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Designing an Advanced Biosensor for Rapid Analysis and Detection of Blood Components

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Abstract— In this study, we propose a novel biosensor based on a hexagonal-shaped microcavity with two slot waveguides within a two-dimensional photonic crystal. The biosensor aims to detect various blood components by utilizing a refractive index measurement. The device operates in the TM-polarized light wavelength range of 1150-1880 nm. It consists of two slot waveguides coupled with a hexagonal-shaped microcavity, formed by removing seven lattice holes. The microcavity is separated from the waveguides by two holes. When the analyte infiltrates the cavity, it induces a change in refractive index, leading to a wavelength shift at the output terminal. The proposed design achieves a high sensitivity of over 687.496 nm/RIU. The simulation of the proposed design is performed using both the Plane Wave Expansion (PWE) method and the Finite-Difference Time-Domain (FDTD) algorithm. The results demonstrate that the slot waveguide configuration provides excellent transmission.

Index Terms— Blood components, micro cavity, PhC biosensor, sensitivity.

I. INTRODUCTION

A photonic crystal (PC) is a dielectric structure with periodicity that enables manipulation and guidance of light on the optical wavelength scale. This concept was initially proposed by E. Yablonovitch and S. John in 1987 [1],[2] and has since been extensively studied both theoretically and experimentally [3]-[8]. The key characteristic of a PC is the existence of a photonic band gap (PBG), which prevents the propagation of light within a specific frequency range. However, introducing defects in the PC disrupts the periodicity of the structure, resulting in strong confinement of the electromagnetic field, small mode volume, and low extinction loss. By adjusting the structural parameters or infusing appropriate materials into the PC's air holes, the propagation of light can be tailored to specific requirements, making PC-based devices highly valuable for applications such as filters [9], demultiplexers [10], switches [11], and polarization converters [12].

Research on the utilization of photonic crystals as sensors shows great promise owing to their exceptional miniaturization (0.1-mm² detection area), high spectral sensitivity, and compatibility with integration into Micro-Electro-Mechanical Systems (MEMS). In this regard, numerous structures based on integrated optics have been suggested to harness the optical characteristics of photonic crystals. These groundbreaking photonic devices find applications in diverse sectors of the industry

and high technology, encompassing telecommunications (photonic crystal fibers), optoelectronics (lasers, photodetectors), and, more recently, bio detection [13]-[17].

Detection utilizing photonic crystals relies on the heightened sensitivity of localized modes observed in the transmission spectra, resulting from variations in the refractive index of the analyte. Extensive research has been conducted on sensors employing two-dimensional microcavity photonic crystals, showcasing their theoretical and experimental prowess in detecting biochemical elements [18], [19]. Additionally, other authors have proposed optical biosensors based on photonic crystal waveguides, some of which are coupled with resonant cavities. These configurations offer several advantages, including compactness, high sensitivity, scalability to multi-channel sensors, a wide range of compatible materials, and parallel measurement capabilities. Recently, these sensors have demonstrated their proficiency in detecting refractive index changes by measuring the shift in resonance wavelength within the transmission spectrum [20]-[22].

In this paper, we present a novel biosensor architecture aimed at achieving higher sensitivity for the detection of blood diseases. The proposed architecture is based on a 2-D Photonic Cristal (PhC) structure with a hexagonal lattice of air holes, incorporating two elliptical waveguides and one microcavity. The selection of physical and geometrical parameters has been carefully optimized to ensure both optimal sensitivities and high transmission values. This biosensor offers several advantages over alternative blood disease detection methods. Firstly, it exhibits significantly enhanced sensitivity, enabling the detection of even the slightest changes in blood composition. Moreover, it boasts high accuracy and can detect a wide range of different diseases.

II. DESCRIPTION OF THE BASIC PHOTONIC CRYSTAL DESIGN

As depicted in Fig. 1(a), the photonic crystal structure utilized in this study has dimensions of (21x19). It comprises a hexagonal lattice with a spatial period of 470 nm. The lattice consists of silicon wafer with periodically arranged air holes ($r = 190$ nm). The refractive index of silicon is $n(\text{Si}) = 3.42$, while the refractive index of air is $n(\text{air}) = 1$. This lattice structure holds practical significance due to its wide transverse electric bandgap and potential applications in photonic integrated circuits and ultra-compact optical sensors.

To determine the photonic band gap (PBG), numerical methods like the plane wave expansion (PWE) theory are commonly employed. In this work, the RSoft software (BandSOLVE) was utilized, which applies the PWE theory to solve the complex Maxwell fully vectorial equations for 2-D periodic dielectric structures. The dispersion diagram was analyzed using a 2-D PWE method. The regular photonic crystal structure exhibits a large bandgap ranging from 1150nm to 1880 nm for TM polarization, while smaller bandgaps are observed for TE polarization (see Fig. 1(b)).

In the band diagram, the horizontal and vertical axes represent the wave vector and normalized frequency, respectively. The wave vector is calculated within the Brillouin zone, which encompasses the entire periodic structure. The normalized frequency of the photonic crystal structure is given by

$\omega a/2\pi c = a/\lambda$, where ω is the angular frequency, a is the lattice constant, c is the speed of light in free space, and λ is the free space wavelength.

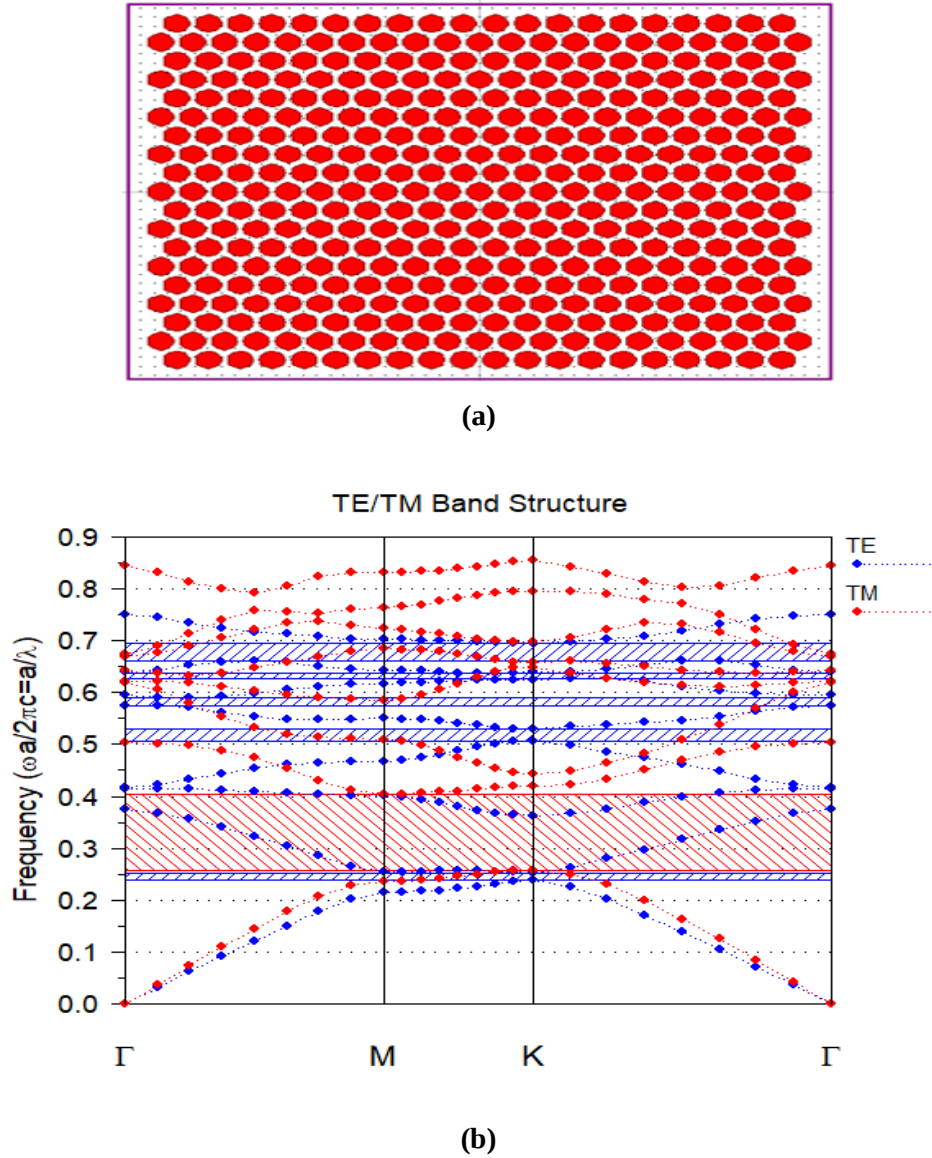


Fig. 1. (a) Schematic of the proposed 2D-PhC structure, (b) Band diagram of the proposed 2D-PhC Structure

III. SIMULATION, RESULTS AND DISCUSSION

A. The First Proposed Design of Photonic Crystal Biosensor (Design A)

The 2D hexagonal shape of our photonic crystal (PC) sensor consists of two horizontally aligned waveguides and a resonant cavity between them. Fig. 2 illustrates our structure. The quasi-waveguides are formed by removing a row of seven air holes (in the ΓK direction), The cavity consists of six infiltrated holes, arranged in a circle around a central hole. The six peripheral holes, with radius $r=0.19\mu\text{m}$, are cyan in color and surround a light-gray central hole with radius $r_c=0.25\mu\text{m}$. On either side of the cavity, two additional holes, one green and with radius $r_1=0.13\mu\text{m}$, the other dark grey and with radius $r_2=0.17\mu\text{m}$, act as separators between the waveguides and the cavity. These holes form a harmonious structure in which each element plays a specific role in the overall

organization of the cavity. Aiming to produce localized optical modes that resonate inside the cavity. During the simulation, a Gaussian light source of 1550nm with TM polarization is positioned at the entrance of the waveguide, while a power monitor is placed at the output end of the waveguide to gather data on transmission spectra.

The spectral response of the cavity without the sample is shown in Fig. 3(a). Under TE polarization, when the PhC cavity is resonant, two sharp Lorentzian-shaped peaks emerge within the complete PhC bandgap. In this situation, the cavity exhibits two resonant modes at wavelengths of 1.25374 μm and 1.69863 μm . To quantitatively assess the structure's sensing properties, the resonant mode at $\lambda = 1.69863 \mu\text{m}$ is selected to monitor the shift in wavelength.

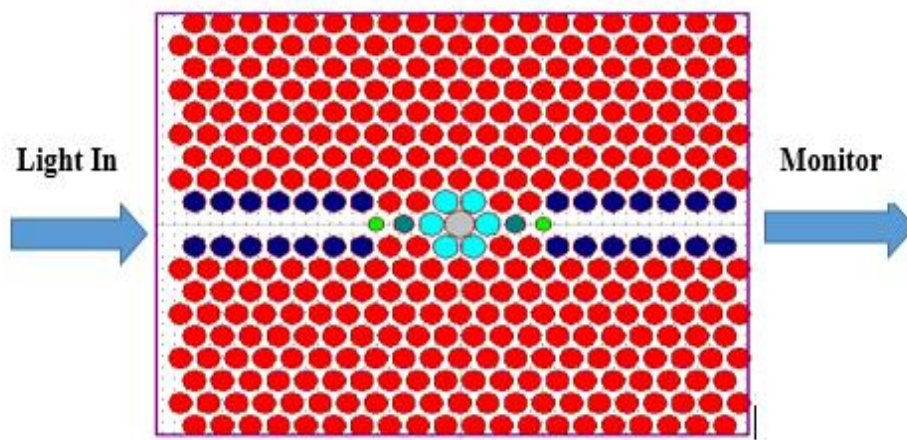


Fig. 2. Schematic of the first proposed 2D-PhC biosensor

To demonstrate the operational principle of the RI biosensor based on the PhC cavity, a series of FDTD simulations were performed, as shown in Fig. 3(b). The initial analysis involved simulating the localized infiltration of de-ionized (DI) water into the sensing region of the cavity, which corresponds to a change in the refractive index (RI) of the holes from 1 (air) to 1.33 (DI water).

The optical detection capabilities of the designed structure were evaluated by quantitatively estimating the sensitivity parameter $S (\Delta\lambda/\Delta n)$, which represents the ratio of the wavelength shift ($\Delta\lambda$) to the change in refractive index (Δn) caused by the analyte infiltration. The results revealed a red shift in the resonant wavelength of the output signal, indicating an increase in the refractive index within the sensing area and confirming successful analyte detection. Specifically, as shown in Fig. 3(b), a refractive index variation of $\Delta n = 0.33$ between air and water led to a spectral red shift of 0.12283 μm , corresponding to an impressive sensitivity of 372.21 nm/RIU (refractive index unit).

B. The Second Proposed Design (Design B)

To enhance the performance of our device by modifying the waveguide shape, we have proposed a biosensor design where the waveguide holes are transformed into slots with a radius of $R=0.19\mu\text{m}$. This results in a slot-shaped waveguide, as illustrated in Fig. 4. The shape and dimensions of the

waveguide play a crucial role in determining the propagation of light within the structure, as well as the localization and resonance of optical modes inside the cavity. By adjusting the size and shape of the waveguide, it becomes possible to optimize the sensor's sensitivity to changes in the analyte's refractive index. However, it is important to acknowledge that other parameters, such as the central wavelength and waveguide shape, also significantly impact the sensor's performance. The geometry of the photonic crystal, with its hexagonal lattice of air holes and elliptical waveguides, plays a crucial role in the confinement of light and its interaction with the analyte. The elliptical waveguides, in particular, allow for the optimization of sensitivity by increasing the overlap between the optical mode and the analyte. This design facilitates a more effective interaction between light and the analyte, enhancing the sensor's detection capabilities. The chosen central wavelength also influences the sensor's performance, as it determines how light is confined within the photonic crystal and how it interacts with the analyte. A precise adjustment of the wavelength amplifies the optical interactions with the analyte by creating resonant conditions that detect changes in its properties, such as its refractive index.

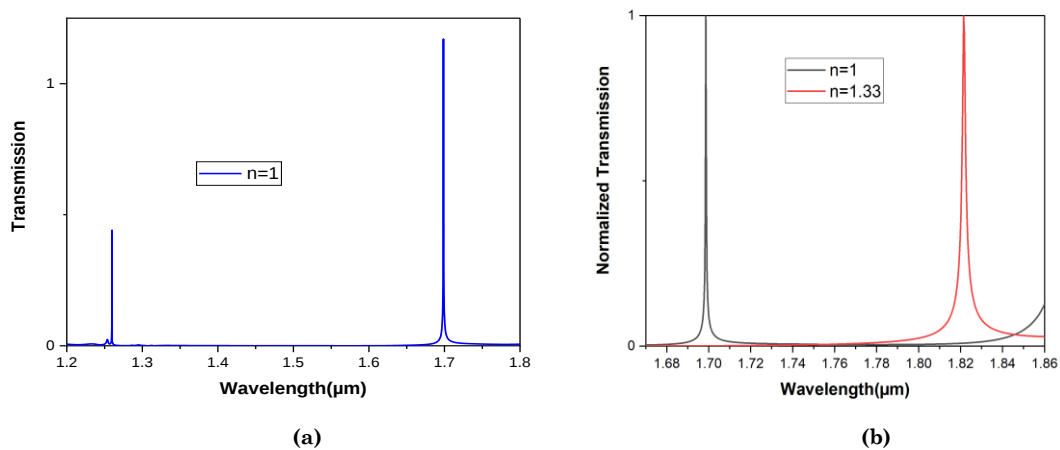


Fig. 3. (a) The transmission spectra of the designed device before the sample infiltration, (b) Normalized transmission spectrum for the first proposed design for $n=1$ and $n=1.33$

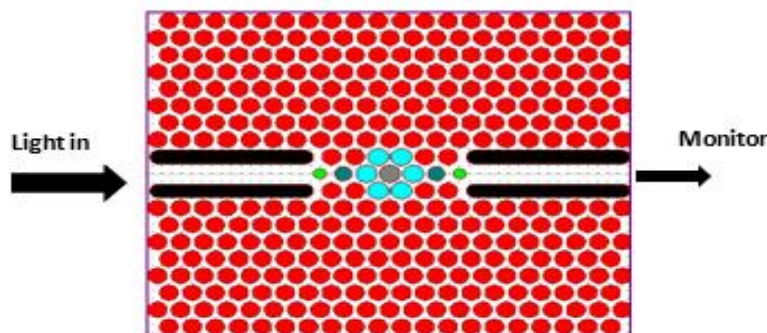


Fig. 4. Schematic of the proposed 2D-PhC biosensor

Initially, the first design was simulated, and it exhibited a sensitivity of 372.21 nm/RIU (refractive

index unit) in detecting changes in the analyte's refractive index, as shown in Fig. 3.

Subsequently, modifications were implemented to enhance the performance of the sensor's structure (first design). These modifications resulted in a significant improvement in light transmission through the sensor. Furthermore, the sensitivity of the sensor also increased, reaching an impressive value of 687.496 nm/RIU, as depicted in Fig. 5. To further optimize performance, it was then necessary to design a structure with a high-quality factor, a crucial requirement for photonic crystal microcavity devices. Indeed, almost all types of integrated optical devices, whether active or passive, based on microcavities are designed to operate only with selective frequency propagation modes. It was thus determined that for a radius of $R=0.24\mu\text{m}$, the quality factor is $Q=2072$.

This interpretation suggests that the structural modifications made to the sensor resulted in a substantial enhancement of its performance. The increased light transmission and sensitivity imply that the sensor is capable of detecting even finer variations in the analyte's refractive index. Such capability can prove highly valuable in applications like blood component detection, where subtle changes can indicate the presence of certain medical conditions. A biosensor consists of two primary components: a bio-receptor and a transducer. The bio-receptor, typically a biological molecule, specifically binds to the analyte or bio-target. The transducer, which can be physical, piezoelectric, thermal, electrochemical, acoustic, or optical, converts the interaction between the analyte and the receptor into a measurable signal.

When the analyte binds to its corresponding receptor on the surface of the sensor, it induces a change in the local refractive index. This change is particularly significant when a high-quality cavity is used, as it tightly confines the electric field. Even slight variations in the refractive index can cause a noticeable shift in the localized mode, leading to a measurable change in the resonance wavelength.

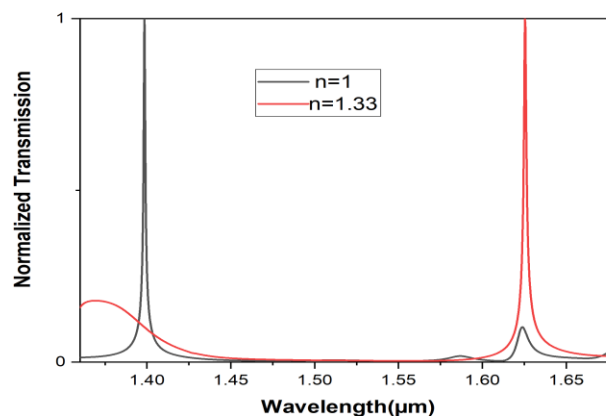


Fig. 5. Normalized transmission spectrum for the second proposed design $n=1$ and $n=1.33$

As depicted in Fig. 6, the Synoptic Biosensor Diagram: Detecting Blood Components, a blood sample is applied to the surface of the photonic crystal sensor, which is usually made from a silicon wafer. When biomolecules in the blood come into contact with the sensor, they alter the refractive

index. These optical changes are then detected and analyzed by computer systems to identify specific blood components.

The transmission spectrum for various blood components is generated using the output from the RSoft simulation tool. A frequency shift is observed as the refractive index changes in relation to the different blood components. Table I. presents the input refractive indices, and the corresponding wavelength shifts for each component. It is crucial to note that in biosensing applications, the magnitude of the resonant wavelength shift depends on several factors, including the effective change in the target's refractive index. Additionally, the relationship between refractive index variation and wavelength shift is influenced by the sensor's design and the optical properties of the materials used. Fig. 7 depicts that the spectral position of the detected resonating peak, located at the end of the output waveguides, shifts towards longer wavelengths as the refractive index (RI) of the biosensor increases. This wavelength shift is observed for RI values of 1.34, 1.35, 1.36, 1.38, 1.43, 1.45, 1.452, respectively, which is consistent with previous studies [5].

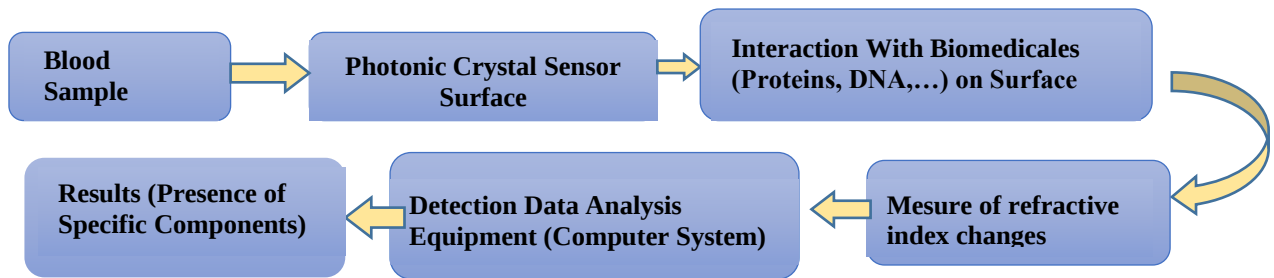


Fig.6. Synoptic Biosensor Diagram: Detection of Blood Components

The analysis of the band structure reveals that the sensor is highly sensitive to minor changes in the refractive index. Fig. 8 clearly shows the direct proportionality between the refractive index and the wavelength demonstrating the sensor's capability to detect even small variations in the sample's refractive index.

TABLE I. THE REFRACTIVE INDEX OF DIFFERENT COMPONENTS IN BLOOD [20]

Name	Refractive Index	Wavelength(μm)
Cytop	1.34	1.632067
Blood Plasma	1.35	1.638753
Ethanol	1.36	1.645224
Emoglobin	1.38	1.658045
Stylgard	1.43	1.690276
Biotine Streptavidin	1.45	1.702941
Polycrylamide	1.452	1.704102

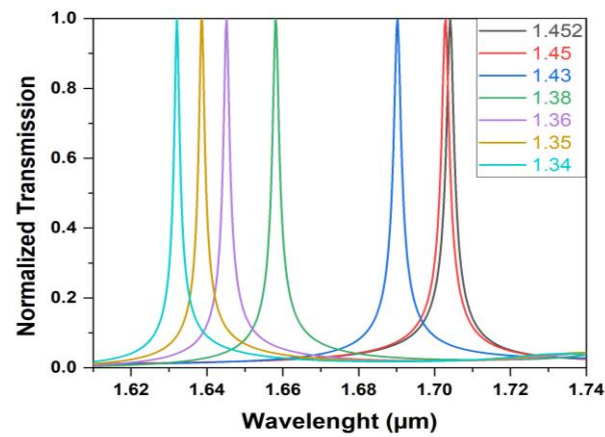


Fig. 7. Variation of the Normalized transmission for different components in blood

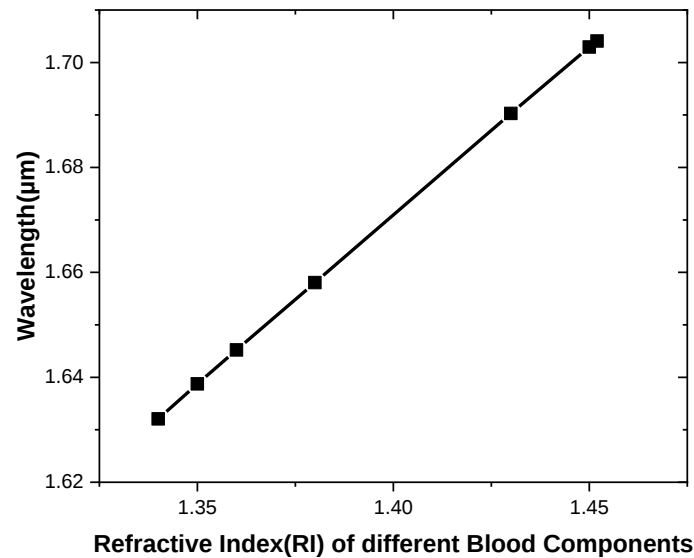


Fig. 8. Refractive index (RI) versus Wavelength

The sensitivity of the sensor is compared with that of similar recent studies, as shown in Table II. The proposed sensor exhibits greater sensitivity than those reported in the references. This highlights the exceptional sensing performance of the sensor presented in this paper.

TABLE II. COMPARISON OF THE PERFORMANCE PARAMETERS BETWEEN SIMILAR RECENT WORKS AND THIS WORK.

Reference	Sensitivity (nm/RIU)	Published Year
[19]	165.45	2013
[20]	343	2015
[5]	462	2017
[10]	609.25	2021
[21]	421	2023
Current work	687.496	/

IV. CONCLUSION

Two photonic crystal refractive index sensor structures were designed and proposed in this paper. The structures were based on a hexagonal lattice. The sensors were numerically simulated using the

finite difference time domain method. The first design exhibited a maximum sensitivity, and minimum detection limit of 372.21 nm/RIU. The second design achieved a record-breaking sensitivity of 687.49 nm/RIU as calculated in this paper. These structures proposed in the study serve as promising candidates for detecting various blood components. The simulation and analysis of the refractive index sensors were conducted using two-dimensional finite difference time domain and plane wave expansion methods. The results demonstrate that the designed structures exhibit remarkable sensitivity to variations in refractive index, capable of detecting a range from 1 to 1.452, and surpassing the performance of previously reported structures in the literature.

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