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Design and Analysis of 2D Photonic Crystal Based Biosensor to Detect Different Blood Components

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Abstract: In this paper, a photonic crystal ring resonator based bio sensor is designed to sense different blood constituents in blood in the wavelength range of 1530 nm–1615 nm for biomedical applications. The blood constituents such as hemoglobin white blood cell, red blood cell, blood sugar, blood urea, albumin, serum bilirubin direct, and ammonia are sensed for the corresponding transmission output power, Q factor, and refractive index changes. As the blood constituent has unique refractive index, the resonant wavelength and output power are varied from one to another, which are used to identify the blood constituents.

Keywords: Photonic crystal; plane wave expansion (PWE); finite difference time domain (FDTD); biosensor; blood components

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1. Introduction

In recent years, several diseases are reported from season to season across the world. It can be identified and rectified by analyzing blood components in a patient [1, 2]. Blood analysis plays a keen role for the detection and prevention of hematological disorders which cause many non-communicable diseases naming cardiovasalar disease, cancer, diabete, respiratory disease, and many unnoticeable diseases which bring 50 million deaths every year worldwide [3–7].

Blood is a body fluid for human which is composed of blood cells suspended in blood plasma about 55%. It also contains proteins, glucose, mineral ions, hormones, albumin, red blood cells, white blood cells, and platelets [8, 9]. The physical, chemical, and biological properties of the blood constituents are varied from person to person and disease to disease. Hence, the dielectric value of blood constituents is unique which is highly useful to identify the diseases for various medical applications [10–12]. The name of the blood components, normal range, and its health issues are reported in Table 1.

The conventional blood analysis is a laboratory analysis taking a blood sample from human body. For majority tests, blood is usually obtained from a patient's vein. There are several methods available to analyze the blood components by using methods such as flame atomic absorption spectrometry, graphite furnace atomic absorption spectrometry, laboratory anodic stripping voltammetry (ASV), portable ASV, and inductively coupled plasma mass spectrometry [13, 14]. The time to analyze the blood is about 24–72 hours. It also requires more blood samples for detection.

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Table 1 Names of the blood components, normal range, and health issues.

Name of the blood components	Normal range	Health issues
Hemoglobin	Male : 13.5 gms/dl–17.0 gms/dl Female : 12.5 gms/dl–15.5 gms/dl	> Lung disease, cancer < anemia
White blood cell	4500 Cells/cumm–11000 Cells/cumm	> Leukemia < infection
Red blood cell	Male: 4.5 Million cells/cumm–6.0 Million cells/cumm	> Heart diseases < anemia
Blood sugar	80 mg/dl–110 mg/dl	> Diabetes
Blood urea	20 mg/dl–40 mg/dl	> Heart diseases < kidney diseases
Albumin	3.4 gms/dl–5.4 gms/dl	> Kidney diseases < liver diseases like hepatitis
Serum bilirubin direct	0.3 mg/dl–1.0 mg/dl Child : up to 11.0	> Jaundice, liver cancer < no issues
Serum bilirubin direct	0 mg/dl–0.3 mg/dl Child : up to 0.25	> Jaundice, liver cancer < no issues
Ammonia	10 mmol/L–47 mmol/L	> Cirrhosis, severe hepatitis < high blood pressure
Alkaline phosphatase	350 IU/L–570 IU/L	> Bone cancer, liver cancer, heart failure < celiac disease (or) deficiency in vitamins and minerals

Alternatively, the optical bio-sensing method is employed for blood analysis which gives results with lesser time and a very small amount of blood samples are sufficient for detection. There are two methods available for blood analysis such as florescence based detection method and label free detection method. As the quantitative analysis of blood is very difficult in florescence based detection, the label free detection method is employed vibrantly. In the label free detection method, the blood analysis is carried out by knowing the value of refractive index of the target sample [14, 15].

The photonic sensing technology using photonic crystal (PC) enables the new measurement possibility for blood constituent analysis. As the permittivity of the biological molecules is greater than those of air and water, the propagation of electromagnetic waves is varied while passing through the structure. Owing to the aforementioned process, the analytes are easily identified and detected, which can be further used for medical applications [16]. PCs are periodic nanostructures that affect the motion of photons in the same way as the periodic potential in a semiconductor crystal affects the electron motion by defining allowed and forbidden electronic energy bands. In general, PCs are composed of periodic dielectric and metallo-dielectric nanostructures which have alternative lower and higher dielectric constant materials in one, two, and/or three dimensions to affect the propagation of electromagnetic waves inside the structure. As a result of this periodicity, the transmission of light is absolutely zero in certain frequency ranges, which is called photonic band gap (PBG) [17, 18]. By introducing defects in these periodic structures, the periodicity and thus the completeness of the PBG are entirely broken, which allows to control and manipulate the light. Two dimensional photonic crystals (2DPC) are receiving much attention from the research and scientific community in designing the optical devices as they have attractive features including better confinement of light, efficient PBG calculation, effective control of spontaneous emission, relatively simple fabrication than 3DPCs, and easy integration with other devices [18]. 2DPC based optical devices, such as optical sensors [19], filters [20], multiplexers, de-multiplexers, directional couplers, power dividers/splitters, logic gates, and switches [21], have already been reported.

Typically, two sensing schemes are reported in the photonic sensing technology, namely, the resonant wavelength shift scheme and the intensity reduction scheme. In the first scheme, the resonant wavelength shift is noticed for different values of analytes. Alternatively, the intensity is reduced while varying the dielectric parameters of the analytes [22–26]. There are several methods reported to sense the refractive index change of various biosensors, namely brass grating, Mach-Zehnder interferometer, and micro ring resonator [23, 24]. The micro ring resonator offers highly desirable results as it provides higher sensitivity and higher output power. However, the bending loss and radiation loss are very high that the radius of the ring resonator is less than 5 μm which can be reduced through a photonic crystal ring resonator [27–34].

In present work, a photonic crystal ring resonator (PCRR) based sensor has been designed and simulated for detection of different blood components, namely, urethame dimethacrylate, bovine serum albumin, polyacrylamide, biotin-streptavidin, sylgard184, glucose (40 gm/ 100 ml), hemoglobin, ethanol, blood pPlasma, cypton, and water, and the effect of sensor parameters are also investigated. In the remaining parts of this paper, Section 2 represents the numerical analysis of the proposed sensor. Section 3 represents the design of PC ring resonator based biosensor of the proposed sensor. The simulation results and its significance are presented in Section 4. Section 5 draws conclusions.

2. Numerical analysis

Usually, the photonic crystals exhibit property called photonic band gap (PBG). Whether photons propagate through the structure or not depends on the wavelength. Disallowed bands of wavelengths are called PBG. There are many methods, such as transfer matrix method (TMM) [35], finite difference time domain (FDTD) method [36], plane wave expansion (PWE) method [37], and finite element method (FEM) [38], are available to analyze the dispersion behavior and transmission spectra of PCs. Each method has its own pros and cons. Among these, PWE and FDTD methods are dominant with respect to their performance, and they also meet the demand to analyze the PC based devices. The PWE method is initially used for theoretical analysis of PC structures, which makes use of the fact that eigen modes in periodic structures can be expressed as a superposition of a set of plane waves. Although this method can obtain an accurate solution for the dispersion properties (propagation modes and band gap) of a PC structure, it has still some a limitation that transmission spectra, field distribution, and back reflections cannot be extracted because it considers only propagating modes. An alternative approach which has been widely adopted to calculate both transmission spectra and field distribution is based on numerical solutions of Maxwell's equations by using the FDTD method. In this analysis, the PWE is used to calculate the band gap and propagation modes of the PC structure whereas 2DFDTD is used to calculate the spectrum of the power transmission [39].

Since the transmission of electromagnetic waves in certain range of frequencies is prohibited, there is no propagation of light over some order of wavelength [40]. The light propagation can be manipulated by the defect mechanism. The line defect in the ring resonator acts as a waveguide. To increase the sensitivity of the PC, the ring resonator is utilized here. In the ring resonator, the resonant wavelength and the output power can be altered whenever the refractive index of the sample gets varied. The PC functions as sensor can be proved by solving Maxwell's electromagnetic equation.

$$\nabla \times \left(\frac{1}{\varepsilon} \nabla \times \mathbf{H} \right) = \left(\frac{\omega}{c} \right)^2 \mathbf{H} \tag{1}$$

where **H** is the magnetic field and C is the speed of light. Also ε is the permittivity (dielectric function $\varepsilon=\eta^2$ or $\eta=\sqrt{\varepsilon}$ where η is the refractive index) and ω is the frequency of resonance. It is observed that when the dielectric function changes, the frequency also changes. From (1), it is noticed that the dielectric function ε is inversely proportional to frequency ω [41, 42]. The sensing performances of the structure can be analyzed by

$$L_{\text{eff}} = Q\lambda / (2\pi\eta) \tag{2}$$

where L_{eff} is the effective interaction length, Q is the resonator quality factor, λ is the resonant wavelength, and η is the refractive index of ring resonator [43].

3. Design of PC ring resonator based biosensor

The designed PC based biosensor consists of the cubic array of circular rod placed in a background of air which is shown in Fig. 1. In the cubic lattice, numbers of rods in X and Z directions are 21 and 17, respectively. The radius of the rod is 100 nm, where the distance between the adjacent two rods is 540 nm, which is also called as lattice constant denoted by "*a*". The dielectric constant of circular silicon rod is 11.97 (refractive index n=3.46) of the structure. The sensor has an elliptical shape of resonator which is placed in the middle of the structure, and the circular rod front and back radius is 100 nm. The sensor contains two ports, namely, input and output ports, which are used to propagate and analyze the optical signal with different wavelengths.

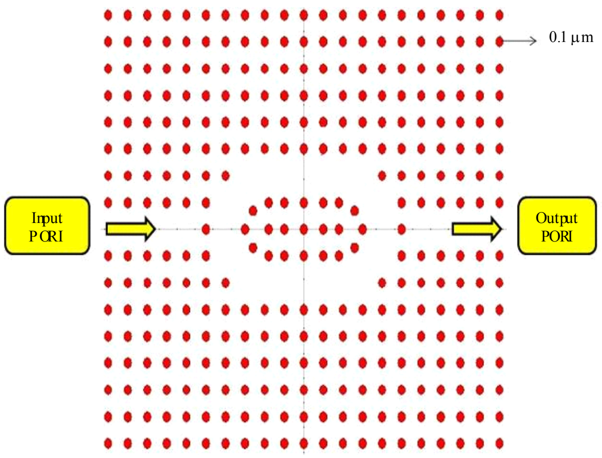


Fig. 1 Proposed biosensor using elliptical ring resonator.

The plane wave expansion method is used to find the PBG of this proposed structure. The propagation mode and PBG of the proposed structure are shown in Fig. 2(a). The normalized frequency of the PC structure is $\omega a/2\pi c=a/\lambda$, where ω is the angular frequency, a is the lattice constant, c is the velocity of light in free space, and λ is the free space wavelength. The band diagram has a PBG of two TE modes at different wavelength ranges, which are 1200 nm to 1800 nm and 814 nm to 748 nm. The PBG ranging from 1200 nm to 1800 nm is appropriate to the third window, and it is accounted for this attempt.

Figure 2(b) depicts the band diagram of the proposed elliptical ring resonator after introducing the line and point defects. The guided mode shows that there is a propagation mode inside the PBG region owing to incorporation of elliptical shape ring resonator in the periodic structure. The sensor is designed through line and point defects. The 3D view of proposed PC based sensor is shown in Fig. 3, which gives the overall size of 11.4 μm × 9.2 μm.

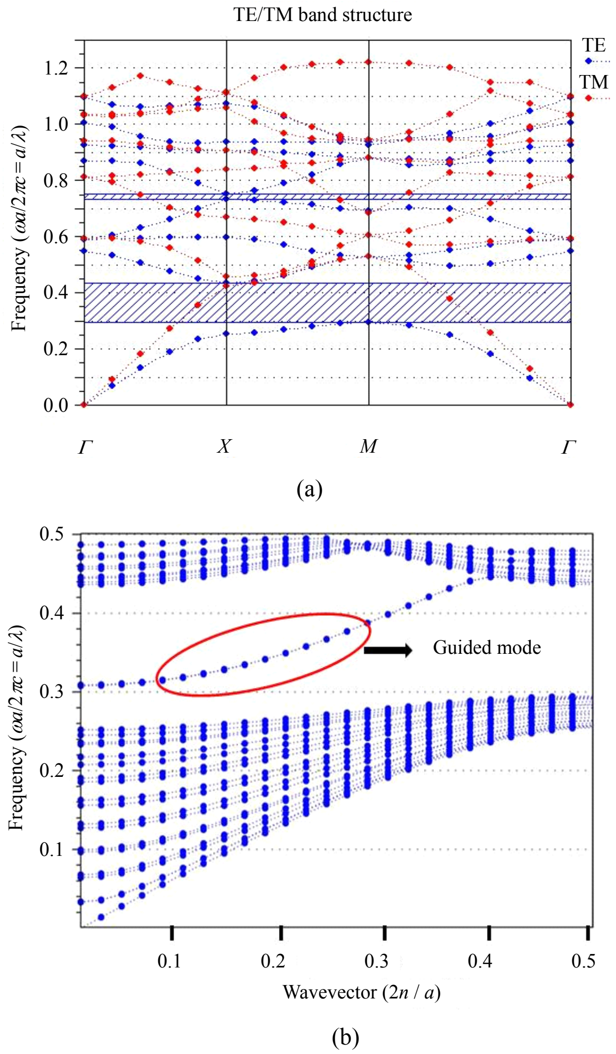


Fig. 2 Band diagram for circular rods in 21 × 17 square lattice: (a) without any defects and (b) with line and point defects.

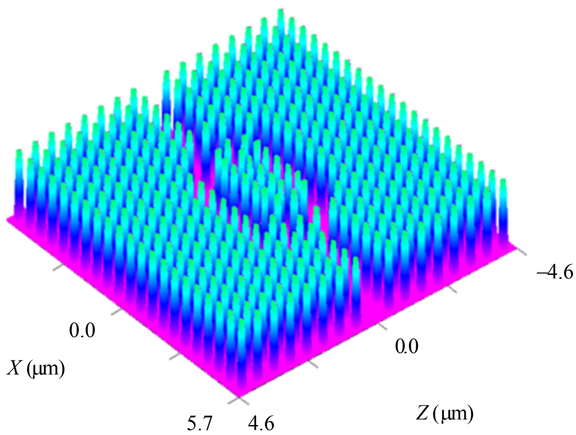


Fig. 3 3D structure of biosensor.

4. Simulation results and discussion

When light signal propagates into the waveguide and passes the elliptical shape of resonator, the output signal power is measured from the power monitor positioned at the output port of the sensor. The obtained output response is used to analyze the resonant wavelength, quality factor, and output power. The normalized transmission spectrum of the sensor is shown in Fig. 4. The resonant wavelength, Q factor, and output efficiency of the sensor at normal condition is 1590 nm, 257.5, and 100%, respectively.

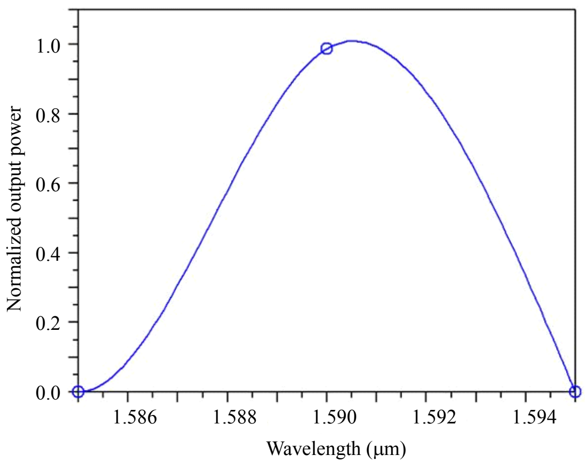
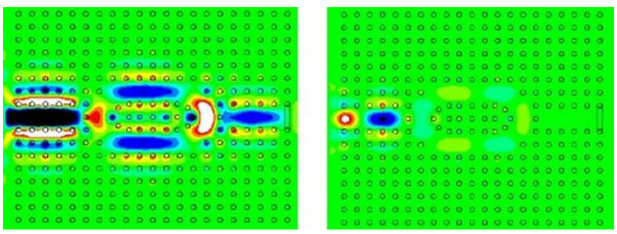


Fig. 4 Normalized transmission spectrum of the proposed biosensor at normal condition.

Figures 5(a) and 5(b) depict the electric field distribution of the proposed sensor at ON resonance and OFF resonance, respectively. At 1590 nm i.e. ON resonance, the input signal is coupled from input waveguide to elliptical resonator which in turn outputs waveguide. Alternatively, the input signal is reflected back to the source at the OFF resonance at 1600 nm.



(a) (b)

Fig. 5 Field distribution of the proposed bio sensor at (a) ON resonance (λ = 1590 nm) and (b) OFF resonance (λ = 1600 nm).

The normalized output spectra of the sensor for different blood components [26–30] are shown in Fig. 6. The transmission spectra are obtained for various biological constituents present in the blood using the output from the FDTD method [31, 32]. The changes in the normalized output transmission spectra and resonant wavelengths have been analyzed according to the change in the dielectric constant of different bio-constituents present in blood. Table 2 shows input dielectric constant (ε_r), normalized transmission power, and resonant wavelength for different blood components present in blood.

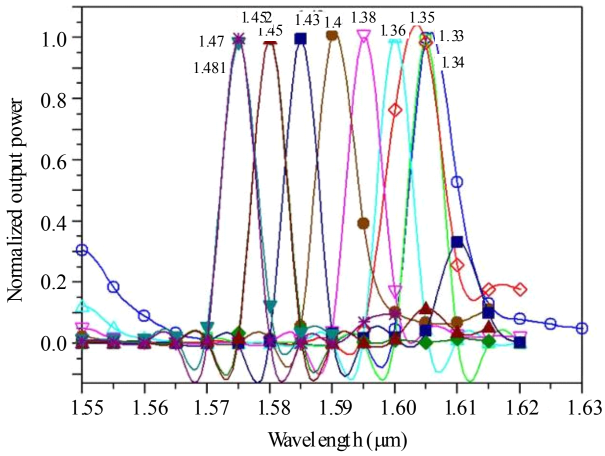


Fig. 6 Normalized output transmission spectra for normal range of blood components in blood.

The blood components with corresponding refractive index, measured value of resonant wavelength, Q factor, and output efficiency are presented in Table 2. The change in the normalized transmission output power levels and equivalent resonant wavelength for every blood component have been shown experimentally, and thus each spectrum will act as a signature of the corresponding blood constituent for the designed sensor.

The design of biosensor using photonic crystal is one of the new areas for medical applications. The accuracy of the proposed model through simulation is about 97% which is sufficient for real-time applications. However, it is essential to account the fabrication tolerance of the proposed biosensor. The fabrication tolerance of the photonic crystal based device is 5% as already reported. In recent years, there are several methods, namely, optical lithography, direct ultraviolet (UV) laser writing, electron beam lithography, focused ion beam lithography, holographic lithography, and so on, are reported to enhance the tolerance level of photonic crystal based optical devices [44].

Table 2 Input refractive index, resonant wavelength, quality factor, and output efficiency for different blood components in blood.

Name of blood components	Refractive index	Resonant wavelength (nm)	Q factor	Output efficiency (%)
Urethame Dimethacrylate	1.481	1575	262	98
Bovine Serum Albumin	1.470	1576	262	99
Polyacrylamide	1.452	1580	263	99
Biotin-Streptavidin	1.450	1580	263	99
Sylgard184	1.430	1585	264	99
Glucose (40 gm/100 ml)	1.400	1590	227	100
Hemoglobin	1.380	1595	265	100
Ethanol	1.360	1600	266	99
Blood Plasma	1.350	1604	160	105
Cypton	1.340	1605	267	98
Water	1.330	1607	178	99

Different blood components and their normal values of functional characteristics are reported in Table 2. If any patient wants to check his/her body through blood test, the minimum amount of sample will be taken from the patient. Then, the functional characteristics will be evaluated and compared with that listed in Table 2. Finally, the actual disease will be identified with less time.

The refractive indexes of the blood components are varied based on its chemical, physical, and biological properties. From Fig. 7, it is investigated that the resonant wavelength of the sensor is shifted into a higher wavelength region when the refractive index of the blood constituent is high. With an increase in the refractive index, the effective dielectric strength of the sensor increases which obviously shifts the resonant wavelength to a higher wavelength region. The functional parameters of the proposed sensor are compared with the reported ones, and the results are listed in Table 3.

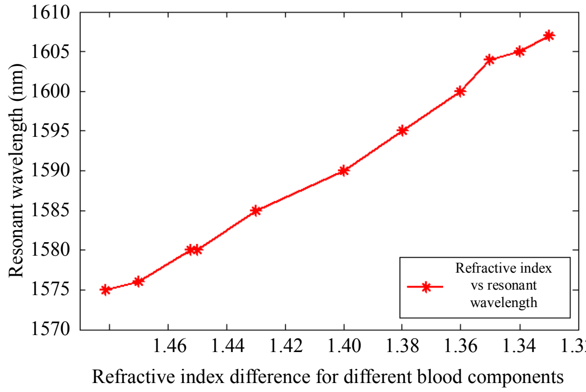


Fig. 7 Refractive index versus resonant wavelength.

Table 3 Comparison of quality factor, sensitivity, detection limit and sensing parameters of the proposed sensor with reported sensors.

Reference	Quality factor	Sensitivity (nm/RIU)	Detection limit (RIU^{-1})	Sensing parameters /RI range
[45]	1727	***	***	Temperature
[46]	***	***	***	Temperature
[47]	5522	***	***	Force
[48]	1737	***	***	Force and pressure
[49]	16000	***	***	Force
[50]	1750	4.125	***	1.33–1.51
[51]	35 517	330	1.24×10^{-5}	Deuterium water and glycerol solution
[52]	2700	***	***	1.33–1.48
[53]	***	260	0.001	Refractive index
[54]	***	84pm/C	0.001	Temperature
[55]	1.15 × 105	462	3.03×10^{-6}	Glucose concentration
This work	262	***	0.002	Blood components

Table 3 lists the comparison of various reported PCRR based structures. From the table, it is noted that these structures are used to sense the physical, chemical, and biological parameters. Moreover, circular, rhombic, and hexagonal structure based ring resonators are highly attractive for different sensing applications and also provide better results. A high transmission efficiency of 100% is achieved by circular ring resonator, however, quality factor and refractive index sensitivity are very low which are overcome by rhombic ring resonator as providing a high refractive sensitivity of 1000 nm/RIU and 100% transmission efficiency. These issues are mitigated by the hexagonal ring resonator which provides a high quality factor of 35 517, and the low detection limit is 1.24×10^{-5} with good sensitivity. All the above, the proposed

PCRR based biosensor for detecting blood components will meet the current demands in medical applications.

5. Conclusions

The two dimensional photonic crystal based biosensor is proposed and designed, and its sensing characteristics are analyzed. The sensor is designed by using two dimensional photonic crystals with the cubic lattice of circular rod surrounded by air. The sensor is operated in the wavelength range from 1570 nm to 1610 nm, which is used for analyzing the resonance wavelength, Q factor, and output power of the sensor. Since the blood components have some specific ranges, if the level increases or decreases, it will create so many problems such as heart attack, hepatitis B and C, anemia, and diabetes, which are known as the hematological disorder. By using the designed sensor, these problems can be detected early and on time thus getting cured possibly. Hence, this work will be highly desirable for medical applications.

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