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Modeling and Simulation of an Optical Sensor for Cancer Cell Detection

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ABSTRACT- In this article, modeling of ring resonator for the identification of the various cancer cells has been proposed. The model exhibits high Q factor and high selectivity for sensing various cancer cells. The parameters of the design are optimized for sensing cancer cells in the sample based on its distinct refractive index. The proposed device has been modeled by the FDTD simulation method which confirms satisfactorily distinct resonant wavelengths for various cancer cells. The device has explored the feasibility of label-free cancer cell sensing with improved characteristics.

General Terms: Refractive-Index, Sensor, FDTD Simulation.
Keywords: Ring Resonator, Photonic Crystal, Optical Sensor, Cancer Cell Detection.

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1. INTRODUCTION

Cancer is very serious disease that can affect any part of the human being. Cancer can be developed at almost any part of the body. According to World Health Organization (WHO) data of 2018, around 9.8 million deaths globally caused by cancer and statics are rising day by day. However, the early-stage detection of cancer growth in body helps to deceases the rate of death tremendously. Hence, over the last few years, the early-stage detection of cancer cell-based research has been increased throughout the world. The cancer cell can be detected at the early stage by various means like the electro-chemical, immune-chemistry, Raman spectroscopy measurement, etc. [1-3].

Very recently, interferometers such as Mach–Zehnder Interferometer, Sagnac Interferometer and Ring Resonator (RR) have exposed their capability to sense numerous physical parameters. Among them, RR-type structure is compact and ultra-fast, compared to its counterparts. Recently, photonic crystal (PhC) based devices are developed for sensing purposes based on the refractive index difference [4-8]. Hence, PhC based device is the suitable candidate for the sensor purpose, as it has high selectivity, sensitivity as well as it possesses high quality factor.

The abnormal and infected cell in human body called cancer cell which can damage organs of the body. The symptom of Cancer disease visible when abnormal cells grow rapidly in the body. The cancer cell has a high number of proteins, and thus. The variation in refractive index (RI) of cancer cell and normal cell helps to identify the cancer in body. The contrast between these two cells can be utilized to design the photonic crystal (PhC) based cancer cell detector. Therefore, in this paper a highly selective PhC based ring resonator (PhCRR) is designed for the bio sensing and detection applications.

The proposed sensor comprises of square rod type structure in the core and to be intruded by the analyte of infected and normal cell. Through this device, the output spectrum has been observed for the infected and normal cells-based analytes. The Q factor and sensitivity of the PhCRR sensor is evaluated by estimating the dip spacing for the blood cancer, breast cancer as well as for gland cancer.

2. MODELING AND METHODOLOGY

The model consists of a two-dimensional PhC used for modeling the biosensor, and the device is based on mechanism of shifting in intensity. Thus, the regulated transmission of high detention of light passes through the model. The periodic arrangement of the dielectric material causes photonic band gap (PBG) in photonic crystal.

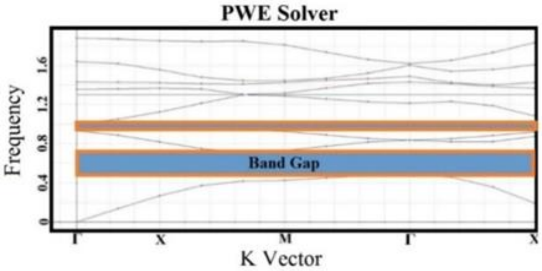

Figure 1: PBG of the proposed device

The band of wavelength which is allowed to pass through PhC is known as PBG and it can be optimized with the refractive index (RI), the radius of the rod and the lattice constant. The PBG diagram as obtained from the FDTD simulation using plane wave expansion (PWE) technique is shown in *figure 1*.

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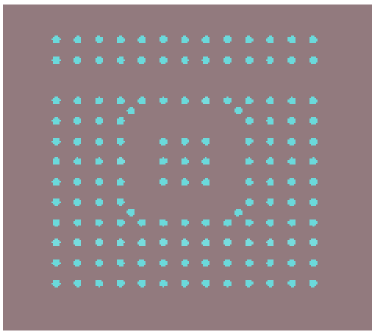
Table 1: Design parameters of the model

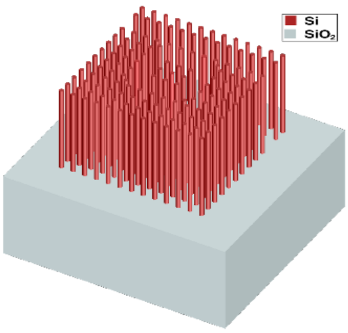
Parameter	Values
Design layout	Rods in air
Si rod radius (r)	0.11 µm
Lattice layout	Square type arrangement
Lattice const. (a)	0.54 µm
RI of Si rod	3.45
RI of reference (normal) cell/ background index	1.35
Source wavelength	1.5 µm to 1.6 µm
PBG	0.48873 to 0.716639 ~ (1395.4 nm to 2046.1 nm)
Footprint	45 µm2
Simulation Platform	FDTD
Polarized mode	TM mode

The PBG ranges of normalized frequencies are calculated from 0.48 to 0.71, from 0.94 to 1 and from 1.2 to 1.3 for TM mode corresponding to the intervals of three wavelengths. For the source light, the wavelength interval of 1500 nm to 1600 nm (0.48 to 0.71) is chosen, as it falls within the calculated optical communication window. The all-other key design configurations are in *table 1*.

The proposed structure is chosen than other available structures because this structure provides good sensitivity comparatively. The ring resonator-based structure is compact and analyzed over the other PhC based structures. The device is modeled and simulated on finite difference time domain (FDTD) platform, as shown in *figure 2* [9].



(a)



(b)

Figure 2: Proposed model (a). Front view (b). Perspective view

The *r/a* is calculated as 0.2 which is obtained through the analysis and simulation. The calculated value is good enough to propagate the light suitably throughout the design. The Si rods are introduced to scatter the light and the coupling length is optimized in the model to enhance its spectral selectivity [10]. The optimization of lattice constant and its response is shown in *figure 3 (a).*

The model comprises of a linear and circular line defect waveguide where, the RI of the various cancer cell is detected and biosensor monitor used to sense the change in intensity. The modeling is performed using Lumerical FDTD simulator. The RI of different cancerous cells are listed below in *table-2*.

Table 2: RI of different cancer cells

Cells	RI
Healthy Cell	1.350
Jurkat	1.390
HeLa	1.392
PC12	1.395
MDA-MB-231	1.399
MCF-7	1.401

3. RESULTS AND DISCUSSION

The output transmissivity of PhCRR sensor are shown in *figure 3*. When the surrounding RI of the PhCRR is changed by some means or dipped into the sample, then the resonance wavelength of the device changes.

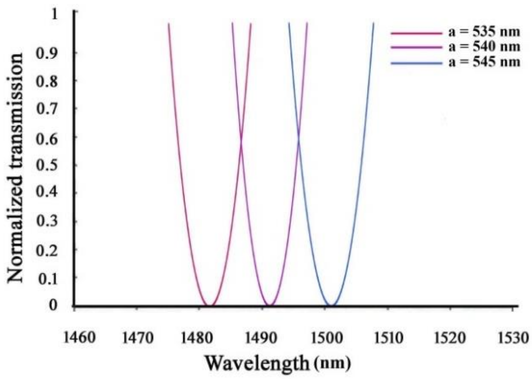


Figure 3(a): Transmission response with variation of a

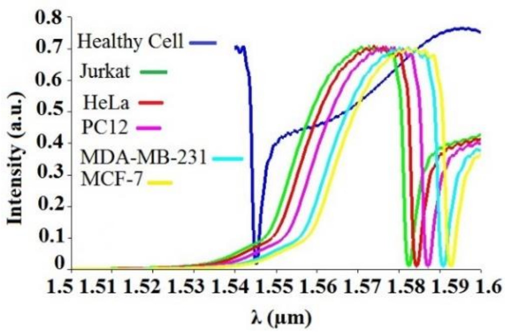


Figure 3(b): Output transmission graph

The change in the shift of resonance conditions indicates the bio-sensing of the device based on the surrounding RI variations. The resonance wavelength and the shift with respect to the healthy cell is shown in *table-3*.

Table 3: RI of different cancer cells

Cells	Resonance Wavelength (µm)	Resonance shift (nm)
Healthy Cell	1.545	
Jurkat	1.582	37 nm
HeLa	1.584	2 nm
PC12	1.587	3 nm
MDA-MB-231	1.591	4 nm
MCF-7	1.593	2 nm

3.1 Sensitivity

The proposed device is enough sensitive to detect the specific cancer cell from the analyte and shown in below expression [11]. The sensitivity (S) depends on ∂λ is the variation in resonating wavelength and ∂RI is the alternation in RI. The sensitivity of the device is calculated as 1 nm /RIU.

$$S = \frac{\partial \lambda}{\partial \mathrm{RI}}$$

3.2 Response Time

The simulated time of response of the model is found to be 40 fs [12].

3.3 Q-Factor

Q. factor is the spectral collection of the resonant condition for a PhCRR and is expressed below [7].

$$Q = \frac{\text{Stored energy}}{\text{Power lost}}$$

The Q-factor of the device for the various cancer cells are in *table-4.*

Table 4: Q value of different cancer cells

Cells	Q Values
Healthy Cell	850
Jurkat	650
HeLa	643
PC12	630
MDA-MB-231	614
MCF-7	600

4. CONCLUSION

The Cancer cell sensing device is proposed. Transmission results with high selectivity with ultra-small footprint of 45 μm^2 of proposed device are compared with other structures. The device has fast response time of 40 fs. Furthermore, the proposed model is stable, simple, feasible and, can be combined into various sensing applications. The comparison of previously reported articles with the proposed model is tabulated in *table 5.*

Table 5: Comparison with other published articles

References	Design	Q-factor	Footprint
[11]	PhC Sagnac Interferoemter	32.5	--
[13]	Rods in SiO_2	25-30	--
[14]	Air holes in Si	418	--
[15]	'L' and an inverted 'L' shaped waveguides hole type sensor	110.53	21x 21
[16]	Grating andwaveguides (Different designs are used)	1200	1x 1 inch
Proposed work	PhCRR	600-650	13 x 13 45 μm^2

The fabrication of the proposed device is possible using e-beam lithography. Precautions should be taken to reduce errors due to proximity effect caused due to the fabrication process. The possible fabrication tolerance range of the proposed device for the radius is around 0.1% and for lattice constant is 0.9 %. The proposed model is advantageous in terms of selectivity, Q-value and size over recently published works. The proposed model is much smaller, compact, thus has lower cost. The prime application of the device is to determine the distinct cancer cells in the human body. The other advantage of the model is to sense all the cancer cells at a time.

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