High-Efficiency Photonic Crystal Fiber Based Sensors for Diverse Optical Sensing Applications

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Abstract : In modern time, PCF based sensors are primarily attribute towards strong light–matter interaction, superior sensitivity, and versatile structural design providing for advanced optical sensing application which collectively enables efficiency and precise sensing. This paper presents a thorough review of photonic crystal fiber (PCF)–based sensing technologies, emphasizing their operating principles, performance metrics, and diverse application domains. It includes an in-depth comparative analysis of PCF sensors used in chemical, biomedical, liquid analyte, biosensing, environmental, and refractive index sensing applications. The sensing efficiency of PCF-based devices depends on numerous factors such as fiber geometry, host material, operating wavelength, light-guiding mechanism, refractive index of the target analyte, air-hole dimensions and distribution, lattice pitch, birefringence, confinement loss, fabrication accuracy, metal or dielectric coatings, surface functionalization, as well as external environmental conditions including temperature and pressure. A wide range of PCF structural designs namely hexagonal, square, circular, triangular, hollow-core, solid-core, rectangular porous, decagonal, elliptical, and asymmetric structures are discussed, with their corresponding sensing mechanisms and design strategies systematically examined. A tabulated comparison of representative PCF sensors is presented, followed by a discussion of current challenges, fabrication limitations .

Keywords: optical fiber; photonic crystal fiber; Refractive index sensors

1. Introduction:

PCF-based sensors for high-sensitivity SPR sensing. Their microstructure design offers improved sensitivity, compact size, and flexibility over conventional methods[1]. Different PCF structures such as D-shaped, dual-core, and hollow-core are analysed for various sensing applications.[2]. A PCF-based refractive index biosensor is planned for detecting blood components such as water, plasma, WBCs, haemoglobin, and RBCs by

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means of mode-coupling theory. Distinct refractive indices of these workings produce separate resonance peak shifts in the transmission spectrum, enabling wavelength-based sensitivity appraisal. Operating over an Refractive index range of 1.33–1.40, it offers high sensitivity, simple fabrication, and rapid detection performance[3]. Many technologies are used as Photonic crystal–based platforms which support a wide variety of photonic technologies such as semiconductor optical amplifiers, Mach–Zehnder interferometers, fibre Bragg gratings, free-space optical and visible light communication systems, and optical modulators[4].In recent scenario for propagate the light, PCF geometry is most beneficial over conventional optical fibre, having a solid or hollow core in which the air-holes pattern is designed [5]. By adapting structural design of photonic crystal fibres the optical field transmission characteristics can be effectively enhanced. Consequently, PCF-based sensors extensively applied in diverse sensing application, including temperature sensing, gas detection using micro structured core PCFs, refractive index sensing, and single-polarisation filtering based on two-core PCF structures[6]. Different material are also castoff for coating over a core like a gold, silver, titanium, zinc cooper etc. The proposed gold-coated PCF plasmonic micro-biosensor is numerically examined with an external sensing approach to reduce fabrication complexity and support real-time detection having high wavelength and amplitude sensitivities of 10,000 nm/RIU and 1250 RIU^{-1}.It is well suited for detecting biological and biochemical liquid analytes inside the Refractive index range of 1.33–1.39[7]. Now a days different shaped of sensors are also proposed which include A PCF-sensor with open D channel and Au-Tio2 plasmonic layer is used for label-free cancer cell detection with a spectral sensitivity of 47,000 nm/RIU. The sensor displays improved FOM, resolution, and detection limits, highlighting its strong potential for biosensing applications[8].Again another, novel D-shaped PCF-based SPR refractive index sensor with a gold-coated open-ring channel is planned and mathematically analysed using the finite element method which operates over an RI range of 1.20–1.29, completing a maximum spectral sensitivity of 11,055 nm/RIU and a high resolution of 9.05×10^{-6} RIU. Its excellent sensing performance makes it a strong applicant for low refractive index detection applications[9]. This review presents a complete summary of recent research on D-shaped optical fibers and their applications in optical sensing. The formations, operating principles, and measurement techniques of various D-shaped fiber sensors are systematically discussed and compared in terms of performance and sensitivity. The reported studies indicate that D-shaped optical fibers facilitate the realization of highly sensitive sensors featuring simple designs, robust mechanical stability, and strong resistance to external interference. The review further emphasizes the current limitations, critical issues, and emerging challenges related to D-shaped optical fiber–based sensing technologies [10].

2. Mechanism and methodology of PCF:

A photonic crystal fiber (PCF)-based sensor uses a microstructured design and operates on light–matter interaction having solid and hollow core. Changes in analyte properties such as refractive index or temperature alter the effective refractive index of the guided mode, while the air-hole structure provides improved control over dispersion and modal behavior compared to conventional fibers[11].These changes cause measurable variations in optical parameters such as resonant wavelength shift, confinement loss, transmission intensity, and phase or polarization response. In coated PCF sensors, guided light at specific wavelengths excites surface plasmon resonance[12]**.** The change in phase-matching condition, resulting in a shift of the resonance peak when we change analyte parameter. Thus, through monitoring the wavelength shift, loss spectrum and intensity variation the presence and concentration of the target analyte can be accurately detected.

Recent photonic crystal fiber sensor designs are widely focused on evaluating key performance parameters such as confinement loss, wavelength sensitivity, amplitude sensitivity [13] detection limit to ensure high sensing accuracy. By carefully engineering the PCF geometry, air-hole arrangement, plasmonic coating, and background material, strong light–matter contact can be achieved, leading to enhanced sensitivity and reduced confinement loss[14][15]. Numerical techniques such as the finite element method are commonly employed to analyses modal properties, resonance behaviors, and loss characteristics. These optimized PCF sensors show superior performance, compactness, and design flexibility, making them highly suitable for chemical, biological, and refractive index–based sensing applications in modern optical sensing platforms. Based on their light-guiding mechanism and core structure Photonic Crystal Fibers are classified, which influence their optical properties of sensor and applications[11].

PCFs are broadly classified into index-guiding and photonic bandgap types. Index-guiding PCFs operate similarly to conventional fibers, with a solid core and air-hole cladding that provides light guidance through total internal reflection. They are widely used for single-mode operation and low bending loss over a wide wavelength range.[12][13].Photonic bandgap (PBG) PCFs guide light using the bandgap effect created by the periodic cladding structure. They typically have a hollow or low-index core, where light is confined because certain wavelengths are blocked from escaping. This allows light to remain guided even when the core has a lower refractive index than the cladding. [14][15][16]. Applications in areas such as gas detection and nonlinear optical systems, particularly in situations where interaction with the fiber material is preferred. Further sub classifications also exist, including hollow-core PCFs**,** large-mode area PCFs**,** polarization-maintaining PCFs, and nonlinear PCFs**,** each optimized for specific functions. The design flexibility in PCFs allows for fine-tuning of dispersion, birefringence, manufacture them highly versatile for a extensive range of photonic applications.

The Figure 1 demonstrates the performance parameters of plasmonic-based PCF sensors, with the central structure on behalf of the sensing platform and neighboring nodes representing critical optical features. These include refractive index, confinement loss, dispersion, mode area, nonlinearity, and numerical aperture, all of which meaningfully impact light propagation and plasmonic resonance characteristics. Proper optimization of these factors enhances light–matter interaction, recovers sensitivity, and reduces propagation loss. Collectively, they determine the overall efficiency and sensing performance of plasmonic PCF sensors.

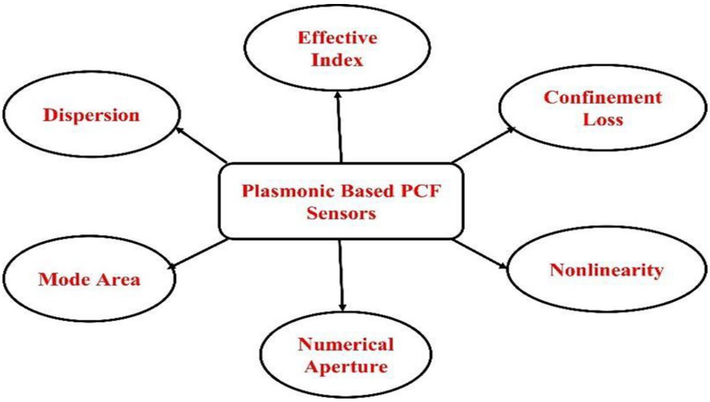

Fig. 1. PCF sensor with Different Optical characteristics.

Photonic crystal fibers are fabricated using specialized methods to create precise air-hole structures along the fiber length. Common techniques include stack-and-draw, fiber drawing, and sol-gel methods[17[[18]. In the stack-and-draw process, silica capillaries and rods are arranged in a desired pattern, enclosed in a jacket, and then heated and drawn into a thin fiber while preserving the air-hole structure..The Fiber is coated with a protective polymer and then wound onto a spool for storage and application[17].Alternative methods such as extrusion used for soft-glass or polymer-based PCFs, sol-gel techniques[18]**,** Mechanical drilling[19] may be used depending on the material and structural difficulty. Truthful control of hole diameter, pitch, and the d/Λ ratio is crucial for determining light confinement, dispersion, and modal behaviour.

3. Literature survey of different shaped of PCF sensor

3.1 Single D shaped PCF sensor: A D-shaped PCF-SPR sensor is proposed for refractive index and temperature sensing using Au and Ag–PDMS layers, analyzed via FEM in COMSOL. It offers high sensitivity up to 56,700 nm/RIU and 17.4 nm/°C temperature response, making it suitable for chemical, biomedical, and environmental applications. **[15].**

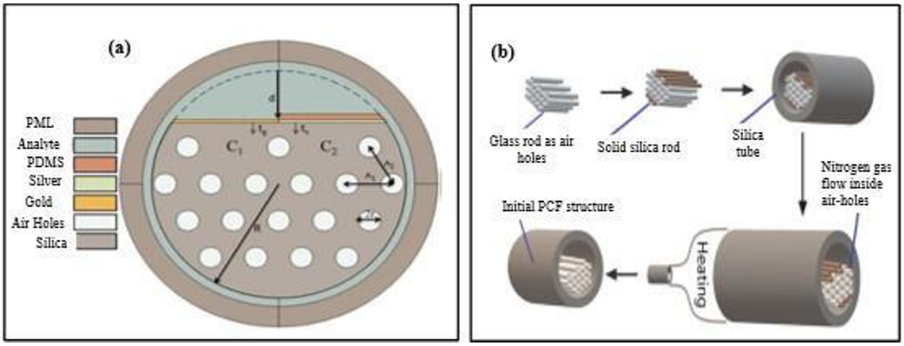

Fig. 2.: (a)cross-section view (b) Experimental model[15]

3.2 Plasmonic temperature sensor using D-shaped photonic crystal fiber : The study reports a D-shaped PCF-based plasmonic temperature sensor operating in the near-infrared region with enhanced fabrication simplicity. The optimized gold–benzene configuration delivers a peak sensitivity of 110 nm/°C, along with a high figure of merit of 5.5/°C and a resolution of 9.09×10^{-4} °C over the 10–70 °C range. The D-shaped geometry simplifies metal deposition and eliminates complex liquid infiltration. Overall, the design demonstrates superior performance compared to existing PCF-based temperature sensors and is well suited for practical sensing applications. [20]

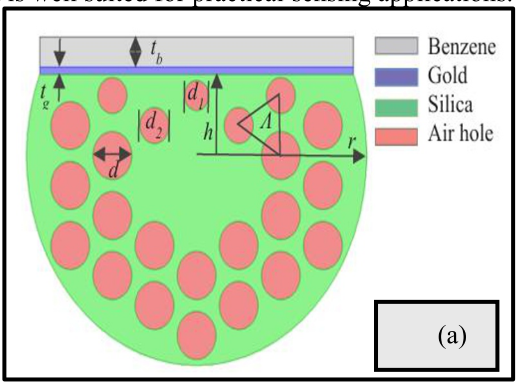

Fig. 3: (a)cross-section view[20]

3.3 D shaped SPR based PCF sensor: The proposed D-shaped SPR-based PCF sensor exhibits high performance over an RI range of 1.37–1.42**.** It achieves a maximum wavelength sensitivity of 19,600 nm/RIU and amplitude sensitivity of about 2300 RIU^{-1}. The sensor operates in the 850–1350 nm range with strong resonance shifts. These results confirm its suitability for precise biomedical and environmental sensing applications[21].

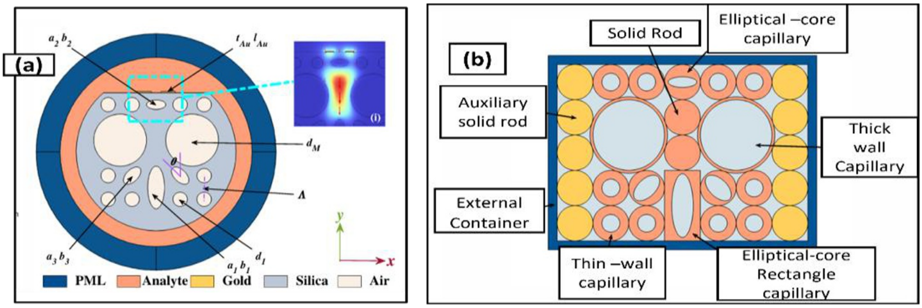

Figure 4: (a) A 2D schematic of the proposed structure.(b)A 2D schematic of the proposed sensor structure in the fabrication process[21].

3.4 D type Dual mode PCF: The proposed D-type dual-mode PCF-SPR sensor operates over an RI range of 1.25–1.37 with high performance. It achieves a maximum sensitivity of 33,000 nm/RIU and resolution of 3.03×10^{-6} RIU, with FOM > 200 RIU^{-1}. The dual-mode design enhances SPR coupling and sensing accuracy, making it suitable for precise optical sensing applications[22].

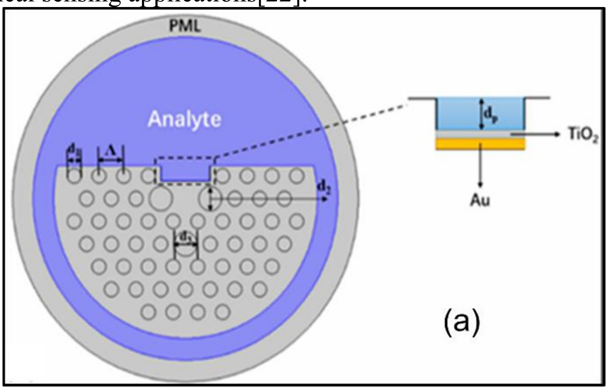

Figure 5: (a) Cross-section of the proposed D-type dual-mode PCF-SPR structure[22].

3.5 Experimental and numerical characterization of a D-shaped PCF refractive index sensor : The fabricated D-shaped PCF-SPR sensor operates over an RI range of 1.33–1.3538 with a wavelength shift from 1606 nm to 1613 nm. It achieves an experimental sensitivity of 294.11 nm/RIU and a resolution of 3.4×10^{-4} RIU. The results confirm its effectiveness for practical biomedical sensing applications[14].

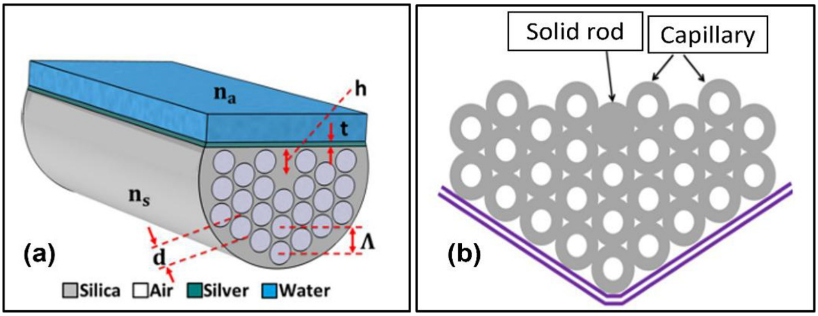

Figure 6: (a) 3-D diagram of the suggested D-shape biosensor (b) Cross-section of the proposed PCF's stacked preform[14]

4. Comparative Analysis of Different D shaped PCF Sensor.

Photonic Crystal Fibers (PCFs) differ from conventional fibers due to their microstructured cladding of air holes along the length. The core can be solid or hollow, guiding light via modified total internal reflection in solid-core PCFs. In hollow-core PCFs, light propagation occurs through the photonic bandgap effect.[23].

The cladding of PCFs consists of regularly arranged air holes (typically hexagonal), where parameters like pitch and hole diameter determine dispersion, confinement, and mode behavior. The ratio (d/Λ) plays a key role in single-mode operation and nonlinearity. A protective silica cladding provides mechanical strength, while a D-shaped PCF with varying air-hole diameters and analyte coating enhances real-time sensing performance.

Table 1. Comparative Analysis Of Different Mode of PCF :

Sr.no	**Parameter**	**Single D-Shaped PCF-SPR Sensor[15]**	**Dual D-Shaped PCF-SPR Sensor**[24]	**Three-Channel PCF-SPR Sensor**[25]
1	**Sensor Type**	Refractive index sensor	High-sensitivity refractive index sensor	Multiparameter sensor (RI, temperature, magnetic field)
2	**Sensor's Schematic Structure**	Side-polished (D-shaped) PCF with metal-coated flat surface	Two parallel symmetrical D-shaped PCFs with metal layers	Hexagonal PCF with multiple air holes filled with analyte
3	**SPR-PCF Design Pattern**	Single plasmonic interaction region	Dual plasmonic coupling between adjacent D-shaped fibers	Three independent SPR channels using Ag film, Au film, and Au nanowire
4	**Fabrication Method**	Stack and draw + side polishing	Stack and draw + dual side polishing	Stack and draw method with selective hole filling
5	**Metal Deposition Method**	Physical vapour deposition / wet chemical deposition	Wet chemical deposition / physical vapour deposition	Electrochemical deposition for films and nanowires
6	**Plasmonic Materials Used**	Gold or silver thin film	Silver thin film	Gold film, silver film, and gold nanowire
7	**Sensing Parameters**	Refractive index only	Refractive index only	Refractive index, temperature, magnetic field
8	**Sensitivity**	~51,200-56,000 nm/RIU	~56,700 nm/RIU	~29,800 nm/RIU

9	**Key Advantages**	Simple structure, easy metal coating	Very high sensitivity and resolution	Simultaneous multiparameter sensing with low cross-interference
10	**Challenges Associated**	Limited sensitivity range; single-parameter sensing	Precise alignment of dual fibers	Structural complexity and selective material filling
11	**Cost**	Low to moderate	Moderate(dual-fibre processing)	Moderate to high due to multiple materials and channels

From the comparison, the Dual D-Shaped PCF-SPR sensor develops as the best design in terms of wavelength sensitivity, achieving the highest reported value (~56,700 nm/RIU) due to enhanced dual plasmonic coupling. The Single D-Shaped PCF-SPR sensor offers relatively lower sensitivity as well as simpler structure and lower fabrication cost. In terms of refractive index sensing range and multiparameter capability, the Three-Channel PCF-SPR sensor is superior, enabling simultaneous RI, temperature, and magnetic field sensing, however at the expense of increased structural complexity and cost. Overall, the dual D-shaped design provides the optimal balance of high sensitivity and sensing performance.

Table 2. Comparative study of different shapes of PCF sensor:

Sr.No	**Sensor types**	**WL Range RI**	**Range in term of RI**	**WS (nm/RIU)**	**AS (RIU^{-1})**	**Ref**
1	Ultra-high sensitivity D-shaped PCF RI sensing	-	1.33-1.395	18,612	-	[26]
2	Dual core PCF -SPR for RI	450-1150 nm	1.33-1.44	11,200	505.037	[27]
3	A Gold-Plated Twin-Core D-Formed Photonic Crystal Fiber (PCF)	0.58-0.72 um	1.40-1.45	18,800	3152.7	[28]
4	Symmetrical Dual D shaped PCF sensor	850-1250 nm	1.36 and 1.41	14660	1222	[29]
5	SPR PCF D shaped	2.35-2.65um	1.20 to 1.29	11055 nm/RIU	-	[9]
6	SPR D-shaped PCF biosensor	1100-1300nm	1.33–1.354	294.11 nm/RIU	-	[15]
7	D-Shaped SPR-Based PCF Sensor	850 to 1350nm.	1.37 to 1.42.	19,600nm/RIU	2300	[21]
8	D-Shaped Photonic Crystal Fiber Refractive Index Sensor	1200-2400nm	1.37–1.41	6000 nm/RIU	-	[30]

The performance of a plasmonic sensor depends on structural parameters like pitch, air-hole diameter, and metal layer thickness, which are optimized individually to improve efficiency. Among these, confinement loss is a key factor affecting accuracy and

sensitivity in SPR sensors. It represents the loss of optical power as light propagates through the PCF core.
Fused silica has been implemented as a ground element. The RI of fused silica used to be determined from Sellmeier's formula as follows:

$$n(\lambda)^2 = 1 + \frac{a_1\lambda^2}{\lambda^2 - b_1^2} + \frac{a_2\lambda^2}{\lambda^2 - b_2^2} + \frac{a_3\lambda^2}{\lambda^2 - b_3^2} \quad (1)$$

Where n is the refractive index of silica, λ is the wavelength in μm, a and b are the Sellmeier coefficient, the Sellmeier coefficients used for the background materials are $a_1 = 0.6961663, a_2 = 0.8974794, a_3 = 0.1162414, b_1 = 0.4079426, b_2 = 0.068404, b_3 = 9.8966161$ [31][32].

The dielectric constant of gold is expressed by Drude-lorentz model

$$\epsilon_{Au} = \epsilon_\infty - \frac{\omega_D^2}{\omega(\omega + j\gamma_D)} + \frac{\Delta\varepsilon.\,\Omega_L^2}{(\omega^2 - \Omega_L^2) + j\Gamma_L\omega} \quad (2)$$

Where ϵ_{Au} The permittivity of dielectric material,ϵ_∞ is the permittivity at high frequency, and its value is 5.9673. The angular frequency can be expressed as $\omega=\frac{2\pi c}{\lambda}$,c is the velocity of light in vacuum. Moreover,ω_D and γ_D are the plasma frequency and damping frequency, respectively. whereas $\frac{\Omega_D}{2\pi}$ =2113.6 THz and $\frac{\gamma_D}{2\pi}$ =15.92 THz. The weighting factor is expressed as $\Delta\varepsilon$ =1.09 while $\frac{\Gamma_L}{2\pi}$ =104.86 THz and $\frac{\Omega_L}{2\pi}$ =650.07 THz are the spectral width and oscillator strength, respectively, of the Lorentz oscillators[33].
The permittivity of Gold can be expressed by Lorentz-Drude model

$$\varepsilon_{Ag} = \varepsilon_\gamma + i\varepsilon_i \quad (3)$$

$$\varepsilon_{Ag} = 1 - \frac{\lambda^2\lambda_c}{\lambda_p^2(\lambda_c + i\lambda)} \quad (4)$$

Whereas,ε_{Ag} The dielectric constant of Ag,ε_γ is the real part and ε_i is the imaginary part , λ_p=0.14541 and the value of λ_c =17.6140.

The radiative energy is absorbed by outer layer of PCF use perfectly matched layer and boundary condition. The equation for confinement loss is formulated as limited loss [34] [35],which give the relationship between Loss and imaginary part of RI by FEM.

$$\alpha \text{ (db/cm)}= 8.686\times\frac{2\pi}{\lambda} \times I_{imag}(n_{eff}) \times 10^4 \quad (5)$$

α is limited loss is wavelength in mm; imaginary part of effective RI is directly proportion to limited loss.

Wavelength sensitivity is obtained from the resonance shift with respect to analyte refractive index change [36][34]

$$S=\frac{\Delta\lambda_{peak}}{\Delta RI} \text{ nm/RIU} \quad (6)$$

5. Conclusion: This paper presents a concise review of PCF-based sensors for high-sensitivity optical sensing, focusing on SPR. Due to their microstructured design and strong light matter interaction, they offer better sensitivity, compactness, and flexibility than conventional systems. Various geometries like D-shaped, dual-core, and hollow-core PCFs are compared for refractive index, biochemical, and environmental sensing applications.

The comparative analysis shows that D-shaped and dual D-shaped PCF-SPR sensors achieve ultra-high sensitivities due to enhanced plasmonic coupling, while hollow-core designs provide low-loss and efficient analyte interaction. Recent advances in fabrication techniques and material integration further support the practical implementation of these sensors. Despite existing challenges related to fabrication tolerance and experimental validation, PCF-based SPR sensors remain a promising platform for next-generation optical sensing and compact multiparameter sensing systems.

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