Biosensor for Detection of Biological Components using Photonic Crystal

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ABSTRACT:
In biosensors, the investigated material is biological components such as cells, proteins, and nucleic acids. All compounds of living organisms have sensors with functions similar to mechanical sensors. Most of these sensors are special cells sensitive to the external environment's physical characteristics such as light, movement, temperature, magnetic field, gravity, humidity, vibration, pressure, electric fields, sound, etc. Biosensors can be made using photonic crystals, an example of which is designed here. In order to check the biomolecule detection ability by the biosensor, the refractive index around the sensing hole is changed and the output transmission spectrum is limited. By changing the refractive index, the transmission spectrum can be measured, which enables the sensor to identify biological molecules. In this study, a sensor was designed that is capable of detecting biological molecules. This sensor has good sensitivity, which makes it capable of measuring in a small size. The sensor can accurately predict the result, so this sensor is very suitable for medical purposes.
KEYWORDS: Biological molecules, Medical, Photonic crystals, Sensors.

1. INTRODUCTION

Sensors have many medical applications such as biomedical research and drug production and testing, environmental analysis, food storage, and chemical industries [1, 2]. Biosensors observe and analyze biological components such as cells, proteins, and nucleic acids [3]. The biosensor consists of a bio-receptor and a transducer that detects the bio-receptor of the target bio-molecule. The transducer is used to convert the bio-molecule into a measurable signal. In biosensors, these two parts are integrated with one device [4]. In the design of biosensors, surface plasmon intensification phenomenon, interference phenomenon, optical waveguide, optical fibers, biological ring based on resonator and photonic crystals have been used [5, 6]. In recent years, photonic crystal biosensors with structures consisting of alternating layers of materials have attracted much attention [7, 8]. Photonic crystals [9-13] have a wide range of applications in communications and devices with sensory applications [14,15] and compared to ordinary optical devices, they have a significant optical limitation. The optical limitation in the photonic band gap and the flexibility of wavelength adjustment with the appropriate adjustment of structural parameters are reasons for paying attention to photonic crystal biosensors. Due to the unique characteristics of photonic crystals, various structures have been designed to be used as sensors. Photonic crystal intensifier nano ring biosensors [16,17] photonic crystal fiber sensors [18] micro and nanophotonic crystal resonator biosensors [19] are examples of designed applications.

In this study, a biosensor based on photonic crystals was presented. The structure was obtained by creating defects in three parts. In order to get the optimal structure, simulation was used and the structure was improved by increasing the number of rods.

2. RELATED WORK

Using photonic crystals with nanoscale structures, sensors are designed that are very sensitive to low refractive index changes with a small sensitive area. These sensors can provide flexibility and integration. Phonon crystal sensors are designed based on the measurement of biomolecules and refractive index properties [20].

Photonic crystals can be used to measure chemical and biochemical parameters [21]. Crystal networks coupled to two waveguides have also been used to detect cancer cells.
The sharp edges in the photonic slits can do the sensing work. This sensor can work in a wide range of wavelengths [22].

The prospect of photonic crystal-based biosensors for disease detection has been investigated. These sensors do not require long measurements, they have

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small dimensions, they are cheap, and they have high reliability [23].

The photonic crystal biosensor is also able to detect various blood components including water, red and white blood cells, and hemoglobin. The plasmonic material of this sensor is made of gold and the sensor is coated with titanium dioxide to work based on the theory of surface plasmon resonance. Sensing is done in the distance between the gold and the sensing channel. Nuclear diffusion occurs in the vicinity of the phase matching point, and the loss peak in the nuclear diffusion mode is very sensitive to different blood compounds with different refractive indices and thus can distinguish blood compounds [24].

3. PREPOSED METHOD

Two-dimensional photonic crystals have been used to design biosensors. This structure consists of an array of silicon rods in an airfield. The presence of circular rods reduces the amount of scattering losses and more effectively controls the propagation of the electric field mode. Their radius is equal to $R_1 = 0 \cdot 4 * a$ where a is the lattice constant and the distance between the centers of the two bars. The photonic crystal is placed in the X-Z plane and arranged in a square arrangement.

A defect has been created in this structure to be used as a biosensor. As seen in Fig. 1, the structure contains three defects. The two defects above are on the left side and the passer on the right side, and one defect is in the center. In this structure, in order to increase the optical limit of the resonator, it was created by reducing the bars. They make small and portable biosensors more feasible.

To create the central defect, first, a 7*7 array is removed and then a rod with a radius $\mathrm{R}_1 = 1 \cdot 32 * \mathrm{a}$ is placed in the center. Around it, two circular structures are arranged in a triangular shape and the radius of each rod is equal $\mathrm{R}_1 = 0 \cdot 4 * \mathrm{a}$.

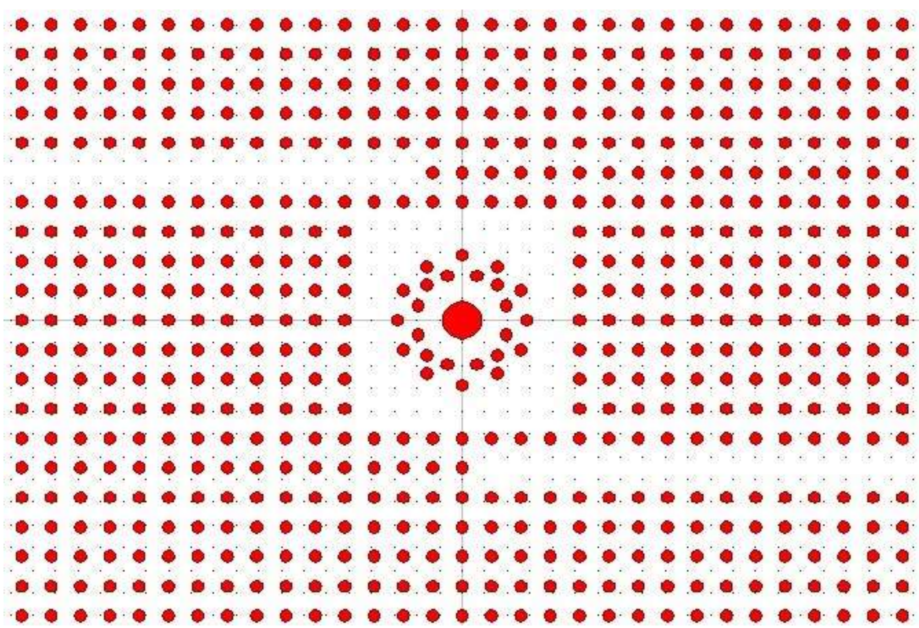


Fig. 1. Biosensor structure, an upper waveguide for light entry and a lower waveguide for the light exit.

In photonics, an energy-free band or stop band refers to a range of photon frequencies in which photons with this frequency cannot pass through the material. This property has made photonic crystals have many applications. The plane wave expansion method is used to obtain the photon stop band. Fig. 2 shows the stop band of the structure. The stop band for TE mode is in the range. $285 \leq \omega a/2\pi c = \frac{a}{\lambda} \leq .415$, and $0.735 \leq \frac{a}{\lambda} \leq 0.745$ where ω is the angular frequency, a is the lattice constant $a = 0.655\mu m$, c is the speed of light in free space, and λ is the free space wavelength.

$$\frac{a}{\lambda} = f \quad (1)$$

$$\lambda = \frac{a}{f} = \frac{0.655}{0.285} = 2.228\mu m$$

$$1.578 \leq \lambda \leq 2.228 .$$

$$0.879 \leq \lambda \leq 0.891$$

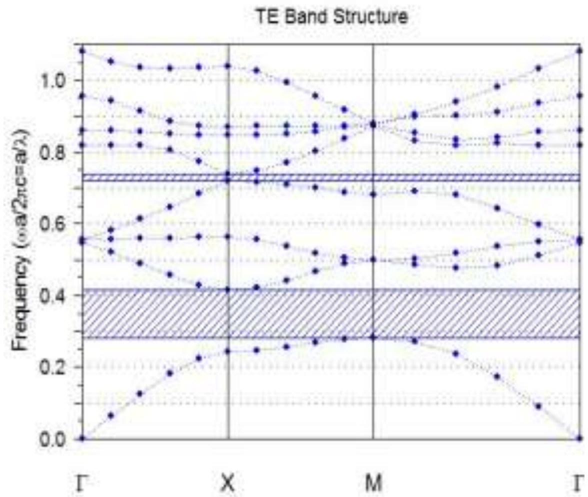


Fig. 2. The stop band of the structure.

4. RESULT

The sensitivity in the biosensor is obtained by using the displacement ratio of the sensitivity wavelength in two ways. In the first method, the magnitude of the sensor's resonance wavelength changes in response to changes in the refractive index, and in the second method, the displacement of the resonance wavelength is defined on the weight of the identified biomolecules.

In order to investigate the biosensor, the finite difference method in the time domain is used for the propagation of electromagnetic surface waves. A two-dimensional Gaussian wave was used for stimulation. Fig. 3 shows the propagation maps using the simulation method.

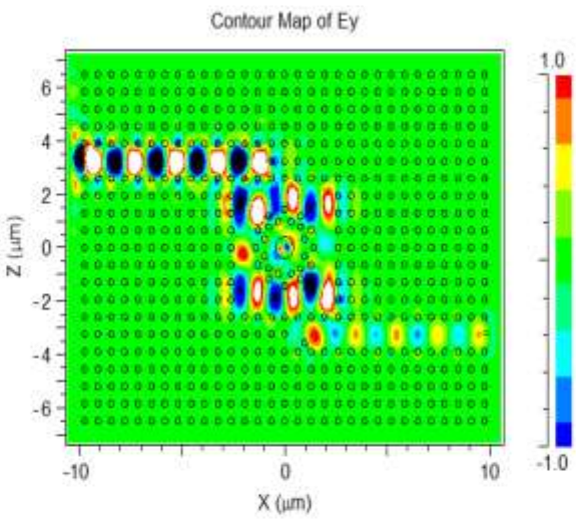


Fig. 3. Propagation maps using simulation method.

The light enters the structure from the entrance part and after passing through the circular path, it is transferred to the exit path.

Fig. 4 shows the monitor changes per wavelength.

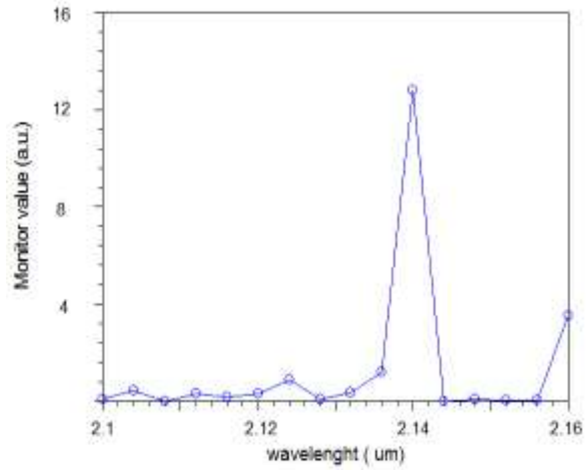


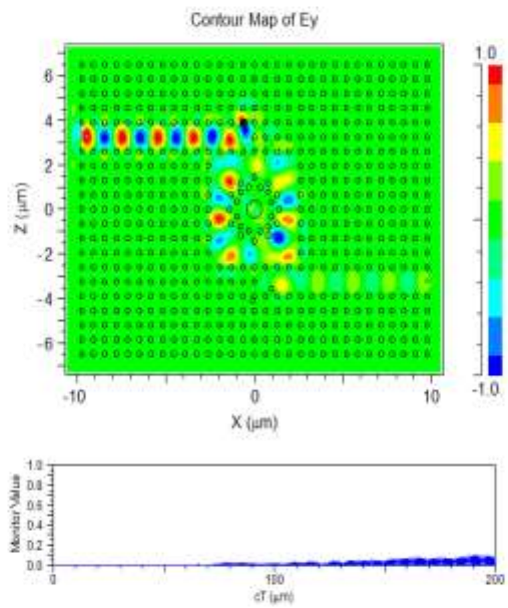
Fig. 4. Monitor changes per wavelength.

The designed sensor is sensitive to the wavelength range of 2.14 μm and has a max.

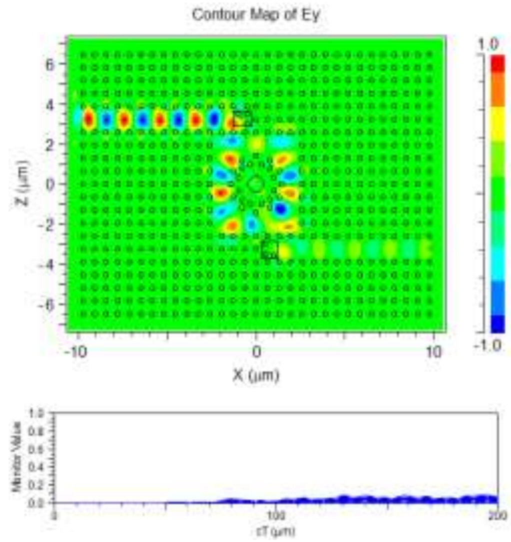
According to the simulation obtained from Fig. 4, we choose the wavelength $\lambda = 2.14\mu m$. The quality factor can be calculated according to the following relationship:

$$Q = \frac{\lambda}{\Delta\lambda} = 267.5 \tag{2}$$

The structure of the designed photonic biosensor can be optimized using several parameters.



(a)



(b)

Fig. 4. (a) Propagation maps in the optimized model, (b) Added holes are indicated by rectangles.

These factors include: adding bars in the structure for effective light diffusion and shortening the response time. For this purpose, 6 holes have been added to the structure, which is shown in Fig. 5-b using a rectangle.

By comparing Fig.s 5(a) and 5(b) find that the response time is shorter and the response can be seen from 50 seconds onwards, if without additional bars the response from 75 seconds onwards is obtained.

In order to check the biomolecule detection ability by the biosensor, the refractive index around the sensing hole is changed and the output transmission spectrum is checked. If the transmission spectrum can be measured by changing the refractive index, the sensor has the ability to identify the biological molecule. Each value of the refractive index can be considered equal to a specific state in the measurement cavity.

A refractive index equal to 1 was taken into account for the main stage of the sensing cavity without biomolecule attachment. The transmission spectrum of the biosensor output in six different refractive indices listed in Table 1 is shown in Fig. 6.

Table 1. Refractive index of materials.

material	Refractive index
Air (without biomolecules)	$n = 1$
Dry weather	$n = 1.243$
aluminum	$n = 1.244$
Water 35 degrees	$n = 1.325$
Water	$n = 1.33$
DNA molecule	$n = 1.45$

According to the obtained results, the resonance wavelength has been transferred to longer wavelengths when the biological molecule is connected to the sensing cavity. Calculation of the sensitivity during the binding of the molecule has been carried out. With biomolecule binding, the dose resonance wavelength is the same as the main resonance wavelength. The sensitivity of the biosensor can be calculated using the following equation.

$$S = \frac{\Delta\lambda}{\Delta N} = \frac{10\mu m}{0.45} = 22.2\,\frac{nm}{RIU} \quad (3)$$

Resonance wavelength transmission by changing the refractive index can be used to identify different biomolecules such as identifying different types of proteins, identifying different types of viruses, identifying DNA molecules, or identifying the concentration of glucose molecules.

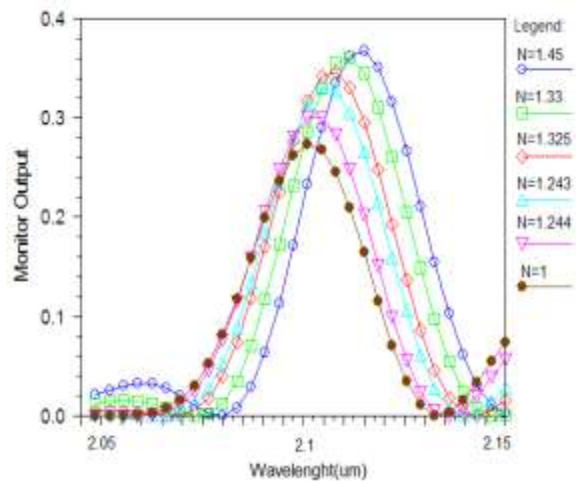


Fig. 6. Output transmission spectrum in the sensor.

5. CONCLUSION

A biosensor based on two-dimensional photonic crystals with a square arrangement was introduced in this research. To increase the efficiency of the two-wavelength sensor was used on both sides of the intensifier to enter and exit the light. By connecting the biological molecule to the sensing cavity, the refractive index of the sensing cavity changed and caused the shift of the intensity wavelength in the output transmission spectrum. The sensitivity is equal and the quality factor is equal. Due to its small size, this sensor is immune to electromagnetic interference and has high quality and sensitivity.

REFERENCES

[1] R. K. Chaudhary, V. Gupta, S. Kalhan, R. Gupta, M. K. Neyaz, J. Sharma, **"The Applications of Biosensors**

and Biochips for Prognosis and Diagnosis of Diseases," Biomaterials-Based Sensors: Recent Advances and Applications, pp. 387-411, 2023.

[2] M. M. Rahman, F. A. Mou, M. I. H. Bhuiyan, M. A. A. Mahmud, M. R. Islam, **"Design and characterization of a photonic crystal fiber for improved THz wave propagation and analytes sensing."** Optical and Quantum Electronics, Vol. *54*, No. 10, pp. 669- 775, 2022.

[3] D. Gowdhami, V. R. Balaji, M. Murugan, S. Robinson, H. Gopalkrishna **"Photonic crystal based biosensors: An overview,"** ISSS Journal of Micro and Smart Systems, Vol. 11, No.1, pp. 147-167, 2022.

[4] M.J. Iqbal, Z. Javed, I. Herrera-Bravo, H. Sadia, F. Anum, S. Raza, A. Tahir, M. N. Shahwani, J. Sharifi-Rad, D. Calina, W. C. Cho, **"Biosensing chips for cancer diagnosis and treatment: a new wave towards clinical innovation,"** Cancer Cell International, Vol. 22, No. 1, pp. 1-16, 2022.

[5] Z. L. Lei, B. Guo, **"2D Material-Based Optical Biosensor: Status and Prospect,"** Advanced Science, Vol. 9, No. 4, pp. 2102924-2102940, 2022.

[6] Y. D. Wu, Y. J. Xu, T. T. Shih, M. H. Cheng, **"Analytical and Numerical Analyses of Multilayer Photonic Metamaterial Slab Optical Waveguide Structures with Kerr-Type Nonlinear Cladding and Substrate,"** Crystals, Vol. 12, No. 5, pp. 628- 640, 2022.

[7] Z. Dorrani **"Simulation of Micro-Displacement Sensor Using Photonic Crystals,"** Quarterly Journal of Optoelectronic, Vol. 1, No. 2, pp. 147-22, 2016.

[8] Z. Dorrani **"Designing Sensor based Surface Plasmon Resonance with Photonic Crystals,"** Quarterly Journal of Optoelectronic, Vol. 1, No. 4, pp. 47-52, 2017.

[9] S. M. Zare, M. EbnAli, M. R. Shayesteh, A. Ebnali Heidari, **"The Structural Design of a Complete Band Gap Using Non-Uniform Photonic Crystals with low index material,"** Majlesi Journal of Electrical Engineering, Vol. 16, No. 3, 2022.

[10] M. Bazargani, B. Gharekhanlou, M. Banihashemi. **"Improvement in the Transmission Coefficient of Photonic Crystal Power Splitter using Selective Optofluidic Infiltration,"** Majlesi Journal of Electrical Engineering, Vol. 16, No. 3, pp. 35-40, 2022.

[11] T.T.B, Le, O. T. T. Chuyen, T. N. Thi, L, C. Van, **"Comparison of Chromatic Dispersion of Circular and Hexagonal Photonic Crystal Fibers with Chloroform-Core,"** Majlesi Journal of Electrical Engineering, Vol. 16, No. 3, pp. 55-61, 2022.

[12] Z. Dorrani, **"Two-dimensional Photonic Crystal Sensor for Detection of Biomaterial,"** Majlesi Journal of Electrical Engineering, Vol. 14, No. 1, pp. 25-28, 2020.

[13] F. Parandin, M. M. Karkhanehchi**, "Low size all optical XOR and NOT logic gates based on two-dimensional photonic crystals,"** Majlesi Journal of Electrical Engineering, Vol. 13, No. 2, pp. 1-5, 2019.

[14] S. Dinodiya, A. Bhargava, **"A comparative analysis of pressure sensing parameters for two dimensional photonic crystal sensors based on Si and GaAs,"** Silicon, Vol. 14, No. 9, pp. 4611-4618, 2022.

[15] T. Zouache, A. Hocini, **"2D photonic crystal indium arsenide based with dual micro-cavities coupled to a waveguide as a platform for a high sensitivity pressure sensor**." Optical and Quantum Electronics, Vol. 55, No. 3, pp. 1-13, 2023.

[16] A. Alioueche, A. Benmerkhi, M. Bouchemat, **"Optical photonic crystal sensor based on U-shaped ring resonator,"** Optical and Quantum Electronics, Vol. 54, No. 12, pp. 831-842, 2023.

[17] D. Gowdhami, V. R. Balaji, B. Murugan, S. Robinson, G. Hegde. **"Photonic crystal based biosensors: An overview,"** ISSS Journal of Micro and Smart Systems, Vol. 11, No. 1, pp. 147-167, 2022.

[18] R. Kanok, P. Hlubina, L. Gembalová, D. Ciprian, **"One-dimensional photonic crystal used for relative humidity sensing based on the phase shift of the Bloch surface waves,"** In Optical Sensing and Detection VII, Vol. 12139, No. 1, pp. 394-399, 2022.

[19] M. Bahadoran, A. K. Seyfari, P. Sanati, L. S Chua, **"Label free identification of the different status of anemia disease using optimized double-slot cascaded microring resonator,"** Scientific Reports, Vol. 12, No. 1, pp. 5548-5559, 2022.

[20] F. Parandin, F. Heidari, Z. Rahimi, S. Olyaee, **"Two-Dimensional photonic crystal Biosensors: A review,"** Optics & laser technology, Vol. 144, No. 1, pp. 107397-10745, 2021.

[21] C. Fenzl, H. Thomas Hir, O. S. Wolfbeis. **"Photonic crystals for chemical sensing and biosensing,"** Angewandte Chemie International Edition, Vol. 53, No. 13, pp. 3318-3335, 2014.

[22] S. Khani, M. Hayati, "Optical biosensors using plasmonic and photonic crystal band-gap structures for the detection of basal cell cancer," Scientific reports, Vol. 12, No. 1, pp. 5246- 5255, 2022.

[23] H. Inan, M. Poyraz, F. Inci, MA. Lifson, M. Baday . T. Brian T. Cunningham, U. Demirci. **"Photonic crystals: emerging biosensors and their promise for point-of-care applications,"** Chemical Society Reviews, Vol. 46, No. 2, pp. 366-388, 2017.

[24] VS. Chaudhary, D. Kumar, GP. Mishra, S. Kumar, **"Plasmonic biosensor with gold and titanium dioxide immobilized on photonic crystal fiber for blood composition detection,"** IEEE Sensors Journal, Vol. 22, No. 9, pp. 8474-8481, 2022.