

# Review on Photonic Crystal Fiber-Based Nanoparticle for Sensing Applications

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## ABSTRACT

*Photonic Crystal Fibers (PCF) have drawn a lot of interest due to their potential to produce a distinctive spectrum of optical properties that are just not feasible in common fiber types, whereas PCF can work in both conditions if the refractive index (RI) of the core is higher than the refractive index of the cladding. In this case light is guided through total internal reflection (TIR), while in the second condition, the refractive index (RI) of the core is lower than the refractive index of the cladding, the light is guided through a photonic bandgap effect, which is not possible with conventional fibers. The surface plasmon resonance (SPR) is used in the sensor design. In this overview, an analysis of current advancements in photonic crystal fiber sensor design for sensing applications is presented, as also the effect of gold and silver nanoparticles and other types of material used to coat optical crystal fibers for sensors, the focus of this article uses of PCF for various sensing applications. such as thermal sensors, gas sensors, and biosensors. These PCFs are available in two types solid core and hollow core. Solid core photonic PCF has traditionally been utilized for sensing applications because the cladding channels can be filled with gas or liquid, acting as a useful form of evanescent wave sensing and also can coat the outer surface with plasmonic material depending on the surface plasmonic resonance phenomenon. Hollow core PCF delivers significant gains because of the presence of samples in the core. Hollow core PCF is used for sensor purposes by filling the core with different types of liquid or gases where the majority of the light is contained, increasing the interaction between light and matter. Due to the exceptional properties that such photonic crystal fiber can give, more sensors are anticipated to be created in the future. The development of various optical sensing methods, their advantages, disadvantages, and potential for point-of-care applications are all thoroughly covered.*

**Keywords:** Photonic Crystal Fiber, sensors, gold nanoparticles (Au); silver nanoparticles (Ag), Surface Plasmon Resonance

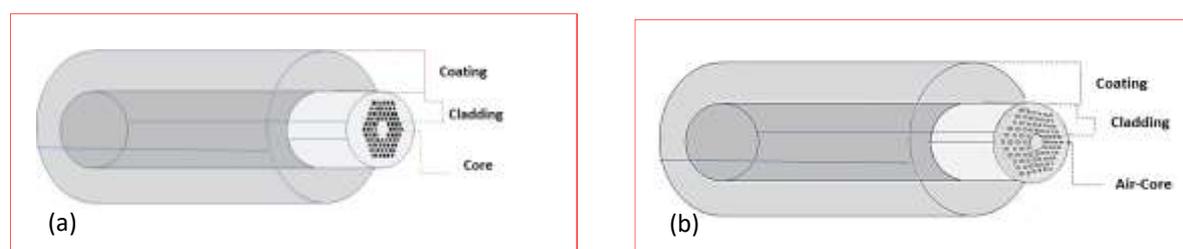
## 1. INTRODUCTION

A photonic crystal fiber (PCF) is a novel form of optical fiber that has an array of air holes running through its direction [1, 2]. PCFs can be divided into two types (Hollow core and solid core) figure (1) depending on whether they use index guiding total internal reflection (TIR) or band gaps to guide light through a specific region of the fiber, figure (2) [3-6].

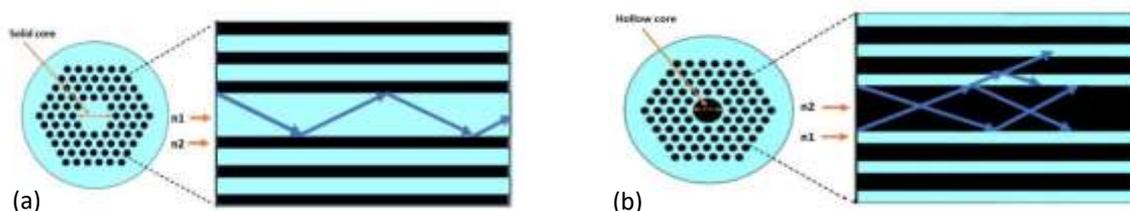
Photonic crystal fiber has made significant progress in optical sensing during the past few years [7, 8]. As a result of PCF's advantages, which include its flexible structure, extremely sensitive and adjustable birefringence characteristics, high confinement, reduced electromagnetic interference, researchers have recently concentrated their efforts on developing novel structures and enhancing the performance characteristics of these sensors [9-13].

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There are many types of photonic crystal fibre based SPR sensors such as D-shaped configuration-based sensors ,nanowire-based sensors , H-Shaped Photonic Crystal sensors, and internal coating and outer coated based PCF sensors [14-17]. In outer surface nanomaterial coated PCF sensors, the incident photon excites the metal's free electrons causes to increased confinement loss and, under specific conditions, the loss is maximum, known as the resonance condition [18-21]. The choice of plasmonic materials has a significant impact on the SPR sensor's performance [22, 23]. The cladding of the fiber is removed in many of these more recent fiber SPR sensing configurations (the sensing region), allowing for the deposition of a nanomaterial layer (often made of Au or Ag) that supports the stimulation of SPR and their interaction with optical waveguide modes of the fiber, when (RI) of analyte's is change, then resonance condition also changes this mechanism is used for detecting the different analyte by measuring the wavelength shift (red or blue shift) at the resonance wavelength [24-29].



**Figure 1.** Schematic diagram for two types of photonic crystal fiber (a) solid-core PCF and (b) hollow-core PCF [6].



**Figure 2.** (a) Total internal reflection (TIR) (b) Band gaps to direct light through a specific region of the fiber [7].

Surface plasmon occurs due to confinement of electromagnetic waves by coupling photons to electrons. At the interface of two materials, the requisite conditions for surface plasmon polaritons generated by an electromagnetic field must be met [30-33]. The true part of relative permittivity of reverse polarities is that they both have one. This is possible when the first material is metal and the second is insulating [34-36]. In plasmonic-based devices, gold (Au), silver (Ag), aluminium (Al) and nickel (Ni) have all been seen [37, 38]. They have a great number of charge carriers because of this, they are commonly employed as plasmonic metals. Ag and Au are the most often utilized metals because of their lower D-electron density [39-42].

Coating plasmonic materials such as gold and silver onto (1) the internal coating and (2) the outer coating of the photonic crystal fiber has resulted in several types of PCF-SPR sensors [43-45]. Two primary issues confront internal coated designs. Firstly, inside the air hole, a homogeneous thin metal covering is fabricated. Secondly, liquid penetration into micron air holes makes it difficult [46-49]. External coating, in which the metal is coated on the outside of the object, is proposed to circumvent these limits. The sensing liquid and fiber surface are poured directly on the metal surface with the help of using D-shaped sensing [50-54].in externally covered designs and the majority of circular [55, 56], Because of the small size of the PCF, adding plasmonic nanomaterial

to the inner surface of the air holes is difficult, thus coating plasmonic nanomaterials onto the outside of the optical fiber is simple and easy [57-59].

## 2. GOLD AND SILVER NANOPARTICLES

Nanotechnology utilizes materials in 1 to 100 nm scales, involving material sciences, biotechnology computer sciences, pharmacy, medicines and engineering [60, 61]. Gold (Au) Nanoparticles have excellent biocompatibility, high density, great conductivity as well as a high surface-to-volume ratio [62-64]. By lowering the concentration of aqueous gold ions in contact with aqueous plant shell extract, the Au-NPs are created by (Garcinia mangos tana technique). Au-NPs have an absorption peak that can be seen using UV-visible spectroscopy in the range of wavelengths (540–800 nm). All diffraction peaks indexed to the 111, 200, 220, & 311 planes at  $2\theta = 38.480, 44.850, 66.050, \text{ and } 78.000$  indicate the efficient production of Au-NPs. TEM is used to investigate primarily spherical particles having diameter of  $32.95 \pm 5.26$  nm. Diffraction peaks found using Fourier Transform Infrared Spectroscopy (FTIR) are identical to those seen in phenols, benzophenones, and anthocyanins, suggesting that these findings might lead to positive agent reduction. Most spherical particles with a diameter of  $32.95 \pm 5.26$  nm are examined using transmission electron microscopy (TEM) [65-69].

Furthermore, due to the unique chemical and physical characteristics of silver nanoparticles, they are used in a different of industries as medical device coatings, optical sensors, food, consumer, health care, and industrial applications [70, 71]. These properties consist of optical, electrical, thermal, and biological properties. The physicochemical properties of nanoparticles determine their behaviour, biodistribution, safety, and efficiency. As a result, characterization of silver nanoparticles is crucial for determining the functional properties of the particles formed. X-ray diffractometry (XRD), UV-visible spectroscopy, atomic force microscopy (AFM), Scanning electron microscopy (SEM) and Transmission electron microscopy (TEM) are used to characterize the samples [72, 73].

## 3. PCF SENSORS

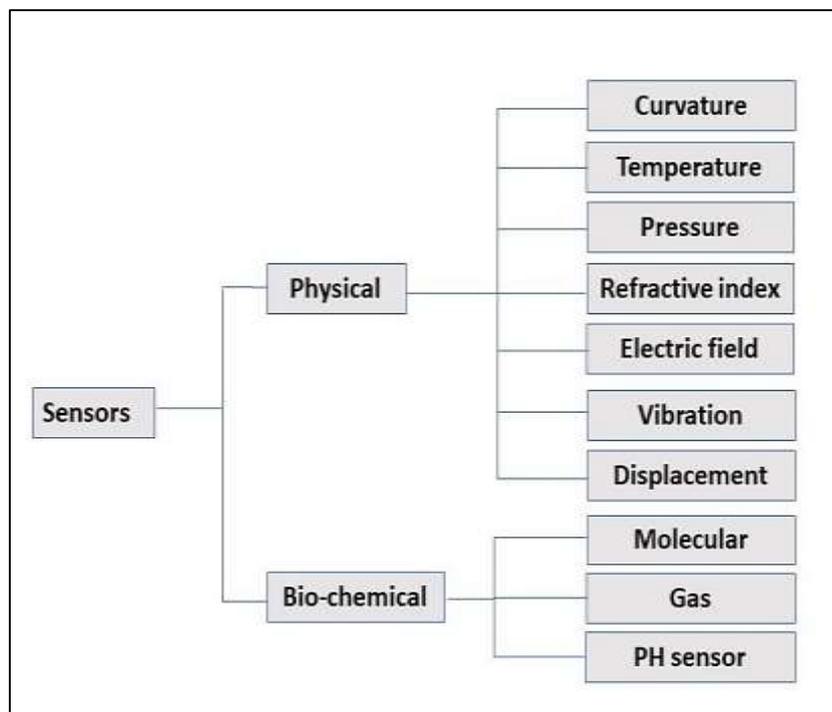
Sensors, in a general sense, are any device that collects and records a signal or physical signal, such as heat, sound, light, pressure, magnetic fields, or any specific movement and then signals or responds to it [74].

1. Sensors of physical nature measure physical parameters such as curvature/bend sensors, magnetic field sensors, electric sensor displacement/strain, temperature sensors, refractive index sensors, pressure sensors, and torque/twist sensors [75].
2. Biochemical sensors: biochemical sensors are used to detect bio and chemical samples due to their characteristics and flexibility to regulate remotely. Because of the air vents that run the length of the PCF clad, PCFs offer the unique benefit of chemical and biological sensing. Gas sensors, moisture sensors, molecular sensors, and pH sensors are examples of biochemical sensors [76]. The world's current PCF sensors are listed in the figure (3) [11, 77].

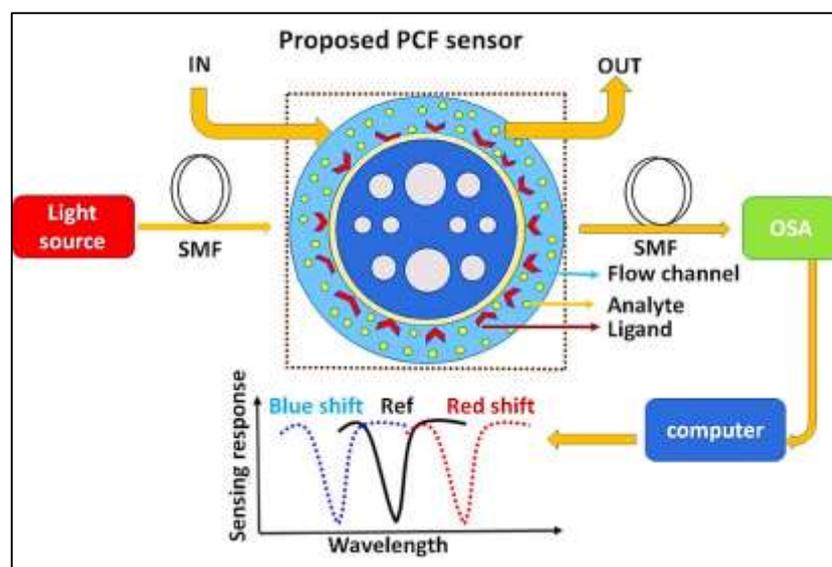
A large plane of possible applications has been discovered based on the unique optical features of PCFs. Photonic crystal fiber-based sensors have several uses, which are shown below:

1. Gas sensors: Gases are invisible and potentially lethal. Various gases have different absorption lines. The colorless vapors are detected depending on the length of the absorption spectrum and refractive index. The photonic crystal fibers (PCF) are used to detect the different types of gases [78].

2. Biosensor: In the presence of a biochemical or analyte, a biosensor detects a wide variety of biologicals, antibodies, and enzymes. PCFs are currently often used to detect biological substances such as glucose, PH, serum protein, and other similar chemicals. [17]. A Schematic diagram represents General setup for biosensing in the Figure (4).



**Figure 3.** Major collection of the world's PCF sensors.



**Figure 4.** Show the General set-up for practical sensing [24].

The photonic crystal fibers or microstructure optical fibers are employed in sensing applications such as biosensors that used surface plasmonic resonance phenomenon [79] and photonic crystal fiber chemical sensing, for example, to detect methanol [80] and refractive index(RI) sensing [81], A D-shaped-PCF with gold grating is used to make a refractive index sensor [82]. A microstructure core (PCF) based gas sensor for detecting colourless or toxic gasses and monitoring air pollution [83].

Some published research in many fields such as optical, biological, and chemical sensors is discussed in this paper. The photonic crystal fiber can be employed as a sensor for biochemical applications. The biosensor is carried out by A. Rifat In 2015 [84] who proposed a simple microstructure optical fiber biosensor using Surface Plasmon Resonance (SPR) with a higher refractive index (RI) sensitivity of roughly 4000 nm/RIU. In 2015 Otupri, R. Akowuah, E. K. Haxha [85] suggested multichannel Photonic Crystal Fibre as biosensor based on SPR backed by a high refractive index out over layer in multi channels allows work in multi modes; multi analyte sensing and self-referencing mode, obtaining maximum refractive index sensitivity of around 4600 nm/RIU. P Vinod Kumar and Snivash in 2019 designed a photonic crystal fiber biosensor using Au layer coatings on the fibre's outer surface. The highest sensitivities of this surface plasmon resonance-based sensor, with a refractive index range of 1.33 to 1.39, are 4300 nm/RIU. In 2019 Mahfuz [86] proposed and evaluated a highly sensitive surface plasmon resonance (SPR)-based photonic crystal fiber (PCF) biosensor that operates in the (1.33 to 1.40 m) wavelength range. The gold and silver plasmonic nanomaterial coating out of surface of the PCF gives a simple design for this sensor and high performance. The suggested sensors have maximum amplitude sensitivities of 1086 RIU<sup>1</sup> and 1656 RIU<sup>1</sup>., respectively, and higher wavelength sensitivity is around 12000 nm.RIU<sup>-1</sup> for both Au and Ag. Mahfuz and his colleagues had the best biosensor sensitivity, with the maximum sensitivity as shown in Table 1.

**Table 1** Sensitivity of (PCF) Biosensor

Sensor sensitivity	The causes of high and low sensitivity
4000 nm/RIU [87]	Plasmonic gold layer are used exterior surface fiber rather than inside the air-holes, resulting in an easier production method.
4600nm/RIU [85]	The plasmonic material is copper (Cu), and graphene is utilized to avoid Cu from oxidizing and improve sensing characteristics.
4300nm/RIU [88]	For increased sensitivity, the plasmonic coating Au has been coating the outer surface of the photonic crystal fiber.
12000 nm/RIU [86]	Gold and silver plasmonic materials were used together to improve sensor performance.

Thermal and refractive-index sensing is the most important technique in many applications. This is done by Momota in 2018 [89] proposed a photonic crystal fibre (PCF) based surface Plasmon resonance (SPR) refractive index sensor. The plasmonic material silver is deposited on the outside surface of the PCF to make production easier and high performance. the maximum sensitivity obtained about 4200 nm/RIU the proposed design has many advantages as easy manufacturing, cheap and reusability, In 2019 Liang [90] suggested a graphene and zinc oxide-coated D shaped photonic crystal fibre refractive index sensor. The polished surface of the sensor is covered with materials such as silver, graphene, and ZnO. This simplifies sensor fabrication and eliminates the challenges of filling the hole with material and covering the hole wall. The highest sensitivity measured was 6000nm/RIU, in 2019, Kaur [91] developed a photonic crystal fiber based SPR sensor with titanium nitride coating for liquid sensing applications for RI=1.40, which has a wavelength sensitivity around 10,000 nm/RIU. The Kaur, V. and Singh, S. proposal achieves the best RI sensor sensitivity; the maximum sensitivity is gated, as observed in table (2).

**Table 2** Sensitivity of (PCF) refractive index sensor

Sensor Sensitivity	Refractive Index	The causes of high and low sensitivity
4200 nm/RIU [89]	1.37	The plasmonic material for the suggested design is silver, which is put on the outside surface of the PCF to make production easier.
6000 nm/RIU [90]	1.37–1.41	The efficiency of the SPR-PCF sensor using graphene / zinc oxide (ZnO) layers has been obtained. graphene and ZnO are utilized to prevent oxygen from oxidizing (silver)
10000 nm/RIU[91]	1.385–1.40mm	To improve performance, a transition metal nitride was used as a new plasmonic material and coupled with PCF.

#### 4. CONCLUSION

Photonic crystal fiber using gold, silver, and other based materials for sensors are reviewed as part of an effort by researchers to develop a range of high-performance sensors for use in the field of optoelectronics. This review covers several aspects, for example, the types of coating and the effect of nanomaterials on sensing PCF for different sensor applications such as refractive index and biosensors. The best sensing value for the refractive index sensor was obtained by presented work of Kaur *et al.* they obtained the highest sensitivity of around 10,000 nm/RIU for refractive indices values of (1.385 to 1.40) and the maximum sensitivity of biosensor was obtained around 12,000 nm/RIU by presented work of Mahfuz *et al.*, Most of the researches was theoretical work, where the best results were obtained under ideal conditions in terms of temperature and humidity as well as manufacturing losses. from the observed the best plasmonic materials are gold and silver, according to most research and results, we conclude that the solid core photonic crystal fiber which operates by TIR is better than the hollow core photonic crystal fiber which operates by photonic band gap.

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