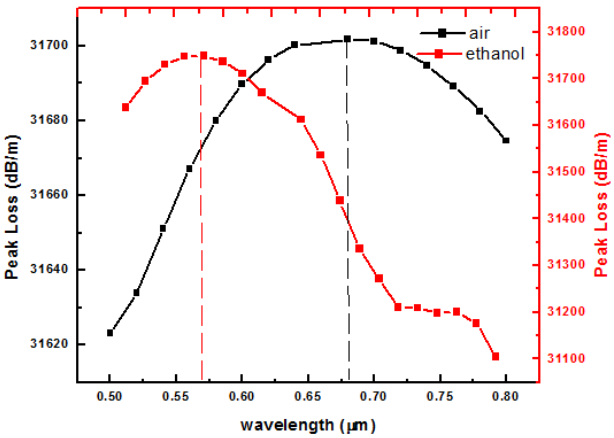

Figure 5 Peak loss for each sensor, the dashed line represents resonant wavelength.

The proposed sensor is very sensitive in response to the changing of the refractive index of the analyte, and also to the small change in analyte refractive index which is lead to a large shift in the loss peak. The peak wavelength shift results obtained by varying the analyte refractive index. The real part of the effective refractive index of plasmonic mode depends strongly on the vicinity layer of the analyte refractive index. Due to the small change of analyte refractive index, the real part of the effective refractive index of SPP mode changes, which causes the change of the phase-matching wavelength between the core guided mode and the SPP mode.

4. CONCLUSIONS

Surface Plasmon Resonance sensor based on Large Mode Area Photonic Crystal Fiber (SPR-LMA-PCF) coated with silver nanoparticles has been presented in this work. The inner air hole ring was infiltrated with silver nanoparticle to make a metallic layer to achieve an SPR phenomenon. The other air holes rings were infiltrated with air and ethanol to study the resolution of the submitted sensor. The real part of the effective refractive index of the core and SPP mode were calculated over a wavelength range (0.5-0.85 μm) through the FEM. The imaginary part was taken to calculate the transmission loss of the sensor. The identity of filled material detects through recognizing the peak of the transmission loss spectrum corresponding to the resonant wavelength of the SPR-PCF based sensor.

The maximum resolution and sensitivity are $5.66*10^{-4}$ RIU, 132.3 nm/RIU respectively in the sensing range of air to ethanol refractive indices are obtained. The submitted PCF-SPR based sensor introduce accurate and good resolving for optical signals which is coming from infiltrated materials which can be within a very small range in the refractive indices of air and ethanol, these types based sensors could be very important in the field of temperature and refractive index sensing applications.

References

[1] J. Knight, T. Birks, P. Russell, D. Atkin, Opt. Lett. 21 (1996) 19.
[2] J. Jensen, P. Hoiby, G. Emiliyanov, O. Bang, L. Pedersen, A. Bjarklev, Opt. Express. 13 (2005) 15.
[3] C. Mouvet, R. Harris, C. Maciag, B. Luff, J. Wilkinson, J. Piehler, Anl. Chim. Acta. 338 (1997) 338.
[4] R. Otupiri, E. Akowuah, S. Haxha, H. Ademgil, F. AbdelMalek , A. Aggoun , IEEE Photon. J. 6 (2014) 4.

[5] J. Ortega-Mendoza, A. Padilla-Vivanco, C. Toxqui-Quilt, P. Zaca-Morán, D. Villegas-Hernández, F. Chávez, Sens. 14 (2014)10.
[6] B. Paul, K. Ahmed, S. Asaduzzaman , M. Islam , Sens. Bio-Sens. Res. 12 (2017) 1.
[7] M. Islam, J. Sultana, K. Ahmed, IEEE Sens. J. 18 (2018) 2.
[8] A. Guerreiro, D. Santos, J. Baptista J, Sens. 19 (2019) 1772.
[9] A. Rifat, R. Ahmed, A. Yestisen, H. Butt, H. Sabouri, G. Mahdiraji , S. Yun , F. Adikan , Sens. Actuators B Chem. 243 (2017) 311.
[10] M. Hasan, S. Akter , A. Rifat., S. Rana , K. Ahmed, R. Ahmed, D. Abbott, IEEE Sens J. 18 (2018) 1.
[11] V. Portosi, D. Laneve, M. Christian Falconi , F. Prudenzano , Sens. 19 (2019) 1892.
[12] X. Zhou, X. Li , S. Li, G. An, T. Cheng, IEEE Trans. Instrum. Meas. 68 (2019) 234.
[13] B. Wang, Q. Wang, IEEE Sens. J. 18 (2018) 8303.
[14] A. Paul, A. Sarkar, A. Rahman, A. Khaleque, IEEE Sens. J. 18 (2018) 5761.
[15] D. Santos, A. Guerreiro, J. Baptista , Opt. Fibre Technol. 33 (2017) 83.
[16] Y.Peng , J. Hou , Z. Huang , Q. Lu , Appl. Opt. 51 (2012) 26.
[17] A. Mahmood , R. Ibrahim , A. Mahmood , Z. Ibrahim , IOP Conf. Series: Journal of Physics: Conf. Series. 1003 (2018) 012118.