Spiral Structured Photonic Crystal Fiber-Based Plasmonic Sensor with Bimetallic Coating

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Abstract. We present a bimetallic coated, low-loss spiral lattice PCF sensor combined with SPR technology that achieves a high sensitivity. The sensing performance and properties of our recommended sensor are realized numerically by the Finite Element Method. Gold is utilized as the plasmonic layer and titanium Oxide (TiO₂), which is sandwiched between the silica glass fiber and the gold coating, forming the bimetallic surface. As TiO₂ has a high refractive index, they create a strong surface plasmon wave in the plasmonic region that attracts the evanescent field originating from the core region and increases the coupling effect plasmonic and core mode. Hence, the bimetallic coating is performed to achieve better sensing performance and strengthen the SPR process for the presented sensor. The presented sensor's nominal tolerance is 12,000 nm/RIU for x-polarization to 11,000 MHz for y-polarization. The presented sensor is intended to be used in several applications and sensing fields due to its high sensitivity.

Keywords: photonic crystal, plasmonic sensor, structural analysis, gold coating, TiO₂

1. Introduction
The SPR technology is highly captivating, its extraordinary sensing properties, and its incredible development in a wide range of various applications [1]. SPR principle describes the surface free electron oscillations' behaviour at the metal-dielectric interface, being Resonance occurs when the incoming light frequency coincides with the stimulated electron frequency at the metal surface [2]. The SPR sensors were first implemented using the prism with a thin coating of the metal film. A plasmatic wave is produced when light passes through the prism and enters the surface superconducting interface. However, they were not suitable due to their high cost, bulky structure, and drawbacks of remote sensing applications [3]. Later, optical fibre-SPR sensors were introduced, but they were also not considered because of their narrow acceptance angles [4].

Recently, PCF-SPR based sensors are being highly investigated owing to their attractive and special optical features [5]. They are applicable for various bio-sensing applications due to their high design flexibility, miniature size, and economical. Moreover, the evanescent field could also be controlled by the PCF-SPR sensors by manipulating its structural parameters. Additionally, they also
revealed tuneable birefringence and confinement loss. Owing to all these appealing features exhibited by the PCF-SPR sensors, the sensor achieves high sensitivity and has great potential for various sensing applications. They are also suitable for remote sensing applications because of the nano-size of the PCF-SPR sensors [5]. Furthermore, the sensitivity can be enhanced by the plasmonic material chosen for the sensor. The frequently used plasmonic metals for the PCF-SPR sensors are chiefly copper, gold, aluminum, and silver [1].

With the extensive improvement in sensing techniques, an additional coating of flimsy metal as titanium oxide (TiO$_2$), indium tin oxide (ITO), and graphene are utilized above the plasmonic layers, which form a bimetallic layer and strengthen the SPR effect. This extra thin layer coating over the plasmonic metal is called bimetallic coating, which improves the sensor’s sensitivity [6].

In this work, we present a PCF-SPR that achieves low loss and high sensitivity, which has a spiral lattice design with a bimetallic coating. We have selected the plasmonic to be gold, and it is further coated with TiO$_2$ externally, which forms a bimetallic layer for the proposed sensor. Further, in this paper, we compare and analyze the sensitivity performance when the plasmonic gold is only coated over the PCF and the improvement in sensitivity when TiO$_2$ is glazed over the plasmonic gold metal. The sensor has a resolution of 12,000 nm. Furthermore, in y-polarization, the sensor gains a narrow bandwidth of 45.91 dB/cm with analyte 1.38 and 33.96 dB/cm for analyte 1.39.

2. Structural Analysis

Figure 1 interprets the 2D cross-sectional view of our presented sensor with spiral lattice. There are 24 air holes arranged in a spiral configuration, six arms, and every arm has four air holes. The angle between every air hole in an arm is placed at a 30-degree position is called an equiangular spiral as a constant of 30-degree angle is maintained between every two air holes in each arm of the spiral. The distance from the first ring’s air hole to the core, $r_0$, is 2.4 µm which is denoted as pitch. Since each arm has four air holes, the distance from the second, third and fourth ring to the center silica core are other pitches as $r_1$, $r_2$, and $r_3$, which denote the values as 2.8 µm, 3.8 µm, and 4.2 µm. The cladding air hole diameter is denoted as $d_a$, $d_b$, and $d$, where $d_a$ the regular air hole diameter, $d_b$ is the amplified air hole diameter, and $d$ is the scaled-down air hole diameter their values as 1 µm, 1.4 µm, and 0.35 µm. The scaled-down air holes are established in cladding as they boost the coupling mechanism amidst surface plasmon in the metal-dielectric region and evanescent field from the core. These air holes are small in size, allowing more space for the light to propagate from the core to the metal-dielectric surface, thus increasing the sensitivity.

![Figure 1: Cross-sectional 2D view of the proposed sensor](image)

Fused silica was the background element opted for the proposed sensor, and its RI is determined by using the Sellier equation [7]:

$$n^2(\lambda) = 1 + \frac{M_1\lambda^2}{\lambda^2-N_1} + \frac{M_2\lambda^2}{\lambda^2-N_2} + \frac{M_3\lambda^2}{\lambda^2-N_3} \quad (1)$$

From (1), RI is denoted by $n$ for specified wavelength, and wavelength is represented by $\lambda$ in µm.
Gold is used as the plasmonic for the PCF and is coated at the external surface. The external coating technique reduces the challenges faced in fabrication and further makes the detection process simple and practical [8]. The plasmonic opted is gold as they expose a large resonant shift. They are also chemically alert and are susceptible to oxidation. The Drude Lorentz Model is used to analyze the dielectric properties of gold. [9];

$$\varepsilon_g(\omega) = \varepsilon_{\infty} - \frac{\omega_D^2}{\omega(\omega+i\gamma_D)} - \frac{\Delta\varepsilon\Omega_L^2}{(\omega^2-\Omega_L^2+i\Gamma_L\omega)}$$ ............................................ (2)

It is known that plasmonic gold exposes very feeble adhesion and may easily flake off from the PCF. So, a flimsy coating of TiO$_2$ is glazed sandwiched between silica and gold, forming a bimetallic layer. This TiO$_2$ film used was non-toxic and also solved the adhesion issue faced by the plasmonic gold. TiO$_2$ has a higher RI than the fiber, which produces free electrons and forms a strong surface plasmon wave in the plasmonic surface. This pulls the evanescent field originating from the core region, thus intensifies the coupling among both the modes [10]. The RI of TiO$_2$ is obtained from [11];

$$n_{TiO_2} = \sqrt{5.913 + \frac{2.441 \times 10^7}{\lambda^2 - 0.803 \times 10^7}}$$ ............................................ (3)

Where $n_{TiO_2}$ refers to RI of TiO$_2$ and $\lambda$ refers to wavelength.

Gold and TiO$_2$ can be applied by utilizing chemical vapor deposition (CVD) and wheel polishing methods [12]. A Perfectly Matched Layer (PML) is additionally applied at the external region of PCF as they eliminate radiated light towards the fiber surface. The COMSOL software with FEM is exploited to observe and inspect the numerical and sensing performance of the presented sensor.

3. Result Analysis

3.1. Electric Field Distribution and Dispersion Relation

The main operation of the PCF-SPR depends on guiding the evanescent field. When the core and cladding are properly designed, it partially penetrates the metal region's evanescent field. As this field collides the metal region, it triggers free electrons in the plasmonic region. As guided evanescent field frequency matches with the surface electrons frequency, then SPW is produced. This is known as Surface Plasmon Polariton (SPP) mode. This evanescent wave spread along with the metal-dielectric interface [13].
Figure 2. Electric Field Distribution for (a) core mode in x-polarization (b) core mode in y-polarization (c) SPP mode (d) coupling among core mode and plasmonic mode in x-polarization (e) coupling among core mode and plasmonic mode in y-polarization.

The distribution of electric field for sensor presented is illustrated in Figure 2 (a) and (b), which represent core mode for x as well as y-polarization, Figure 2 (c) represent SPP mode for presented sensor and coupling amongst both the plasmonic and core mode for x as well as y-polarization is displayed in Figure 2 (d) and (e). Figures 3 and 4 display the dispersion correlation for gold coating and gold with TiO\textsubscript{2} coating, respectively. When the effective index of core guided mode and SPP mode intersect at a particular wavelength, this condition is known as Resonance, and the corresponding wavelength is called the resonant wavelength. During Resonance, the coupling mechanism occurs amongst the SPP and core modes. Furthermore, a large absorption loss peak transpires that is recognized as the phase-matching point. Figure 3 shows that for single layer gold coating, Resonance occurs at wavelengths of 1.67, 1.63 µm in x and y-polarization for sample solution 1.38, and at wavelengths of 1.75, 1.72 µm in x and y-polarization for sample solution 1.39. Figure 4 shows that the Resonance occurs at wavelengths of 1.68 m and 1.67 m in x and y-polarisation for analyte 1.38 and wavelengths of 1.8 m and 1.78 m in x and y polarisation analyte 1.39 with a bimetallic coating. Confinement loss is an influential parameter in PCF which is calculated from the expression;

\[
\alpha_L \left( \frac{\text{dB}}{\text{cm}} \right) = 8.686 \times k_0 \text{Im}(n_{\text{eff}}) \times 10^4 \quad (4)
\]

where, wavelength is indicated by \( \lambda \) in microns, 
\( k_0 = \frac{2\pi}{\lambda} \) denotes free space number,
\( \text{Im}(n_{\text{eff}}) \) signifies the effective refractive index of the imaginary part.

Another vital parameter in PCF-SPR sensor to calculate its sensing performance is sensitivity. They are realized by [14];

\[
S_\lambda \left( \frac{\text{nm}}{\text{RIU}} \right) = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_a} \quad (5)
\]

where \( \Delta \lambda_{\text{peak}} \) is variation in a shift of wavelength peak and \( \Delta n_a \) is a difference in the analyte’s refractive index.

3.2. Gold Coating

Gold was the preferred plasmonic for the presented PCF-SPR sensor [15]. The comparison is done for the analyte 1.38 and 1.39 with only the plasmonic gold-coated externally over the PCF. It is observed from Figures 3(a) and (b) that the maximum loss peak is observed as 161.09 dB/cm for analyte 1.38 for x-polarization and 49.97 dB/cm for y-polarization. Similarly, the maximum loss for analyte 1.39 is 142.50, 45.48 dB/cm for x and y-polarization. Moreover, from Figure 3(a) and (b), it is evident that, for the analyte 1.38, the coupling amongst the SPP and core-guided happens at 1.67 µm and 1.63 µm for x-polarization and y-polarization. Similarly, for the analyte 1.39, it is analyzed from Figure 3(a).
that the coupling between the modes happens at 1.75 µm for *x*-polarization, and in Figure 3(b), it is observed that coupling happens at 1.72 µm for *y*-polarization. This exposes a blue shift where there is a shift of 0.08 nm and 0.09 nm between the analyte for *x* and *y* polarization.

![Figure 3](image)

**Figure 3:** Loss spectrum along with dispersion relation for gold coating in (a) *x*-polarization and (b) *y*-polarizations.

### 3.3. Gold With TiO$_2$ Coating

Gold faces adhesion trouble and may flake off easily from the surface of PCF. To overcome this issue, a flimsy coating of TiO$_2$ was glazed amidst the plasmonic gold and silica glass, forming a bimetallic layer. TiO$_2$ is non-toxic and has a high refractive index, making it a better choice to be coated over the metal gold. The TiO$_2$ film was glazed over gold. The results are observed and compared for the analytes 1.38 and 1.39. We can study from Figures 4(a) and (b) that the maximum loss peak for analyte 1.38 is 131.62 dB. Likewise, for analyte 1.39, we can declare that the maximum loss for *x* and *y*-polarization is 116.94 dB/cm and 33.96 dB/cm. Also, from Figure 4(a) and (b), for the analyte 1.38, it is studied that the coupling that happens amid plasmonic and core mode happens at 1.68, 1.67 µm.

Similarly, from Figure 4(a), we can say that the coupling for analyte 1.39 happens at 1.8 µm for *x*-polarization. In Figure 4(b), it can be noticed that coupling happens at 1.78 µm for *y*-polarization.
This exposes a blue shift where there is a shift of 0.012 nm and 0.011 nm between the analysis for x and y polarization.

3.4. Comparison in Performance of Gold Layer and Bimetallic Layer

The single layer and bimetallic layer were analyzed for the analyte 1.38 and 1.39. When comparing the two results, it is crystal clear that the bimetallic layer's sensitivity is higher than the single coated layer. Moreover, the loss obtained by the bimetallic layer is much lower when compared with the single layer. We can conclude that the bimetallic layer is more effective than single layer coating as they help increase the sensing performance of the sensor and produce a low loss. Since the second layer coating has high RI, they generate more free electrons, strengthening the surface plasmon wave and attracting the evanescent field from the core, which boosts the coupling effect between both modes. Thus, having a bimetallic coated surface is more efficient and practically applicable as they produce high sensitivity with low loss.

4. Conclusion

To conclude, we compare the sensing performance for single layer gold coating and bimetallic coating of gold and TiO$_2$. The presented sensor exposes high sensitivity and low loss for the bimetallic coating than the single gold coating layer. The sensor is designed in a spiral lattice with air holes settled uniquely. The air holes are also scaled down for light to penetrate freely and produce a robust coupling effect amongst core and SPP mode. The metal layers are coated at the external surface to limit the fabrication issues and make the detection process simple and effective. The analysis is carried out by numerical simulation using the FEM method. Low loss of 45.91 dB/cm for analyte 1.38 and 33.96 dB/cm for analyte 1.39 is obtained for y-polarization. The presented sensor achieving high sensitivity and low loss is highly utilized in a wide area of sensing applications.

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