Recent advances in crystal photonic sensors in medical applications: A review

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Abstract

Due to the characteristics of photonic crystal sensors of accuracy in performance, high sensitivity, speed of detection and diagnosis, low manufacturing cost and ease of use, sensors have been used in many medical applications, such as surgery, patient condition monitoring, heart and bone diseases, diabetes, and others. This paper reviews 76 recent research articles published on the use of sensors in biomedical applications. In this paper, the focus was on the applications of sensors in detecting blood components, malaria, cancer, and bacteria present in water.

Keywords: *photonic; crystal; sensors; blood; malaria; cancer; bacteria.*

التطورات الحديثة في اجهزة الاستشعار البلورية الفوتونية في التطبيقات الطبية

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الملخص

نظرا لما تمتاز به اجهزه الاستشعار البلورية الفوتونية من دقة في الأداء، وحساسية عالية، وسرعة في الكشف، والتشخيص، وقله تكلفه التصنيع وسهولة الاستخدام. تم استخدام اجهزة الاستشعار في العديد من التطبيقات الطبية مثل تطبيقات الجراحة والمراقبة لحالة المريض وامراض القلب والعظام والسكري وغيرها. تستعرض هذه الورقة 76 مقالة بحثية حديثة منشورة حول استخدام اجهزة الاستشعار في التطبيقات الطبية الحيوية. في هذه الدراسة تم التركيز على تطبيقات اجهزة الاستشعار في الكشف عن مكونات الدم والملاريا والسرطان والبكتيريا الموجودة في المياه.

الكلمات المفتاحية: الفوتونية- البلورة- المستشعرات- الدم –الملاريا –السرطان -البكتيريا

1. Introduction

Photonic crystals are periodic structures with a regular refractive index designed in one, two, or three dimensions [Aly & et al,2020, Gandhi & et al,2021]. They are compositions of insulating and metallic materials discovered in 1987 by (Yablonovitch) [Aly & et al,2020]. and (John) [Saini & Awasthi,2022].These crystals exhibit periodic changes in their refractive index, leading to the creation of photonic band gaps that prevent light from propagating through specific ranges [Chattopadhyay & et al,2023]. Figure [1 a] illustrates this structure.

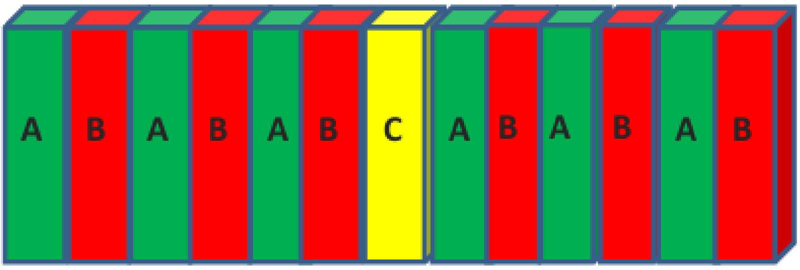
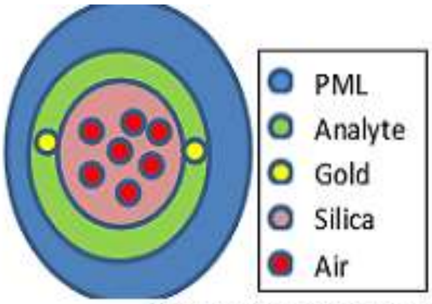


Figure 1 a) Schematic view of a defective photon crystal sensor



b) Cross- section of sensor

Where C is the defect layer created in the middle of a one-dimensional photonic crystal, consisting of alternating layers of A and B. The letters A and B are used to represent layers made from materials such as silicon(Si) and lanthanum (LAFN7).

Blood is the most important functional fluid in the human body, consisting of a very large number of vital components exceeding 4000 [Saini & Awasthi,2022]. Plasma, which constitutes more than half of the blood components, is considered the liquid component of blood and is composed of proteins such as(white blood cells and red blood cells) [Eid & et al,2021a]. with hemoglobin being the primary protein in red blood cells [Saini & Awasthi,2022]. Plasma components also include antibodies, enzymes, hormones, and other components. Blood plasma is widely used in diagnosis due to its richness in providing information about the patient's health condition. [Chattopadhyay & et al,2023]. Blood disorders are responsible for a range of non-communicable diseases such as 12diabetes, coronary artery disease, cancer, respiratory diseases [Saini & Awasthi,2022]. and kidneys [Aly & et al,2020] . It is essential to examine blood to detect these diseases [Saini & Awasthi,2022]. Additionally, measuring creatinine levels in the blood helps determine kidney risks [Saini & Awasthi,2022]. Furthermore, determining the zinc levels in the blood, which assists in treating acne, scars, hair loss, skin diseases [Hani &et al,2020].

Malaria is a serious and deadly parasitic disease [Huang &et al, 2023, Karki &et al,2024a, Tammam &et al,2021] It is mainly spread [Karki &et al,2024a]. through the bite of the female (Anopheles) mosquito, which carries the Plasmodium parasite [Huang &et al, 2023, Karki &et al,2024a, N .Manjunatha &et al,2023]. The parasite goes through three different stages:(the ring stage, trophozoite stage, and schizont stage) [Huang &et al, 2023, Karki &et al,2024a, N .Manjunatha &et al,2023, Shafkat &et al,2021]. Tropical and subtropical regions are the most affected areas by malaria [Huang &et al, 2023, N .Manjunatha &et al,2023].Malaria infection leads to the destruction of red blood cells, affects the liver and kidneys, and impairs respiration [N .Manjunatha &et al,2023] causing severe health risks and sometimes death [Karki &et al,2024a].

According to the World Health Organization reports in 2022, there were 247 million cases worldwide in 2021, with 619,000 deaths [Huang &et al, 2023]. This is compared to 228 million cases and 405,000 deaths in 2018.[Huang &et al, 2023, Karki &et al,2024a, Shafkat &et al,2021, Tammam &et al,2021]. Therefore, early diagnosis of malaria [Huang &et al, 2023, Karki &et al,2024a]. is crucial to speed up treatment [Huang &et al, 2023, Tammam &et al,2021] and reduce fatalities [Huang &et al, 2023]. Photonics-based sensor devices with high sensitivity, quick response, and excellent accuracy have been developed for the purpose of early diagnosis and detection of malaria [N .Manjunatha &et al,2023].

The abnormal growth of cells in the human body leads to the development of cancer [Panda &et al,2021]. Types of brain tumors and cancer remain among the most critical health issues worldwide [Eid & et al,2021b, Mohammed &et al,2023]. Cancer is considered the most common disease globally, with various types such as skin, blood, neck, breast, cervical cancers, and others [Eid & et al,2021b, Yasli ,2021]. Cancer has become the second leading cause of death worldwide [Eid & et al,2021b]. According to the International Agency for Research on Cancer, there were approximately 18.1 million new cancer cases and 9.6 million deaths in 2018 [Eid & et al,2021b, Panda &et al,2021]. Detecting and diagnosing cancer requires precise and costly methods for detection, diagnosis, and treatment [Chaudhary & et al,2024]. Recognizing cancer in its early stages is crucial and necessary for successful treatment [Yasli ,2021].

The presence of impurities and harmful bacteria causing diseases in drinking water can enter our bodies and lead to the spread of diseases such as diarrhea, severe abdominal pain, hepatitis, and other illnesses, posing a significant health concern, especially in densely populated cities [Daher &et al,2022, Gandhi & et al,2023, Kumar & et al,2023]. Diarrhea is the third leading cause of death in children under the age of five, claiming the lives of 443,832 children annually, according to the World Health Organization [Kumar & et al,2023].

In recent years, much attention has been given to ensuring the safety of food and drinking water worldwide [Aly & et al,2022, Guliy& et al,2023]. Traditional methods of monitoring water purity are limited in terms of sensitivity and speed, highlighting the need for more advanced technologies. This has led to the development of photonic crystal sensors for detecting water purity [Guliy& et al,2023, Kebaili & et al,2024].

Now, there is an increasing importance placed on examining and analyzing various conditions such as clinical diagnosis, biomedical research, nanotechnology, water monitoring, and food safety. For these purposes, different biosensors based on photonic crystals have been designed and implemented [Parandin &et al,2022]. This study addressed a variety of biosensors based on photonic crystals, utilizing various methods to analyze and evaluate the performance of these devices. Additionally, different simulation programs were used to simulate the operation and design of these biosensors. Based on this, Table 1 illustrates the most important methods and programs used.

Table 1: The most important methods and programs used

Method				Simulation software				
TMM	PWE	FEM	FDTD	Comsol	Matlab	Rsoft	OptiFDTD	ref
		√		√				1
√					√			2

√					√			3
√								4
√								5
√								6
			√					8
√								10
√								11
			√					16
		√						18
				√				19
		√						20
√					√			23
√								24
				√				27
√								29
		√						30
		√		√				31
√								33
	√						√	34
√								35
√				√				36
						√		37
			√					38
		√						40
			√					41
			√					42
			√					43
			√			√		46
√					√			47
√					√			48
		√						49
	√		√					50
			√					53
	√		√					54
		√						55
√								56
√				√				57
√								58
	√							59
	√		√					60
			√					61
			√					62
			√					63
√					√			64

√					√			68
			√					69
√		√						70
					√			71
√								72
√								5
	√		√					74
		√						77
√								78

TM M = Transport Matrix Method
FEM =Finite Element Method
PWE = Plane Wave Expansion
FDTD = Finite Difference Time –Domain

2. Medical Applications of Photonic Crystal Sensors

2-1. Application of photonic crystal sensors in the detection of blood components

Aly et al. designed a new biosensor based on photonic crystal (PC) for detecting the concentration of creatinine in blood. Creatinine is considered a vital indicator for a small but important part of kidney function impairment. The transmission spectra of electrically insulated photonic crystal defects, such as one-dimensional defects, were theoretically studied. The transmission spectra show resonant peaks within the band gap indicating so-called defect modes, which depend on parameters such as creatinine concentration in the blood, defect layer thickness, and angle of incidence. The proposed sensor was able to detect physiological levels of creatinine in human blood serum [Aly & et al,2020]. Gandhi et al. proposed a design of a biosensor consisting of a ring-shaped photonic crystal with one-dimensional defect made of porous silicon atoms. This device has the ability to sense very subtle differences in the refractive index of blood serum samples with varying concentrations of creatinine and is used in diagnosing kidney diseases ranging from mild to chronic by measuring the concentration of creatinine in blood serum samples of patients. This device showed a high sensitivity value, can be easily designed, and provide high performance under natural conditions [Gandhi & et al,2021]. Parandin et al. discussed a photonic crystal biosensor with air-insulated rods was designed and simulated. This sensor features a circular nanoring photonic crystal between the inner and outer waveguides. The purpose of designing this sensor is to examine blood components. When connected to the measuring rod, this sensor exhibited different refractive indices. An important characteristic of this proposed structure is that the radii of the insulating rods are mostly identical. The results showed that photonic band gaps ranging from 1.26 to 1.92 micrometers were created in this range where no wavelength propagation is possible [Parandin &et al,2022]. Mohammed et al. studied a medical biosensor based on two-dimensional photonic crystals was designed, simulated, and evaluated. The proposed design successfully distinguished and accurately identified the ten common types of blood components. The sensitivity levels, quality factor, and compactness of the proposed design were excellent compared to relevant literature, as well as in terms of cost. A comparison was made between this work and the relevant literature [Mohammed &et al,2019]. Chattopadhyay et al. presented in this study a new and enhanced sensor design based on photonic crystals for the detection and diagnosis of blood plasma. They utilized a 532-nanometer laser light source. The designed sensor demonstrated efficient detection of both normal and infected blood plasma during simulation, with the ability to identify various types of plasma effectively. The proposed sensor achieved ideal sensitivity. This device has great potential for various diagnostic applications that require minimal sample size and high sensitivity measurements [Chattopadhyay & et al,2023]. Hani et al. a sensor device was developed to detect zinc and monitor its concentration in human blood for both males and females. By using different types of single-mode fibers and photonic crystal fibers, and by studying the results of the laser output, the detection can be observed by tuning the laser wavelength as the zinc concentration changes. High sensitivity was achieved by reducing the dimensions [Hani &et al,2020]. Rashidnia et al. studied biological sensors based on two-dimensional photonic crystal waveguides were designed and simulated. The sensors include a ring resonator and rely on changes in the refractive index of red blood cells. The proposed device structure consists of an elliptical photonic crystal ring resonator and two linear waveguide arms. The proposed sensor was used to detect the phases of Plasmodium falciparum in red blood cells and diagnose malaria. The design distinguishes between normal red blood cells and those infected with Plasmodium falciparum with high sensitivity. This highly miniaturized sensor device is extremely suitable for lab-on-chip applications [Rashidnia &et al,2022]. Eid et al. proposed a photonic crystal hollow-core fiber sensor was analyzed to identify various components present in human blood. Simulation was used to visualize the fibers and explore the performance of this sensor device. The presented fibers were numerically analyzed in the terahertz spectrum from 1.5 to 3 terahertz. The numerical analysis indicated that the proposed sensor device provides very high relative sensitivity with low confinement losses for red blood cells, hemoglobin, white blood cells, plasma, and water. Additionally, the proposed sensor device offers very low effective material loss and very high numerical aperture for all blood components with the same geometrical parameter [Eid & et al,2021a]. Ibrahim et al. high sensitivity detection of creatinine levels in blood was achieved using THz photonic crystal fibers. The sensing technique relied on enhancing light-analyte interaction by leaking analyzer into air holes present in the fiber core region. The proposed sensing operation was based on studying the light-analyte interaction at different creatinine concentrations by detecting the change in refractive index of the analyzer relative to the creatinine level in blood in the THz range of 0.5-1.5 THz. Effective refractive index (neff), effective material loss (EML), effective area (Aeff), and relative sensitivity coefficient were detected. Various geometric parameters were studied to enhance device sensitivity. The proposed sensor device demonstrated good performance in measuring creatinine levels in blood [Ibrahim &et al,2023]. Chattopadhyay et al. presented a new design for a blood plasma sensor based on photonic crystals, utilizing a laser light source with a wavelength of 532 nanometers. Precise tuning of the device's properties was achieved by incorporating defects within a two-dimensional crystal based on the type of introduced impurities. During simulation, the proposed device demonstrated the capability to detect both infected and normal blood plasma. Device parameters were optimized, resulting in ideal sensitivity, making the device suitable for precise diagnosis in low-volume blood plasma.

This flexible and enhanced proposed device is used in applications with minimal sample volume and high sensitivity [Chattopadhyay & et al,2023]. Matar et al. focused on the biosensing capabilities of defective one-dimensional (1D) photonic crystal. The researchers proposed a bio-device by creating a defect layer of air in the middle of a photonic crystal to form a modified defect photonic crystal. The results related to defect layer thickness were calculated at values of 200 and 700 nanometers. Sensitivity, figure of merit, and quality factor for the proposed device were computed. This study succeeded in examining components of blood smears, hemoglobin, and plasma in both normal and infected blood samples simultaneously [Matar &et al,2022]. Sani et al. proposed a new design for a high-sensitivity two-dimensional photonic crystal sensor based on deviation resonances in a free spectral range of approximately 630 nanometers. This proposed sensor was used for analyzing blood components and detecting cancer patients in the deviation wavelength range between 1.19760511 and 1.19760519 micrometers. Additionally, this proposed sensor device was utilized in detecting diabetic patients at deviation wavelengths between 1.19760511 and 1.19760525 micrometers. Sensitivity values, quality factor, and figure+e of merit (FOM) were obtained. Blood, urine, and tears samples were used for disease detection purposes [Sani &et al,2020]. Rafiee et al. studied a two-dimensional biosensor device based on photonic crystal rods was proposed and studied. Photonic band gaps and field distribution spectra were extracted through simulation. This design features two ports: the first port is capable of accurately detecting hemoglobin concentrations, aiding doctors in diagnosing anemia in early stages. Additionally, the second port can diagnose creatinine concentrations in blood samples, assisting doctors in diagnosing kidney diseases. This proposed structure is considered an excellent candidate for biosensing applications in integrated optical circuits [Rafiee ,2024]. Nijhum et al. proposed a biological sensor device for the early detection of malaria caused by the growth of the Plasmodium falciparum parasite in human red blood cells. The researchers utilized D-shaped photonic crystal fibers (PCF) for this purpose. They numerically verified the characteristics of this proposed sensor device and obtained maximum sensitivity and quality factor for the three stages of the Plasmodium parasite's life cycle. Based on the results and practical implementation, the researchers considered the proposed sensor device to be highly suitable for identifying the stages of Plasmodium falciparum in red blood cells for malaria diagnosis [Nijhum &Ahmed,2023].

Table 2: The most important parameters of sensors used in detecting blood components

Phases	Sensitivity (nm/RIU)	Q factor	FOM (RIU^{-1})	DL(RIU)	ref
	306.25	2.5*10^5	10.3*10^4		4
	12.5				13
	637~640.3	(.74~1.15)*10^5	(1.96~2.6)*10^4	(1.9~2.6)*10^-6	24
	428.6	10^4	10^4		48
	306.25	7324.29			50
	1.14	5166	2.94	.04	59
hemoglobin con creatinine con	1785 1087	110.8~118.92 155~168	142.8~144.01 112.3~113.9	(6.943~7.002)*10^-4 (8.78~8.94) *10^-4	60

	10000	6141.56	48543±118		66

2-2. Application of photonic crystal sensors in malaria detection

D Gowdhan et al. designed a two-dimensional photonic crystal (2D-PC) structure to detect malaria infection indicators at different stages and healthy red blood cells based on the principle of effective refractive index modification. The researchers designed this proposed bio-sensor device with a dual-nanohole plasmonic cavity in the center of a hexagonal lattice with air holes on a silicon disk. The researchers followed rigorous methods to evaluate the performance of this proposed sensor device, calculated various design parameters, and found it to have moderate sensitivity, high quality factor, and high transmission rate. This proposed design for the dual-nanohole bio-sensor device stood out for its ultra-small size, approximately 43.46 square micrometers [Gowdhami & Balaji ,2024]. Wekalao et al. focused on developing a highly sensitive and efficient graphene nanostructured sensor device for early detection of malaria. They optimized the proposed device to achieve the highest sensitivity for early and rapid detection of malaria. The aim of this work was to create a low-cost and effective biosensor for early detection of malaria patients in resource-limited environments [Wekalao & et al,2023]. Kumar et al. aimed to detect dengue virus using a surface plasmon resonance-based biosensor device utilizing copper and black phosphorus. The researchers were able to use this proposed device to detect infected and healthy blood samples. They studied the performance parameters and worked on improving the performance by optimizing the thickness of the copper layer. The researchers studied the performance parameters with the optimized copper layer thickness for the proposed sensor device and the results showed improvement in sensitivity and Figure of Merit (FoM). Additionally, the electric field and penetration depth (PD) for the same sample were calculated [Kumar & et al,2023]. Chowdhury et al. investigated the potential of generating complete optical band gaps and features of fundamental sensor devices in quasi-periodic metal-dielectric photonic structures using a Fibonacci sequence arrangement of SiO_2 and Ta_2O_5 layers. The proposed structures contained a central cavity designed for comprehensive analysis of blood samples. During theoretical analysis, the researchers observed the formation of three low-reflectivity band edges. The researchers studied the stages of malaria parasites in infected blood and noted an increase in the refractive index at each stage. To achieve superior performance for this proposed design, the researchers studied the impact of cavity thickness on the excited modes, and the maximum values for sensitivity and quality factor were determined. This study included different stages of cells, including normal red blood cells. This work helped in identifying the various stages of parasites [Chaudhary & et al,2024] . Chaudhary et al. introduced a biological sensor device based on photonic crystal fibers (PCF) and plasmonic surface sensing for the early detection of malaria in humans. The working principle of this proposed design relied on the refractive index change of the studied blood sample, leading to a resonance wavelength shift in the surface plasmon resonance (SPR). Different stages of malaria-infected blood cells were detected using this proposed sensor device by measuring the resonance wavelength shift. The researchers calculated the sensitivity at different stages of malaria parasites in both x and y polarizations. This design of the proposed sensor device was deemed suitable for the early diagnosis of malaria patients [Chaudhary & et al,2021]. Meshginqalam et al.proposed a highly sensitive sensor device based on solid-core photonic crystal fibers. In this proposed design, the researchers used gold wires in the refractive index range from 1.36 to 1.40 instead of using layers. This structural design enabled the researchers to utilize this sensor device in diagnosing malaria. The performance of the proposed sensor device was analyzed for the x and y polarizations. Three different stages of malaria infection were studied. Additionally, the sensitivity in the x and y polarizations was calculated, and the researchers found that the sensitivity was higher in the x polarization, while the Figure of Merit (FoM) was higher in the y polarization [Meshginqalam & Barvestani, 2022]. Singh et al. proposed a highly sensitive biological sensor device by applying numerical simulation based on the angular interrogation method to model a high-performance surface plasmon resonance sensor at a wavelength of 633 nanometers. The researchers used this proposed device to detect malaria at different stages and with a wide sensing range for refractive index from 1.369 to 1.409. They obtained angular sensitivity values that allow for rapid and accurate diagnosis [Singh &et al,2024]. Kumar et al. proposed a design of a sensor device using Photonic Crystal Fibers (PCF) based on Surface Plasmon Resonance (SPR) sensing. The researchers utilized this proposed sensor device to detect malaria-infected red blood cells and hemoglobin concentration by comparing the resonance wavelength of blood cell samples. They employed Machine Learning (ML) algorithm analysis method in simulating the proposed sensor device. Sensitivity values were obtained for the three stages. This proposed sensor device excelled in performance and was considered the optimal alternative to existing sensor devices for malaria detection [Kumar &et al,2023]. Panda et al. presented a new design for a Surface Plasmon Resonance (SPR) sensor device for detecting various stages of malaria. The performance of the proposed sensor device was enhanced by changing the thickness and number of layers, as well as the angle of reflection. The researchers found that using a class of two-dimensional materials improved the performance of the sensor device compared to traditional SPR devices. Various performance parameters such as sensitivity, quality factor, and others were calculated for the proposed sensor device and compared with previous works to demonstrate the superiority of this design [Panda & Pukhrambam ,2022]. Fatema et al. proposed a Surface Plasmon Resonance (SPR) sensor device based on Photonic Crystal Fibers (PCFs). This design included three adjacent hexagonal lattices. The researchers used the sensor device to detect biological molecules with very high sensitivity in a refractive index (RI) range from 1.32 to 1.42. It was also employed to detect malaria-infected blood cells in all different stages with Plasmodium falciparum and at an early stage. Furthermore, the proposed sensor device was able to detect various biological molecules such as viruses, proton nuclear strips, and others [Fatema &et al,2024]. Jaiswal et al. proposed a unique design for a Surface Plasmon Resonance (SPR) sensor device for detecting malaria at its various stages, based on the device structure configured on a Kretschmann setup consisting of multiple layers. The researchers worked on enhancing sensitivity by studying the thickness and number of layers. They also applied the electric field distribution and field enhancement factor to verify the reflection angle location and extremely high sensitivity. The researchers found that this device operated excellently in detecting at the loop stage [Jaiswal & et al, 2024]. Sahoo et al.

presented a design and simulation of a perpendicular sensor device made of two-dimensional photonic crystal (2D PC) for detecting parasitic diseases such as malaria. The proposed sensor device excelled in its high capability to detect and identify various stages of malaria. The performance of this device was improved through the repeated ring structure based on PC, making it more sensitive with good transmission efficiency compared to other optical devices. Additionally, this proposed structural design stood out for its simplicity and compact size [Sahoo & Varshney,2023b]. Singh et al. proposed a highly sensitive dual-metal surface plasmon resonance (SPR) biosensor device for detecting malaria at its various stages. The device structure is based on a Kretschmann configuration consisting of multiple layers. The performance of this proposed sensor device relied on the angular interrogation method. Additionally, this sensor device excelled in its high capability to detect different stages of malaria within a refractive index (RI) range from 1.370 to 1.410, as well as its excellent performance. The researchers achieved optimized values for angular sensitivity in different stages of malaria with this proposed sensor device [Singh &et al,2023]. Tammam et al. offered a one-dimensional defective photonic crystal which was examined as a biosensor for detecting malaria. Human red blood cells were used as a sample defect in the proposed optical device. The transmission spectra were analyzed. Significant changes in the sample refractive index greatly affect the transmission resonance peak, and this shift in the peak plays a key role in the device operation. Relatively high sensitivity was discovered, along with figure of merit and quality factor. The proposed optical sensor is relatively superior to other available sensors for detecting malaria [Tammam &et al,2021]. Saini et al. studied the biosensing capabilities of defective one-dimensional photonic crystals for detecting malaria infection from the early stage to the advanced stage by examining various samples containing red blood cells types A, B, C, D and E. This study was conducted for a range of cavity thicknesses, and the study showed that the design performance reaches its maximum value at a thickness of 5,000 nanometers. Consequently, the design became very useful for identifying individuals suffering from advanced-stage malaria infection due to the accuracy of the results. High values were also obtained for the quality factor and maximum performance factor [Saini & Awasthi,2022]. Shafkat et al. proposed a simple sensor device designed with photonic crystal fiber technology to detect malaria infection based on the refractive index changes of red blood cells associated with the stages of the malaria parasite. The initial structure of the PCF sensor device consists of dual rings of circular air gaps arranged in a hexagonal configuration. A horizontal oval channel in the center of the fibers contains a sample of red blood cells. The design parameters of the proposed sensor device were optimized to achieve the best possible results. The highest spectral sensitivity was achieved with values of approximately 11,428.57 nanometers per refractive index unit for malaria-infected red blood cells during the ring stages [Shafkat &et al,2021]. The highly sensitive Kretschmann geometry was analyzed(by Karki et al). which relied on a biosensor device for detecting all stages of malaria. This proposed biosensor relied on changes in the refractive index of red blood cells throughout the lifecycle of the malaria parasite. Transmission spectra were calculated, as well as sensitivity and quality factor [Karki &et al,2024a]. Huang et al. offered a biological sensor developed for malaria detection in the short infrared range using total plasmonic reflection within photonic bandgaps. The reflection spectrum of the electromagnetic waves for the proposed sensor device was calculated. The proposed sensor device operates by measuring the shift in the resonant reflectance dip position of total plasmonic reflection, which can be used to identify various stages of malaria infection. The performance of the proposed sensor device was optimized under different reflection angles by adjusting the thickness of the silver layers and the blood sample [Huang &et al, 2023]. Ankita et al. proposed an improved design for an optical biological sensor using a metal/defective/metal multilayer optical crystal for diagnosing malaria. The defective layer was tailored to match different concentrations of hemoglobin associated with malaria stages. The transmission, reflection, and absorption were evaluated. Various parameters such as the width of the metal layer, incident angle, refractive index, and defective layer were altered to analyze the adjustable properties. It was found that increasing the thickness of the metal layer and the incident angle improved the defect mode. Additionally, it was observed that the transmission peak decreased with the incident angle on TE polarization. The proposed biological sensor was found to have high sensitivity for diagnosing malaria compared to previous studies [Ankita et al,2022]. N. Manjunatha et al. presented a biological sensor device for a dual-nanorod nano-cavity to distinguish distinctive stages of the malaria parasite in red blood cells (RBCs) for early malaria detection. This proposed biological sensor device enabled the creation of a label-free biosensing environment where optical and scattering properties were analyzed. By utilizing this biological sensor device with a sensing region for the analyte, changes in refractive index were detected to differentiate between normal red blood cells and cells infected with the malaria parasite. The results indicated that the proposed biological sensor device exhibited high sensitivity, a high quality factor (Q), low detection limit (Dl), and a high figure of merit (FOM) [N .Manjunatha &et al,2023]. Mohammed et al. worked on designing, simulating, and evaluating two-dimensional photonic crystal (PhC) biological sensors based on light refractive index. The goal was to propose designs for effective malaria stage detection. The first design was manufactured using current technology and exhibited acceptable sensitivity with reasonable quality factors in a size of(11.4 × 9.2) square micrometers. The second design required advanced manufacturing techniques but outperformed the first design with superior sensitivity and quality factors in a size of(9.4 × 5.5) square micrometers. The researchers operated at a wavelength of 1.55 micrometers. The proposed design showed precise performance compared to similar studies for malaria detection [Mohammed &et al,2020]. Ankita et al. presented a single-dimensional photonic crystal biological sensor device with a layer for diagnosing malaria. By varying the concentration, a significant change in the refractive index was observed. This change in refractive index shifted the corresponding transmission peaks, enabling the diagnosis of malaria. The researchers obtained sensitivity values, quality factors, and the minimum detection limit, with a response time of 73.8 femtoseconds [Ankita et al,2021]. Azad et al. proposed an alternative optical methodology using a compact and user-friendly device based on photonic crystal fibers (PCF). They synthetically produced the malaria pigment known as hemazoin (SHz), which distinguishes itself from other blood components by its exceptional magnetic-optical properties. This enabled it to act as a dollar entity in response to the magnetic field. The prepared sample was characterized morphologically and structurally. The researchers presented a sensor device containing a detection threshold of 7.2 parasites per microliter, significantly lower than the clinically significant level (50-100 parasites per microliter) [Azad &et al,2023]. Kumar et al. utilized the refractive index variation from infected blood cells to normal blood cells to design a photonic biological sensor device for rapidly detecting malaria in humans with high speed and very short time. The researchers placed the extracted sample into the cavities of the proposed sensor device and directed a light beam with a wavelength range of 1.85 to 1.95 micrometers inside the device. They obtained the quality factor and sensitivity for this device [Kumar & et al,2021]. Tayoub et al. suggested designing a two-dimensional ring-shaped photonic crystal sensor device to measure the refractive index increment for diagnosing malaria-infected red blood cells. The device operates under vertically polarized light (TM mode) within a wavelength range from 1130 to 1860 nanometers. The researchers achieved high sensitivity and an exceptional quality factor (Q-factor) for the proposed design. Additionally, the proposed device stands out for its extremely compact size [Tayoub &et al,2023]. Karki et al. conducted a comprehensive study of an SPR sensor device constructed in a Kretschmann configuration to detect different stages of malaria. The researchers numerically analyzed this based on a bimetallic layer and an MXene layer. Through this design, the researchers were able to achieve early detection of malaria with good sensitivity, rapid response, and high accuracy. The proposed sensitive device consists of a BK7 prism and layers of Ag-MXene-Au and graphene. Values of (DA) detection accuracy and (FoM) figure of merit were obtained to verify the performance of this sensitive device [Karki &et al,2024b].

Table 3: The most important parameters of sensors used in detecting malaria

Sensitivity	Q factor	FOM (RIU^{-1})	DL (RIU)	ref
1114 nm/RIU				5
495.73 nm/RIU	2.03*10^5		8.07*10^-6	6
383-425 nm/RIU				15
217.5 nm/RIU	6151.58		4*10^-3	16
23000 nm/RIU				22
26000 nm/RIU		3.88*10^4	2.87*10^-6	29
301.1667 deg/RIU		39.879		36
225 nm/RIU	214			41
798.143 nm/RIU	988.926	4496.079	222.4*10^-6	54
240.10 deg/RIU		78.46		57
327.7 nm/RIU	69389.7	32770		64
1472 nm/RIU	1076	1022		73
700 nm/RIU	10^6	10^6	10^-7	74
300 GHz/RIU		.887-1.587		75

Table 4: Various parameters of malaria infected blood sample with defect

Phases	Sensitivity	Q factor	FOM (RIU^{-1})	DL (RIU)	ref
ring, trophozoite schizont	13714.29 nm/RIU 9789.47 nm/RIU 8068.97 nm/RIU				14

ring, trophozoite schizont	387 deg/RIU 305 deg/RIU 273 deg/RIU	107.12			33
ring, trophozoite	227.9 deg/RIU 258.28 deg/RIU	31 35.5			35
ring, trophozoite schizont	12142 nm/RIU 9736 nm/RIU 8241 nm/RIU				40
Plasma Platelts Hemoglobin	150.55 deg/RIU 226.73 deg/RIU 295.58 deg/RIU				44
X Y	38571 nm/RIU 31429 nm/RIU		438.41 522.25		49
ring, trophozoite schizont normal	741.30 nm/RIU 759.65 nm/RIU 777.61 nm/RIU 731.20 nm/RIU	1755.69 2430.21 2576.14 1535.27			51 A
ring, trophozoite schizont normal	406.13 nm/RIU 416.27 nm/RIU 427.18 nm/RIU 401.44 nm/RIU	5978.36 5390 5974.8 7187.27			51 b
ring, trophozoite schizont	42857.14 nm/RIU 22105.26 nm/RIU 16206.90 nm/RIU		596.90 423.98 341.63		55
ring, trophozoite schizont	11428.57 nm/RIU 9473.68 nm/RIU 9655.17 nm/RIU				67
ring, trophozoite schizont	550 nm/RIU 551.9 nm/RIU 551.4 nm/RIU		7857 7884 7877	8*10^-6 7.9*10^-6 7.9*10^-6	68
ring, trophozoite schizont	367 deg/RIU 297 deg/RIU 269 deg/RIU				70
ring, trophozoite schizont	364 deg/RIU 296 deg/RIU 267 deg/RIU				71

2-3. Application of photonic crystal sensors in cancer detection

Yang et al. proposed a biosensor for detecting cancer cells based on a silicon photonic crystal with a hexagonal ring resonator inserted into a triangular lattice matrix. The sensor relies on changes in the refractive index, as cancer cells and normal cells have different refractive indices. This device was used to detect them [Yang & Xiang,2023]. An innovative photonic biosensor device has been proposed by Panda et al. based on defective monolithic light crystals integrated with graphene, to detect various cancer cells such as basal cell carcinoma, cervical cancer, and breast cancer in real-time. The transmission and absorption spectra of the different cells were studied. The cornerstone of this work relied on testing the wavelength shift of the resonant mode pattern formed within the transmission and absorption spectra. The proposed structure was optimized in terms of material selection, thickness of insulating layers, period of insulating layers, defect layer thickness, and angle of incidence to image an efficient cancer sensor [Panda &et al,2021]. Yasli et al. discussed a biosensor device based on surface plasmon resonance of photonic crystal fibers was designed for early detection of six types of cancer cells. Spectral interrogation and capacitance methods were used to detect differences in the refractive index of cancer cells. Sensitivity was obtained at 7142.86 nanometers per refractive index unit for Mcf with spectral interrogation and a refractive index of 757 for capacitance methods for Hela cells [Yasli ,2021]. Mohammed et al. presented a biomedical photonic sensor capable of accurately detecting and distinguishing between normal and abnormal brain tissues. The proposed sensor has the ability to differentiate between 11 different types of brain lesions, tumors, and cancerous tissues with precision and simultaneously with acceptable sensitivity and high quality factor compared to other optical detection techniques. This work introduced two different designs that can be manufactured based on current technology and both designs are compact. The study also provided a comparison with relevant literature on similar brain tissue sensing devices [Mohammed &et al,2023]. Eid et al. aproposal a new was introduced for a biological sensor to effectively detect cancer cells in blood and skin based on photonic crystal fibers. The model was built, numerically analyzed, and the simulation of the proposed model demonstrated its efficiency in detecting cancer cells. Several parameters suggest that the proposed sensor achieved optimal results at a frequency of 2 terahertz. At this point, sensitivities in detecting blood cancer cells (Jurkat) and normal cells, skin cancer cells and normal basal cells, and water with different ratios were achieved. Simulation results also suggest that the proposed sensor has very low material loss and confinement values. Additionally, the simple rectangular-based model provides ease of use [Eid & et al,2021b]. Jabin et al. showed for the first time, photonic crystal hollow-core fibers were introduced in the history of biological sensing, utilizing a novel design in fiber optics for biological sensing applications, particularly for detecting cancer cells such as blood cancer, cervical cancer, pancreatic cancer, breast cancer, and skin cancer. The evaluation was conducted both experimentally and numerically. Approximately 22,105 mesh elements were included in the simulation, and the numerical analysis was validated using simulation software that considered refractive indices. Other parameters, such as birefringence, coupling length, mode confinement, transmissivity, wavelength sensitivity, and refractive index sensitivity, were evaluated through refractive index parameters for the cell [Jabin & et al, 2020]. Nouman et al. a theoretical investigation was conducted on how to detect various brain lesions using one-dimensional photonic crystal. The optical properties of one-dimensional photonic crystals were analyzed, and the device performance was verified by measuring redshift in the vibrational wavelength when the refractive index of the lesion layer changed from 1.3333 to 1.4833. High sensitivity and high-quality factor were achieved for this design [Nouman &et al,2020]. Khani et al. proposed two new designs for optical sensors to detect cancer cells. These structures consisted of one-dimensional photonic crystal (PC) lattices and two metal-insulator-metal (MIM) plasmonic waves. The PC lattices were generated in the central part of the structures, forming photonic bandgap (PBG) regions that contained sharp edges in the transmission spectrum acting as suitable filters for sensing applications. This allowed for the use of the proposed sensors over a wide wavelength range. Researchers achieved maximum values for sensitivity and figure of merit (FOM). Due to the simplicity and high sensitivity of the proposed sensors, they became suitable filters for biological sensing applications [Khani & Mohsen,2022]. Kalyani et al. proposed an optical sensor design for detecting melanoma (skin cancer) using two-dimensional photonic crystals based on nano-cavities and micro-cavities. A normal cell and a melanoma cell with refractive indices of 1.35 and 1.59 were utilized in the designs. Changes in wavelength shift according to the refractive index were detected by the biological device. Changes in the resulting transmission spectrum and quality factor were observed with wavelength shift, indicating the detection of melanoma (skin cancer). Results were analyzed and compared to evaluate the accuracy and sensor transfer. An optical bandgap was obtained from 1316 nanometers to 1940 nanometers, and a continuous wave was used with a modified frequency of 1550 nanometers in this design. The proposed device was used in medical applications due to its accuracy in results and short response time [Kalyani & Sharma,2022]. Baraty et al. proposed the use of ring resonators in a two-dimensional (2D) photonic crystal biological sensor device. The structure consisted of a cubic lattice with a periodic array of silicon rods with a refractive index of n = 3.46 surrounded by air background. When the refractive index changes, the resonance wavelength shifts, triggering the sensing mechanism. This aids in identifying both natural and cancerous cells. Average sensitivity values, quality factor, FOM, and transmission were obtained for the designed structure. This proposed design is utilized in high-quality promising applications [Baraty & Hamedi ,2023]. Momeni et al. aimed to propose a new design for diagnosing basal cell carcinoma (BCC) using refractive index-based photonic crystals in a two-dimensional structure (PCs). This design consisted of a square array of GaAs rods in SiO2. The structure included waveguide modes for input and output, as well as a small cavity. By using some PC rods to separate the cavity from the waveguides for input and output, the results showed that injecting an analyte into the cavity changes its refractive index, resulting in a resonance wavelength shift in the transmission spectrum. High sensitivity coefficient, figure of merit (FoM), and quality factor (Q) were obtained [Momeni &et al,2021]. Bounaas et al. discussed a one-dimensional (1D) photonic crystal sensor that was optimized for detecting different types of cancer cells. The sensing region was formed by a vertical slot (VS) inserted into a periodic Bragg mirror. The operation principle of the structure relied on changing the refractive index (RI) of the analyte integrated in the VS, leading to a shift in the resonant wavelength peak. The results of digital simulation showed that the final optimized sensor had high sensitivity compared to other similar devices [Bounaas & Labbani,2021]. EL Mouncharih et al. utilized the finite-difference time-domain method in a two-dimensional theoretical study of the optical properties of a two-dimensional photonic crystal biological sensor. This design involved silicon rods arranged in a square lattice in an air substrate with waveguide modes and a nanocavity. Six different cells were placed at the defect point, including Jurkat, HeLa, PC-12, MDA-MB-231, MCF-7, and basal cells. These cells were penetrated, and as a result, researchers were able to detect cancerous and benign states of these cells through resonance peaks in the spectrum. Sensitivity, quality factor, detection limit, and figure of merit were examined with different values for sensing radius optimization purposes. Lastly, the proposed sensor device, a miniature structure with high sensitivity, is used in cancer cell detection models [EL Mouncharih &et al,2023]. L Guruprasad et al. proposed a new design for cancer detection with high quality factor and sensitivity. The design consisted of photonic crystal structures containing two types of cavities for waveguides: triangular and interconnected circular cavities. The researchers determined the sensitivity of the gaps and rod sensitivities, as well as the quality factor (Q) [Guruprasad & Rashmi,2021]. Heidari et al. presented a new two-dimensional photonic crystal biological sensor designed to detect various types of cancer cells, with verification of the associated parameters. The proposed structure featured nanoscale circular cavities with a sensing region at the center, tested with different cancer cells such as skin, cervical, blood, and others. This design stood out for its high-quality factor, high figure of merit (FOM) values, low detection limit (Dl), and acceptable sensitivity [Heidari & Sharifi ,2024]. Malek et al. focused on the properties of a defective one-dimensional photonic crystal for the rapid detection of brain tumors. They utilized a 1D photonic crystal design with its cavity coated with SiO_2 particles added in a conductive material layer called a nanocomposite layer to facilitate the external defect tuning based on the temperature inside the supra-bandgap gap, in addition to changing the angle of incidence. Firstly, to achieve the maximum performance of this proposed design, optimized internal parameters were selected. Secondly, to enhance performance by sensitivity and quality factor for tuning the external defect mode, the researchers studied the effect of changing the angle of incidence. Additionally, the researchers studied the impact of changing the temperature of the nanocomposite layers on the position and intensity of the defect mode inside the supra-bandgap gap.The results of this study are highly beneficial in designing biological sensor structures [Malek &et al,2022]. Aly et al. theoretically investigated the design of a defective one-dimensional photonic crystal for ultra-precise detection of cancer cells. The researchers individually studied different samples of cancer cells by varying the number of periods, defect layer thickness, and angle until the proposed design achieved high sensitivity. The proposed design relied on the principle of detecting changes in the refractive index of the different samples. This design resulted in a shift in the defect position from 1538 to 1648 nanometers, corresponding to the sample containing Glioblastoma cells and the natural sample with refractive indices of 1.4470 and 1.350 respectively [Aly & et al,2023]. Asuvaran et al. a two-dimensional photonic crystal biological sensor device supported by electromagnetic radiation was designed to detect the refractive index (RI) of different brain tissues during robot-assisted surgical procedures. This device operates in the ultraviolet to infrared radiation range and is designed deeply to impact changes in the refractive index of various tissues. Due to the variation in refractive index among different tissues, the proposed device was able to distinguish between tumors, cancerous tissues, and healthy brain tissues [Asuvaran & Elatharasan,2022]. Sharifi et al. presented a design and numerical analysis of an optical crystalline sensor device for detecting changes in the refractive index in human blood. The proposed biological sensor device was utilized in the early diagnosis of cancer cells and various viruses. The proposed sensor design consisted of an elliptical-shaped oscillator and waveguide, designed using silicon pillars in a two-dimensional square lattice, optimized for detecting cells and viruses across a wide range of refractive indices (1.330 to 1.401). The proposed sensor device excelled in both quality factor and high sensitivity values, positioning it as a prominent candidate in the medical sensing field within the terahertz range [Sharifi & Eskandari,2024]. Sani et al. proposed a refractive index sensor device based on photonic crystal for the simultaneous detection of cancer and diabetes. The proposed structure consisted of silicon pillars in an air layer arranged in a hexagonal lattice forming the basic structure. The researchers used the finite difference method to analyze and simulate the sensor transmission properties for the studied sample. The diagnosis of three types of cancer and diabetes relied on changes in the refractive index in the studied samples when applying a laser source at 1550 nanometers. The researchers adjusted the quality factor and sensitivity of the proposed structure by changing the sensor's geometry. It was revealed that the transmission power ranged from 91% to 100%, depending on the sample [Sani &et al,2022].

Table 5: The most important parameters of sensors used in detecting cancer

Phases	Sensitivity (nm/RIU)	Q factor	FOM(RIU^{-1})	DL (RIU)	ref
	4270.525928	15037.89162	14711.45719	0.114566*10^-6	3
	324.28	3690	888.88		9
	3201				11
	1350	15.03	10.07462	0.0993	21
Normal Abnormal	214.28	13353 3053	172.35	5.8*10^-4	28
	18115.94			0.014	31
Nano cavity str Micro cavity str		382.70 362.52			34
Biosensor I Biosensor II	718.6 714.3	207.4 8o.16	156.217 60.1		38
Rods in Air(RIA) Holes in Slab(HIS)	1200 800	2902 2100			46
	4139.24	1.003*10^3	1.250*10^3	3.99*10^-5	47
	1332	16254		9.08*10^-6	52
	730	161	11428		53
	3080.808		6.1*10^7	1.83073*10^-9	56
	290	2270.74	1074.04		58
	3080	946.50	1550.11	31*10^-6	65
	650~900	190	105	1*10^-4	69
	915.75	980		236*10^-6	76
MCF-7 Hela(amplitude)	7142.86 -757 U^{-1}				77

2-4. Application of photonic crystal sensors in bacteria detection

Alhamss et al. proposed a new model for a Photonic Crystal Fiber (PCF) sensor device to detect waterborne cholera and E. coli bacteria. The core region of the proposed PCF sensor device design consisted of a single rectangle, while the cladding region contained 32 rectangular air holes. The researchers analyzed the model numerically and structurally and concluded from simulation results that the proposed sensor device is effective in detecting bacterial samples. The performance of the proposed sensor device was evaluated by detecting various parameters such as high relative sensitivity, low effective area, digital aperture, and other parameters, demonstrating the effectiveness of this device. Additionally, this proposed design was characterized by its simplicity, facilitating the manufacturing process of the PCF sensor device [Alhamss & et al,2023]. Zaman et al. discussed using defective one-dimensional photonic crystals to detect waterborne bacteria. The sensing mechanism relied on changes in the refractive index. The researchers evaluated the performance of the proposed sensor device by studying the impact of different parameters such as the angle of incidence, defect layer thickness, and number of periods until they reached the optimal condition. The proposed sensor device demonstrated high sensitivity. Performance parameters such as quality factor and detection limit were calculated for this proposed sensor device. Additionally, this design was characterized by its simplicity and excellent performance, making the sensor device important for effectively detecting bacteria in drinking water [Zaman &et al,2023]. Gowda et al. proposed a design for a two-dimensional photonic crystal sensor device to be used in detecting and identifying the presence of bacteria in contaminated water. To analyze the sensor, the researchers utilized the MIT-MEEP simulation tool and employed a simulation tool for solving electromagnetic scattering equations as an input in Meep to analyze transmission and reflection spectra at the Massachusetts Institute of Technology. The final responses of various bacteria in the proposed design were analyzed based on changes in the refractive index of the bacteria, leading to variations in wavelength, light frequency, and central frequency. The researchers found that the changes in wavelength and frequency were significant [Gowda & et al,2023]. Suthar et al. aimed to explore a defective one-dimensional photonic crystal structure for use as an optical sensor device in detecting bacteria in pure water. The researchers utilized a quarter-wave structure in the application of the proposed optical sensor device. A graded refractive index profile for the layers was applied to enhance the sensitivity of the proposed sensor device. Various parameters of the proposed structure were studied [Suthar & Bhargava,2023]. Du Zhenhua et al. proposed an optical sensor device in the form of an elliptical photonic crystal fiber with an open ring channel, which could enhance the performance of the sensor device. The researchers used gold as a plasmonic material and coated it on the open ring channel. They examined the sensitivity of wavelength, intensity sensitivity, optical spectrum leakage, and studied the impact of structural parameters on the performance of this proposed device. The researchers found in their numerical results that the proposed sensor device exhibited a wide detection range in the refractive index (RI) from 1.20 to 1.40. Additionally, this proposed sensor device had maximum sensitivity. This sensor device was used to detect pathogens in water and glucose concentration [Du Zhenhua & Liu,2024]. Kulkarni et al. introduced a new design for an optical sensor for detecting bacteria in water. In this proposed design, the researchers used a pair of two-dimensional crystalline structures (a, b) and analyzed them. The researchers modeled the proposed design structures and studied the optical properties of various bacteria in water. This design relied on the principle of refractive index in the two structures [Kulkarni &et al,2020]. Daher et al. worked on developing a new sensor for detecting waterborne bacteria based on a one-dimensional defective two-dimensional photonic crystal. A resonant peak was created within the optical band gap. The sensor relied on the difference in refractive index between pure water samples and waterborne bacteria samples. The researchers studied the effects of several factors on sensitivity, such as the angle of incidence, thickness of the defective layer, thickness of the periodic layers, and the number of periods. The proposed sensor exhibited very high sensitivity and is characterized by a simple design that can be easily manufactured [Daher &et al,2022]. Kumar et al. proposed a flexible ring resonator model based on photonic crystal for detecting various impurities in water samples. The model exhibited a high quality factor and good sensitivity in detecting different types of impurities. The parameters of this design for impurity sensing in water samples were optimized based on their refractive index characteristics. This design has a fast response time. The main goal of this design is to identify distinctive bacterial impurities in water samples, and the device can be used as a lab-on-a-chip [www.who.int,17/3/2024]. In their paper, Gandhi et al. discussed a new method for detecting anthrax bacteria and various bacterial cells present in water samples was studied through the design of a one-dimensional biological sensor. This was achieved by linking two layers of one-dimensional circular photonic crystals with a defect layer d. The study was conducted in the visible spectrum region of the electromagnetic spectrum. Seven water samples containing different cells were examined. Various parameters such as sensitivity, quality factor, detection limit, and minimum detection limit were identified to assess the overall performance of the proposed biological sensor device. This study opens up a new path for favoring one-dimensional biological sensors based on circular photonic crystals over other sensor devices [Gandhi & et al,2023]. Jahan et al. discussed an optical surface plasmon resonance (SPR) sensor device for detecting Pseudomonas bacteria based on photonic crystal fibers (PCF) with attractive performance characteristics were proposed. The proposed sensor device was designed using a simple circular lattice of photonic crystal fibers, coated with a chemically stable thin layer of gold. The sensor device's performance was numerically investigated using finite element (FE) simulation, and high sensitivity for wavelength and intensity was achieved. Additionally, the device exhibited excellent spectral accuracy of 5.26×10^{-6} RIU. The performance accuracy of the sensor device was also examined by altering various parameters such as the air hole diameter, bandgap, and gold layer thickness. This proposed sensor device is highly effective in detecting Pseudomonas bacteria, as well as other organic compounds and biological solutions [Jahan & et al,2021]. Aly et al. A two-dimensional photonic biosensor device composed of two photonic crystals fabricated from GaP and SiO_2 has been designed. The researchers studied the impact of varying the cavity thickness and the corresponding incidence angle for TE wave on the proposed structure's transmittance theoretically. Various design parameters, such as sensitivity (S), figure of merit (FOM), resolution (RS), limit of detection (LOD), quality factor (Q), and others, were calculated theoretically to evaluate the performance of the proposed device. This study also demonstrated the capability to distinguish between different microbiological samples and between bacterial cells and seeds [Aly & et al,2022]. Birhanu et al. theoretically investigated the effective detection of bacteria in blood using a one-dimensional photonic crystal biosensor (1D PCB). The researchers examined the impact of varying the type, thickness, and number of insulating layers and surface roughness on the sensitivity of the 1D PCB (S). They also determined the values of the quality factor (QF) and detection accuracy (DA). To enhance the device performance, researchers found that adding insulating layers with increased surface roughness thickness improved the device's performance. The proposed sensor device excelled in accuracy, speed, ease of manufacturing, and cost-effectiveness, making it significant in the fields of medical and biological applications [Birhanu & et al,2024]. Sahoo et al. analyzed and modeled an elliptical-shaped photonic crystal ring resonator for detecting viral and bacterial infections. The working principle of this proposed optical design relied on the shift in the reflected peak wavelength corresponding to the small change in refractive index. The researchers found that the proposed sensor device achieved high sensitivity. Additionally, the quality factor was calculated [Sahoo & Varshney,2023a]. Kumar et al. presented modeling a refractive index sensor device using a photonic crystal ring resonator. The proposed sensor device exhibited high selectivity and a high-quality factor when detecting various bacterial water samples, being highly sensitive in real-time. The proposed sensor device was considered very important for on-site detection. The researchers utilized a silicon-on-insulator platform in the design of the proposed sensor device [Kumar & et al,2022]. Sharan et al. conducted experimental investigations on the cancer cell detection capabilities with high sensitivity using a one-dimensional photonic crystal with a defect. The researchers tested the performance of the proposed biological device containing samples with cancer cells by varying the number of periods, defect layer thickness, and the angle of incidence for polarized light. This proposed biological device relied on detecting slight changes in the refractive index for samples containing different cancer cells. Under optimal conditions, the structure provided a transmission at the defect site ranging from 1538 to 1648 nanometers, consistent with samples containing normal cells and glioblastoma cells. The researchers achieved maximum sensitivity, quality factor (Q), and figure of merit (FOM) in this study [Sharan &et al,2024]. Kebaili et al. aimed to design a sensor based on a two-dimensional photonic crystal structure to examine optical transitions resulting from differences in the refractive indices of bacteria as light passes through the sensor structure. The simulation process showed that fluctuations in the refractive indices of bacteria significantly impact the signal frequency and wavelength. Five different types of bacteria were detected in drinking water. The study demonstrated the success of the sensor in detecting bacteria in contaminated water [Kebaili & et al,2024].

Table 6: The most important parameters of sensors used in detecting bacteria

phases	Sensitivity (nm/RIU)	Q factorm,,,,,,m	FOM (RIU^{-1})	DL (RIU)	ref
	333~337	(1.3~1.7)*10^3	(6.7~8.5)*10^2	(6~7.4)*10^-5	2
	509	51			10
	3639.53	7521.26	8977.98	1.77*10^-5	17
Wavelength amplitude	21000 455.45				18
	472.794	8000	5200		23
Wavelength amplitude	20000 1380		470.59		32
	834.344				37
	232	980			43
Tb HBV	881.25 555.55	624.37	346.38		62

	550	29260	18500	2.773*10^-6	68
	2801.515	29554.04			72
	2486.57	5455.70	6262.31	2.72*10^-5	78

3. Conclusion

In this study, we reviewed 76 recent research papers discussing the use of photonic sensor devices in medical applications. The focus was on detecting malaria, cancer, blood cells, and bacteria in water. The calculations were processed using various statistical methods such as FEM, TMM, PWE, and FDTD. Different simulation software as MATLAB , Rsoft , Comsol ,and OptiFDTD were used to detect various parameters of the sensors, including sensitivity, quality factor, figure of merit, and detection limit. The results were presented in tables .

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