Surface Plasmon Resonance–Based Refractive Index Biosensor: an External Sensing Approach

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Abstract
A surface plasmon resonance (SPR)-based sensor founded on photonic crystal fiber (PCF) is suggested and numerically analyzed in the manuscript. The refractive index (RI) detecting SPR-based sensor has the ability to identify the analyte range from 1.33 to 1.4. Pure silica is used as a base material and it has high RI value than the analyte RI. Furthermore, an analyte layer and chemically stable gold (Au) layer are also placed at the sensor design. The simulations are done based on the finite element method (FEM). Here, the scaled-down approach has the necessity to increase phase matching point within the core mode and surface plasmon polariton (SPP) mode which tends to the sensor to reach high sensitivity response. At the intersect point of core and SPP mode, the loss curve shows a maximum peak value. The suggested sensor shows the highest wavelength sensitivity (WS) response of 35,943.22 nm/RIU, amplitude sensitivity (AS) response of 2321.36 RIU−1, sensor resolution of 9.04 × 10−6 RIU, and figure of merit (FOM) value of 600. It is noted that all the optical parameters show better performance analysis. Furthermore, an external sensing approach provides more fabrication feasibility which marks the offered sensor more suitable for practical experimentation. Besides, the investigated sensor provides the maximum and rapid sensing performance that will be helpful for microfluidic analyte detection, detection of biomolecules, medical diagnostics, virus detection, security, and bio-imaging.

Keywords Surface plasmon resonance (SPR) · Optical fiber sensors · Photonic crystal fiber (PCF) · Plasmonic Material · High sensitivity

Introduction
In the twenty-first century, photonic crystal fiber (PCF) forms a new way for the improvement of refractive index (RI)-based sensors. It is also known as micro-structured optical fibers or the holey fibers [1]. Light is confined through the fundamental core of the PCF-based structure. The characteristics and performances of the optical sensor can be extended through the use of various liquids [2], metals [3], liquid crystal [4], or oil [5]. In the past decades, PCF-based surface plasmon resonance (SPR) sensor was the most explored technique than the other structures such as modal interferometers [6], fiber bragg grating (FBGs) [7], micro-ring resonator, multimode interference, long-period fiber gratings (LPFGs) [8], and resonant mirror [9]. Besides, the non-PCF-based SPR sensors were also analyzed in [10, 11]. The SPR-based sensor was introduced first both for bio sensing and gas-detection in 1983 [12]. Basically, SPR is the combination of the PCF technology and plasmonic science where gold (Au) is applied as a plasmonic material and the
analyte is used as an investigated liquid. In the SPR-based technology, light conducts electrons between the interface of the gold and analyte. Previously, prism and metal layer were used in the SPR-based sensor but due to some limitations, recently, PCF-based SPR technology has drawn attention for a large number of advantages. This SPR sensor is able to overcome the limitations of bulky and remote sensing features [13]. The noticeable features of SPR sensor are effectiveness [14], low loss [15], real-time detection [16], broad mode area [17], and so on. Moreover, SPR-based sensing technique has a large number of applications on control food quality [18], environment monitoring [19], gas detection, medical diagnostics [20], bio-molecular analyte detection, security, virus detection [21], and bio-imaging [16].

Various analyses have been performed to design a sensor with high sensitivity response. To rise the sensing performance as well as minimize the loss value is the main focus of the investigations. From the previous analysis, the maximum wavelength sensitivity response of 5500 nm/RIU was noted for a liquid-core PCF-based plasmonic sensor [22]. More investigations were performed to improve the sensing performance in addition to reduce the loss value. Additionally, Dash and Jha [23] anticipated a graphene-based D-shaped PCF biosensor and obtained the sensing response of 3700 nm/RIU and the amplitude sensitivity response of 216 RIU\(^{-1}\). Though the wavelength sensitivity (WS) response was lower than the previous analysis but a new parameter of amplitude sensitivity response was indicated here. Later, more investigations were performed to increase the amplitude sensitivity (AS) response. Likewise, a graphene-based PCF sensor was demonstrated and shown the highest amplitude sensitivity response of 860 RIU\(^{-1}\) and also reported the resolution as 4\(\times\)10\(^{-5}\) RIU with the loss value of 160 dB/cm [13]. Moreover, dual-core D-shape PCF sensor was suggested to get the sensitivity and resolution value of 14,660 nm/RIU and 6.82\(\times\)10\(^{-6}\) RIU respectively with the loss value of 80 dB/cm [24]. Furthermore, the WS and AS responses of 25,000 nm/RIU and 1411 RIU\(^{-1}\) was achieved with the highest figure of merit (FOM) value of 502 for the analyte RI range from 1.33 to 1.38 [25]. In recent years, more researches have been performed on the design, materials, and analytes to get high sensitivity responses. Recently, in the year 2020, a duplex core SPR sensor has been intended and reported the AS response of 1770 RIU\(^{-1}\) for the analyte RI value from 1.33 to 1.40 and the WS response of 10,700 nm/RIU is noted [26]. Additionally, the WS response of 45,003.05 nm/RIU has been achieved using an Au layer thickness of 50 nm [27]. The reported sensitivity was better than the previous works but the gold layer thickness was very high.

In this manuscript, an SPR-based sensor structure is designed using an external sensing mechanism. The suggested sensor is highly sensitive to detect the unknown analyte. Additionally, scaling down air hole diameter controls the light-guiding mechanism [28]. Basically, scaling down air holes provides better propagation and light direction that is responsible to increase the coupling between core and SPP mode. The offered sensor provides maximum sensitivity response with a low loss value. The numerical investigations have been performed based on the FEM method. The main goal of this investigation is to gain high WS and AS with better resolution, and maximum value of FOM. The manufacture feasibility of the suggested sensor will help to explore the opportunity for commercial utilization.

**Design and Methodology**

The structural cross-sectional three-dimensional vision of the proposed sensor is given in Fig. 1a. The proposed design is chosen to make it simple to determine the SPR and coupling modes. The
mesh analysis for the structural view is also shown in Fig. 1b. There are 10,126 domain elements in the entire mesh. The mode distribution fields are also exhibited in Fig. 1c-e for the core, SPP, and coupling modes respectively. The numerical examinations of the simulated sensor are carried out using the commercially available COMSOL Multiphysics (version 5.5). The FEM is used for further investigations which makes the boundary conditions and perfect match layer (PML) is also used to reduce the scattering of light. The structural parameters of the design are chosen through the variations of the value of parameters. Finally, three layers and different sizes of air holes are selected with diameters of 1.6 µm, 1.2 µm, and 0.8 µm respectively. The angle between two large air holes is 90°. For each part angle between small air holes is 45°. The thickness of the layers of gold and analyte is taken at 20 nm and 0.7 µm respectively. The PML layer of the proposed sensor has been used as 1 µm. Typically, the PML layer is used to fascinate the scattering of light.

The PML layer of the structure is marked by blue color in Fig. 1a. Besides, the fundamental core mode propagates light at the core region, the SPP mode creates plasmon at the interface between the gold layer and analyte layer, and the coupling mode indicates the more scattering of light from core mode to the SPP mode. This coupling or phase matching occurs at the point of highest peak loss. All these mode distributions are highlighted into the sub figures of Fig. 1c-e.

Figure 2a shows a generalized schematic block diagram of the experimental functioning of the suggested sensor, despite the fact that the inquiry is simulation-based. A light source (broadband or monochromatic) can carry the optical power into single-mode fiber (SMF). The connection between the light and PCF can be established through upper standard SMF. On the other hand, lower standard SMF can connect PCF and optical spectrum analyzer (OSA). Furthermore, OSA or photo-detector can easily detect the transferred light. Moreover, a computer display has been used to observe the outputs. The inlet and outlet section can control the flow or change of the analyte through withdrawal or pumping process. In Fig. 2b, the free electrons of the sensor are shown moving through the contact between the gold layer and the analyte.

When light strikes the gold layer, free electron oscillations begin at the interface of the Au and analyte layers. When light is supplied from an optical light source, it is transmitted through the fiber sensor, resulting in various modes such as core and SPP. Coupling mode is obtained at a site with a significant loss value. The Optical Source Analyzer can accomplish these modes and their related output values.

**Fabrication**

Internal and exterior sensing techniques [29] are two types of sensor construction processes. Internal air holes are covered with plasmonic materials and analytes in the internal detecting technique [30]. As a result, the fabrication process is complex due to the requirement for liquid infiltration and selective metal coverage. External sensing has recently become a popular method, owing to its ease of production [31]. The plasmonic material coating and analyte layer are kept outside of the PCF sensor in this method of sensing. When it comes to real-time applications, external sensing is preferable than internal sensing. This approach allows for easy control of layer thickness, layer deposition, and analyte filling. The circular air holes can also be easily made using capillary stacking and stack-and-draw techniques [32].

**Numerical Analysis**

In the proposed investigation, silica or silicon dioxide (SiO₂) is used as both ground material and PML layer. The air holes are
arranged in three different layers within the silica. The RI value of SiO$_2$ is changed with the variations of the operating wavelength. All the equations are analyzed for the temperature 20 °C. The analytes of lower RI can easily be sensed by using silica. Sellmeier Eq. (1) is used to measure the dispersion values of silica.

$$n_{\text{silica}}(\lambda) = \sqrt{1 + \sum_{i=1}^{j} \frac{A_i \lambda^2}{\lambda^2 - B_i^2}}$$

where, $\lambda$ (µm) denotes the wavelength and the constant values of the Sellmeier coefficients can be represented by $A_i$ and $B_i$. These fixed values of $A_1$, $A_2$, $A_3$, $B_1$, $B_2$, and $B_3$ are 0.696750, 0.408218, 0.890815, 0.069066, 0.115662, and 9.900559 respectively [33].

At the time of light propagation within the core region, free electrons start moving through the plasmonic material. As a result, an oscillation is generated at the interface of the plasmonic material and the metal-dielectric. Mainly, the execution of the SPR sensor depends on the plasmonic material and the metal-dielectric. Among them, though silver offers a better resonance peak, it is a chemically unstable material [35]. To overcome this problem of oxidization, gold can be used as it is reliable and chemically stable material than all other materials [36]. This is the main reason to select a tiny gold layer for this analysis. The RI of gold can be chosen from Drude–Lorenz Eq. (2).

$$\varepsilon_{\text{Au}} = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega (\omega + j\gamma_D)} + \frac{\Delta \varepsilon \Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L \omega}$$

where, $\varepsilon_{\text{Au}}$ refers to the gold permittivity. The constant coefficient values are chosen from Rakić et al. [36]. Moreover, FEM is used to numerically simulate the planned SPR-based sensor design. In addition, a wide range of wavelength is analyzed for the suggested sensor.

Therefore, the loss spectrum of the core mode can be measured from the unreal part of the effective RI values using Eq. (3) [37]. Based on the loss curve, the effectiveness of the sensor has been realized.

$$a_{\text{Loss}}(dB/cm) = 8.686 \times k_0 \Imag(n_{\text{eff}}) \times 10^4$$

Here, $k_0$ refers to the free space wave number whose value is $k_0 = 2\pi / \lambda$. $\Imag(n_{\text{eff}})$ defines the unreal part of the effective RI, and $\lambda$ is the operating wavelength.

The AS response can be evaluated from the loss peak of the anticipated sensor. It is also known as cost-effective method. This parameter can be measured using the amplitude interrogation method following Eq. (4) [38].

$$S_A(\text{RIU}^{-1}) = \frac{-1}{a(\lambda, n_a)} \frac{\delta a(\lambda, n_a)}{\delta n_a}$$

where $a(\lambda, n_a)$ indicates the overall loss value for the effective RI which is equal to $n_a$. $\delta a(\lambda, n_a)$ represents the change of two consecutive loss peaks for the variations of the analyte RI, and $\delta n_a$ refers to the change of RI values.

Besides, the wavelength sensitivity (WS) response is a vital parameter for the performance analysis of a sensor. Usually, the wavelength interrogation method displays maximum sensing performance from the amplitude interrogation method [30]. The WS response of the simulated structure can be determined by using Eq. (5) [30]:

$$S_A(\text{nm/RIU}) = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_a}$$

where $\Delta \lambda_{\text{peak}}$ and $\Delta n_a$ denote the alteration between the resonance peaks and the analyte RI respectively.

Sensor resolution is also another parameter to evaluate sensor performance. It controls the degree of dielectric RI detection. This parameter can be calculated by Eq. (6) [39]:

$$R(\text{RIU}^{-1}) = \frac{\Delta n_a \Delta \lambda_{\text{min}}}{\Delta \lambda_{\text{peak}}}$$

where, $\Delta n_a$ refers to the difference of analyte RI, $\lambda_{\text{min}}$ indicates the minimum peak wavelength, and $\Delta \lambda_{\text{peak}}$ specifies the difference of the peak wavelengths.

Figure of merit (FOM) can be evaluated from the value of WS or AS. The FOM can be calculated by Eq. (7) [40].

$$\text{FOM}(\text{RIU}^{-1}) = \frac{S_A}{\text{FWHM}}$$

where $S_A$ mentions the value of WS. Therefore, FWHM specifies the full width of half maximum peak resonance. The parameters of this investigation are summarized in Table 1. All the parameters are upheld here to visualize at a glance.

### Results and Discussion

The RI (real value) of the fundamental and SPP modes intersect at a point where the operational wavelength gets a loss intense peak in the SPR-based process. The phase-matching condition [41] is named after this event. In Fig. 3, the dispersion relation is maintained for the analyte RI 1.33, and two intersect points for the proposed sensor are obtained. At wavelengths of 1.48 µm and 1.6 µm, the true value of core and SPP mode intersects. Extreme energy is transferred from the fundamental core mode to the SPP mode at phase-matching points or intersect points.

The dispersion relations for the different analytes are also exposed in Fig. 4. It is realized that the intersect points are
growing with the variations of analyte RI. The first intersect points are found at the operating wavelength that 1.48 μm, 1.49 μm, 1.52 μm, and 1.525 μm and the second intersect points are gained at the operating wavelength 1.6 μm, 1.61 μm, 1.63 μm, and 1.645 μm for the analyte 1.33, 1.34, 1.37, and 1.38 respectively. Due to the variations of analyte RI, the phase-matching wavelengths are indicated through green and red line for the respective core and SPP modes.

At the phase-matching points, the loss value shows the maximum peak value. The confinement loss values for the offered sensor are exhibited in Fig. 5 for the variants of the analyte RI within 1.33 to 1.4 where two loss peak points have been achieved. Moreover, the second peak shows a higher value than the first peak. Different color lines have been used to clearly identify the loss values for each analytic RI. It is noticed that the highest loss value is obtained for the analyte 1.38 at the wavelength of 1.645 μm. At that point, the maximum loss value of 580.34 dB/cm is attained. Besides, the zoom portion of the first peak and second peak is also displayed in Fig. 5b, c. The loss peak points gradually shift with the variation of analyte. The low loss value is gained for the analyte 1.33. So that, it is cleared that the loss values are increasing with regard to the rise of analyte RI. The low loss value of 27 dB/cm and the extreme peak loss value of 277 dB/cm are reached for the proposed sensor design. Basically, the low loss values define the sensor effectiveness as well as scattering. The low-loss sensor is most suitable for practical implementation. Based on these peak loss values, another important parameter named amplitude sensitivity can be easily derived.

The AS is also a vital parameter for the measurement of sensor efficiency. The values of the AS mostly depend on the peak values of the confinement losses. To gain the high AS response, the offered structure has been reshaped and resized. The corresponding AS response for the suggested sensor scheme is given in Fig. 6. The AS response for the two-loss peaks are revealed in Fig. 6a, b. The first part of the amplitude sensitivity response is downward up to the peak point. After reaching the peak point, the graphs again show upward characteristics. The maximum AS response

diagram
of $-2321.36$ RIU$^{-1}$ is attained for the design at the wavelength of 1.645 μm for the RI 1.38. Besides, in the first peak value, the maximum AS is noted as $-1197.57$ RIU$^{-1}$ for the analyte 1.34. Comparing two of these values, the maximum response is noticed for the RI 1.38. Based on this AS response, the sensor’s compactness can also be determined. So, from the confinement loss analysis and AS response investigation, the maximum performance analyte is selected as 1.38. Now, it is also an important task to analyze the performance according to the gold layer variations.

The conforming loss spectrum for the variations of the Au layer is exhibited in Fig. 7 with the corresponding mode field distributions. The four-colored lines of red, blue, green, and violet are used to indicate the four gold layer thicknesses. The extreme loss peak of 960 dB/cm is gained for the Au layer wideness of 50 nm at the operating wavelength of 1.62 μm. Moreover, a low loss value is obtained for the thickness of 20 nm at the operating wavelength of 1.63 μm. The loss curve is increasing with the rise of Au thickness. As the Au layer is costly, so based on this problem and loss
curve analysis, 20-nm thickness is picked for the sensor design.

Gold layer thickness is varied from 20 to 40 nm. As much amount of gold is responsible to costly fiber, in the contrary, little amount of gold cannot give better outcomes. For this reason, the thickness of 20 nm is chosen for this investigation.

Moreover, the air hole diameter is also changed for further investigations. Among the three-layer air holes, the innermost air holes of the design are tuned and the obtained results are shown in Fig. 8. In the meantime, the diameters of the smaller air holes are also changed but the results do not affect any more by these variations. As a result, the outcomes of the smaller air hole diameter changes are not highlighted here. The variations of the larger air hole diameters affect the loss value highly. From the graphical observation, it is pointed that two sharp loss peaks are gained for the diameter of 1.6 μm. The diameter

![Amplitude sensitivity response with respect to the wavelength change for the variations of analyte from 1.33 to 1.4.](image1)

![Loss spectrum with respect to the variations of gold layer from 20 to 50 nm](image2)
value is changed from 1.2 to 2 μm. It is investigated that the light scattering is high for the diameter of 2 μm, as well as the diameter of 1.2 μm also responsible for scattering some light from the core to the gold layer. From this analysis, the air hole diameter of 1.6 μm is chosen for performing more operations.

The corresponding AS responses for the air hole diameter variations are upheld in Fig. 9. Three peaks are found for the three values. Among them, the maximum response of $-2151.39$ RIU$^{-1}$ is gained for air hole diameter of 1.6 μm at the wavelength of 1.63 μm. The lowest peak is attained for the diameter of 2 μm at the operating wavelength of 1.47 μm. Additionally, the middle average value of $-1883.52$ RIU$^{-1}$ is achieved for the air hole diameter of 1.2 μm at the wavelength of 1.51 μm.

Another significant parameter is wavelength sensitivity (WS) response. Based on this parameter, the effectiveness and the overall performance can be analyzed. As there is a noticeable value of WS is achieved, so it can be claimed that the proposed sensor will fit for practical use by reducing fabrication complexity with high sensitivity response.

In Fig. 10, two bar graphs are displayed where the violet graph indicates the values for the first peak value and the green bar graph defines the values for the second peak values. For the analyte 1.33 to 1.4, the first loss peak values have given lower peak values than the second peak. Otherwise, the WS responses are higher for the first peak than the second peak value. Moreover, the maximum WS response of 35,943.22 nm/RIU is attained for the RI 1.38 and the second-highest value of 25,646.58 nm/RIU is reached for the RI 1.39. Both WS response values are noted for the second peak values. This high sensitivity response will help the structure suitable for more accurate sensing performance. From Fig. 10, it can be said that the WS response is
gradually growing from analyte 1.33 to 1.38. On the other hand, after reaching the highest sensitivity response, it is started to decrease. Similarly, in the second peak, it is seen that WS is increasing and after reaching a particular point, the value is decreasing again.

Based on the loss spectrum and sensitivity analysis, the dip wavelength for the simulated structure is cleared in Fig. 11. The resonance wavelengths for the variations of analyte 1.33 to 1.4 are observed here. The polynomial fitting responses for the analyte RI changes are analyzed where the fitting responses have been given for first and second peak values respectively. The polynomial fitting response is indicated by red and green markers. Besides, the linear fit curve is also drawn using red and green dash lines to determine the similarity between them.

The resolution of a sensor specifies the smallest RI changes detection capability. It can be calculated through the peak wavelength differences. The suggested sensor resolution of \(9.04 \times 10^{-6} \text{RIU}\) for the analyte 1.40 is obtained by considering the gold layer wideness of 20 nm. As a result, the offered sensor is adept to detect \(10^{-6}\) order of the RI change.

The figure of merit (FOM) specifies the overall quality of a device. Usually, the high value of FOM indicates high performance. The high value of FOM depends on high sensing performance and low full width half maximum (FWHM) value. FOM becomes high when the sensitivity response shows the highest value. In the proposed work, the FWHM value is decreasing significantly as well as the sensitivity response is increasing. As FOM can be measured through the sensitivity response and FWHM, so the proposed sensor shows the maximum FOM value of 600 \(\text{RIU}^{-1}\) for the RI 1.38 with the FWHM value of 60. On the contrary, the minimum value of FOM of 212 is gained for the analyte 1.37. The respective FWHM and FOM are presented in Fig. 12 where diamond shape markers are used to clarify the value of FWHM, and circular shape markers are used to indicate the value of FOM.

At that moment, the overall simulation analysis of the designed sensor design is summarized in Table 2. A large number of parameters have been observed for the effectiveness and quality measurement of the sensor. From Table 2, it is noticeable that good outcomes have been achieved for the respective sensor design. Due to the low confinement loss value of 299.39 dB/cm, the maximum values of wavelength sensitivity, amplitude sensitivity, resolution, and FOM values which are 35,943.22 nm/RIU, 2321.36 RIU\(^{-1}\), \(9.04 \times 10^{-6}\) RIU, and 600 RIU\(^{-1}\), respectively, have been gained. These high values of the sensor will make the simulated structure more operative.

From Table 3, it is clearly visible that the offered structure shows an improved performance compared to the existing sensors. Based on the operating wavelength and the variations of analytes from 1.33 to 1.4, the FOM reaches 600 value that is much more than the previously noted values.
Fig. 12 Full width half maximum (FWHM) and figure of merit (FOM) variations

### Table 2 Overall performance examination of the proposed sensor’s sensing parameters

| Analyte RI | PW (nm) | PL (dB/cm) | WS (nm/RIU⁻¹) | AS (RIU⁻¹) | Resolution (RIU⁻¹) (× 10⁻⁶) | FWHM | FOM |
|------------|---------|------------|----------------|-------------|-------------------------------|------|-----|
| 1.33       | 1480    | 1600       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.34       | 1490    | 1610       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.35       | 1500    | 1610       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.36       | 1510    | 1620       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.37       | 1520    | 1630       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.38       | 1525    | 1645       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.39       | 1530    | 1665       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |
| 1.40       | 1540    | 1680       | 276.66         | 379.65      | 18,429.38                     | 18,429.38 | 8.05 | 461  |

### Table 3 Performance analysis of the proposed sensor in comparison to previous works

| Analyte RI | Wavelength sensitivity (nm/RIU⁻¹) | Resolution (RIU⁻¹) | Amplitude sensitivity (RIU⁻¹) | FOM | Ref |
|------------|-----------------------------------|---------------------|-------------------------------|-----|-----|
| 1.33–1.38  | 4600                              | 2.17×10⁻⁵           | 420.4                         |     | [44]|
| 1.33–1.42  | 11,000                            | 9.1×10⁻⁶            | 1420                          | 407 | [45]|
| 1.40–1.43  | 15,180                            | 5.68×10⁻⁶           | -                             |     | [46]|
| 1.40–1.44  | 9600                              | 1.04×10⁻⁵           | 1739.26                       |     | [47]|
| 1.33–1.38  | 10,493                            | 9.53×10⁻⁶           | -                             |     | [48]|
| 1.20–1.40  | 3751.5                            | 1×10⁻⁵              | -                             |     | [49]|
| 1.33–1.39  | 30,000                            | 3.33×10⁻⁶           | 1212                          | 508 | [23]|
| 1.18–1.36  | 20,000                            | 5×10⁻⁶              | 1054                          |     | [24]|
| 1.33–1.37  | 5000                              | 4×10⁻⁵              | 860                           | 47  | [9] |
| 1.33–1.38  | 25,000                            | 4×10⁻⁶              | 1411                          | 502 | [25]|
| 1.33–1.40  | 10,700                            | 9.34×10⁻⁶           | 1770                          |     | [26]|
| 1.32–1.32  | 13,750                            | 7.2×10⁻⁶            | 400                           |     | [12]|
| 1.46–1.48  | 10,800                            | 1.95×10⁻⁵           | 514                           |     | [13]|
| 1.33–1.40  | 12,000                            | 8.33×10⁻⁶           | -                             |     | [50]|
| 1.36–1.41  | 8000                              | 1.25×10⁻⁵           | 1560                          | 266 | [15]|
| 1.33–1.40  | 35,943.22                         | 9.04×10⁻⁶           | 2321.36                       | 600 | This work |
In addition, the wavelength and amplitude sensitivities also indicate a good improvement parallel to the prior works. Although the resolution value is not as high as found in the previous analysis, this response is good enough for the detection capability. Based on these good outcomes, the designed sensor can be used in the field of sensing for the detection of different analytes [42, 43].

Conclusion

The FEM method is used to construct and investigate an SPR-based multi-layer sensor with an external sensing mechanism. Several parameters of the sensor are optimized to get better sensing outcomes. The simulated structure attains maximum WS and AS response of 35,943.22 nm/RIU, and 2321.36 RIU$^{-1}$. Besides, a large FOM value of 600 is obtained. Moreover, the sensor has scaled small analyte variation detection capability. Gold is used as a plasmonic material that has major impact on sensing by creating a phase-matching phenomenon. When the RI values of two core and SPP modes cross, the phase-matching point can be obtained at that point. In this wavelength, the loss value reaches the high peak value. A maximum peak loss value of 580.34 dB/cm is noticed for the operating wavelength of 1.63 μm. The examined structure can sense a wide range of RI from 1.33 ≤ n_a ≤ 1.4. Due to the favorable features such as high WS and AS sensitivity responses and high value of FOM, the sensor will be helpful for practical use in sensing. Furthermore, the investigated sensor can be the prospective candidate for a large number of applications such as chemical detection, gas detection, medical diagnostics, security, virus detection, and bio-imaging.

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Availability of Data and Material Available from the corresponding author on reasonable request. Recourses: COMSOL Multiphysics software (version 5.5) could be downloaded from here: https://www.comsol.com/comsol-multiphysics.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Conflict of Interest The authors declare no competing interests.

References

1. Russell PSJ (2006) Photonic-crystal fibers. J Light Technol 24(12):4729–4749
2. Wang Y, Yang M, Wang DN, Liao CR (2011) Selectively infiltrated photonic crystal fiber with ultrahigh temperature sensitivity. IEEE Photonics Technol Lett 23(20):1520–1522
3. Zhang S, Yu X, Zhang Y, Shum P, Zhang Y, Xia L, Liu D (2012) Theoretical study of dual-core photonic crystal fibers with metal wire. IEEE Photonics J 4(4):1178–1187
4. Chen HL, Li SG, Fan ZK, An GW, Li JS, Han Y (2014) A novel polarization splitter based on dual-core photonic crystal fiber with a liquid crystal modulation core. IEEE Photonics J 6(4):1–9
5. Geng Y, Li X, Tan X, Deng Y, Hong X (2013) Compact and ultrasensitive temperature sensor with a fully liquid-filled photonic crystal fiber Mach-Zehnder interferometer. IEEE Sens J 14(1):167–170
6. Zhou J, Wang Y, Liao C, Sun B, He J, Yin G, Liu S, Li Z, Wang G, Zhong X, Zhao J (2015) Intensity modulated refractive index sensor based on optical fiber Michelson interferometer. Sens Actuators B Chem 208:315–319
7. Iadicicco A, Cusano A, Campopiano S, Cutolo A, Giordano M (2005) Thinned fiber Bragg gratings as refractive index sensors. IEEE Sens J 5(6):1288–1295
8. Patrick HJ, Kersey AD, Bucholtz F (1998) Analysis of the response of long period fiber gratings to external index of refraction. J Lightwave Technol 16(9):1606
9. James SW, Tatam RP (2003) Optical fibre long-period grating sensors: characteristics and application. Meas Sci Technol 14(5):R49
10. González-Vila Á, Ioannou A, Loyer M, Debligny M, Lahem D, Caucheteur C (2018) Surface plasmon resonance sensing in gaseous media with optical fiber gratings. Opt Lett 43(10):2308–2311
11. Zhou X, Li x, Cheng T, Li S, An G (2018) Graphene enhanced optical fiber SPR sensor for liquid concentration measurement. Opt Fiber Technol 43:62–62
12. Liedberg B, Nylander C, Lunström I (1983) Surface plasmon resonance for gas detection and biosensing. Sens Actuators 4:299–304
13. Dash JN, Jha R (2014) Graphene-based birefringent photonic crystal fiber sensor using surface plasmon resonance. IEEE Photonics Technol Lett 26(11):1092–1095
14. Homola J, Yee SS, Gauglitz G (1999) Surface plasmon resonance sensors. Sens Actuators B Chem 54(1–2):3–15
15. Tajima K, Zhou J, Nakajima K, Sato K (2004) Ultralow loss and long length photonic crystal fiber. J Lightwave Technol 22(1):7
16. Carrascosa LG, Sina AAJ, Palanisamy R, Sepulveda B, Otte MA, Rauf S, Shiddiky MJ, Trau M (2014) Molecular inversion probe-based SPR biosensing for specific, label-free and real-time detection of regional DNA methylation. Chem Commun 50(27):3585–3588
17. Matsui T, Zhou J, Nakajima K, Sankawa I (2005) Dispersion-flattened photonic crystal fiber with large effective area and low confinement loss. J Lightwave Technol 23(12):4178–4183
18. Poli F, Cucinotta A, Selleri S (2007) Photonic crystal fibers: properties and applications, vol 102. Springer Science & Business Media
19. Rindorf L, Jensen JB, Dufva M, Pedersen LH, Heiby PE, Bang O (2006) Photonic crystal fiber long-period gratings for biochemical sensing. Opt Express 14(18):8224–8231
20. Krohn DA, MacDougall T, Mendez A (2014) Fiber optic sensors: fundamentals and applications. Spie Press, Bellingham, WA

21. Rifat AA, Mahdiraji GA, Sua YM, Ahmed R, Shee YG, Adikan FM (2016) Highly sensitive multi-core flat fiber surface plasmon resonance refractive index sensor. Opt Express 24(3):2485–2495

22. Shuai B, Xia L, Liu D (2012) Co-existence of positive and negative refractive index sensitivity in the liquid-core photonic crystal fiber based plasmonic sensor. Opt Express 20(23):25858–25866

23. Dash JN, Jha R (2015) On the performance of graphene-based D-shaped photonic crystal fibre biosensor using surface plasmon resonance. Plasmonics 10(5):1123–1131

24. Liu C, Su W, Liu Q, Lu X, Wang F, Sun T, Chu PK (2018) Symmetrical dual D-shape photonic crystal fibers for surface plasmon resonance sensing. Opt Express 26(7):9039–9049

25. Islam MS, Cordeiro CM, Sultana J, Aoni RA, Feng S, Ahmed R, Dorraki M, Dinovitser A, Ng BWH, Abbott D (2019) A Hi-Bi ultra-sensitive surface plasmon resonance fiber sensor. IEEE access 7:79085–79094

26. Shafkat A (2020) Analysis of a gold coated plasmonic sensor based on a duplex core photonic crystal fiber. Sens Bio-Sens Res 28:100324

27. Abdullah H, Ahmed K, Mitu SA (2020) Ultrahigh sensitivity refractive index biosensor based on gold coated nano-film photonic crystal fiber. Results Phys 17:103–151

28. Aoni RA, Ahmed R, Razzak SA (2013) Design and simulation of dual-concentric-core photonic crystal fiber for dispersion compensation. In: CIOMP-OSA summer session on optical engineering, design and manufacturing (p Tu2). Optical Society of America

29. Hu DII, Ho HP (2017) Recent advances in plasmonic photonic crystal fibers: design, fabrication and applications. Adv Opt Photonics 9(2):257–314

30. Akowuah EK, Gorman T, Ademgil H, Hazha S, Robinson GK, Oliver JV (2012) Numerical analysis of a photonic crystal fiber for biosensing applications. IEEE J Quantum Electron 48(11):1403–1410

31. Liu C, Yang L, Liu Q, Wang F, Sun Z, Sun T, Mu H, Chu PK (2018) Analysis of a surface plasmon resonance probe based on photonic crystal fibers for low refractive index detection. Plasmonics 13(3):779–784

32. Guiyao Z, Zhiyun H, Shuguang L, Lantian H (2006) Fabrication of glass photonic crystal fibers with a die-cast process. Appl Opt 45(18):4433–4436

33. Brückner V (2011) To the use of Sellmeier formula. Senior Experten Service (SES) Bonn and HfT Leipzig. Germany: 42:242–250

34. Dash JN, Jha R (2014) SPR biosensor based on polymer PCF coated with conducting metal oxide. IEEE Photonics Technol Lett 26(6):595–598

35. Liu Q, Li S, Chen H, Li J, Fan Z (2015) High-sensitivity plasmonic temperature sensor based on photonic crystal fiber coated with nanoscale gold film. Appl Phys Express 8(4):046701

36. Rakić AD, Djurišić AB, Elazar JM, Majewski ML (1998) Optical properties of metallic films for vertical-cavity optoelectronic devices. Appl Opt 37(22):5271–5283

37. Kaur V, Singh S (2019) Design of titanium nitride coated PCF-SPR sensor for liquid sensing applications. Opt Fiber Technol 48:159–164

38. Monir MK, Hasan M, Paul BK, Ahmed K, El-Khozondar HJ, Amiri IS (2019) High birefringent, low loss and flattened dispersion asymmetric slotted core-based photonic crystal fiber in THz regime. Int J Mod Phys B 33(20):1950218

39. Hautakorpi M, Mattinen M, Ludvigsen H (2008) Surface-plasmon-resonance sensor based on three-hole microstructured optical fiber. Opt Express 16(12):8427–8432

40. Mishra AK, Mishra SK, Gupta BD (2015) SPR based fiber optic sensor for refractive index sensing with enhanced detection accuracy and figure of merit in visible region. Opt Commun 344:86–91

41. Caucheteur C, Guo T, Albert J (2015) Review of plasmonic fiber optic biochemical sensors: improving the limit of detection. Anal Bioanal Chem 407:3883–3897

42. Omar NAS, Ramli I, Fen YW, Abdullah J, Daud NFM, Daniyal WMEMM, Mahdi MA (2021) A sensing approach for manganese ion detection by carbon dots nanocomposite thin film-based surface plasmon resonance sensor. Optik 167435

43. Hashim HS, Fen YW, Omar NAS, Fauzi NIM, Daniyal WMEMM (2021) Recent advances of priority phenolic compounds detection using phenol oxidases-based electrochemical and optical sensors. Measurement 184:109855

44. Paul AK, Sarkar AK, Islam MH, Morshed M (2018) Dual core photonic crystal fiber based surface plasmon resonance biosensor. Optik 170:400–408

45. Rifat AA, Haider F, Ahmed R, Mahdiraji GA, Adikan FM, Miroshnichenko AE (2018) Highly sensitive selectively coated photonic crystal fiber-based plasmonic sensor. Opt Lett 43(4):891–894

46. Mahfuz MA, Hossain M, Haque E, Hai NH, Namithra Y, Ahmed F (2019) A bimetallic-coated, low propagation loss, photonic crystal fiber based plasmonic refractive index sensor. Sensors 19(17):3794

47. Li D, Zhang W, Liu H, Hu J, Zhou G (2017) High sensitivity refractive index sensor based on multicoring photonic crystal fiber with surface plasmon resonance at near-infrared wavelength. IEEE Photonics J 9(2):1–8

48. Ahmed T, Paul AK, Anower MS, Razzak SA (2019) Surface plasmon resonance biosensor based on hexagonal lattice dual-core photonic crystal fiber. Appl Opt 58(31):8416–8422

49. Mollah MA, Paul AK, Razzak SMA (2018) Dual polarized plasmonic refractive index sensor based on photonic crystal fiber. In: 2018 10th International conference on electrical and computer engineering (ICECE). IEEE, pp 73-76

50. Al Mahfuz M, Mollah MA, Momota MR, Paul AK, Masud A, Akter S, Hasan SR (2019) Highly sensitive photonic crystal fiber plasmonic biosensor: design and analysis. Opt Mater 90:315–321

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