

Chapter 4

Rectangular shape cladding based photonic crystal fiber surface plasmon resonance based refractive index sensor

This chapter has a rectangular shape cladding based photonic crystal fiber sensor for refractive index sensing. An adhesive strip layer of TiO_2 is sandwiched between PCF and plasmonic material gold to enhance the sensitive response of the proposed sensor. We have designed and simulated this PCF structure through finite element method based COMSOL Multiphysics software. This sensor structure has improved results in maximum wavelength sensitivity, amplitude sensitivity, and sensor resolution. There are so many applications based on the refractive index of analyte samples; hence, this sensor can be used in the dairy industry for different animal milk detection. Apart from this, it has a wide range of applications in various fields of science and engineering.

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4.1 Introduction

In recent years, several technologies have evolved in the sensing field ¹⁴². In different areas, sensors have played a vital role in physics, chemistry, biomedical, and biochemical fields. Among these so many available technologies, surface plasmon resonance (SPR) based sensing technology is the most promising, encouraging, and effective method for sensing purposes ¹⁴³. SPR-based pressure, temperature, bio-imaging, environmental monitoring, and drug detection ⁴⁷ sensors are found to be productive. Apart from this in optoelectronic devices ¹⁴⁴, monitoring of thin film thickness ¹⁴⁵ and tunable filter ¹⁴⁶ SPR technology has made its mark. The free electron oscillates at the interface of the conductor, dielectric known as plasma oscillation, and the quanta of these oscillations are known as surface plasmon waves (SPWs). Their existence is being validated by electron energy loss experiments ¹⁴⁷. When the frequency (ω) of the incident p-polarized photon wave matches the frequency of the surface plasmon wave (generated on conductor–dielectric interface), then a resonance condition takes place which is very sensitive to the refractive index of the surrounding medium. At this resonance frequency, the energy and momentum of the incident photon couple with SPW quanta for which a maximum transmission loss of the optical system is observed ¹⁴⁸. Experimental validation of the SPR sensor was given by Kretschmann and Raether ⁶⁴ and Otto ⁶⁵ in which light incident at the interface of conductor prism is at an angle greater than the critical angle for the SPR sensing phenomenon. Though the above configuration provided high sensitivity, accuracy, and label-free detection ¹⁴⁹, their bulky size arrangement barricades the path of their practical implementation ¹²². Optical fiber is a substitute for this bulky size conductor-prism arrangement for SPR sensing due to its compact size and flexibility.

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The merit of optical fiber is that it has minimum confinement loss in the visible region with mechanical stability and it is way better for sensing purpose. But along with it, the demerit of optical fiber is that it has less tuning parameters to enhance the sensitivity of the sensor¹²³. After optical fiber sensor demerit, next in the row is the photonic crystal fiber (PCF) sensor due to its concise size, lightweight, and cost-effectiveness, and the most important feature is tunable optical fiber parameters that make PCF more attractive in the field of optical sensing application¹²⁴. With enhanced sensitivity and low confinement loss (a key parameter of a sensor), PCF is being used in different fields of sensing such as temperature sensors, pressure sensors, strain sensors, alcohol sensors, and refractive index (RI) sensors. On the basis of the plasmonic layer coating method, PCF can be categorized into two categories: (a) internal sensing mechanism and (b) external sensing mechanism. In the internal sensing approach, layer of plasmonic material is coated inside the air holes of PCF^{73 91}. So many researchers have performed their research on this internal sensing approach^{73 74 125}. Ghahramani et al. recently reported an internal sensing mechanism-based PCF sensor with maximum wave-length sensitivity of 15,167 nm/RIU and maximum amplitude sensitivity of 207 RIU⁻¹⁷³. Although this methodology is unique and advanced, it is too difficult to fill different analytes every time in the holes; hence, it is challenging to implement it practically¹⁵⁰. Due to so many deficiencies in this mechanism, the external sensing mechanism plays an important role in the sensing field. In the external coating method, plasmonic material is done outside of the fiber; hence, analyte is directly in contact with it^{126 75}. Maximum wavelength sensitivity of the external sensing-based sensor was obtained 15,180 nm/RIU for analyte 1.40 – 1.43 by Liu et al. There is so much work being done so far in this field, but improvisation regarding wavelength sensitivity, amplitude sensitivity, and other parameters is required^{127 129 151}.

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In this research work, a rectangular shape cladding-based PCF with a hexagonal core structure has been proposed. Using hexagonal core type PCF sensitivity is enhanced and hence we have worked to enhance sensitivity response than to our previously reported work. We have used SPR technology for sensing and gold (Au) as a plasmonic material because of its chemical stability. An adhesive layer of oxide of titanium (TiO_2) is sandwiched between conductor–dielectric interface to improve both the wavelength sensitivity and the amplitude sensitivity of the sensor with a low confinement loss factor. For an effortless fabrication process and convenient application purpose, we have used an external sensing based mechanism process. For the simulation of the proposed sensor, the finite element method (FEM) based COMSOL Multiphysics software version 6.0 has been employed. Altering the different parameters of the proposed structure, such as air hole size, pitch size, gold layer, and TiO_2 layer thickness, we have investigated the optimized parameters. We have used best-optimized parameters to intensify the sensitivity of the sensor. A wide range of refractive indices (RI) of analytes has been overlooked. Hence, along with biochemical and biomedical fields, different dairy products can also be detected with the help of our proposed sensor structure.

4.2 Theoretical description

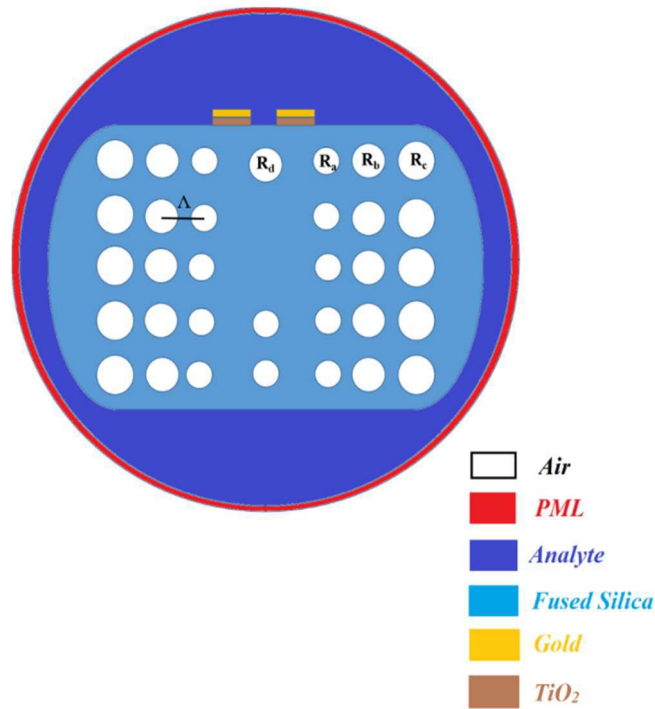


Figure 4.1 Cross section view of proposed sensor

Figure 4.1 represents the cross-section of the proposed PCF sensor. It has air holes of different radii arranged in a rectangular shape in the cladding portion of PCF. Using hexagonal symmetry in the core, the sensitivity factor of the sensor has been enhanced. The upper portion of the PCF is removed to make it flat like D-shaped fiber structure over which two strips of (TiO₂) and (Au) have been polished. The geometrical parameter of the PCF fiber has a vital role in the sensing mechanism. A slight variation in air hole diameters, pitch size, gold layer thickness, and TiO₂ layer thickness alters the sensitivity of the PCF sensor. The radius of air holes in the cladding portion is $R_a = 0.60 \mu\text{m}$, $R_b = 0.70 \mu\text{m}$, $R_c = 0.60 \mu\text{m}$, and $R_d = 0.70 \mu\text{m}$. The distance between two consecutive air holes is called pitch, which we have taken as $\Lambda = 2.6 \mu\text{m}$, and outer radius of our

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PCF structure is 11 μm . These parameters have optimized after several simulations which are best fitted for our proposed sensor structure.

The complete sensing process is depicted in figure 4.2. The thicknesses of gold and TiO_2 strips are $t_{\text{Au}} = 70 \text{ nm}$ and $t_{\text{TiO}_2} = 20 \text{ nm}$, respectively. Fused silica is the background material of our PCF whose refractive index varies with the wavelength of an incident EM wave, and it is given by Sellmeier's equation (2.1) ¹⁵²

The refractive index of plasmonic material gold is given by Drude – Lorentz model and computed by the following equation (3.1) ¹⁵²

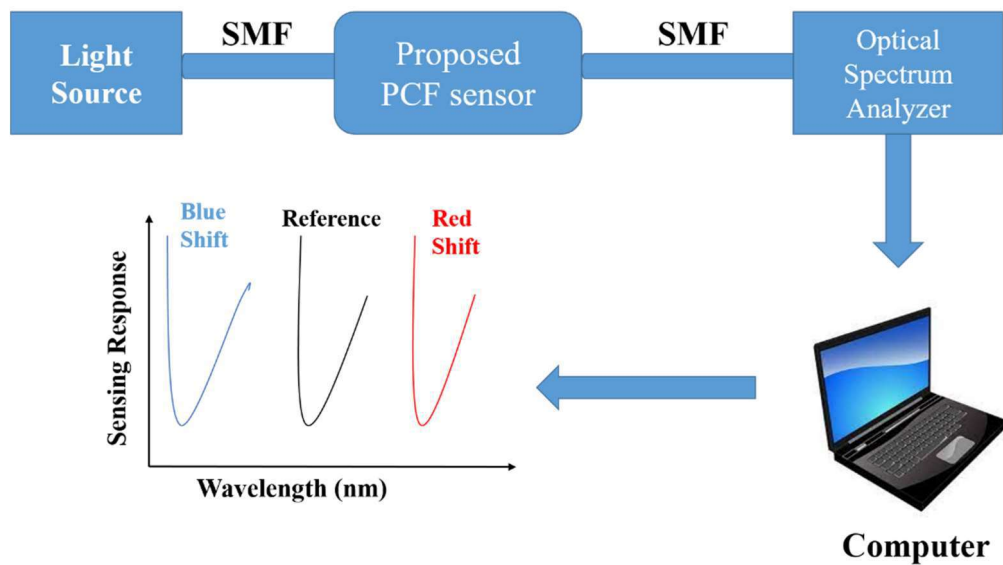


Figure 4.2 Complete setup of sensing process for proposed sensor.

An adhesive layer of TiO_2 is sandwiched between the gold layer and fused silica whose refractive index is given by equation (3.2) ^{152 111}

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This buffer layer of TiO₂ works as a catalyst between a plasmonic layer of Au and fiber, which supports plasmonic excitation, causing evanescent wave penetration to increase the interaction of plasmon polariton and analyte.

The EM wave which propagates toward the boundary of the fiber can theoretically be absorbed with no reflection by using a phase matching layer (PML) whose thickness is taken 10% to the size of the fiber for better optimization results¹⁰⁵. Numerical simulation and mode analysis of the proposed PCF sensor are being performed by finite element method-based COMSOL Multiphysics software¹⁵³. In COMSOL software, starting from Maxwell's equation, derivation of a set of coupled partial differential equations (PDEs) is computed, and their solution provides longitudinal electric and magnetic field components. To improve the detection accuracy of the PCF sensor, an extremely fine element based physics control mesh has been used during simulation.

4.3 Result and Simulation

Starting with simulation in COMSOL Multiphysics software version 6.0, EM-wave (p-polarized) propagates through the core that generates evanescent wave at the interface of conductor–dielectric interface. Due to excitation through evanescent waves, SPWs are generated. Having a proper and well settled arrangement of core and cladding air holes, a stream of the electromagnetic wave reaches interface to excite the surface electrons. In resonance condition, the real part of the effective index (n_{eff}) of both core mode and SPP mode is matched, which results in a high amount of energy transfer from core to SPP, which is termed as confinement loss. The dispersion profile of core guided mode, plasmonic mode, and confinement loss is depicted in figure 4.3.

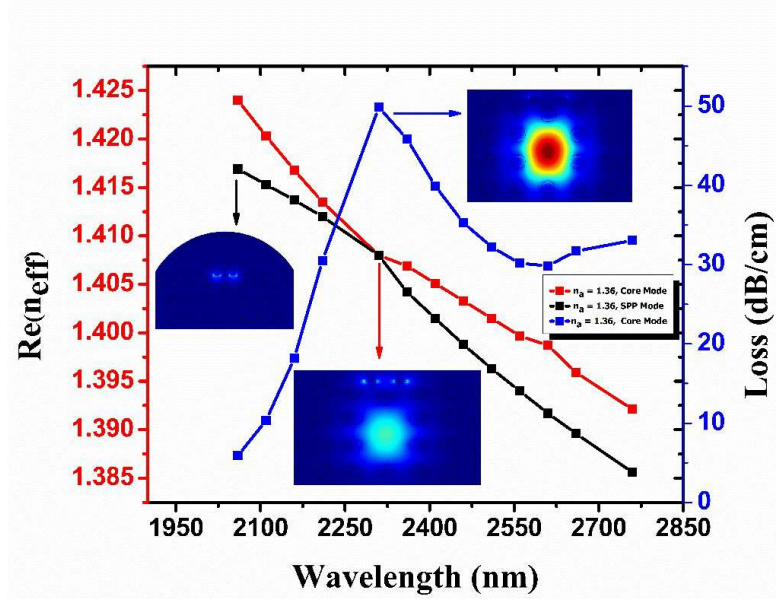


Figure 4.3 Dispersion profile for analyte RI $n_a = 1.38$.

Plasmonic layer (Au) and adhesive layer (TiO_2) strips are along the positive y-direction over the flat surface of fiber so when EM wave propagates through the core, transverse electric field (TE^y) mode is along (+) ve y-direction; hence, evanescent wave is along the same direction to excite the electrons at conductor dielectric interface. In the presence of a finite number of air holes in the cladding region, light passes out from the core region to the interface called confinement loss. It is given by the following equation (1.7) ¹⁰⁸

By changing the radius of the air hole, we get a reduction in confinement loss. Altering the radius of air holes $R_a = 0.50 \mu\text{m} - 0.60 \mu\text{m}$, $R_b = 0.60 \mu\text{m} - 0.70 \mu\text{m}$, $R_c = 0.70 \mu\text{m} - 0.80 \mu\text{m}$, and $R_d = 0.62 \mu\text{m} - 0.70 \mu\text{m}$, there is a reduction in confinement loss, as shown in figure 4.4 (a), (b) and figure 4.5 (a), (b). It is because with increasing radius of air hole size, coupling decreases between core-guided mode and plasmonic mode ¹³⁹

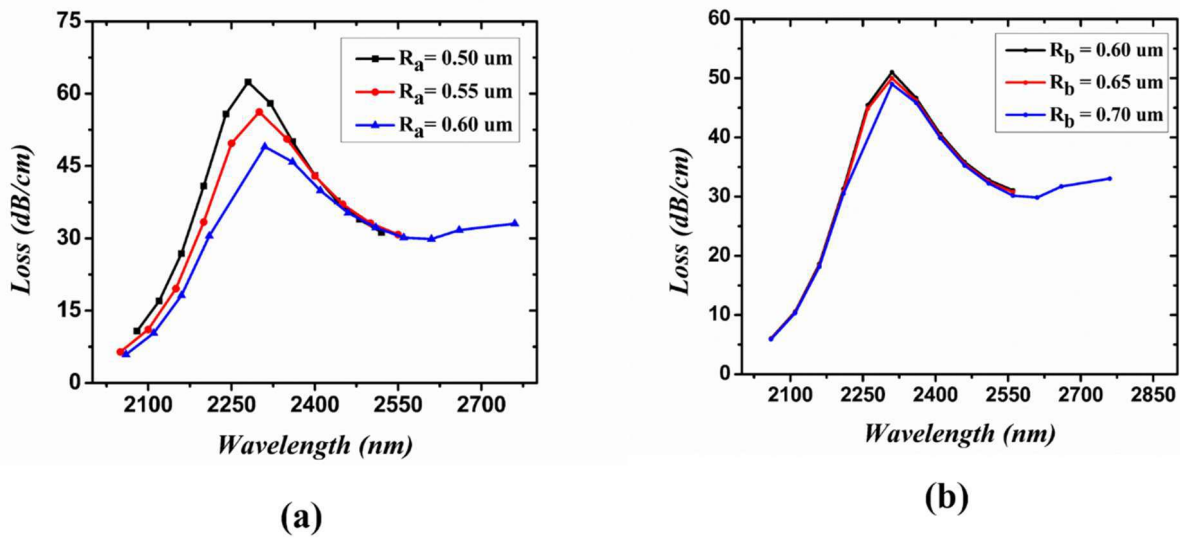


Figure 4.4 Graph of wavelength vs. loss (dB/cm) for variation of radius (a) R_a (b) R_b for analyte RI $n_a = 1.38$.

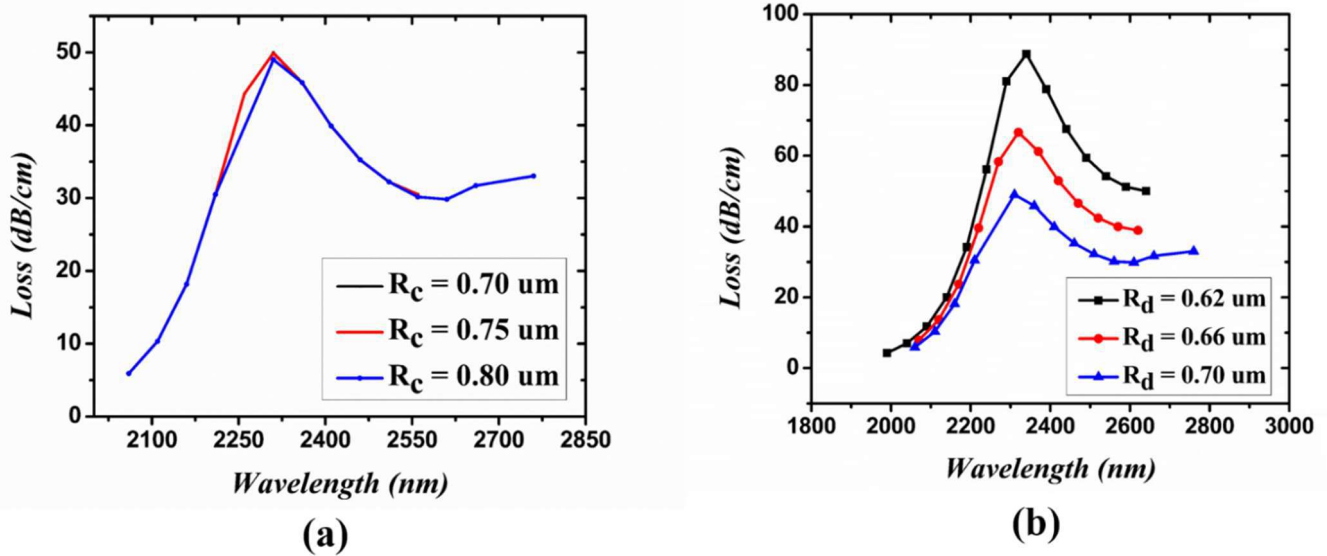


Figure 4.5 Graph of wavelength vs. loss (dB/cm) for variation of radius (a) R_c (b) R_d for analyte RI $n_a = 1.38$.

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The thickness of the plasmonic layer, which is the gold in our sensor, plays a crucial role in sensing performance. Increasing the thickness of the gold layer from $t_{Au} = 66 \text{ nm} - 70 \text{ nm}$, there is decay in confinement loss with the redshift of resonance wavelength shown in figure 4.6. This decay in confinement loss is because by increasing the thickness of the metal layer there is low penetration of electric field inside the analyte due to high damping loss¹¹². So for the finest sensing performance, we choose the thickness of the gold layer to 70 nm. Moving forward to figure 4.7, on the varying thickness of TiO_2 from $t_{\text{TiO}_2} = 15 \text{ nm} - 25 \text{ nm}$, a decrement in the confinement loss is seen at 20 nm layer thickness, which is advantageous for our proposed structure. Hence, we took this thickness of PCF sensor to enhance sensitivity.

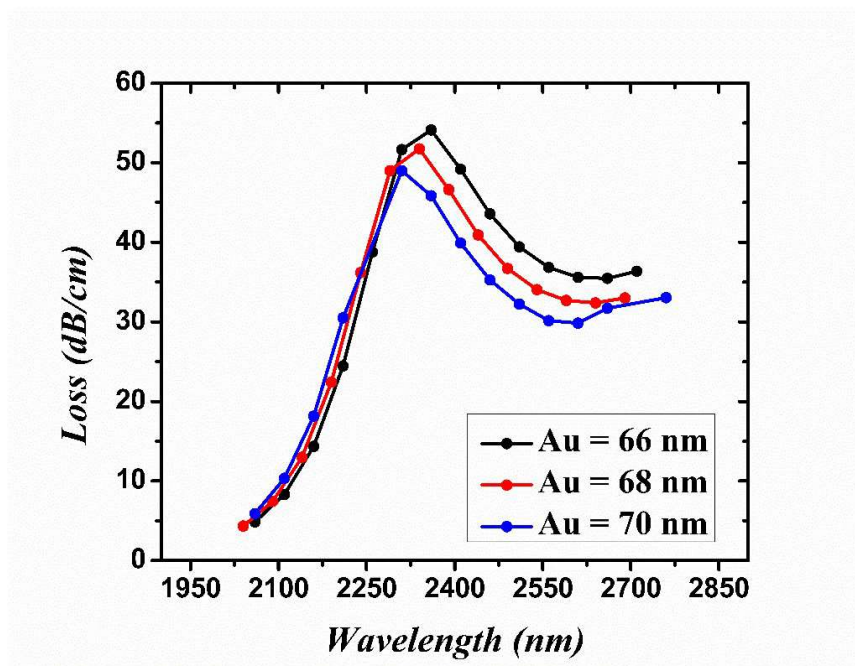


Figure 4.6 Wavelength vs. Loss (dB/cm) for gold thickness variation for analyte RI $n_a = 1.38$.

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The derivative of resonance wavelength w.r.t refractive index (RI) of the analyte in sensing of fiber sensor is called wavelength sensitivity (S) given by the following equation (2.2) ¹¹²

Our PCF sensor has obtained maximum wavelength sensitivity of 40,000 nm/RIU for analyte RI difference 1.38–1.39 depicted in figure 4.8. Beside maximum wavelength sensitivity (S), the average sensitivity of our sensor for analyte range 1.32–1.39 is 14,285 nm/RIU.

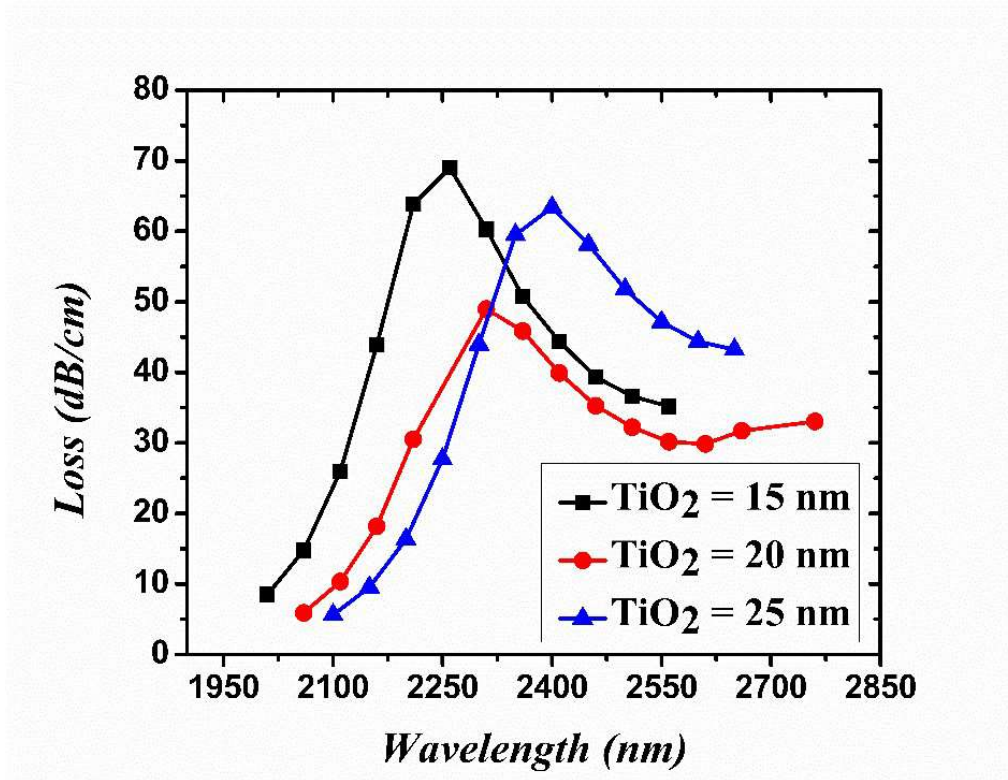


Figure 4.7 Variation of TiO₂ thickness for analyte RI $n_a = 1.38$.

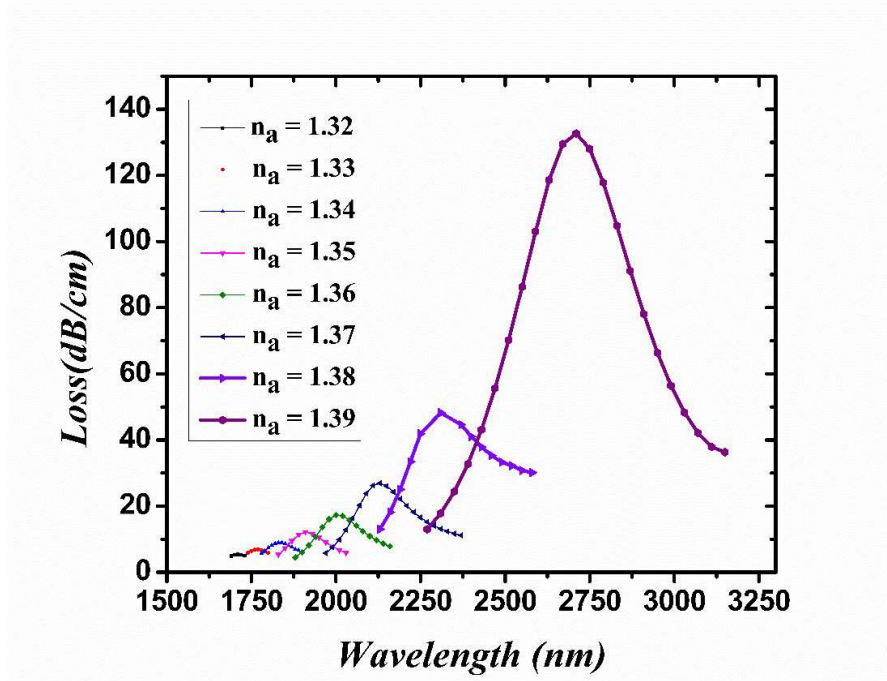


Figure 4.8 Wavelength vs. loss graph for analyte range $n_a = 1.32 - 1.39$.

There is one other parameter other than maximum wavelength sensitivity (S) known as the amplitude sensitivity method with higher accuracy to inspect the sensing performance of our PCF sensor. The expression of amplitude sensitivity is given by the following equation (2.3) ¹⁵⁴

The maximum value amplitude sensitivity for gold thickness $t_{Au} = 70 \text{ nm}$ is 328 RIU^{-1} for the refractive index of analyte 1.38 shown in figure 4.9.

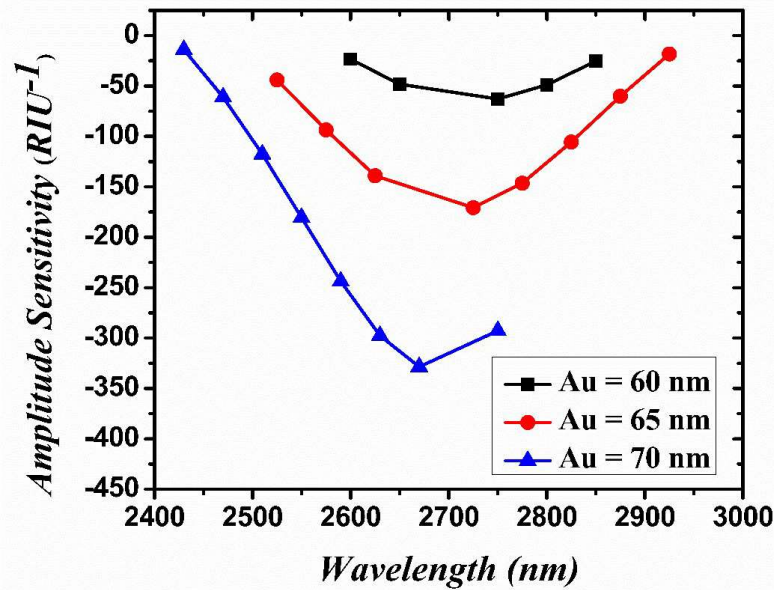


Figure 4.9 Amplitude sensitivity variation with gold (Au) thickness.

Resolution is an important factor for the determination of the minimum change in sensor parameters.

The term wavelength resolution is calculated by equation (2.4) ⁵⁹.

The minimum spectral wavelength resolution of value $\Delta\lambda_{min} = 0.1 \text{ nm}$ with the peak shift peak $\Delta\lambda_{peak}$ of value 400 nm for refractive index variation from 1.38 to 1.39. We get a resolution of 2.5×10^{-6} RIU, and the respective detection accuracy is up to the order of 10^{-6} . Table 4.1 captures all detail of our proposed rectangular shape cladding sensor for the complete analyte range 1.32–1.39.

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Table 4.1 Achievement of proposed sensor

Analyte (RI)	Peak loss (dB/cm)	Resonance wavelength (nm)	Peak shift wavelength (nm)	Sensitivity (nm/RIU)	Wavelength Resolution (RIU)
1.32	6	1710	60	6,000	1.67×10^{-5}
1.33	7	1770	70	7,000	1.43×10^{-5}
1.34	9	1840	70	7,000	1.43×10^{-5}
1.35	13	1910	90	9,000	1.11×10^{-5}
1.36	18	2000	130	13,000	7.69×10^{-6}
1.37	27	2130	180	18,000	5.55×10^{-6}
1.38	50	2310	400	40,000	2.5×10^{-6}
1.39	133	2710	NA	NA	NA

There are so many applications based on the PCF fiber sensing method in different fields of physics, chemistry, and biology. In the biochemical field, different kinds of acids, enzymes, and proteins can be sensed cancer cell detection⁵⁹, pH detection¹⁵⁵, blood testing, and red blood cell (RBC) detection¹⁵⁶. There are so many different animals that provide us with milk which contains a number of proteins, vitamins, and nutrition with low fat. Milk is an important part of our life; hence, its quality factor is quite important for the better health of the human being. Dairy products such as milk of different animals such as goats, cows, buffalo, and camels are based on their refractive index (RI) property. Milk of different animals using their refractive index (RI) properties can be analyzed with the help of our proposed sensor. Among the animal's goats, cows, and buffalo, goat milk has high surface tension, viscosity, and high acidity than cow milk followed by buffalo milk.

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Since our sensor is focused on the RI parameter of the analyte, we use animal milk as the analyte for our sensor. The mean value of RI of goat milk is 1.3424 ± 0.0036 , cow milk is 1.3426 ± 0.0036 , buffalo milk is 1.3420 ± 0.0047 , and camel milk is 1.3423 ^{157 158}. A detailed comparison between our proposed structure properties with other available sensors is tabulated in table 4.2.

A statistical measurement of the proposed sensor has been done in terms of R^2 which defines how accurately data is fitted to the regression line. Polynomial fitting of the curve between resonance wavelength and analyte RI is mentioned in figure 4.10. In this, we obtain the maximum value of R^2 of 0.99373 representing the better result of sensing.

4.4 Fabrication Technique

There are technologies available nowadays to fabricate any desired shape of PCF with any kind of core and cladding structure⁶⁶. Stack and draw is one of the prominent and convenient methods to draw the desired structure of the PCF sensor. Azab, Mohammad Y., et al. have experimentally fabricated the PCF structure using the same stack and draw technique¹⁹².

In this method, glass rods, tubes, and capillaries of different appearances (circular, rectangular, square, etc.) are stacked according to the preferred structure. This accomplished preform is drawn into microstructure rods and then at last in optical fiber. The above process keeps on repeating until we get the required structure and dimension (pitch, air hole size, diameter of the fiber, etc.). A detailed explanation of the stack and draw method is given in reference¹⁰⁰. The sol-gel method is also a complimentary method of the stack and draws process where the mold has an array of mandrels of the desired shape of air holes spewed in colloidal silica solution. The mandrel elements are removed in the wet gel stage. After this process thermodynamic process plays a role to remove water and contaminants of transient metal and organic materials.

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Applied pressure on air holes provides the required size and air-filling fraction of fiber ¹⁵⁹. The next task after the formation of PCF is the side polishing of the fiber. Due to the very small size of the fiber, uniform polishing is one of the difficult tasks. For this, we provide the support of silica block due to having the same material as fiber silica, and fiber is held in V-groove-shaped holder. Fiber is polished with some easy steps as mentioned in references ^{139 160}. Now, moving toward the coating process of fiber, the coating on the curved shape of the fiber for the surface of fiber is a challenging job, this is why we use flat plasmonic layer coating over the fiber surface. Two strips of plasmonic layer gold (Au) and of adhesive layer TiO₂ are being coated over the flat surface with the help of the chemical vapor deposition method (CVD). This process of thin film depositing is far better than other methods such as sputtering and evaporation methods ¹³⁶.

Table 4.2 Comparison with some recent research papers solely based on simulation

References	Structure Type	RI range	Wavelength Resolution (RIU)	Wavelength Sensitivity (nm/RIU)	Amplitude Sensitivity (RIU ⁻¹)
¹⁶¹	V-shaped PCF sensor	1.47–1.52	NA	18,000	NA
¹⁶²	Broad-range PCF sensor	1.35–1.40	2×10^{-5}	10,000	1115
¹⁶³	Tunable liquid core PCF	1.42–1.44	NA	3200	NA
¹⁶⁴	Dual core PCF sensor	1.33–1.42	3.39×10^{-6}	29,500	NA
¹⁶⁵	D-shaped PCF sensor	1.33–1.40	7.14×10^{-6}	14,300	NA
¹⁶⁶	Dual core SPR sensor	1.46–1.50	1.00×10^{-4}	1000	NA
¹⁶⁷	Double loss peak based	1.35–1.38	5.291×10^{-6}	18,900	NA
¹⁶⁸	D-shape-based PCF sensor	1.36–1.37	8.7×10^{-6}	11,500	230
¹⁵¹	Novel birefringent PCF sensor	1.33–1.34	5×10^{-6}	2000	NA
¹⁶⁹	D-shaped low RI detection sensor	1.3490–1.4010 1.3415–1.3468 1.3490	1.51×10^{-6}	72.7 3973.8	NA
Our Structure	Rectangular cladding PCF	1.32–1.39	2.5×10^{-6}	40,000	328

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4.5 Conclusion

Here, we summarize the article regarding our rectangular shape cladding surface plasmon resonance-based photonic crystal fiber refractive index (RI) sensor for a range of RI 1.32 – 1.39. With an idea of an external sensing mechanism using gold (Au) as a plasmonic layer with TiO₂ as an adhesive layer, we have obtained maximum wavelength sensitivity of 40,000 nm/RIU and average wavelength sensitivity of 14,285 nm/RIU; along with this amplitude sensitivity is 328 RIU⁻¹. The resolution of our sensor for RI 1.39 is 2.5×10^{-6} RIU with a best polynomial curve fitting with R² value 0.9937. Fabrication with newly developed technologies such as stack and draw and sol–gel method sensors can easily be fabricated. Along with biomedical and biochemical fields, we have opened the door for a new field, which is milk sensor based on the RI parameter of different animals such as cow, camel, goat, and buffalo, which can easily be detected with our PCF sensor, and this is very valuable for our daily life. In the next work we have improved the sensing range from low refractive index range to high index range of refractive index.