Design of 2D photonic crystal biosensor to detect blood components

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Abstract
Photonic crystals are periodic structures made of insulators. They are the best option to design biosensors. In this paper, a photonic crystal biosensor containing insulation rods in the air was designed and simulated. This biosensor was used as a photonic crystal circular nano-ring between the internal and external waveguides. At the end of the internal waveguide, a defect exists to create an increase in the coupling distance. This causes the quality factor and resonant wavelength displacement to increase. The purpose of designing this sensor is to check blood ingredients. After connecting to a measuring rod, this sensor shows different refractive indices. Another important characteristic of the proposed structure is that most radiuses of dielectric rods are identical. This causes the sensor construction to be easy. The plane-wave expansion method is utilized to calculate the band structure. The results show that a photonic band gap with a wavelength from 1.26 to 1.92 μm is created at this distance where no wavelength can spread. In this work, the Q-factor, detection limit, figure of merit, and sensitivity of the proposed photonic crystal were recorded as 5166, 0.021RIU⁻¹, 9.84 nm/RIU, and 2.94 nm/RIU.

Keywords Photonic crystal biosensor · PBG · Band structure

1 Introduction
A photonic crystal is a structure whose refractive index changes alternatively, and this change can be one-, two-, and three-dimensional. Indeed, these structures are dual semiconductor crystals and influence the photon’s movement. The photonic crystals are alternative micro-nano structures of dielectric, which influence the pathway of the electromagnetic

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wave. This function is very similar to the alternative potential, which influences electrons to move with the creation of forbidden and permitted energy bands in semiconductors. The base function of these crystals is based on the internal alternative change of the refractive index in the crystal. Comparing other existing photonic structures, photonic crystal structures have a better optical limitation. This optical limitation is created due to the photonic band gap, which exists in all directions of the alternative structure. In a photonic crystal structure, this gap includes frequencies on which electromagnetic waves are not allowed to spread. In a photonic crystal structure, insulation materials with low loss can be used to control the spread of electromagnetic waves in some directions, especially with certain frequencies (Vahdati and Parandin 2019). Photonic crystals have many capabilities in designing optical circuits. One of their applications is in digital circuits so that they can be used in the design of logic gates (Parandin and Mahtabi 2021; Farmani et al. 2019; Parandin et al. 2018; Saghaei et al. 2017; Parandin and Moayed 2020; Olyaei et al. 2018), comparators (Parandin 2021; Parandin et al. 2021a), adders, subtractions (Abdollahi and Parandin 2019; Parandin and Karkhanehchi 2019; Karkhanehchi et al. 2017; Parandin et al. 2021b), decoders, encoders (Mehdizadeh et al. 2016; Parandin and Sheykhian 2022; Ouahab and Naoum 2016; Parandin 2019) and other logic circuits.

Nowadays, the importance of analyzing different cases such as clinical diagnosis, biomedical research, medical health, nano, forensic medicine, and food is increasing. For this purpose, so far, different biosensors were designed and implemented (Alipour et al. 2018; Farmani and Mir 2019; Emami Nejad et al. 2019; Mozaffari and Farmani 2020; Ghanbari et al. 2017; Ghoshal et al. 2010; Monosk et al. 2012; Olyaei and Dehghani 2013; Olyaei and Naraghi 2013; Olyaei et al. 2019; Parandin et al. 2021c). A biosensor was designed such that it only responds to a special substance, and the consequence of this reaction is the messages and signals sent to the processing part. Each biosensor has two parts: receiver and converter. The main job of the bio-receiver is to detect analyte interactions. On the other hand, the converter converts these detections and reactions to signals that can measure them until the function is performed easily (Bohunicky and Mousa 2010; Fan et al. 2008). The biosensor is described as a set of means which usually detect an interesting substance in electrical, optical, and thermal forms using special biochemical reactions mediated by isolated enzymes, tissues, cells, or any chemical elements. These sensors are many applications. For example, we can mention the following uses such as in very small devices embedded in the human body, chemical and biological wars, pesticides, and harmful bacteria.

According to the technological progress in electronics areas and the decrease in dimensions of the relevant device, a tendetowards micro-sensors and nano-sensors are becoming more and more. One of the best options is photonic crystal biosensors (Bohunicky and Mousa 2011; Olyaei et al. 2014; Baqir et al. 2018; Farmani et al. 2018; Olyaei and Mohebzadeh-Bahabady 2014).

In Tavousi et al. (2018), a biosensor was designed based on a circular resonant nanoring between upper and lower waves. Several insulation rods have been displaced and lied near each other to increase the optical limitation. In (Arunkumar et al. 2019), a biosensor based on insulation rods in the air was presented. In this structure, an ellipse-shaped nano-ring has been embedded between the waveguide in output and input. An insulation rod was located between the internal waveguide and nano-ring to increase optical coupling and quality factor. In Maache et al. (2020), a biosensor based on one-dimensional photonic crystal defects was presented. In this sensor, the biosensor function was studied using the Trimmed Mean of the M-values (TMM) approach. The outcome parameters can obtain the concentration of Creatine in blood, the thickness of the violation layer, etc.
In Bijalwan et al. (2020), a biosensor based on the air cavities was presented on a silicon plate. This sensor was constructed from the defects in the form of a capsule between two waveguides. These capsule defects lie at the center of this structure. This sensor was designed to detect glucose concentration in the human body.

In Lidiya et al. (2019), a one-dimensional photonic crystal biosensor was presented to detect blood plasma and cancer cells. The interesting structure was constructed by lying on a compressed layer between two identical photonic crystal structures of Silica and Titanium.

In Rahman et al. (2020) an octagonal-shaped hollow core with eight head star cladding PCF is designed and investigated for different crucial optical properties of cholesterol sensing in liquid samples. In (Parandin and Heidari 2020) a biosensor based on a photonic crystal is designed. This sensor has two adjacent circular nano-rings that allow coupling between the waveguides and the nano-ring resonator. The simulation results show that the designed biosensor has a high quality factor and by attaching the biomolecule to it, the displacement of the resonant wavelength is well-formed.

A photonic crystal biosensor was studied and analyzed. The interesting structure includes photonic crystal insolation rods in the air platform. Hence, blood ingredients are reviewed and obtained by connecting the desired biomolecules to measure rods of the biosensor structure, refractive index, sensitivity, and other parameters of each desired substance.

2 Photonic crystal biosensors

Photonic crystal structures have a better optical limitation than other optical devices, and they can limit light to a special place and be resistant to electromagnetic interference. A measure of biosensors is based on the focus of an electrical field on a region with a low refractive index. This causes the sensitivity of the biosensor to increase and the smallest change in the refractive index to be detected. The photonic crystal biosensors are easily able to be integrated due to having a small measure area. In the biosensors based on photonic crystals, the measurable parameter is identified using the change analysis of the refractive index in the photonic crystal structure (Olyaeea and Naraghi 2013).

There are multiple important parameters in the biosensors that are the base mechanisms for the assessment and measurement of this kind of sensor (Olyae et al. 2014). Of the most important parameters in photonic crystal sensors is the quality factor which is given as follows (Eq. 1):

$$Q = \frac{\lambda_0}{\Delta\lambda_{FWHM}}$$

where $\lambda$ is a central resonant wavelength, and $\Delta\lambda_{FWHM}$ is the spectral width of half maximum for the central transmission spectrum.

Another parameter of biosensors is sensitivity. The sensitivity is the level of a change in passing a signal at a biosensor in response to analyte connection change in a sensing hole. It is defined as follows (Eq. 2).

$$s = \frac{\Delta\lambda}{\Delta n}$$

where $\Delta\lambda$ is the transmission spectrum displacement and $\Delta n$ is the refractive index changes.

Another important parameter is the detection limit which is obtained as follows (Eq. 3).
where $\lambda$ is a resonant wavelength, $S$ is the sensitivity, and $Q$ is the quality factor.

The next parameter is the figure of merit (FOM) which is determined as follows (Eq. 4).

$$\text{FOM} = \frac{SQ}{\lambda}$$

where $S$ is the sensitivity, $Q$ is the quality factor, and $\lambda$ is a resonant wavelength.

### 3 Sensor design and simulation results

It used a two-dimensional photonic crystal structure to create an interesting biosensor. This structure includes dielectric rods in the air. In this structure, dielectric rods have a refractive index of 3.5 located in the air with a refractive index of 1 so the number of 22 rods in the horizontal direction and 16 rods in the vertical direction were arranged. The structure size is 113 $\mu$m$^2$. The lattice constant of this structure is equal to 600 nm, and the radius of insulation rods is equal to 120 nm. The simulation results show that a forbidden photonic band has been created for transverse electric (TE) and transverse magnetic (TM) modes of optical waves to calculate the proposed lattice band structure. Figure 1 depicts the band structure results.

To reach a biosensor using a two-dimensional photonic crystal structure, input and output pathways are required. Therefore, using linear defects, a pathway is created for an input that the input source is located at the beginning of the pathway. A circle-shaped resonator is used between input and output to assign the resonant wavelength and filter other wavelengths. This resonator was created by a sort of rod in a circular form. This circle-shaped pathway was created to spread the light to the output at a resonant frequency.
One of the rods omitted in a resonator input causes the input frequency spectrum to decrease in the output and acts as a small resonator. On the other hand, it decreases the spectrum width in the output. In Fig. 2, the implemented structure can be seen.

In this structure, 36 rods were tested to be connected with a biosensor inside a nanoring. But eventually, the rod S13 was selected as the best rod to be connected with the biosensor.

In Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, the sensor output was depicted in terms of the refractive indices of blood ingredients, respectively. As you see in Table 1, the refractive index of blood ingredients connected to this rod, quality factor, sensitivity, detection limit, and finally FOM were depicted in this structure.

In Fig. 3, we can observe the sensor output without any biomolecule in the measuring rod. The sensor output has a wavelength of 1.541 in the reference mode, and the full width is 0.4 in half of the background. The quality factor in this mode is equal to 3875.

In Fig. 4, the output sensor was depicted when blood plasma is connected to the measure rod S13. The output spectrum is in the wavelength range from 1.54 to 1.55, and its output power is approximately 0.3. The refractive index of blood plasma is equal to 1.35. Furthermore, its quality factor and sensitivity are 3875 and 14.14, respectively.

In Fig. 5, the output sensor against of Bovine-Serum-Albumin connection to the measuring rod can be observed. The power of sensor output is equal to 0.8 when the biomolecule
The refractive index of Bovine-Serum-Albumin is equal to 1.47, and the full width is 0.3 in its half of the background. Its quality factor and sensitivity have obtained 5166 and 0.63, respectively.

### Table 1

| Name                        | RI  | $\Delta \lambda_{\text{FWHM}}$ | Wavelength (nm) | Q-Factor (nm/RIU) | Sensitivity (nm/RIU) | DL FOM (RIU) |
|-----------------------------|-----|---------------------------------|-----------------|-------------------|----------------------|--------------|
| Reference                   | 1   | 0.4                             | 1541            |                   | –                    | –            |
| Blood Plasma                | 1.35| 0.4                             | 1542            | 3875              | 2.85                 | 0.013        | 7.16         |
| Bovine-Serum-Albumin        | 1.47| 0.3                             | 1542            | 5166              | 1.91                 | 0.015        | 6.39         |
| Ethanol                     | 1.36| 0.4                             | 1542            | 3875              | 2.22                 | 0.017        | 5.57         |
| Hemoglobin                  | 1.34| 0.3                             | 1542            | 5166              | 2.94                 | 0.010        | 9.84         |
| PolyaCRYlamide              | 1.452| 0.3                             | 1542            | 5166              | 1.99                 | 0.014        | 6.66         |
| Sylgard184_Glucose          | 1.4 | 0.3                             | 1542            | 5166              | 2                    | 0.014        | 6.70         |
| Urethane-Dimeth-acrylate    | 1.481| 0.4                             | 1542            | 3875              | 1.87                 | 0.021        | 4.69         |
| Water                       | 1.33| 0.4                             | 1542            | 3875              | 2.72                 | 0.014        | 6.83         |
| Cypton                      | 1.34| 0.3                             | 1542            | 5166              | 2.94                 | 0.010        | 9.84         |

**Fig. 4** Sensor output for Blood Plasma

**Fig. 5** Sensor output for Bovine-Serum-Albumin

is connected to the measuring rod. Furthermore, its wavelength is 1.542. The refractive index of Bovine-Serum-Albumin is equal to 1.47, and the full width is 0.3 in its half of the background. Its quality factor and sensitivity have obtained 5166 and 0.63, respectively.
In Fig. 6, the sensor output against the ethanol connection to a sensing hole can be seen. Its output power is approximately equal to 0.36 in the range from 1.542 to 1.55. The refractive index of ethanol is 1.36, as well as its quality factor and sensitivity, are 1.11 and 3875, respectively, when ethanol is connected to the measuring rod.
In Fig. 7, the sensor output can be seen when blood hemoglobin is connected to the measure rod S13. The refractive index of blood hemoglobin is 1.34, and the output power of the sensor connected to the measuring rod is equal to 0.45. The quality factor and sensitivity of which are 5166 and 0.88, respectively.
When polyacrylamide is connected to a measuring rod, the sensor output is approximately equal to 0.72 in the wavelength range from 1.540 to 1.550. The refractive index of polyacrylamide is equal to 1.452 as well as its quality factor and sensitivity are 5166 and 0.66, respectively. Thus, the full width is equal to 0.3 in half of the background (Fig. 8).

Sylgard184_Glucose has a refractive index of 1.4. When it is connected to the measuring rod, the full width is 0.3 in half of the background. Its wavelength is 1.542, as well as its quality factor and sensitivity, are 5166 and 0.75, respectively. The output power of the sensor is approximately equal to 0.52 when the substance is connected to the measuring rod (Fig. 9).

In Fig. 10, Urethame-Dimethacrylate was connected to the measuring rod, and its output power is approximately equal to 0.8. The refractive index of this substance is 1.481, and the full length is 0.4 in its half of the background. The quality factor and sensitivity of this sensor are 3875 and 0.83, respectively.

One of the blood ingredients is water. The refractive index of water is equal to 1.33. The output power of this sensor per each water connection to the measuring rod is equal to 0.32.
in the wavelength of 1.542. The full length is 0.4 in half of the background. The quality factor and sensitivity of that are 3875 and 1.2, respectively (Fig. 11).

One of the other blood ingredients is Cypton. Its refractive index is equal to 1.34. The full length is 0.3 in its half of the background in the wavelength of 1.542. The power output of this sensor is approximately 0.28. The quality factor and sensitivity of that have obtained 5166 and 0.88, respectively (Fig. 12).

In Fig. 13, all blood ingredients were depicted and compared with the reference mode. The wavelength of the reference mode is 1.541, and other measured wavelengths are about 1.542. When a biomolecule is connected to a measuring rod, it causes the resonant wavelength to be displaced. Moreover, the output power of the sensor was doubled, and this causes the sensor output to be easily detected.

In Table 1, all ingredients were addressed and compared. Parameters of this table include the wavelength, quality factor, sensitivity, detection limit, and FOM. According to the table, the resonant wavelength changes from the reference mode due to connecting the biomolecule with different refractive indices and creating a displacement. Moreover, the higher the refractive index than 1, the more quality factor is. The sensitivity of substances such as blood plasma, ethanol, and water has the highest value. Therefore, these substances have the highest FOM. According to the table, the interest structure has a good optical limitation and the resonant nan-ring located between internal and external waveguides has the highest performance to boost the quality factor and displace the resonant wavelength. This sensor has a photonic crystal circular nano-ring which creates the proper optical interaction with the analyte.

Therefore, in Table 2, the current structure can be compared with other similar works.

In this work, a circular resonator nano-ring is used. As a result, the quality factor has increased better than in similar works, and the sensitivity has greatly improved. The figure of merit (FOM) has also increased and the detection limit (DL) has an acceptable value.

### 4 Conclusion

In this paper, the blood ingredients were addressed by a photonic crystal biosensor. This sensor has a circular nano-ring between internal and external waveguides. This structure was designed to obtain the high resonant wavelength displacement, quality factor, and

| Reference                  | Wavelength (nm) | Q-Factor | Sensitivity (nm/RIU) | DL (RIU-1) | FOM (nm/RIU) |
|----------------------------|-----------------|----------|----------------------|------------|--------------|
| Tavousi et al. (2018)      | 1545–1565       | 2500     | 690                  | –          | 1400         |
| Arunkumar et al. (2019)    | 1570–1610       | 262      | –                    | 0.002      | –            |
| Maache et al. (2020)       | –               | 2066.44  | 546.72               | 1.44       | –            |
| Bijalwan et al. (2020)     | –               | 19.82    | 74.5                 | –          | –            |
| Lidiya et al. (2019)       | –               | –        | 0.83                 | –          | –            |
| Sharma and Kumar (2021)    | –               | 1569     | 203.09               | –          | –            |
| Matar et al. (2022)        | –               | 103–104  | 277.1–428.6          | –          | 104          |
| This work                  | 1541–1550       | 5166     | 1.87–2.94            | 0.021      | 9.84         |
sensitivity when the biomolecules are connected to a measuring rod. The quality factor and sensitivity are 5166 and 2.94 nm/RIU. Also, figure of merit (FOM) and detection limit (DL) is equal to 9.84 nm/RIU and 0.021 RIU\(^{-1}\). One of the proper characteristics of this sensor is that it can assign multiple rods to sense a biomolecule. In the input of sensor, the coupling distance has increased because of the creation of a point defect. Hence, this causes the quality factor and resonant wavelength displacement to increase.

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** Declarations**

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