

# Photonic Crystal Fiber-Based Selective Blood Components Optical Sensor with a Ring Core in THz Range

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## Original Research Abstract

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In this study, a highly sensitive optical sensor based on a photonic crystal fiber (PCF) is designed and simulated for the detection of blood components. The proposed structure employs a two-dimensional photonic crystal with a hexagonal lattice of air holes embedded in a silica dielectric. A hollow circular ring is incorporated at the fiber's core, serving as the sensing region where blood components are introduced. Changes in the refractive index of this region caused by the presence of different blood constituents directly affect the fiber's optical properties, including dispersion, confinement loss, and effective refractive index. Through comprehensive numerical simulations, these parameters were systematically analyzed across various wavelengths and frequencies. The results revealed distinct optical responses for each blood component, particularly within the 1.2  $\mu\text{m}$  to 1.4  $\mu\text{m}$  wavelength range, indicating high potential for selective detection and calibration. The designed sensor demonstrates excellent capability for distinguishing between different blood components, positioning it as a promising candidate for compact and accurate biomedical diagnostic applications.

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## 1. Introduction

In recent years, optical sensors have emerged as powerful tools across various domains, particularly in the biomedical field, due to their superior performance in speed, sensitivity, and immunity to electromagnetic interference. Traditional electronic sensors, while widely used, face limitations such as susceptibility to noise and slower response times [1,3]. To address these issues, the integration of photonic technologies has opened new avenues for designing advanced biosensors that rely solely on light propagation for signal acquisition and transmission. All-optical sensors, in particular, operate by converting biological phenomena into measurable optical signals, enabling real-time, high-

fidelity analysis without requiring electronic signal processing in intermediate stages [4,5]. Among the numerous platforms available for optical sensing, photonic crystals have garnered significant attention owing to their unique capability to manipulate light through periodic dielectric structures [6-8]. Photonic crystal fibers (PCFs), a subclass of these structures, have proven particularly advantageous for biosensing applications. They offer design flexibility, strong light-matter interaction, and tunability in optical characteristics through geometrical modifications. These attributes have positioned PCFs as leading candidates for detecting biological agents such as blood components, cancer cells, and pathogenic substances [8-12]. Depending on the configuration, PCFs can be

broadly categorized into hollow-core and solid-core designs, each with benefits and limitations. Hollow-core PCFs are known for their high sensitivity and narrow transmission spectra, but their performance is heavily reliant on the precise arrangement of air holes, making them complex to fabricate and maintain [13]. Conversely, solid-core PCFs offer improved mechanical robustness and ease of fabrication, though typically at the cost of reduced sensitivity [14]. To overcome these challenges and enhance sensitivity without compromising structural simplicity, researchers have proposed a range of innovative PCF designs. For instance, Park et al. introduced a high-index GeO<sub>2</sub>-doped silica ring surrounding a hollow core, significantly improving sensitivity and reducing confinement loss [15]. Olyaei et al. designed a modified hexagonal arrangement of air holes around a GeO<sub>2</sub>-doped ring core. By optimizing parameters such as core diameter, pitch, and number of hole layers, they achieved a relative sensitivity of 13.23% with a minimal confinement loss of  $3.77 \times 10^{-6}$  dB/m [16]. Morshed et al. further enhanced this approach by introducing four non-circular rings around the doped core, increasing the sensitivity to 16.88% while minimizing confinement loss to  $1.765 \times 10^{-8}$  dB/m [17]. The same research group later optimized this structure for toxic gas detection, including CH<sub>4</sub> and HF, achieving a remarkable sensitivity of over 42.47% and a confinement loss of  $4.783 \times 10^{-6}$  dB/m [18]. In an alternative configuration, P<sub>2</sub>O<sub>5</sub> was used in the outer ring to compare confinement losses with the GeO<sub>2</sub>-doped core, suggesting potential for further performance tuning [19]. Other notable advancements include hybrid microstructured PCFs, such as those proposed by Kawsar et al., where the core-cladding system is optimized for detecting benzene, ethanol, and water, offering a maximum sensitivity of 49.29% and an impressively low confinement loss of  $3.13 \times 10^{-10}$  dB/m for benzene detection [20]. On the experimental front, Dinish et al. demonstrated the practical viability of hollow-core PCFs for cancer cell detection, achieving a detection limit of 100 pg of protein in a sample volume of merely 10 nL [21]. In addition to gas and chemical sensing, PCFs have shown tremendous promise in biomedical diagnostics, especially for blood analysis. Blood is a complex fluid composed of numerous constituents, each with a distinct refractive index. This property makes it an ideal candidate for optical differentiation via refractive-index modulation.

Arunkumar et al [5] leveraged a photonic crystal-based resonant ring structure to detect multiple blood components, including hemoglobin, red and white blood cells, glucose, urea, albumin, and bilirubin by analyzing variations in resonance wavelengths and output power. Similarly, Wang et al [22] designed a two-zone PCF structure capable of detecting both minor and major refractive index changes using a self-collimation mechanism. Motivated by these advancements, the current work presents the design and simulation of an all-optical sensor based on a photonic crystal fiber optimized for blood component detection. The proposed structure employs a two-dimensional photonic crystal

with a hexagonal array of air holes embedded in a silica background, incorporating a hollow dielectric ring in the fiber core as the sensing region. By monitoring the optical characteristics such as dispersion, loss, and effective refractive index in response to various blood constituents in the sensing region, the sensor demonstrates high potential for accurate, rapid biomedical diagnostics.

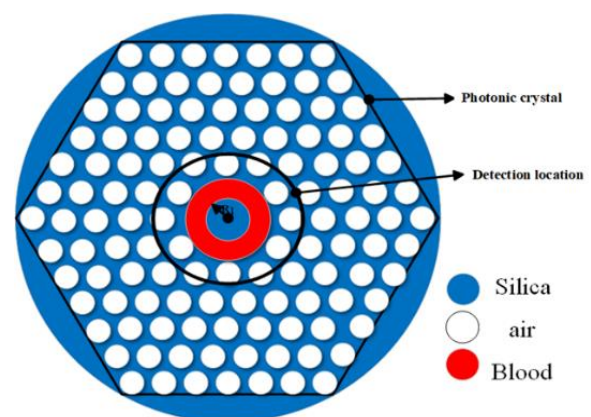
## 2. The proposed structure

The proposed photonic crystal fiber (PCF) sensor for detecting blood components is based on a two-dimensional photonic crystal architecture with a hexagonal lattice. This structure is fabricated using silica, as detailed in Table 1. A schematic representation of the sensor's geometry is provided in Figure 1. As illustrated in Figure 1, the photonic crystal comprises periodically arranged air holes embedded within a dielectric silica substrate, forming the foundational optical framework.

To configure a fiber geometry with a circular core suitable for sensing, the design incorporates a central silica core and an adjacent circular ring structure, which serves as the dedicated sensing region. This ring, essentially a hollow cylindrical cavity integrated within the photonic crystal structure, is designated for the introduction of blood samples. Since the refractive index within this region directly influences the photonic behavior of the entire structure, any variation in the blood sample's optical properties will manifest as measurable changes in the fiber's optical response.

The sensor's detection mechanism is fundamentally based on the refractive index modulation introduced by the blood analytes.

Each constituent of blood exhibits a distinct refractive index, and by engineering the fiber parameters such as the geometry of the sensing ring and the surrounding photonic structure, it becomes feasible to isolate and identify specific optical signatures corresponding to different blood components. The photonic crystal structure in this design features a lattice constant of 2  $\mu\text{m}$  and an air hole radius of 0.6  $\mu\text{m}$ , arranged in a matrix of 12 rows and 12 columns.



**Figure 1.** Photonic crystal fiber structure with ring core. The designated sensing region, clearly marked in Figure 1a, exhibits changes in its optical transmission

characteristics upon the infusion of biological samples. These variations can be calibrated to yield accurate identification of individual blood elements based on their unique interactions with the optical field. The refractive index of the silica material, which constitutes the background medium of the photonic crystal structure, plays a crucial role in determining the light propagation characteristics within the fiber. This refractive index is not constant but varies with wavelength, and it is accurately modeled using the Sellmeier equation [23], a well-known dispersion relation for dielectric materials. The Equation is given as:

$$n(\lambda) = \sqrt{1 + \frac{A_1\lambda^2}{\lambda^2 - C_1} + \frac{A_2\lambda^2}{\lambda^2 - C_2} + \frac{A_3\lambda^2}{\lambda^2 - C_3}} \quad (1)$$

Where  $n(\lambda)$  is the refractive index as a function of the wavelength  $\lambda$ , and  $A_i$  and  $C_i$  are the material-specific Sellmeier coefficients, typically determined through experimental fitting [23]. This wavelength-dependent refractive index is essential in simulating and analyzing the photonic bandgap behavior and mode confinement within the PCF sensor, thereby enabling precise control over its sensitivity and detection capabilities. In Equation (1), the parameter values used are consistent with those provided in Table 1, which are based on the foundational literature that forms the basis of this study.

These parameters have been carefully selected to ensure alignment with the established optical properties of silica, the background material used in the photonic crystal fiber (PCF) structure. By adhering closely to the reference values reported in the seminal work, the modeling framework achieves greater reliability and reproducibility.

This alignment not only strengthens the physical accuracy of the simulations but also enhances the credibility of the sensor's predicted performance, ensuring that the computational outcomes reflect real-world material behavior under similar conditions.

### 3. Methodology

The proposed photonic crystal fiber (PCF)-based sensor for blood component detection was investigated through numerical simulations using the Finite Element Method (FEM), which enabled precise modeling of electromagnetic wave propagation and detailed evaluation of the sensor's spectral response and refractive index sensitivity. The PCF structure, including the core, photonic cladding rings, and material dispersion properties, was rigorously defined, and Perfectly Matched Layer (PML) boundary conditions were applied to suppress spurious reflections and ensure accurate representation of light confinement and guidance within the fiber. Key parameters, including input wavelength, refractive indices of the core and cladding, and geometrical dimensions of the fiber, were systematically varied to optimize the sensor's performance in detecting subtle changes in blood composition. All simulations were performed using

Lumerical, which provides a robust FEM environment for modeling complex photonic structures and accurately predicting their optical behavior.

### 4. Simulation and results

Following the design phase, it becomes essential to rigorously assess the performance of the proposed photonic crystal fiber (PCF) structure in its intended role as a sensor for the detection of blood components. To this end, a comprehensive investigation into the optical behavior of the structure will be conducted. Given that the design is fundamentally a fiber-based configuration, it is crucial to perform a detailed analysis and characterization of its optical fiber properties to ensure optimal sensing performance for each specific blood constituent.

The ability of the sensor to produce unique and distinguishable optical responses for different blood components will serve as a key validation metric for the effectiveness and reliability of the design. Should the optical behaviors fail to exhibit adequate differentiation across the various components, a redesign or modification of the current architecture would be warranted.

In this context, three critical optical parameters known as chromatic dispersion, confinement loss, and effective refractive-index, must be examined in detail. These parameters directly influence the interaction of light with the analyte and are instrumental in determining the sensor's precision and sensitivity. As previously introduced, each of these metrics will be systematically evaluated in relation to the proposed PCF structure. For this analysis, five representative blood components have been selected based on their biomedical significance. The refractive index values and classification of these components are summarized in Table 2, serving as the basis for the diagnostic evaluations that follow [23].

The identification of specific blood components within the measurement area can be achieved by analyzing the dispersion values at a designated wavelength. Through the calibration of these dispersion values, it becomes feasible to develop a sensor capable of detecting various blood components with high accuracy. A noteworthy observation emerging from the analysis of the dispersion diagram, as depicted in Figure 2, is the pronounced divergence among the dispersion curves within the wavelength interval of 1.2  $\mu\text{m}$  to 1.4  $\mu\text{m}$ . This considerable separation suggests that this spectral window may represent an optimal region for sensor calibration, offering enhanced potential for achieving high sensitivity and specificity in the detection of blood components. The clear distinction between the dispersion profiles corresponding to different analytes implies that the proposed structure can effectively differentiate between subtle variations in refractive index, a key requirement for accurate biosensing.

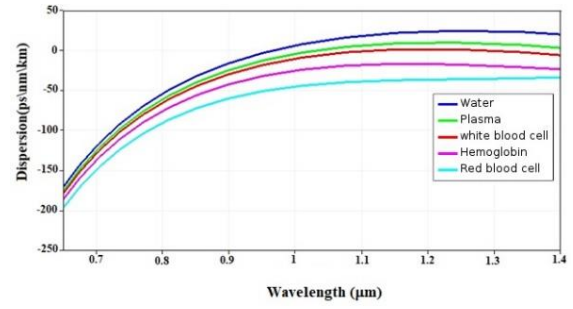
Another essential metric in evaluating the performance of optical fibers is the confinement loss, which plays a pivotal role in determining the sensitivity and efficiency of photonic crystal fiber (PCF)-based sensors. Figure 3 presents a detailed analysis of structural losses across

varying wavelengths for each of the selected blood components. As shown in **Figure 3**, the fiber exhibits unique and distinguishable loss profiles for each analyte. This differentiation in loss behavior, consistent with the dispersion trends observed earlier, reinforces the potential of the proposed structure to serve as a highly selective and sensitive optical sensor. By calibrating the sensor based on these distinct loss signatures, it is possible to enhance detection accuracy and tailor the sensing response for specific diagnostic targets.

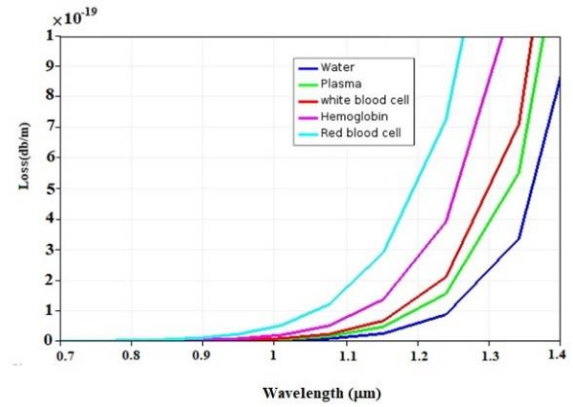
The effective refractive index constitutes a fundamental parameter in the design and performance evaluation of photonic crystal fibers (PCFs), particularly in the context of sensing applications. Since the interaction between light and various analytes, such as blood components, alters the refractive index profile of the sensing region, it is imperative to thoroughly investigate this parameter throughout the design process.

In **Figure 4**, the variation of the effective refractive index as a function of wavelength is presented for the selected blood components. The results demonstrate a clear trend: as the wavelength increases, the effective refractive index systematically decreases, while a decrease in wavelength leads to an increase in the refractive index. These variations highlight the sensitivity of the fiber’s optical response to both wavelength and the specific analyte present, making it a critical metric for sensor calibration and optimization.

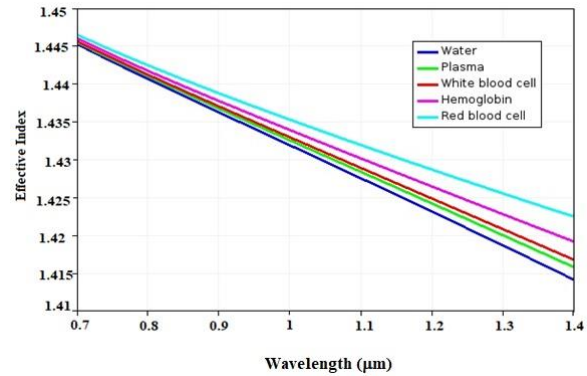
Moreover, as shown in **Figure 5**, the spectral sensitivity curve of the sensor in the wavelength range of 700 nm to 1400 nm exhibits a continuous and significant increase in sensitivity with increasing wavelength, rising from approximately 10 nm/RIU in the visible region to over 580 nm/RIU at 1400 nm.



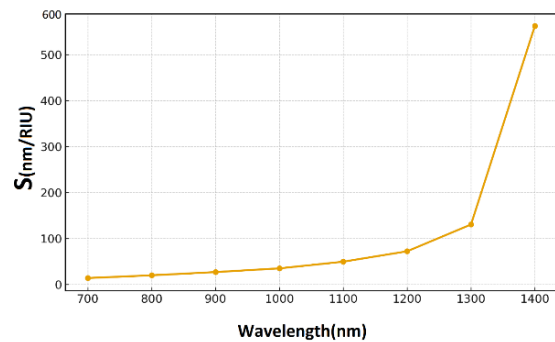
**Figure 2.** The dispersion diagram of the proposed structure



**Figure 3.** The Loss diagrams versus wavelength



**Figure 4.** The variation effective refractive index versus wavelength



**Figure 5.** sensitivity curve of the sensor

**Table 1.** The value of the main parameters

Parameter	Value
$A_1$	0.6961663
$A_2$	0.4079426
$A_3$	0.8974794
$C_1$	0.00467914826
$C_2$	0.0135120631
$C_3$	97.9340025

**Table 2.** The refractive index of blood components

Blood Component	Refractive index
Water	1.33
Plasma	1.35
white blood cell	1.36
Hemoglobin	1.38
red blood cell	1.4

**Table 3.** Comparative Table of the Proposed Structure with Similar Works

Ref No.	Sensor Structure Type	RI Range	Sensitivity (nm/RIU)	Loss(dB/m)	Numerical Method
[24]	PCF	1.36 – 1.41	14,500	-	FEM
[25]	PCF	1.00 – 1.08	1,450–3,000	$10^{-6}$	FDE
[26]	MZI-based PCF	1.440 – 1.450 (film)	221	-	FEM
[27]	D-shaped PCF	1.23 – 1.43	70,000	$2.59 \times 10^{-2}$	FEM
[28]	PCF	1.00 – 1.08	1,450–3,000	$10^{-6}$	FDE
[29]	Hexagonal H-PCF	1.354 – 1.407	90.65–94.4	$2.11 \times 10^{-9}$ dB/m	FV-FEM
This work	Hexagonal H-PCF	1.33-1.4	540	$2.11 \times 10^{-19}$	FEM

This pronounced enhancement can be attributed to the deeper penetration of the electromagnetic field into the sample medium and the strengthened optical interaction between the guided optical mode and the analyte in the near-infrared (NIR) region. Within this spectral range, the plasmonic or photonic field becomes more strongly confined at the sensor analyte interface, making the device highly responsive to small variations in the refractive index of the surrounding medium. From a physical perspective, the increase in wavelength amplifies the interaction between the optical field and the effective refractive index, resulting in larger phase shifts and more pronounced resonance wavelength shifts.

Moreover, wavelengths above 1200 nm lie within the biological transparency window, where the absorption coefficients of water, hemoglobin, and other blood constituents are minimal. Consequently, optical losses are reduced, and the signal-to-noise ratio is significantly improved. These characteristics indicate that operating the sensor in longer wavelength regions enhances not only its spectral sensitivity but also its optical stability and detection precision. Therefore, selecting the near-infrared region, particularly the 1200 nm to 1400 nm range, as the optimal operational window can provide superior performance in refractive index-based detection of blood components, enabling high spectral resolution, accuracy, and linear response to biochemical variations.

Table 3 compares six photonic crystal fiber (PCF)-based sensors in terms of structure type, refractive index range, maximum wavelength sensitivity, loss characteristics, and numerical method used.

## 5. Conclusion

In this study, a novel photonic crystal fiber (PCF) sensor design was proposed for the detection and differentiation of various blood components based on their unique optical responses. The structure was based on a two-dimensional hexagonal photonic crystal configuration fabricated from silica, with a circular hollow ring designated as the sensing region. The analysis focused on three key optical parameters: dispersion, confinement

loss, and effective refractive index, each of which was evaluated with respect to both wavelength and frequency. The simulation results demonstrated clear distinctions in the optical behavior of the sensor for different blood components, particularly within the wavelength range of 1.2  $\mu\text{m}$  to 1.4  $\mu\text{m}$ , which emerged as an optimal operational window due to enhanced sensitivity. The dispersion curves showed significant separation among the analytes, while the loss characteristics and effective refractive index profiles further confirmed the structure's ability to reliably differentiate between blood constituents. These findings affirm the potential of the proposed PCF design as a highly sensitive and tunable optical biosensor. Future work may focus on the experimental realization of the design, as well as further optimization of the structural parameters to enhance performance for specific biomedical diagnostic applications.

### Authors Contribution

All authors have contributed equally to prepare the paper.

### Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

### Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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