Design and Analysis of 2D Photonic Crystal-Based Biosensor for Cancerous Cell Detection

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***Abstract*—This paper presents a new design of a biosensor, aiming to detect cancerous cells, based on a two-dimensional silicon-rods-in-air photonic crystal (PhC) nanocavity. The impact of radius-variation of the nanocavity-rods on the biosensor characteristics has been examined. A sensitivity of 600 nm/RIU and quality factor of 3835.9 were achieved, resulting in a low detection limit of 6.36×10^{-5} RIU and a high Figure of Merit of 1572.094 RIU^{-1}. Therefore, the proposed structure can be utilized for various medical diagnostic applications including label-free detection of cancerous cells.**

***Index Terms*—Photonic crystal, photonic band-Gap, sensitivity, cancerous cells detection, finite-difference time-domain (FDTD)**

I. Introduction

Cancer is the rapid, abnormal growth of cells in the body, which is hardly curable at its advanced stage. On the other hand, it often shows no early symptoms, and, thereby, most of the diagnoses occurs at their advanced stage. Early detection may noticeably enhance the chances of survival. However, present pathological processes of detecting cancerous cells requires significant time for producing the result, which increases the patient-pipeline massively in a highly-populated country like - India. Thereby, we require an efficient as well as time-effective method for detecting cancer cells. In this context, biosensors, especially the label-free biosensors, shows the optimum efficacy [1]. Biosensors use immobilized biological materials like enzymes, antibodies, and cells for detection. Photonic-biosensors, particularly those made with photonic crystals (PhCs), are on emerging research focus, both in the optical and medical fields. PhC-structures can be made with Various high-dielectric materials, which make it a versatile platform for different sensing applications [2]. PhC is a synthesized periodic dielectric structure that creates photonic bandgaps (PBGs), which gives us a higher degree of freedom for designing efficient biosensors.

Therefore, in this article, we are proposing a new design of a PhC-based biosensor, made using an array of air-surrounded silicon rods. The design has been optimized for preferred performance by adjusting the radius of the rods.

II. Designing of Biosensor

Figure 1(a) illustrates the design of the PhC-based nanocavity sensor, made with a 2D array of 23x23 silicon rods (refractive index = 3.48) arranged in a hexagonal lattice within the air background. The default radius of the rods is taken as $0.222\,a$ ($\approx$ $91\,nm$), where $a = 410\,nm$ is the lattice constant. The plane wave expansion (PWE) and finite-difference time-domain (FDTD) methods are used to analyze the PhC structure [3]. The dispersion diagram of the bulk 2D-PhC structure, shown in Fig. 1(b), indicates a wide band gap for the TE mode with (a/λ) ranges from 0.2591 (i.e. 1582.4 nm) to 0.40994 (i.e. 1000.146 nm). Within this wide range of wavelengths, the standard telecommunication wavelength, i.e. 1550 nm, is mapped at $0.265\,(a/\lambda)$, and, hence, is considered as the operating wavelength.

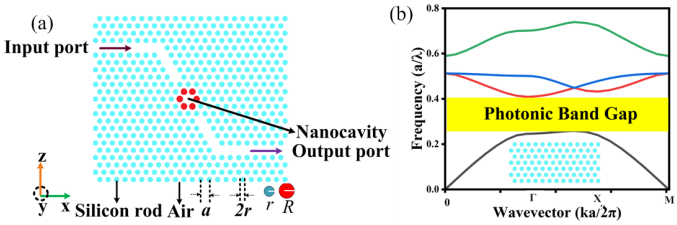

Fig. 1. Schematic of the designed PhC-based biosensor containing two waveguides and a nanocavity. (b) Dispersion diagram of the bulk PhC illustrating the PBG.

The biosensor structure is shown in fig.1, which is composed of three W1 waveguides - one (input) from the left, another (output) towards the right, and the third is connecting these two waveguides at an angle of 60°. The nanocavity is integrated within the connecting waveguide. The radius of the rods of the nanocavity has been taken as 105 nm. The nanocavity resonates at a particular wavelength and strongly couples the input to output waveguides at this wavelength only. As a result, an analyte strongly interacts with light within the nanocavity and becomes capable of changing the cavity's resonant wavelength.

III. Results and Discussion

The 2D FDTD technique is utilized to assess the biosensor's performance [5]. A TE-polarized Gaussian optical pulse having an FWHM of 50 fs, centered at 1550 nm wavelength, is launched at the input port. The pulse assimilates the characteristics of an impulse. Further, the transmittance spectra are monitored at the output port by normalizing the output power with the source at every wavelength. Figure 2 depicts

TABLE I
SIMULATION OUTCOMES FOR DIFFERENT RODS' RADIUS VALUES AT THE NANOCAVITY.

Cancer cell	Sensor parameters	Radius R(nm)				
		85	95	105	115	125
skin cancer (Basal cell)	Wavelength shift	12.5	12.5	11.7	10.6	9.4
	Q-factor	1949.5	3274.2	3399.4	2020.6	12588
	Sensitivity	645	625	585	530	470
	Detection limit*	0.06737	0.040954	6.9×10^{-5}	1.315×10^{-4}	2.453×10^{-5}
	FOM*	957.31	1525.893	1449.13	760.433	4076.032
MDA-MB-231 (Breast cell)	Wavelength shift	8.9	8.7	7.9	7.2	6.2
	Q-factor	2132.2	3454.8	3835.9	2992.3	9539.8
	Sensitivity	635.714	621.43	564.285	514.286	442.86
	Detection limit*	9.779×10^{-5}	6.3×10^{-5}	6.3917×10^{-5}	9.646×10^{-5}	3.4565×10^{-5}
	FOM*	1022.61	1587.14	1564.76	1084.95	9539.8
Cervical cancer (Hela cell)	Wavelength shift	15.2	14.9	14.1	12.6	11.4
	Q-factor	2060.7	3382.2	3658.1	2601.4	10647
	Sensitivity	633.34	620.834	587.5	525	475
	Detection limit*	1.012×10^{-4}	6.42×10^{-5}	6.418×10^{-5}	1.036×10^{-4}	2.88×10^{-5}
	FOM*	987.90	1557.357	1558.02	965.32	3470.57
Blood cancer (Jurkat cell)	Wavelength shift	8.7	8.6	8.4	7.1	6.3
	Q-factor	2041.2	3362.8	3611.1	2496.9	10970
	Sensitivity	621.43	614.286	600	507.14	450
	Detection limit*	1.040×10^{-4}	6.52×10^{-5}	6.36×10^{-5}	1.116×10^{-4}	2.949×10^{-5}
	FOM*	961.17	1533.23	1572.094	895.78	3390.68

*based on the expression given in [4]

the electric field's y-directed component propagation in the PhC structure without an analyte. The optical field is observed to be well confined within the cavity. Thereafter, the sensor's performances are analyzed by varying the radius (R) of the Si rods at the nanocavity. Table I presents the Q-factor, sensitivity, Detection Limit (DL), and Figure of Merit (FOM) of the sensor for four distinct cancerous cells when compared with their normal cells, at various R-values. The optimal R-value for the nanocavity is found to be R=105 nm, providing adequate sensitivity and Q-factor. The shift in resonance wavelength for each type of cell is monitored and plotted in Fig. 3. Finally, the results suggest that this sensor holds promise for label-free, on-chip detection in applications involving cancerous cell biomarkers.

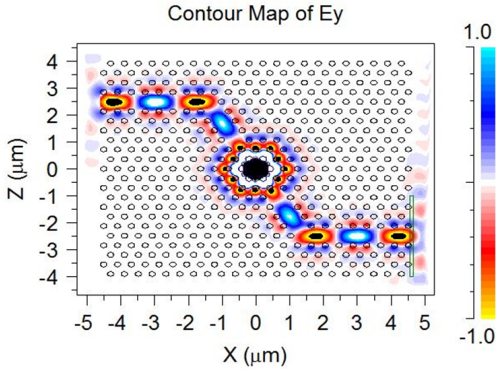

Fig. 2. The propagating mode normalized electric field intensity in a photonic crystal biosensor.

IV. CONCLUSION

A 2D PhC-nanocavity-based biosensor is proposed. The biosensor is incredibly sensitive and compact in footprint. The radius of the nanocavity-rod is optimized to attain a maximum sensitivity of 600 nm/RIU, Q-factor of 3362.8, a detection limit of 6.36×10^{-5}, and a FOM of 1572.094 RIU^{-1}. The sensor characteristics are evaluated for four different cancer cell types, and seen to offer a tremendous performance.

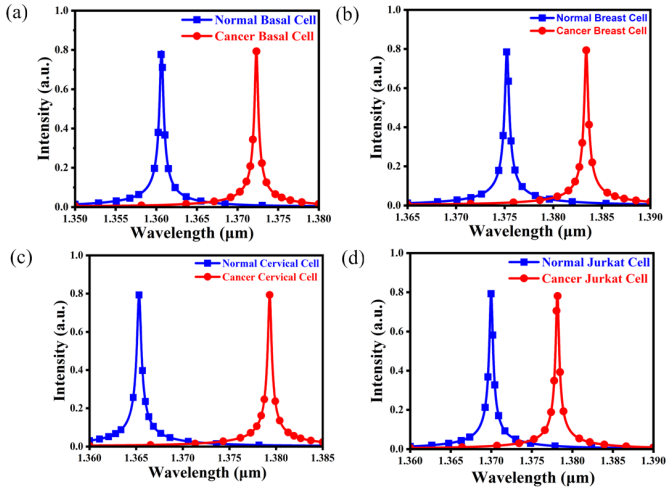

Fig. 3. Transmission spectra of designed PhC biosensor for normal and cancerous cells, including: (a) Basal cell, (b) Breast cell, (c) Cervical cell, (d) Jurkat cell, and (e) PC-12 cell.

Therefore, the proposed biosensor can be used for label-free sensing, which potentially aids early detection of cancerous cells and other bio-molecules.

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