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Design of 2D photonic crystal biosensor for HIV detection using Nano cavity and micro cavity based structure

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ABSTRACT:
In this research paper we propose a design of photonics crystal based biosensors for HIV detection by using refractive index of normal blood sample (1.35) and infected HIV blood sample (1.42). 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 08µm wafer dimensions. In this paper, we propose the nanocavity and microcavity based photonics crystal biosensor. Blood sample is deposited inside the nano cavity and microcavity and based on the refractive index of HIV infected sample to the normal blood sample there will be shift in the wavelength at the output terminal. 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 sensor achieved high Q factor 681.15 in nanocavity structure and 592.11 in microcavity structure during simulation. The comparison is also done between both the structure that which sensor is having fast, accurate and better transmission. The proposed biosensor uses both nanocavity and microcavity structure, thus both designs are compatible for detecting HIV in photonics platform.

Keywords: Photonic Crystal; Refractive index; Human immunodeficiency virus; Finite difference time domain; Photonic bandgap

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I. INTRODUCTION

The photonics crystal based biosensors provides fast and accurate results in the field of medical and biological applications. Photonics based devices have a better confinement of light due to the photonic bandgap. The bandgap does not allow the light to passes through the walls of the created waveguide. In photonic biosensing environment, the volume of detecting sample is in terms of micro or nano scale and the indicating output frequency spectrum is highly dependent on refractive index [1]. Photonic crystal has a many advantage such as easy fabrication, better light confinement through the bends, small in size, fast, reliable, sensitive, low power consumption etc. Photonics crystal based biosensors are used for early and fast detection of various virological generated diseases such as Malariya, Dengue, Cancer, HIV,COVID-19 etc.

In this research paper we propose the photonics crystal based biosensors for HIV detection. Human immunodeficiency virus (HIV) is an infection that attacks the body's immune system, specifically the white blood cells called CD4 cells. HIV destroys these CD4 cells, weakening a person's immunity against opportunistic infections, such as tuberculosis and fungal infections, severe bacterial infections and some cancers [2].

There are numerous methods to detect HIV. Detection using conventional method is more complex and time consuming process. Therefore to evade this a label free detection method is time saving, easy and provide accurate results. Photonic crystal biosensor is label-free detection and its detection method is based on bio-sample refractive index depends on chemical, physical and mechanical composition.

In the past few years various research has been done by the researchers on various virological diseases. **Wu N et al.** presented a novel silver nanocluster (AgNCs) is in situ generated and served as fluorescence probes for the ultrasensitive HIV/HCV DNA detection by combing Exo III-assisted target recycling amplification (ERA) with rolling circle amplification (RCA). As an important key element of this sensor, the padlock probes (PLP) of RCA are exquisitely designed to compose of a guanine-rich (G-rich) region [3]. **Hemanth Kumar et al.** presented a design of multipurpose biosensor for detection of sickle cell anemia, HIV and

cholesterol by its refractive index using FDTD method. In this paper simulation is done by using FDTD method. When body gets infected there will be changes in physical as well as biological composition results in disparity of refractive index of biological component. Resonating frequency is displayed in DFT monitor at the output waveguide [1]. **Haq Nawaz et al.** presented a book chapter in which different electrochemical biosensor techniques, which have employed for the detection of the HIV infection have been reviewed [4]. **Amanda Bacon et al.** has presented a review paper of HIV Self Testing Technologies and Promising Approaches for the Next Generation [5].

In this research paper, the proposed model is designed using 2D photonics crystal technique and the simulation is done by opti-FDTD (Finite difference time domain) software. Different types of photonics crystal based structure such as nanocavity based biosensor, microcavity based biosensors, optical fiber based biosensors etc. can be designed. In this paper, we propose the nanocavity and microcavity based photonics crystal biosensor. The comparison is also done between these two structures that which design will provide the fast, accurate and good transmission spectrum. PWE band solver is also used in this paper for band gap calculation in the waveguide.

II. PROPOSED DESIGN OF BIOSENSORS

For the proposed nanocavity and microcavity based biosensor design, the FDTD simulation tool is used for the simulation. Both the 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 proposed both the structure uses 2D rectangular lattice with silicon rods and air in background wafer. Both type of structure have 21x15 silicon rods are used in Z and X directions and wafer dimensions are 8x12 µm and lattice constant (.55 um) are also used in the structures. For the propagation of light inside the structure an optical wavelength 1550 nm continuous wave is used in the input side on both the structures. Two observation points are also used on the output port to detect the input wave. 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 normal cell (1.35) and R.I. of HIV virus (1.42) are used [1] in the nanocavity and microcavity structure and change of wavelength shift according to refractive index are sense by bio sensor. To design the nanocavity and microcavity based biosensor we are using same layout of proposed biosensor by slightly changes the radius of silicon rods.

2.1 Nano cavity based photonics crystal biosensor for HIV detection

In this design (Fig.1), we used two types of refractive index in the two nano cavity. One type of refractive index (1.35) is used for normal blood sample and other type of refractive index (1.42) is used for infected HIV virus. Two nano cavities are created by reducing a radius of silicon rods from .11 um to .1 um. The sensing mechanism of the proposed design is used to change the R.I. of analytes which led to shifting in transmission.

Fig.2 indicates the 3D view of the nanocavity based sensor structure in which the silicon rods are suspended into the air configuration.

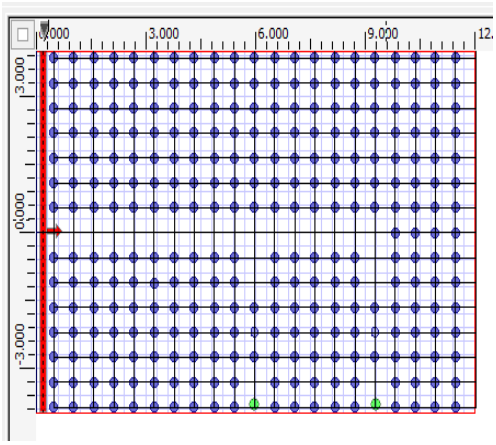

Fig.1: Nano cavity based photonics crystal biosensor layout in nanocavity based sensor

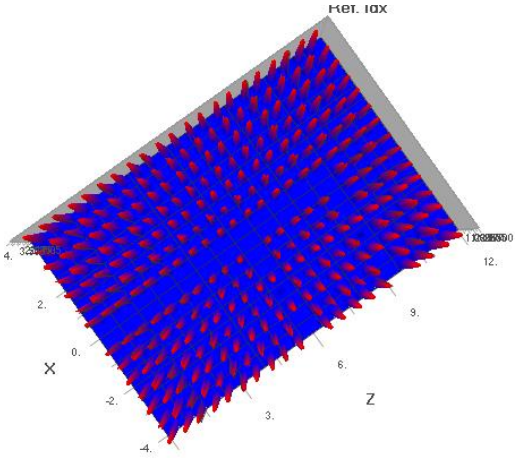

Fig.2: Silicon rods in air configuration

2.2 Micro cavity based photonics crystal biosensor for HIV detection

In this design (Fig.3), by using the same structure of proposed biosensor, two microcavities are created by changing the radius of silicon rods from .11 µm to .12 µm. The sensing mechanism of proposed design is used to change the R.I. of analytes which led to shifting in transmission.
Figure 4 indicates the 3D view of microcavity based sensor structure in which the silicon rods are suspended into the air configuration.

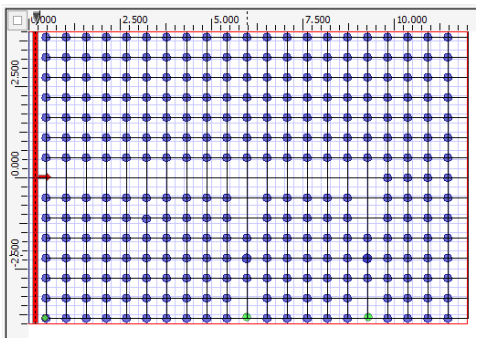

Fig.3: Microcavity based photonics crystal biosensor layout

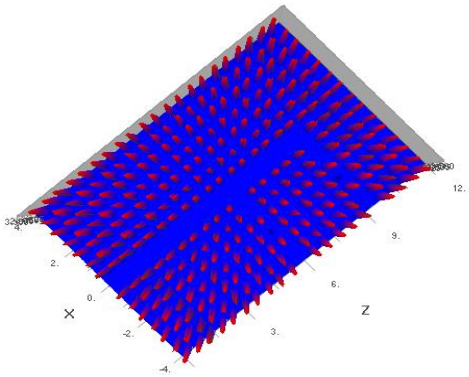

Fig.4: Silicon rods in air configuration in microcavity based sensor

2.3 Band diagram of nanocavity and microcavity structures

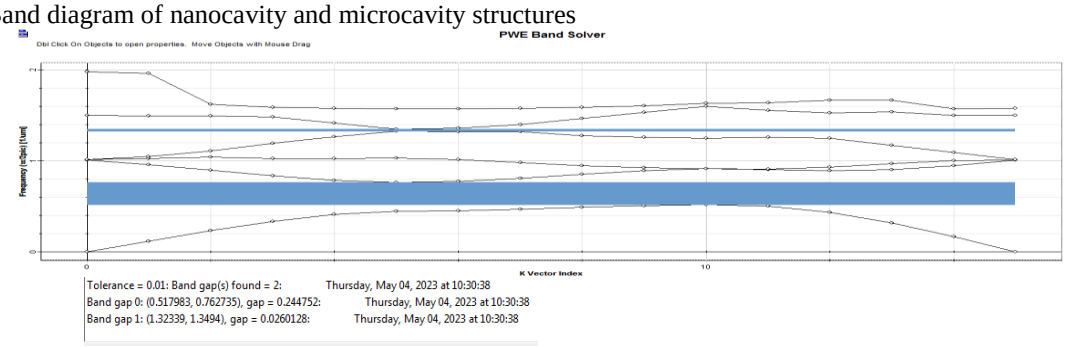

Fig.5: TE band gap diagram of design 1 using PWE band solver

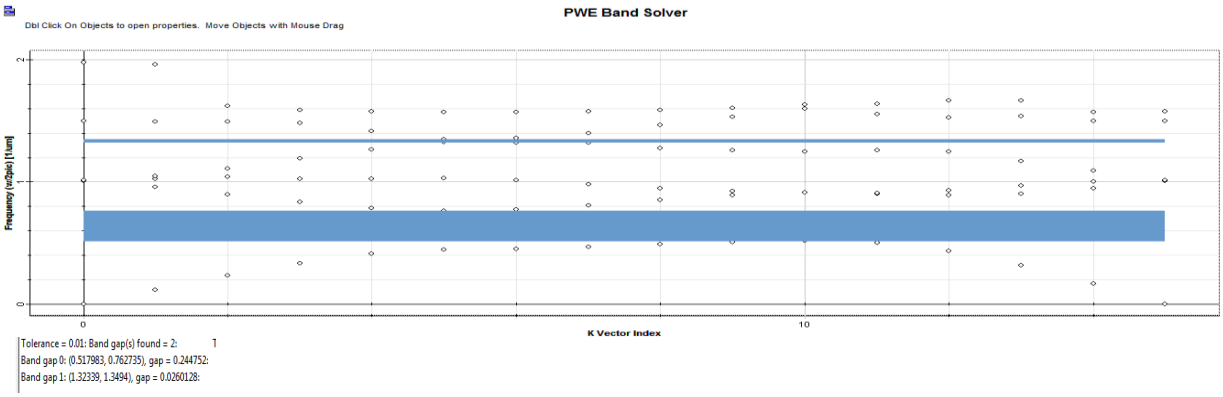

Fig.6: TE band gap diagram of design 2 using PWE band solver

Above band diagram (Fig.5 and Fig.6) of both sensor structures 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 741 nm and 755 nm. As our 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 2.1 Design parameter and its value used in biosensor nanocavity and microcavity 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 normal blood sample	1.35
6.	Refractive index of HIV infected sample	1.42
7.	Input wavelength	1550nm
8.	Wafer dimensions	8x12 µm
9.	PBG range	1311nm-1930nm
10.	Polarization	TE

The above table shows the design parameters and their values which are used in nanocavity and microcavity based sensor structure for HIV detection.

III. SIMULATION AND RESULTS

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.

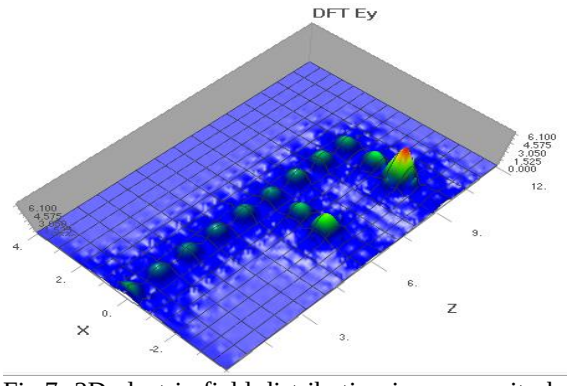

Fig.7: 2D electric field distribution in nanocavity based sensor

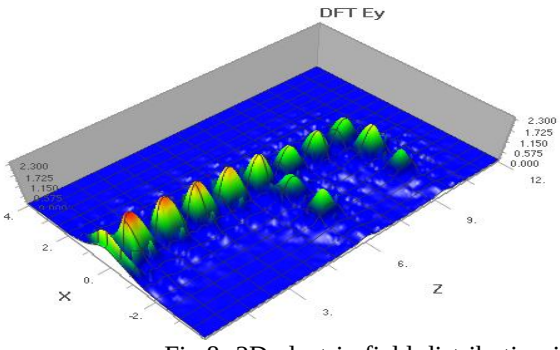

Fig.8: 2D electric field distribution in microcavity based sensor

Above figures (Fig.7,8) shows the 2D electric field distribution of the nanocavity and microcavity based sensor at 1550nm. In this the electric field of the waveguide is fully coupled in the nanocavity and microcavity and reaches at the output port.

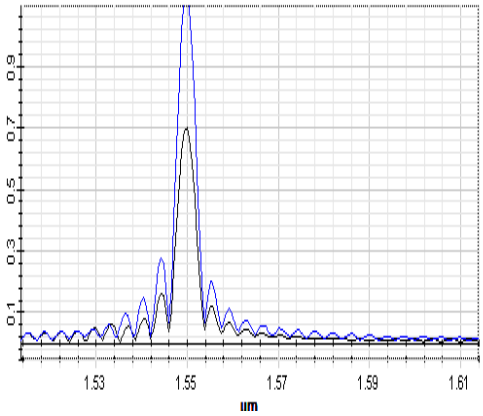

Fig.9: Transmission graph of nanocavity based biosensor

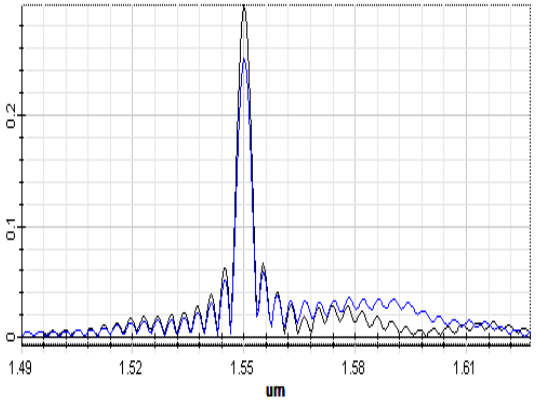

Fig.10: Transmission graph of microcavity based biosensor

Above figure (9&10) shows the output transmission spectra of normal blood sample and HIV infected sample in nanocavity and microcavty based biosensor at refractive index 1.35 and 1.42. The black curve depicts normal blood sample response and blue curve depicts HIV infected sample response in both diagrams.

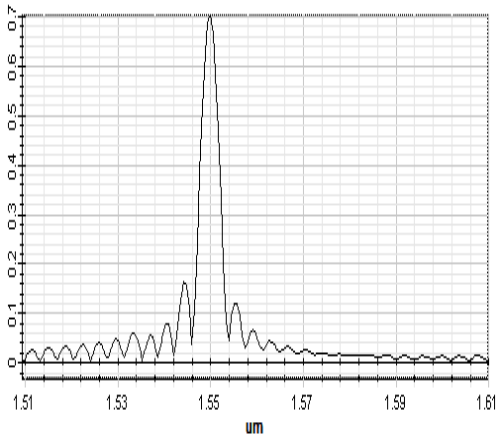

Fig.11: Transmission graph of normal sample in nanocavity based sensor

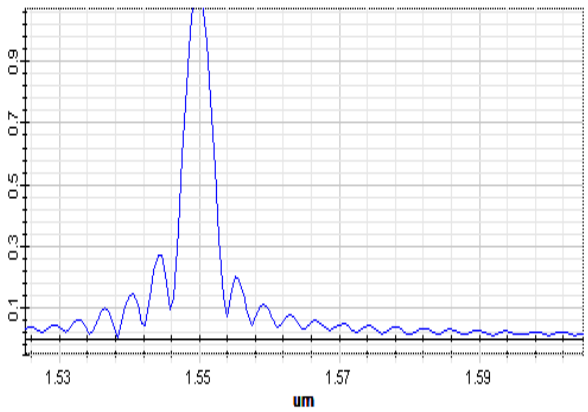

Fig.12:Transmission graph of infected HIV sample in nanocavity based sensor

Above figure 11 and 12 shows the transmission graph of normal and infected HIV sample in nanocavity based biosensor at 1.35 and 1.42 refractive index. In this refractive index, transmission is 70% for normal sample and 99% for infected HIV sample. As the sensitivity of any biosensor is defined by its Q (quality factor). Therefore $Q = \lambda/\Delta\lambda$

Where λ is the resonance wavelength and $\Delta\lambda$ is the full width half maximum (FWHM).

Q factor also helps us to decide whether nanocavity or micro cavity biosensor is better. Using information window we can calculate the quality factor of both sensors.

Using above formula the quality factor of normal cell response in nanocavity based sensor is 474.36 and for infected sample, quality factor is 681.15.

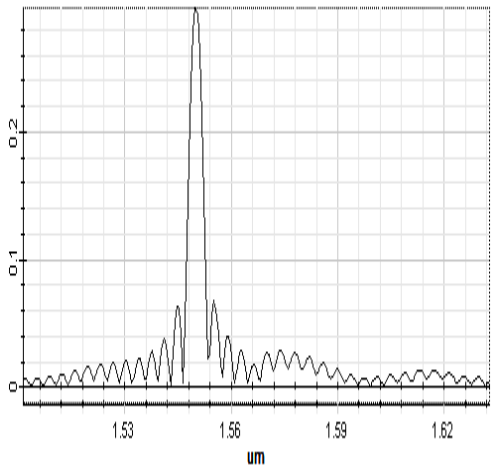

Fig.13:Transmission graph of normal cell in microcavity based sensor

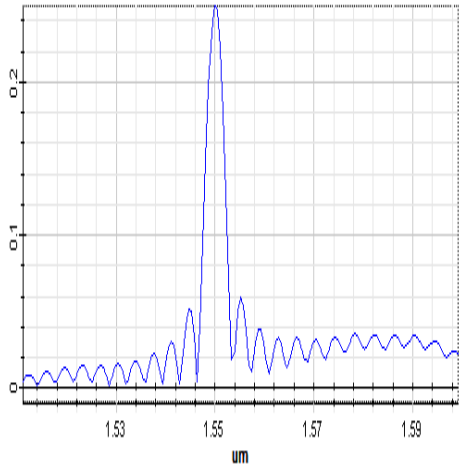

Fig.14:Transmission graph of HIV cell in microcavity based sensor

Above figure 13 and 14 shows a transmission graph of HIV Cell in microcavity based biosensor at refractive index 1.35 and 1.42. Using this refractive index, transmission is 30% and 25%. Quality factor of normal cell response in microcavity based sensor is 450.36 and for infected sample, quality factor is 592.14.

Table 3.1 Transmission Spectrum and quality factor according to their refractive index used in nanocavity based biosensor.

Cell Name	Refractive index	Transmission	Wavelength (µm)	Q-factor
Normal Cell	1.35	70%	1.55003	474.36
HIV Cell	1.42	99%	1.54782	681.15

Table 3.2 Transmission Spectrum, quality factor and wavelength according to their refractive index used in microcavity based biosensor.

Cell Name	Refractive index	Transmission	Wavelength (µm)	Q-factor
Normal Cell	1.35	30%	1.55009	450.36
HIV Cell	1.42	25%	1.55009	592.14

Above tables shows the transmission of normal cell and HIV cell with their respective refractive index in different cavities. The nano cavities and microcavities are filled according to their refractive index and transmission results measured. As the sensitivity of any biosensor is defined by its Q factor, therefore the above table also shows the Q factor of biosensors and thus result of this Q factor helps us to decide whether nanocavity or micro cavity biosensor is better. In above tables 3.1 and 3.2, the results shows that the quality factor and transmission of nanocavity based sensor structure at wavelength 1550 nm are good in comparison with microcavity based sensor structure. Thus nanocavity based structure provides good accuracy and better transmission.

IV. CONCLUSION

In this paper we have designed nano cavity and microcavity based biosensor structures for HIV detection. Detection of HIV in humans using conventional method is more complex and time consuming process. Therefore to evade this a label free detection method is used to design nanocavity and microcavity based sensors using photonics platform by using refractive index of normal blood sample and infected HIV blood sample. All the simulation work are done using OptiFDTD simulation software and PWE band solver are used for band gap calculation. . High transmission spectrum (99%) and quality factor (681.15) are observed in nanocavity based sensor structure in

comparison with microcavity based sensor structure. Both designs are helpful to detect HIV. The proposed sensor design can predict results accurately and in short time with good accuracy and better transmission. The wafer dimensions of both biosensors are 12µm X 08µm. Therefore it can be embedded in hand held devices.

DISCLOSURES

The authors have no conflict of interest.

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