[Manipal Journal of Science and Technology](https://impressions.manipal.edu/mjst)

Volume 9 | Issue 1 Article 5

6-30-2024

Detection of tuberculosis using 2-D photonic crystal-based biosensor

Markov Vladimir
National Research University of Electronic Technology, Russian Federation, markov.vova2003@yandex.ru

Skobelev Maksim
National Research University of Electronic Technology, Russian Federation, ckobelev.maxone@gmail.com

Neeraja Patil
Dayananda Sagar University, Bengaluru, neerajapatil2003@gmail.com

Prathap P B
Malnad College of Engineering, Hassan, prathap90.mysore@gmail.com

Saara K
Dayananda Sagar University, Bengaluru, saara-ece@dsu.edu.in

Research Article

Detection of tuberculosis using 2-D photonic crystal-based biosensor

Markov Vladimir, Skobelev Maksim, Neeraja Patil, Prathap P B, Saara K*

Email: markov.vova2003@yandex.ru, ckobelev.maxone@gmail.com, neerajapatil2003@gmail.com prathap90.mysore@gmail.com, saara-ece@dsu.edu.in

Abstract

While there has been a significant increase in healthcare demands and the need for precise clinical judgment, it is important to note that the performance enhancement of photonic crystal sensors is not solely attributed to this surge in demand. Instead, photonic crystal-based biosensors have demonstrated improved performance over conventional biosensors. In this study, a 2-D photonic crystal-based biosensor with a square lattice structure, measuring 6 x 6 µm in length and width respectively, was proposed. The biosensor utilizes Titanium Dioxide (TiO2) as a sensing material, where TiO2 is employed to attract target molecules present in the sample. The proposed biosensor was designed and simulated using the Finite-Difference Time-Domain (FDTD) method. In the simulation framework, the immobilization of target molecules on TiO2 was explicitly modelled, including the definition of TiO2's optical properties, implementation of absorption mechanisms related to immobilization, and consideration of surface functionalization processes. Simulation results confirm the detection of target molecules, showing a significant wavelength shift with a sensitivity of more than 80 nm/RIU and a quality factor of 5000.

Keywords: Biosensor, FDTD, Photonic Crystal, Titanium dioxide, Tuberculosis

I. Introduction

Tuberculosis (TB) continues to pose a significant global health challenge, with millions of new cases and fatalities reported annually by the World Health Organization (WHO) [1]. Timely and accurate diagnosis is critical for effective TB management, especially in regions with limited healthcare infrastructure. However, conventional diagnostic methods such as sputum smear microscopy and culture-based techniques have limitations in terms of sensitivity and speed [2]. Hence, there is a pressing need for innovative diagnostic approaches to improve TB detection, particularly in resource-constrained settings. In recent years, biosensor technology has emerged as a promising tool for the rapid and sensitive detection of infectious diseases, including TB. Biosensors offer several advantages, including real-time monitoring, simplicity, portability, and potential for point-of-care applications [3, 4].

Among biosensor platforms, photonic crystal-based biosensors are gaining attention due to their sensitivity, label-free detection, and compatibility with microfluidic systems. Photonic crystals, nanostructures that manipulate light, provide a unique platform for capturing biomolecular interactions with high specificity, and sensitivity [5].

Photonic crystals are periodic nanostructures that manipulate light propagation through

Markov Vladimir[1,2], Skobelev Maksim[1,2], Neeraja Patil[1], Prathap P B[1,3], Saara K[1*]

[1]Department of Electronics and Communication Engineering, School of Engineering, Dayananda Sagar University, Bengaluru, India-560 114

[2]Department of Electronics and Nanoelectronics Engineering, National Research University of Electronic Technology, Russian Federation

[3]Department of Electronics and Communication Engineering, Malnad College of Engineering, Hassan, India- 573 202

Manuscript received: 11-04-2023

Revision accepted: 09-05-2023

* Corresponding Author

How to cite this article: Markov Vladimir, Skobelev Maksim, Neeraja Patil, Prathap P B, Saara K "Detection of tuberculosis using 2-D photonic crystal-based biosensor", *Manipal J. Sci. Tech.*, vol.9(1), 30-33, 2024.

Published by Impressions@MAHE, 2024

periodic modulation of the refractive index. This manipulation creates photonic bandgaps, which interact strongly with light and enable precise control of optical properties. By incorporating biomolecular recognition elements onto the photonic crystal surface, such as antibodies, changes in the local refractive index caused by target analyte binding can be detected with high sensitivity. Titanium dioxide (TiO_2), known for its unique optical properties, has been extensively utilized in photonic crystal-based biosensors [6, 7]. Its high refractive index, biocompatibility, and ease of fabrication make TiO_2 an ideal material for creating photonic crystal structures with tailored optical responses. By integrating TiO_2 into the sensor platform, enhanced light-matter interactions, and improved sensitivity can be achieved, leading to superior detection performance. This paper describes the design of a 2-D Photonic Crystal (PhC) based biosensor intended for tuberculosis detection. These structures are widely utilized due to their efficient light confinement and easily controlled propagating mode. The sensor utilizes SiO_2, gold, and titanium dioxide materials. In this proposed design, various stages of tuberculosis cells are employed as the analyte, causing a shift in the resonance wavelength due to variations in refractive indices across the disease stages. To simulate and analyze the design, the FDTD platform has been employed.

II. Proposed Sensor Design

The optical biosensor for TB detection is designed using a structure with a two-dimensional square lattice arrangement of 11x11 rods, each outer rod has a radius of 225 nm and the central rod's radius is 320 nm. The base material of Silicon dioxide (SiO_2) provides mechanical support, and the lattice constant is set at 520 nm, determined from a literature review. The dimension of the base material is chosen to be designed for 6 X 6 µm. The top side of the base is covered with a 0.1µm thick gold film to reduce light absorption by the base and increase light interaction with the sensor. Light transmission is provided by a linear defect in the structure, which plays the role of a waveguide. Titanium dioxide rods are positioned along the X and Y axes within an air background on the slab of SiO_2. The height of Titanium dioxide rods is 1500 nm. Figure 1 illustrates the top XY perspective of the proposed sensor, while Figures 2 and 3 display the XZ and 3D perspective views, respectively.

Light from a Gaussian source with a wavelength of (280-284) nm is fed through the input port of the sensor. The passed light data is collected by a monitor located at the output of the line defect. Blood samples from patients with varying degrees of disease severity are used as analytes. The RI values for TB decrease as the infection severity increases [8]. This variation in refractive index induces a shift in the resonance wavelength which can be observed and analyzed. The resulting graph is used to investigate various parameters including Quality factor and Sensitivity. The modelling is done on the FDTD platform.

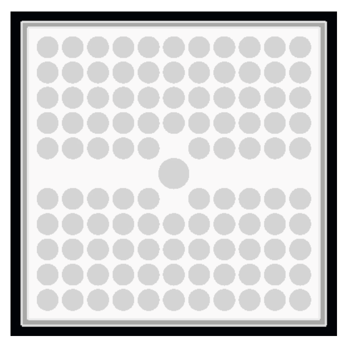

Fig 1. XY view of the proposed sensor

Fig 2. XZ view of the proposed sensor

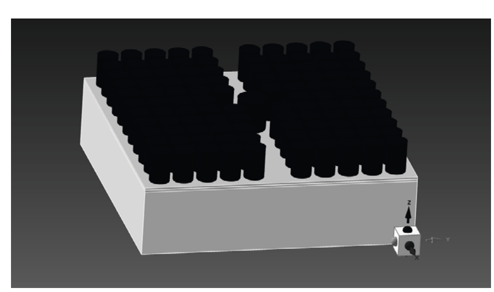

Fig 3. Perspective view

Table I: Design Specifications

Parameters	Details
Lattice structure	Square lattice
Number of rods	11x11
Radius of outer rods	225 nm
Radius of central rod	320 nm
Height of rods	1.5 µm
Lattice constant	520 nm
RI of base material (SiO2)	1.48
RI of sensor material (TiO2)	2.72
Wavelength of input light	280 - 284 nm

III. Simulation and Result

The TiO_2 rods in the design serve as the attractor of the analyte. The analyte is fixed on the rods and thus changes their refractive index. Depending on the presence or absence of TB disease, the refractive index will have different values. We analyzed four samples: one healthy blood sample and three blood samples from TB patients. The exact value of the resonance wavelength differs for different samples, which can be used to determine the presence or absence of the disease. The FDTD method is used to simulate the model and to obtain the results. Figure 4 shows the output transmittance plot for different blood samples, which clearly shows the shift of the peak values of the resonance wavelength as a dependency of the change in refractive index. The corresponding results are shown in Table II and Figure 4.

Table II: Output Data of the Device

Analyte	RI	Resonance wavelength (nm)
Normal blood	2.730	282.764
Tuberculosis-1	2.720	281.946
Tuberculosis-2	2.715	281.554
Tuberculosis-3	2.710	281.128

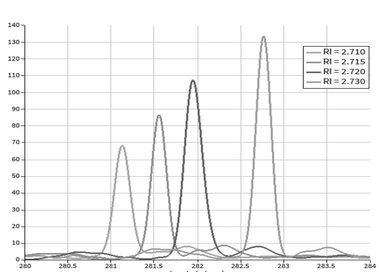

Fig 4: Normalized output transmission spectrum

IV. Discussion

The sensor based on photonic crystals is tuned and analyzed in terms of sensitivity, full-width half maximum FWHM, and quality factor.

A. Sensitivity

The sensitivity of the optical sensor is affected by specific settings that need to be tuned to achieve optimal performance. In the proposed model, the radius of the central rod in the line defect and the lattice constant of the rods have been optimized. The sensitivity of the model is determined by the ratio of the shift in the resonance wavelength to the change in the refractive index [9]:

$$S = \frac{\Delta\lambda}{\Delta n} \tag{1}$$

Here, $\Delta\lambda$ is the difference between peak wavelength values and Δn is the change in the refractive index. We derived the sensitivity for the resonance wavelength of diseased blood samples. Table III shows the sensitivity expressed in terms of nm/RIU.

Table III: Sensitivity for Tuberculosis Samples

Analyte	Refractive Index	Resonance wavelength (nm)	S (nm/RIU)
Tuberculosis -1	2.720	281.946	82
Tuberculosis -2	2.715	281.554	81
Tuberculosis -3	2.710	281.128	82

B. Full Width Half maximum (FWHM) and Quality factor

The quality factor is an important parameter in a photonic crystal-based sensor because it characterizes the resonance behaviour of the sensor. The quality factor represents the sharpness of the resonance peak in the sensor's spectrum. It is defined as the ratio of the resonance wavelength λ_0 to the full width at half maximum (FWHM) $\Delta\lambda$ of the resonance peak:

$$Q = \frac{\lambda_0}{\Delta\lambda} \tag{2}$$

FWHM is determined as the difference between wavelengths at an intensity equal to half the intensity observed at the resonance wavelength. Table IV summarises the values of the quality factor. High quality factor of over 5000 is achieved from the samples.

Table IV: Quality Factor for TB Infections

Analyte	Refractive Index (RI)	Resonance wavelength (nm)	Quality Factor (Q)
Normal blood	2.730	282.764	7441
Tuberculosis-1	2.720	281.946	5874
Tuberculosis-2	2.715	281.554	6120
Tuberculosis-3	2.710	281.128	5020

V. Conclusion

In this paper, a two-dimensional photonic crystal biosensor for TB disease detection is developed. It is simulated using the FDTD method and showed a resultant sensitivity of more than 80 nm/RIU and a quality factor of at least 5000. The proposed biosensor effectively detects the presence of TB by sensing the wavelength shift that occurred because of a change in the refractive index of blood. The sensor utilizes SiO_2, gold, and titanium dioxide materials. They provide good fixation of the analyte and increase the interaction of light with the analyte. This work can be further evaluated in the future to assess the performance of the biosensor using certain parameters such as signal-to-noise ratio (SNR) and limit of detection [10].

References

1. (2023) The WHO website. [Online].
2. Available: https://www.who.int/news-room/fact-sheets/detail/tuberculosis
3. Desikan, Prabha. (2013). *Sputum smear microscopy in tuberculosis: Is it still relevant? The Indian journal of medical research.* 137. 442-4.
4. Ranjan, Pushpesh & Singhal, Ayushi & Sadique, et al. (2022). *Scope of biosensors, commercial aspects, and miniaturized devices for point-of-care testing from lab to clinics applications*. 10.1016/B978-0-12-823424-2.00004-1.
5. Vasan, Arvind & Mahadeo, Dinesh & Doraiswami, Ravi & Huang, Yunhan & Pecht, Michael. (2013). *Point-of-care biosensor system. Frontiers in bioscience (Scholar edition).* S5. 39-71.
6. Inan, Hakan & Poyraz, Muhammet & Inci, Fatih & Lifson, Mark & Baday, Murat & Cunningham, Brian & Demirci, Utkan. (2016). *Photonic crystals: Emerging biosensors and their promise for point-of-care applications. Chemical Society reviews*. 46. 10.1039/c6cs00206d.
7. Haider, Adawiya & Jameel, Zainab N. & Al-Hussaini, Imad. (2019). *Review on: Titanium Dioxide Applications. Energy Procedia.* 157. 17-29. 10.1016/j.egypro.2018.11.159.Ge, Shunhao & Sang, Dandan & Zou, Liangrui & Yao, Yu & Zhou, Chuandong & Fu, Hailong & Xi, Hongzhu & Fan, Jianchao & Meng, Lijian & Wang, Cong. (2023). *A Review on the Progress of Optoelectronic Devices Based on TiO2 Thin Films and Nanomaterials. Nanomaterials*. 13. 1141. 10.3390/nano13071141.
8. Rupinder Kaur & Gaurav Kumar Bharti & Ashutosh Tripathi. (2023). *Modeling of 2D Photonic Crystal Based Sensor for the Detection of Tuberculosis Disease*. 10.1109/I2CT57861.2023.10126357
9. Fallahi, Vahid & Kordrostami, Zoheir & Hosseini, Mehdi. (2024). *Sensitivity and quality factor improvement of photonic crystal sensors by geometrical optimization of waveguides and micro-ring resonators combination. Scientific Reports.* 14. 10.1038/s41598-024-52363-2.
10. Zhou, Xiaoyan & Zhang, Lin & Pang, Wei. (2016). *Performance and noise analysis of optical microresonator-based biochemical sensors using intensity detection.* Optics Express. 24. 18197. 10.1364/OE.24.018197.