# *Design and analysis of some surface plasmon resonance based photonic crystal fiber refractive index sensors*

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# Chapter 6
## Summary and Future Scope

*We have summarized and concluded our complete thesis work in this last chapter of the thesis. In this section of the thesis, we have described the future scope and the future work to be carried out.*

## Chapter 6: Summary Conclusion and Future scope

### 6.1 Summary

Here is the summary of my complete thesis,

1. We have designed and analyzed PCF based on four different sensor structures designed by COMSOL Multiphysics software and analyzed by finite element method (FEM). All the PCF structures are solid cores guided by modified total internal reflection (M – TIR) with finite air holes arranged in different geometry in the cladding region. This sensing mechanism is completely based on the surface plasmon resonance (SPR) phenomenon.
2. In the first PCF structure, we have designed and analyzed two metal wire-assisted PCF structures based on the SPR phenomenon using three different plasmonic materials, Copper (Cu), Gold (Au), and Silver (Ag), one by one, and having a broad comparison among them. The output results are in favor of copper (Cu) metal based PCF structure which provides enhanced results compared to gold (Au) and silver (Ag) based PCF structure in the manner of maximum wavelength sensitivity ($S_\lambda$), amplitude sensitivity ($S_A$), and sensor resolution (R). Hence, the designed PCF structure using copper metal is cost–effective with a highly sensitive response.
3. The second PCF structure is flat on both sides and polished with plasmonic material gold (Au) for the SPR principle. An adhesive layer of titanium di oxide ($TiO_2$) is implemented as a catalyst between gold and analyte sample to enhance the interaction. The cladding is formed of a finite number of air holes of different sizes to achieve low confinement loss. The structure parameters are optimized to the maximum level to achieve high sensing performance and stability. The sensor performance is judged in terms of maximum wavelength sensitivity ($S_\lambda$), amplitude sensitivity ($S_A$), the figure of merit (FOM) and sensor

resolution (R). Fabrication methods have also been explained to fabricate this simple PCF structure.

4. Next in the row, a rectangular shape cladding based PCF structure for refractive index sensing based on the SRP principle has been proposed. This structure has a hexagonal core surrounded by air holes of non–identical diameter. The titanium dioxide ($TiO_2$) strip is sandwiched between PCF and the plasmonic strip of gold (Au). A complete experimental setup has been proposed. The analyte sample (RI range $n_a = 1.32 - 1.39$) is externally placed in contact with PCF following the external sensing approach. This sensor structure is compatible with different sensing fields such as biochemical, biomedical, and food and beverage industries to check out the quality of the sample.
5. In the last, we have proposed a dual core PCF structure based on the SPR principle for a wider range of analyte sample refractive index (RI) range. The PCF structure is grazed from four sides to form C – shape structure. The plasmonic layer of gold (Au) with a catalyst layer of $TiO_2$ is applied to excite the surface plasmon. This type of structure supports a long range analyte sensing range $n_a = 1.21 - 1.39$ with high sensing performance. Due to this long range analyte sampling, our proposed sensor is compatible with many sensing applications for different chemicals, biochemical, acids, etc.

### 6.2 Conclusion

Here I conclude my complete thesis. All four PCF sensors with different geometrical structures have been proposed to achieve higher sensing performance. We have implemented SPR based label-free detection method compiled with a PCF structure for real-time detection.

# Chapter 6: Summary Conclusion and Future scope

A detailed analyzed result and its application in different sensing fields have been concluded in this section as follows.

1. First, a solid core PCF (SC - PCF) has been proposed with metal wires assisted on both sides of the PCF. The SPR phenomenon has been applied to produce the surface plasmon effect. A comparison among copper, gold, and silver metal based PCF has been performed. The analyte sample has a refractive index range $n_a = 1.31 - 1.36$, and we analyze that copper wires assisted PCF to obtain maximum wavelength sensitivity $S_\lambda = 7300\, nm/RIU$, maximum amplitude sensitivity $S_A = 597\ RIU^{-1}$, and wavelength resolution $R = 1.36 \times 10^{-5}\ RIU$ for analyte sample RI $n_a = 1.35$. The obtained results are better than the results obtained for gold (Au), the maximum wavelength sensitivity $S_\lambda = 6200\, nm/RIU$, maximum amplitude sensitivity $S_A = 422\ RIU^{-1}$, and wavelength resolution $R = 1.61 \times 10^{-5}\ RIU$ for analyte sample RI $n_a = 1.34$, and for silver (Ag), the maximum wavelength sensitivity $S_\lambda = 6100\, nm/RIU$, maximum amplitude sensitivity $S_A = 560\ RIU^{-1}$, and wavelength resolution $R = 1.63 \times 10^{-5}\ RIU$ for analyte sample RI $n_a = 1.34$. So, the proposed sensor structure is cost–efficient, and it has the potential to be used in different sensing applications.
2. Second, we have designed both sides of the flat PCF structure using the SPR technique, and this structure has been analyzed with the help of the FEM method. A combination of gold with $TiO_2$ works as a plasmonic layer over the PCF flat surface based on an external sensing approach. The simulation results show that the analyte sample refractive index range $n_a = 1.30 - 1.40$, the maximum wavelength sensitivity is $S_\lambda = 22800 \frac{nm}{RIU}$, amplitude sensitivity $S_A = 947\ RIU^{-1}$amplitude sensitivity $S_A = 947\ RIU^{-1}$, figure of merit (FOM) = 507 $RIU^{-1}$, and sensor resolution is R = $4.38 \times 10^{-6}$ RIU is obtained.

The sensor may be very useful for cancer cell detection (RI range $n_a = 1.36 - 1.40$), which is the primary application of this PCF sensor. The fabrication process can easily be performed by new technologies such as the stack and draw method, sol–gel method, etc.

3. Next, we have a rectangular cladding based PCF sensor structure using the SPR phenomenon for analyte sample refractive index RI range $n_a = 1.32 - 1.39$. There is a strip of plasmonic material gold with an adhesive layer of $TiO_2$ over the PCF structure based on an external sensing mechanism approach to obtain maximum wavelength sensitivity $S_\lambda = 40000\ nm/RIU$ with an average wavelength sensitivity of 14285 nm/RIU. The maximum amplitude sensitivity $S_A = 328\ RIU^{-1}$ and sensor resolution R = 2.5 × $10^{-6}$ RIU. The polynomial fitting curve provides the best value of $R^2 = 0.9937$. This PCF sensor can be used in different fields, such as biochemical and biomedical fields, due to its highly sensitive response. One of the prime applications of this sensor structure is to use this sensor structure in the dairy industry to sense the different animal milk. Among the cow, goat, and buffalo milk, goat milk has high surface tension, viscosity, and acidic composition than cow milk and followed by buffalo milk. The mean value of the refractive index of goat milk is 1.3424 $\pm$ 0.0036, cow milk is 1.3426 $\pm$ 0.0036, and buffalo milk is 1.3420 $\pm$ 0.0047. All these refractive indices lie in our proposed sensor structure refractive index range. Hence, they can easily be detected.
4. Last in the row, a dual-core PCF sensor based on the SPR phenomenon for a wide range of analyte sample RI range $n_a = 1.21 - 1.39$ has been proposed and analyzed. This refractive index sensor has the beauty to detect long range with maximum wavelength sensitive response of $S_\lambda = 35000\ nm/RIU$, with an average sensitivity of 6368 nm/RIU. The amplitude sensitivity $S_A = 373\ RIU^{-1}$ and sensor resolution is in order of $10^{-6}$.

The figure of merit (FOM) is an essential tool for practical implementation and has a value of 259 $RIU^{-1}$. The fabrication process for experimental implementation can easily be performed with the newly available technologies such as sol–gel method, stack and draw process, extrusion process, and injection molding process. Among these methods, the stack and draw process is the most reliable and less time-consuming process. Due to low range analyte sample detection, this PCF sensor structure can be used to detect different chemicals, acids, alcohols, and pregnancy tests.

### 6.3 Future scope

In the modern era, the sensor is one of the prime tools in any field of science and engineering. There has been tremendous growth in sensing over the last decades. From the above discussion in this thesis, it is clear that PCF based sensors have many futuristic possibilities. Since the SPR principle-based PCF sensors are free from labels requirement and provide real time detection. The photonic crystal fiber based sensors will be a prime tool for the future sensing journey due to their compact structure, flexibility, different geometrical parameter alteration, robustness, and immunity to EM wave interference. In the prospect of fabrication, a very small length of PCF is required as a sensing probe; hence it is cost – efficient in the fabrication. Due to such exponential growth in the sensing field, PCF based sensors will definitely make a mark in the different industries such as biomedical sensing, biochemical sensing, food and beverage, and dairy industries. All the current limitations in the sensing field (in remote sensing area, hazardous environment sensing) can easily be overcome with the help of PCF sensor in every field of science in the future.