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Nanocavity based 2D photonics crystal based biosensor for COVID-19 detection

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ABSTRACT

Abstract: In this research paper the author(s) propose a design of nanocavity based 2D photonics crystal biosensors for COVID-19 detection. The proposed model is designed using 2D photonics crystal technique and the simulation is done by Opti-FDTD (Finite difference time domain) software. The proposed biosensor has 12µm X 8.5 µm wafer dimensions. In this paperthe proposed structure has designed by using of healthy blood sample (1.3348000) and different refractive index of different blood samples infected by SARS-CoV-2 virus under different concentrations of human monoclonal IgG are used in the nanocavity structure. The target sample can be identified by observing the shift in resonant wavelength. PWE band solver is also used for band gap calculation in the waveguide. The band gap range of structure is 1311nm-1930nm and 1550 nm continuous modulated wave input is used in the proposed design. The proposed biosensor has 12µm X 8.5 µm wafer dimensions. The proposed sensor achieved high Q factor 593.875, maximum sensitivity 369.761nm/RIU and the minimum detection limit .000703 RIU.

Key words: Photonic crystal biosensor; Photonic bandgap; Refractive index; SARS-CoV-2 virus

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INTRODUCTION

Recently, Photonic based biosensors have emerged as a promising alternative for medical diagnostics, offering a versatile technology for rapid and sensitive analysis of biomarkers in a label-free format and integrated in point-of-care (POC) devices. These sensors has tremendous potential because of its obvious advantages in sensitivity, stability, miniaturization, portability, remote monitoring etc. These sensors are self-contained device which gives analytical information using bio recognition element. These are designed as a lab-on-chip and contained optical components that are light sources, detectors and sensors.

Nowadays, to detect various disease such as Dengue, Malaria, Cancer, Human Immunodeficiency Virus, COVID-19 virus etc. photonic crystal based biosensors plays very important role. With the help of these sensors fast and reliable detection of various disease can be possible.

Notably, COVID-19 outbreaks worldwide have attracted attention in the year Dec. 2019. There have been 456,797,217 confirmed cases of COVID-19, including 6,043,094 deaths, reported to WHO [1]. To detect various disease conventional diagnostic method like RT-PCR (Reverse Transcriptase Polymerase Chain Reaction) is a time consuming process and this technique requires expensive equipment and reagents for the diagnosis purpose[2].

Presently, various conventional techniques are available for COVID-19 detection like CT-scan, PCR, Sequencing, CRISPR, ELISA, LFA, LAMP. Detection using these techniques are time consuming process and expensive.

Therefore, for early and fast detection photonic crystal biosensors plays important role [1-9]. In this research paper, we propose a design of nanocavity based 2D photonic crystal biosensor for the detection of COVID-19 and the simulation is done by opti-FDTD (Finite difference time domain) software. Nanocavity structure offer higher light energy confinement than ordinary cavities, which means stronger light-material interactions, and therefore lower lasing threshold provided the quality factor of the resonator is high[3]. Nanophotonic resonators can be made with photonic crystals, silicon, diamond, or metals such as gold [4]. The Nano cavity is formed by changing the radius of a single rod in air structure.

PROPOSED DESIGN OF BIOSENSOR

The proposed design structure uses a 2D rectangular lattice with silicon rods and air in background wafer. Transverse electric (TE) mode is used for propagation of light inside the structure. The structure have 21x15 silicon rods in Z and X directions with lattice constant (.55 µm) and wafer dimensions are 8.5x12 µm. For the propagation of light inside the structure an optical wavelength 1550 nm continuous modulated wave is used in the input side. The refractive index of silicon material is 3.45 and air is 1. The radius of silicon rods are 110 nm.

In this paper, R.I. of healthy blood sample (1.3348000) and different refractive index of different blood samples infected by SARS-CoV-2 virus under different concentrations of human monoclonal IgG are used [9] in the nanocavity structure and change of wavelength shift according to refractive index are sense by bio sensor. By reducing the radius of silicon rods from .11 µm to .1 µm we can design the nanocavity based biosensor.

II.I. Nano cavity based photonics crystal biosensor for COVID-19 detection

In the proposed structure of biosensor (fig.1), six nanocavities are created by changing the radius of silicon rods from .11 µm to .1 µm. The sensing mechanism of proposed design is used to change the R.I. of analytes which led to shifting in transmission. Fig.2 indicates the 3D view of nanocavity based sensor structure in which the silicon rods are suspended into the air configuration.

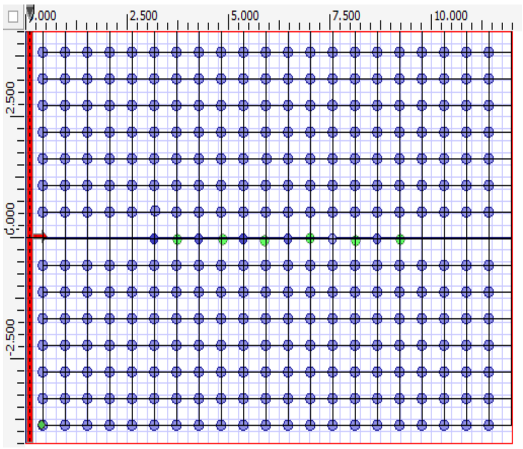


Fig.1: Nanocavity based photonics crystal layout

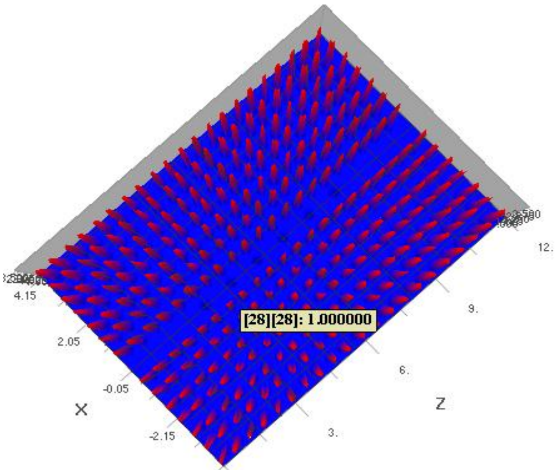
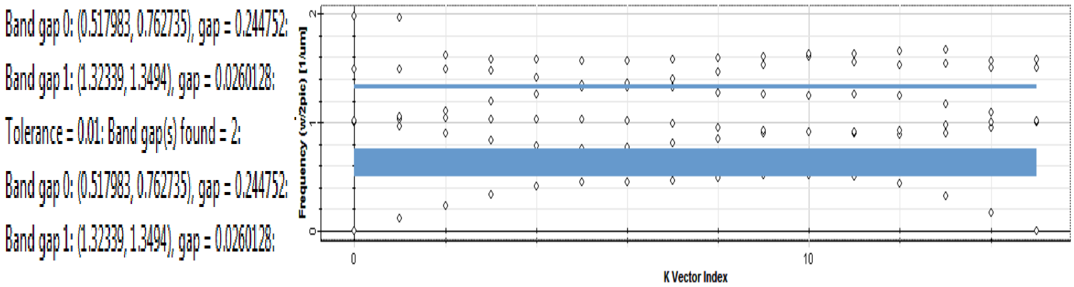


Fig.2: Silicon rods in air configuration

II. Band diagram of nanocavity structures



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Band gap 0: (0.517983, 0.762735), gap = 0.244752:
Band gap 1: (1.32339, 1.3494), gap = 0.0260128:
Tolerance = 0.01: Band gap(s) found = 2:
Band gap 0: (0.517983, 0.762735), gap = 0.244752:
Band gap 1: (1.32339, 1.3494), gap = 0.0260128:
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Fig.3: TE band gap diagram using PWE band solver

Above band diagram (Fig. 3) gives the Photonic Band Gap for Transverse Electric (TE) modes. The band gap structure depends upon three parameters, refractive index of material, lattice constant, and ratio of radius to lattice constant (r/a). The Plane wave expansion (PWE) method is used, to estimate the band gap and propagation modes of the photonics crystal structure without and with defects.

The complete structure of both biosensors are having two band gaps. The first photonic band gap (PBG 0) is in the range between the wavelength 1311 nm and 1930 nm, and the second band gap (PBG 1) is from 7410 nm and 7556 nm. As the proposed designed structure lie in the first PBG range (1311nm-1930nm). Therefore, in this paper the first PBG range is considered. Continuous wave is used in this paper at wavelength 1550 nm and its wavelength is exactly center wavelength of this PBG wavelength range.

Table 1.1 Design parameter and different values used innanocavity based sensors

S.No.	Name of parameters	Values
1.	Radius of silicon (rod)	110nm
2.	Lattice constant	550nm
3.	Refractive index of Si	3.45
4.	Refractive index of Wafer (air)	1
5.	Refractive index of healthy blood sample	1.3348000
6.	Refractive index of infected blood sample at Monoclonal IgG concentrations (nM)	
	Monoclonal IgG concentrations (nM)	Refractive index
	0	1.3348000
	1.74	1.3355323
	3.47	1.3362604
	6.94	1.3377208
	13.9	1.3406500
	27.8	1.3465000
7.	Input wavelength	1550nm
8.	Wafer dimensions	8.5x12 µm
9.	PBG range	1311nm-1930nm
10.	Polarization	TE

The above table shows the design parameters and their values which are used in nanocavity based sensor structure for COVID-19 detection. In above table (S.No.6) shows the refractive index of the human mAbs IgG at different concentrations (Nano Mole-nM). From Table 1.1, we can see that as monoclonal IgG concentrations in the blood increase, the refractive index of the samples increases accordingly [9].

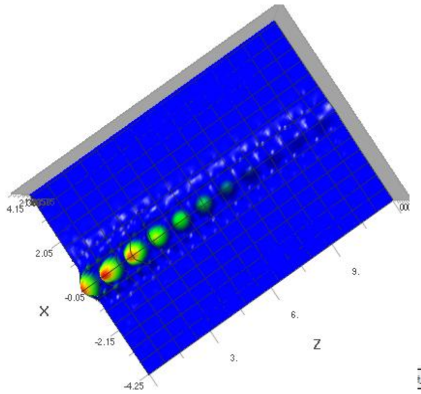
SIMULATION AND RESULTS

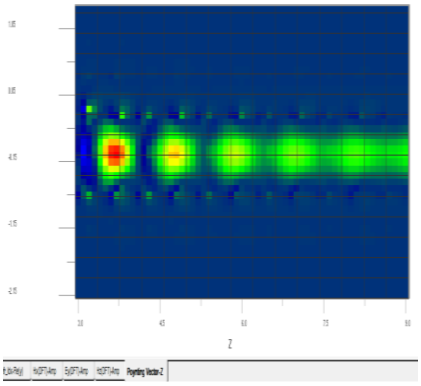
In this paper, OptiFDTD simulation software is used for the designing and simulation purpose. A continuous wave is applied at the input side with wavelength 1550 nm. At this wavelength the waveguide is fully coupled and reached at the output port. Therefore at this wavelength very small amount of losses occurs inside the structure. So it is considered as a resonance wavelength of this structure. The transverse electric (TE) polarization mode is selected for the propagation of light inside the structure. Good performance of biosensor is achieved by getting a high transmission spectrum. Some common parameters used to analyze sensors are the quality factor (Q), detection limit (DL), and sensitivity (S). As the sensitivity of any biosensor is defined by its Q factor. To enhance the sensing performance of sensor, a higher Q value is desirable because sharper peaks with high Q values are much easier to detect. Therefore it can be calculated as:

Q(quality factor) = $\lambda/\Delta\lambda$, Where λ is the resonance wavelength and $\Delta\lambda$ is the full width half maximum (FWHM)
S (sensitivity) =$\Delta\lambda/\Delta n$, Where $\Delta\lambda$ is the wavelength shift per R.I. and Δn is the change in R.I.

DL (Detection limit) is defined as the lowest concentration of a component that can be detected using a given analytical method and it can be calculated as:

DL (Detection limit) =$\lambda/10QS$, Where Q is the quality factor and S is the sensitivity of a sensor.





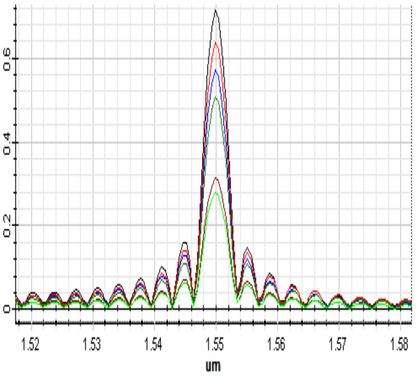


Fig.4 (a): 2D electric field distribution in nanocavity sensor Fig.4(b) Pointing vector-zFig.5: Transmission graph of sensor

Above figures 4(a) and 4(b) shows the 2D electric field distribution and pointing vector-zof the nanocavity based sensor at 1550nm. In this the electric field of the waveguide is fully coupled in the nanocavity and reaches at the output port.

Above figure 5 shows the output transmission spectra of healthy blood sample and different infected sample of COVID-19 (as shown in table 1). In fig.5 the black curve depicts healthy blood sample response and other curve depicts different infected sample response of COVID-19.

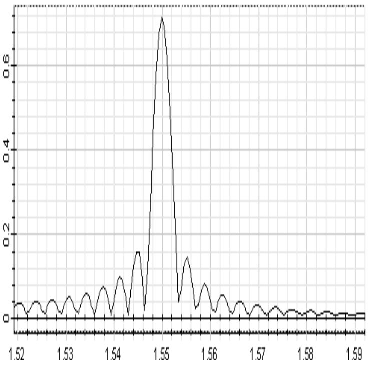


Fig.5(a)

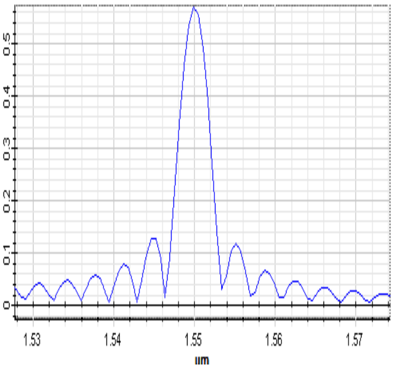


Fig.5(b)

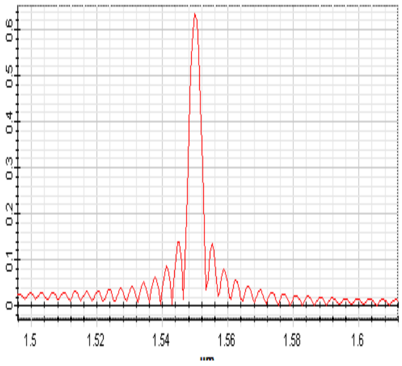


Fig.5(c)

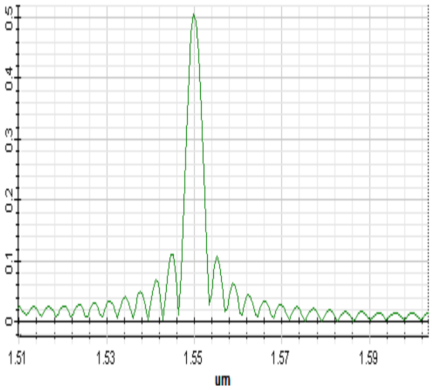


Fig.5(d)

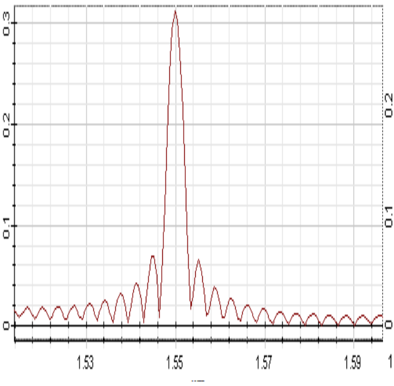


Fig.5(e)

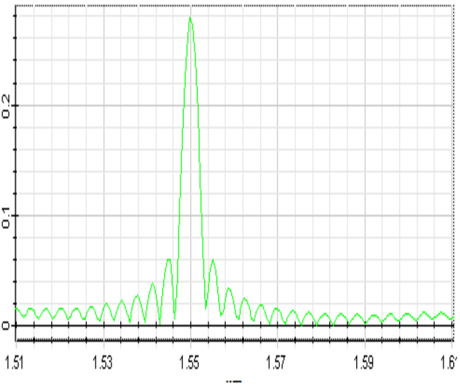


Fig.5(f)

Above fig.5 (a) shows the transmission is 72% for healthy blood sampleat R.I. (1.334800).Highest Q factor is achieved 318.923.
Above fig. 5(b) shows the transmission is 57% at R.I. (1.3355323) of blood samples infected by SARS-CoV-2 virus under (1.74) concentrations of human monoclonal IgG and achieved Q factor is 469.497.
Above fig.5(c) shows the transmission is 62% at R.I. (1.3362604) of blood samples infected by SARS-CoV-2 virus under (3.47) concentrations of human monoclonal IgG and achieved Q factor is 593.875.
Above fig.5 (d) shows the transmission is 50% at R.I. (1.3377208) of blood samples infected by SARS-CoV-2 virus under (6.94) concentrations of human monoclonal IgG and achieved Q factor is 404.196.
Above fig.5 (e) shows the transmission is 32% at R.I. (1.3406500) of blood samples infected by SARS-CoV-2 virus under (13.9) concentrations of human monoclonal IgG and achieved Q factor is 425.645.
Above fig.5 (f) shows the transmission is 28% at R.I. (1.3465000) of blood samples infected by SARS-CoV-2 virus under (27.8) concentrations of human monoclonal IgG and achieved Q factor is 489.677.

Table 1.2 Transmission Spectrum and quality factor according to their refractive index used in nanocavity based biosensor.

Sample Name	Monoclonal IgG concentrations (nM)	Refractive index	Transmission	Resonant Wavelength (nm)	Q-factor
Healthy blood sample	0	1.3348000	72%	1544.34	381.923
Infected samples	1.74	1.3355323	57%	1542.82	469.497

	3.47	1.3362604	62%	1544.88	593.875
	6.94	1.3377208	50%	1543.65	404.196
	13.9	1.3406500	32%	1544.21	425.645
	27.8	1.3465000	28%	1538.50	489.677

Above tables 1.2 shows the transmission of healthy blood sample and different blood samples infected by SARS-CoV-2 virus under different concentrations of human monoclonal IgG in different cavities. The nanocavities are filled according to their refractive index and transmission results measured. To enhance the sensing performance, a higher Q value is desirable. It is observed highest Q factor is achieved 593.875 at R.I. (1.3362604) of blood samples infected by SARS-CoV-2 virus under (3.47) concentrations of human monoclonal IgG and the maximum sensitivity 369.761nm/RIU and the minimum detection limit .000703 RIU is achieved.

CONCLUSION

In this paper, author(s) have designed nanocavity based biosensor structures for COVID-19 detection. Detection of COVID-19 in humans using conventional RT-PCR method is more complex and time consuming process. Therefore to evade this a label free detection method is used to design nanocavity based sensors using photonics platform by using refractive index of healthy blood sample and different blood samples infected by SARS-CoV-2 virus under different concentrations of human monoclonal IgG. All the simulation work are done using Opti FDTD simulation software and PWE band solver are used for band gap calculation. High quality factor (593.875) is observed in nanocavity based sensor structure. The proposed sensor shows good results with better transmission and achieved maximum sensitivity 369.761nm/RIU and the minimum detection limit .000703 RIU. Thus it can be helpful for COVID-19 detection.

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