DESIGNING OF BIOSENSORS BASED ON PHOTONIC CRYSTAL FIBERS AND THEIR PERFORMANCE ANALYSIS

A Thesis Submitted in Fulfillment of the Requirement for the Award of the Degree of

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In

Electronics and Communication Engineering

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CERTIFICATE

I, Sakshi hereby declare that the work which is being presented in the dissertation entitled, **"Designing of Biosensors based on Photonic Crystal Fibers and their Performance Analysis"** by me in partial fulfilment of the requirement for the award of degree of M.E in Electronics and Communication submitted in Electronics and Communication Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of Dr. R.S. Kaler, Senior Professor, ECED and Deputy Director, Thapar University Patiala.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

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ABSTRACT

Photonic crystal fibres are drawing attention these days due to their various improved features than the conventional optical fibres. Photonic crystal fibres are having various applications among which one is Sensing. They are used for sensing of chemicals, Gases, temperature, pressure and biological analytes also. There is an increasing demand of photonic crystal based Biosensors for the detection of various biological analytes like DNA, Blood cells like RBC, WBC, Haemoglobin, Cell components like nucleus, mitochondria and various such analytes.

In this dissertation, three types of Biosensors are designed. In the first design, the S-shaped Waveguide is generated by introducing line defects in the sensor. The design comprises of silicon rods in air background. This biosensor is used for the detection of various cell components like nucleus, ctyosol and mitochondria. Then the design is modified by adding Silicon reflectors The design is further optimized with reflectors of different materials. It is observed that maximum sensitivity is obtained with the Silicon reflectors.

In the second design, a two dimensional photonic crystal biosensor is designed which consists of two C-shaped Cavities and a nano-ring resonator with a fixed horizontal distance between two cavities. A coupling occurs in the ring resonator. Then the design is optimized by reducing the horizontal distance between two cavities and then results are compared.

In the third biosensor design, hexagonal cavity is generated for the detection of different blood cells. Infiltration of the silicon rods which lie along the hexagonal cavity is done with Gallium Arsenide rods. This sensor also provides very high sensitivity.

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GAAS INFILTRATED HEXAGONAL CAVITY PHOTONIC CRYSTAL SESNOR FOR DETECTION OF VARIOUS BLOOD COMPONENTS.

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1. One Dimesional-1D
2. Two Dimensional-2D
3. Three Dimesnional-3D
4. Photonic crystal-PC
5. Photonic Crystal Fibres-PCF
6. Photonic crytal Waveguides-PCW
7. Transverse Electric-TE
8. Transverse Magnetic-TM
9. Photonic Band Gap-PBG
10. Silicon-on-insulator-SOI
11. Refractive Index-RI
12. Micro Electro Mechanical system-MEMS
13. Finite Difference Time Domain-FDTD
14. Refractive Index Unit-RIU
15. Silicon dioxide-Si02
16. Gallium Arsenide-GaAs
17. Indium Arsenide-InAs
18. Plane Wave Expansion-PWE
19. Very Large Scale Integration-VLSI
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Semiconductor-CMOS 21.Reb Blood Cells-RBC
22. White Blood Cells-WBC
23. Deoxyribonucleic Acid-DNA
24. Haemoglobin-Hb
25. Quality Factor-Q

CHAPTER-1

INTRODUCTION

An incredible growth and advancement has been achieved by the fibre optics technology. Earlier fibre optics were considered as a source of transmitting light used for telecommunication industry. Due to enormous research in field of fibre optics, they become capable of transmitting a large amount of data. Later due to further advancements, they are used for sensing applications. Optical fibre sensors are developed and they are easily accessible due to their extensive benefits. These sensors are deployed in communication, electrical field and also in medical fields for sensing applications. But for broader areas of fibre optic sensing, photonic crystal waveguide sensors are developed. Photonic crystal waveguide sensors are used for sensing of different parameters like pressure, temperature, detection of different analytes and many more such applications.

1.1 FIBRE OPTIC SENSORS

Different sensing applications need the data to be tracked from those areas which are difficult to be accessed. Three basic requirements for achieving the sensing applications are:

1. A Sensor is required for sensing different parameters like temperature, pressure etc and then it generates information related to these parameters and sends that information so that it can be utilized for further applications.

2. Transmission lines are also required.

3. Proper platform is required to modify the data into such format which could be easily interpreted by users [1].

Different types of sensors can be selected depending upon our requirement and the transmission lines which are used are mainly copper cables. In fiber optic sensors, interaction occurs between the analyte to be detected and the light which results in modifications in the optical properties and those modifications reflect the information about analytes [1].

1.2 WORKING OF FIBER OPTIC SENSOR

A fiber optic sensor comprises of a light source, optical fibre, sensing element and a detector

In a fibre optic sensor, modulation of few parameters of the light occurs which causes modifications in properties of optical signal which is obtained at receiver [2].

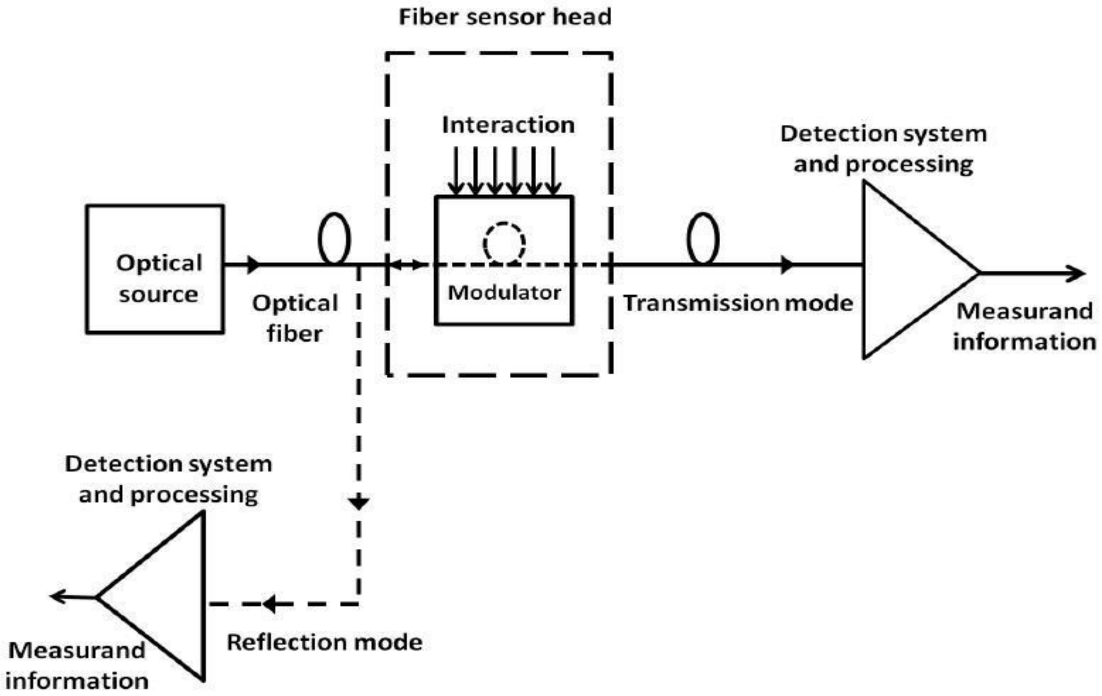


Figure1.1 Operation of fibre optic sensor

From above diagram it is clear that light is generated from optical source and passed though the optical fibre. Then interaction occurs between light and some external quantity and then the obtained modified signal is passed to the detector. Information about the element which is to be detected is obtained from this modified light. The sensor works in reflection mode or in transmission mode [3].

1.3 LIMITATIONS OF FIBER OPTIC SENSORS

No doubt fibre optic sensors are better than the conventional sensors but there are some limitations of the fibre optic sensors which are explained as follows:

1. Cost: Conventional sensors are cheaper than the fibre optic sensors.

2. Ambient Light: In fibre optic sensor, interference can occur between ambient light and signal of interest. So, few measurements have to be done in dark.

3. Response Time: In case of multi phase sensing, the response time of sensor is usually long.

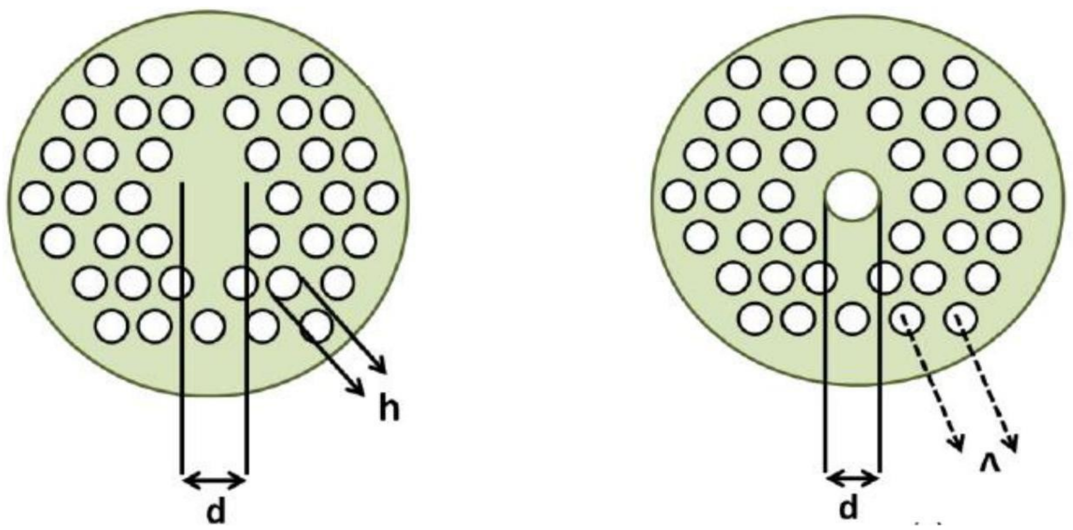
4. Dynamic Range: Operational dynamic range in case of fibre optic sensors is less than conventional electrical sensors.

5. Data Interpretation: Data interpretation is difficult in case of optical fibres because data is obtained with respect to other parameters [2].

1.4PHOTONIC CRYSTALS FIBRES

Photonic crystals are having a periodic structure throughout its all dimensions and are an optical medium in which there is a periodic modulation of the refractive index. In photonic crystal fibres basically there are two phenomenon of guiding light. In solid-core photonic crystal fibres, confinement of light is done by mechanism of total internal reflection in a region having greater refractive index and same guiding mechanism is followed in optical fibres.

In hollow-core fibres, confinement of light is done by the mechanism of photonic band gap in a region which is having low refractive index than its surroundings. Photonic crystal provides flexibility in the designing of the fibres. Different designs of photonic crystal fibres can be achieved by varying the designing parameters like dimensions of the fibre, lattice constant, shape of the air-holes, and radius of the air holes. Different optical characteristics are achieved even due to small variations in the designing [4].



(a) Solid core fibre (b) Hollow core fibre

Figure 1.2 Solid Core Fibre and Hollow Core Fibre

1.5 CATEGORIES OF PHOTONIC CRYSTAL

Photonic crystals are classified into three main types depending upon their structure which are explained as follows:

In 1D Photonic Crystals, permittivity is periodically modulated along one direction and there is a uniformity of structure in remaining two directions. 1D Photonic crystal allows the variations only in terms of refractive index, thickness of layer and number of layers. Therefore, it allows very less variations in its periodic structure [5].

2D Photonic crystals are having a periodic modulation of permittivity in two directions and there is a uniformity of the medium in third direction. So, various configurations are allowed in two dimensional photonic crystals. In these crystals, elements position and shape can be changed thereby allowing infinite types of lattice. But due to technical reasons, only square and hexagonal photonic crystals are used. The unit cell of square lattice is square shaped and that of hexagonal lattice hexagon shaped. All the elements of a particular type are having shape throughout the structure.

3D Photonic crystals are having a periodic modulation of permittivity in all the three directions. Very large number of configurations are possible in three dimensional photonic crystals that that of 1D or 2D photonic crystals. By the changing the geometry, various types of lattice are possible. 3D Photonic crystals are having same geometry as that of solid state crystals [5].

It is practically difficult to fabricate three dimensional photonic crystals because the distance between the centres of two holes which is also known as lattice constant is very small than that of one dimensional and two dimensional photonic crystals. The designs of one dimensional, two dimensional and three dimensional photonic crystals is shown in the diagram below [6].

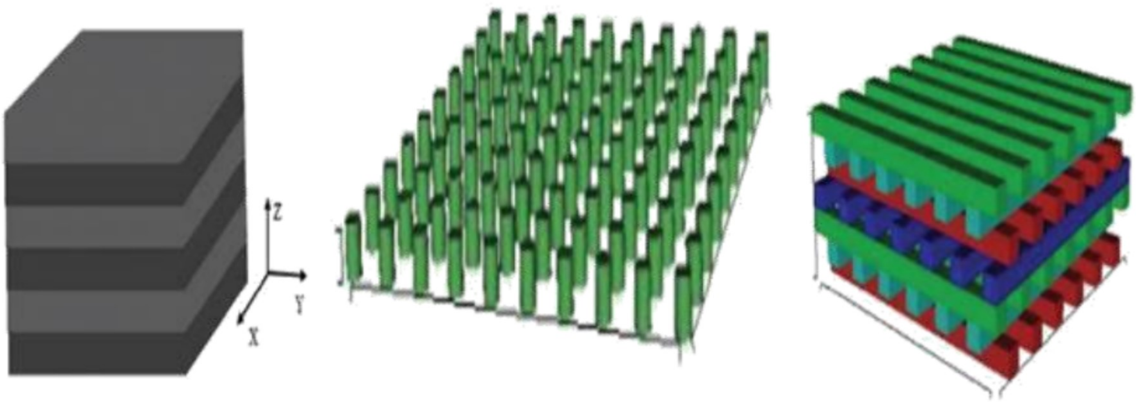


Figure 1.3 Design of one dimensional, two dimensional and three dimensional photonic crystals [6].

1.6 DEFECTS IN PHOTONIC CRYSTALS

Photonic crystals are having a periodic structure throughout its all dimensions. In order to implement various optical functions, it is necessary to insert the defects in the structure which may be extended defects or they can be localised defects. These defects affect the periodicity of the crystal and in turn disturb the periodicity. Due to this disturbance of the symmetry of the crystal, the Bloch modes will not be the solution of Maxwell's equation. So, approximations need to be done [7].

1.6.1 POINT DEFECTS

1.6.1.1 PHOTONIC CRYSTALS HAVING POINT DEFECTS ALONG ONE DIRECTION

Due to alteration of the refractive index or by modification of the width of any one layer of the crystal, Point defects can be realized. These irregularities have similarities to Fabry perot irregularities. With the alteration of refractive index, the electromagnetic modes originate at different frequencies in the photonic band gap [7].

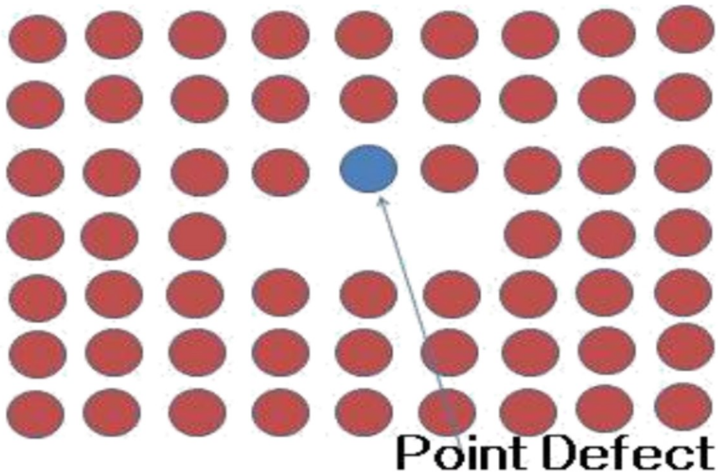


Figure 1.4 Photonic Crystal Containing a Point Defect

1.6.1.2 PHOTONIC CRYSTALS HAVING POINT DEFECTS ALONG TWO AND THREE DIRECTIONS

By changing refractive index, by altering dimensions of arrangement, disturbing periodic patterns or by introducing a new pattern, Point defects can be generated. Due to generation of a point defect, distinct energy levels occur in the band gaps of the design. If the photonic band gaps are Omni directional, the modes will be localised electromagnetic modes which are in contradiction with the one dimensional photonic crystals. If above requirement is satisfied, then electric and magnetic fields occurs in area having irregularities and evanescent in nearby areas. If band gap is not Omni directional, then there will be a leakage of a part of electromagnetic energy from the defect region in those directions in which propagation is possible [7].

1.6.2 EXTENDED DEFECTS

Extended defects having one, two, or three dimensions can be generated in photonic crystals having greater or same dimension. One dimensional extended defect is studied much more than all other extended defects because of their use as a waveguides in the photonic crystals . So, formation of two or three dimensional extended defects can be considered as the one dimensional waveguides joined successively from one end to another and their orientation is along various directions. This allows the light to propagate along with any path and in any direction inside the photonic crystal.

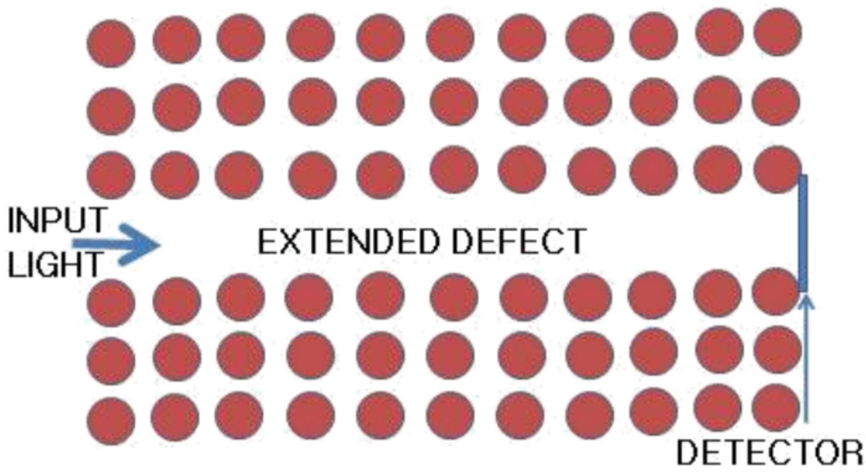


Figure 1.5 Extended Defect in Photonic Crystal

The illustration of irregularities in one direction is a two-dimensional crystal having a linear waveguide. In order to actually realize the one dimensional defect, similar point defects are aligned along the required direction by providing a proper spacing in between them. Every point defect within the photonic crystal acts as an optical resonator. Sometimes a coupling might occur between these point defects only if the distance between them is considerably small enough.

A transmission band is generated which consists of infinite number of coupled modes because of the occurrence of pairing among various similar resonators. One more technique of generation of linear waveguide within a 2-D photonic crystal is by modification or by removal of one or whole rows of holes on the photonic crystal in the desired directions [7].

1.7 BAND DIAGRAM WITHIN A PCF

Existence of photonic band gap within design concludes practical importance of the photonic crystal. The photonic band gap comprises of those energy or frequency ranges where there is restriction to the propagation of light within the photonic crystal. Whenever the radiation having frequency which lies within the photonic band gap falls on the structure, it gets completely reflected back. By generating new irregularities in regular alignment of structure, radiations will be allowed to travel through the design which is corresponding to the frequency of the defect [5].

The band diagram of Photonic crystal provides tremendous information about properties of the photonic crystals. The band structure of the photonic crystal is interpreted with various Eigen-states or Eigen-frequencies of design which is periodic. Within the photonic crystals, the generating Eigen frequencies are known as resonant frequency of photonic crystal structure.

Due to the infinite periodic structure of the photonic crystal, various Fresnel reflections occur at the interface of media. There is an occurrence of constructive interference and destructive interference among forward and backward radiations due to which some waves are transmitted while others are reflected back. Every Eigen-state is corresponding to the definitive value of wave vector. The band structure of one dimensional photonic crystal is shown in the Figure below [5].

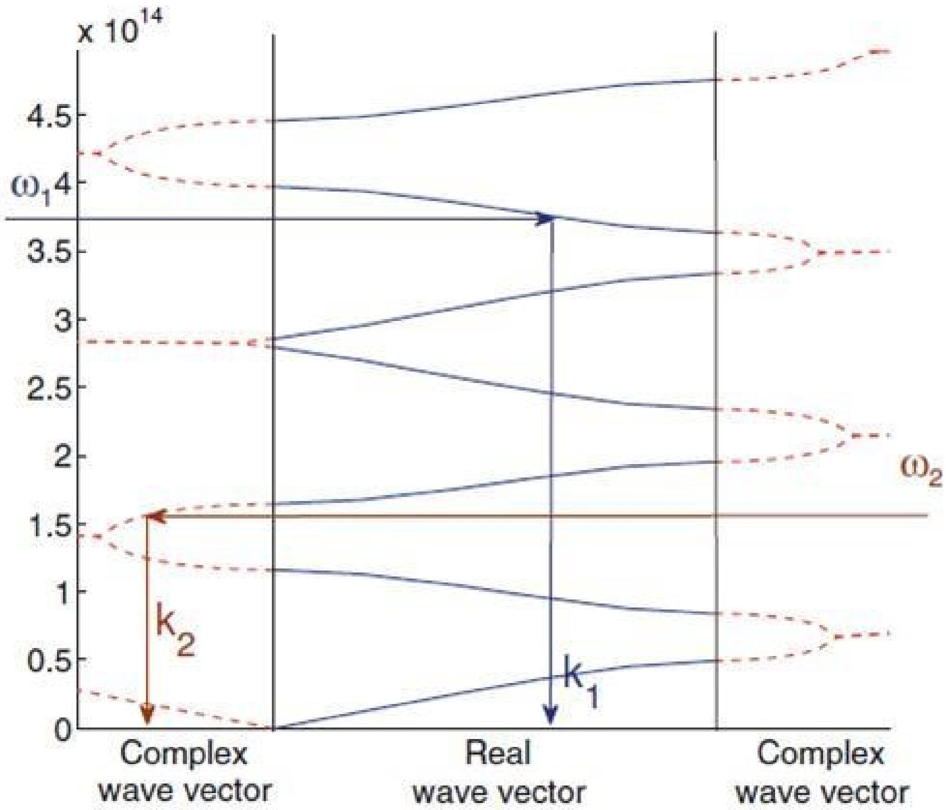


Figure 1.6 Band Diagram of Photonic Crystal

In Figure 1.6 the horizontal axis shows wave vector of the radiation and resonating frequencies are represented by vertical axis. If rays having frequency 1 is incident on the

Photonic crystal, it will occupy the exact wave vector k1 corresponding to those which are allowed by the structure and the radiating frequencies 1 are represented by k1. Therefore the rays travel along the design.

When rays are having a frequency of 2, it is observed that it will fall at those values of the frequency in which there are no real values allowed, therefore this will correspond to attenuation. So, these two cases explain the main foundations of the study of the band diagram of the design.

Few values of the frequencies are passed and some are prohibited and both are present in the same media. The rays are allowed to pass through the design in those frequency values which are allowed. All other values of frequency are sent back. The frequency values which are not passed are known as Photonic band gap [5].

1.8 MODELS FOR INFINITE CRYSTALS

There are two models in order to analyze the properties of photonic crystals which are plane wave expansion method and the Maxwell's equation. A brief idea about these two models is gives as under:

1.8.1 PLANE WAVE EXPANSION METHOD

This model is applicable to photonic crystals and is based on the assumption that it is in infinitely extended among all the directions of the crystal. This technique is implemented for interpretation of photonic band gaps within the design. But this method is having a limitation because in actual, the crystal is not always infinite so the results obtained are not accurately valid.

1.8.2MAXWELL'S EQUATINON

To obtain electric field and the magnetic field components of the electromagnetic modes occurring inside the photonic crystals, following Maxwell equations are solved [5].

— (1)

— (2)

(3)

[5] (4)

By, substituting the value B=μH, D= E, J=0 and S=0 in above equations 1, 2, 3, and 4, we get the following equations[2]

By arranging above equations, we get the main Maxwell equation.

{}

E represents the electric field, H represents magnetic field, D represents electric field displacement, B represents magnetic induction field, J is current density and is free charge density.

1.9 GUIDING MECHANISM

To transmit light in core in order to obtain a guided mode in an optical fibre with a propagation constant of value along the fibre axis and this is unable to propagate in the cladding portion of the optical fibre. In an infinite homogenous medium of the photonic crystal, the largest value of having refractive index n which is allowed to exist is , where is the propagation constant of the free space. The effective refractive index of the material is basically defined by value of [4].

1.9.1 MODIFIED TOTAL INTERNAL REFLECTION

A two-dimensional photonic crystal is modified as a fibre by taking refractive index of core much greater than that of the refractive index of the cladding. A photonic crystal fibre which is formed by a solid silica core which is enclosed by a cladding of photonic crystal having a triangular lattice of air- holes is an example of such type of structures [4]. This type of fibres is called index-guiding photonic crystal fibres. These fibres guide light through them by the phenomenon of total internal reflection also known as modified total internal reflection.

1.9.2 PHOTONIC BANDGAP GUIDANCE

Photonic crystal cladding has some gaps in between the structure where propagating modes are not allowed. The ranges of such modal index are⁄ . The photonic band gap are same as that of the two dimensional band gaps which are used for the characterization of the light circuits but the difference is that in case of photonic band gaps, the propagation is possible only with a non zero value of . These fibres do not depend on total internal reflection for the guidance of light so these fibres are somewhat similar to that of Bragg Fibres. Light guidance with total internal reflection is not possible here because for total internal reflection, the refractive index of core must be greater than that of the cladding but here no such material is having refractive index less than that of air at optical frequencies. In order to guide light the guided mode must be having⁄ , because this condition is necessary for the propagation of light within the core which cannot escape into cladding.

The first hollow photonic crystal fibre comprises of a lattice of air holes arranged in triangular manner and in order to form core, seven capillaries are removed from the centre of fibre. Larger the size of core, larger is the possibilities of having guided mode. Coloured modes are sent into the fibre if the white light is guided into the core of the fibre. This shows that the guiding of light is possible in restricted wavelengths only and that which corresponds to the photonic band gaps [4].

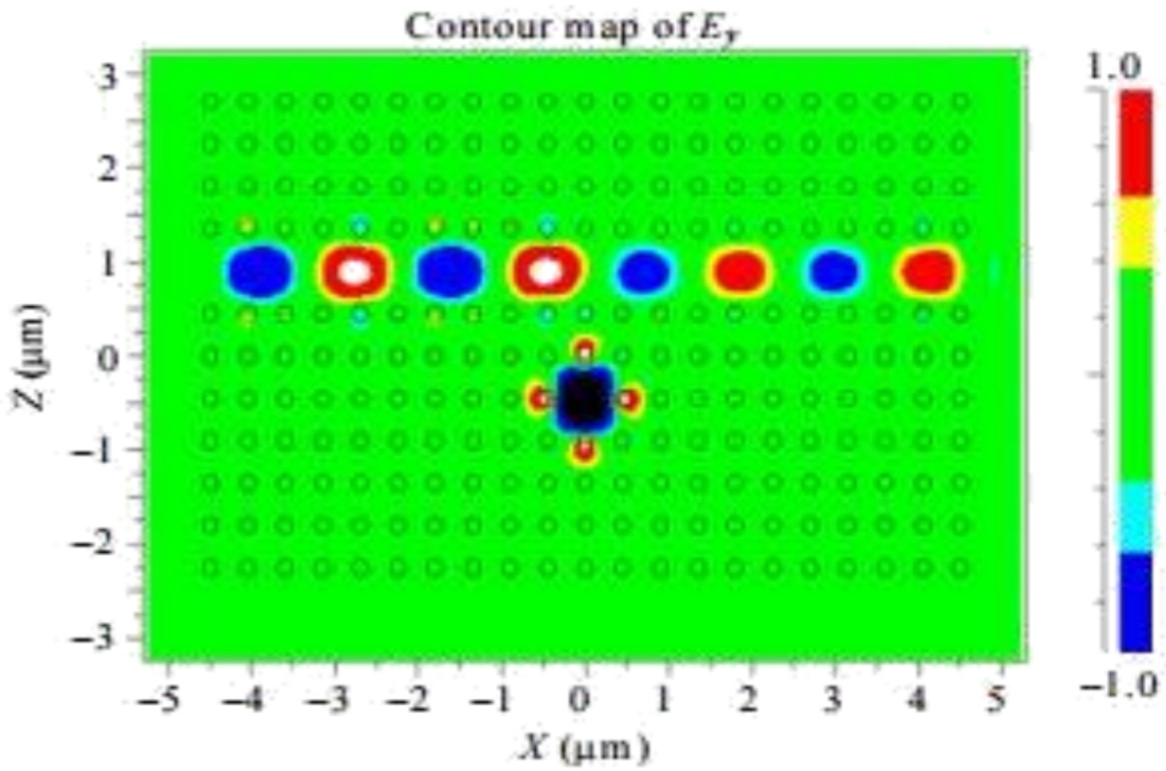


Figure 1.7 Light guiding through a Photonic crystal fibre

1.10 FACTORS AFFECTING DESIGN OF PHOTONIC CRYSTAL FIBRE

Material: For designing the photonic crystal fibres with wide photonic band gap, very high variations in the refractive index should be maintained within the prevailing materials. Different types of materials used for the designing of the sensors includes silicon dioxide, Indium Arsenide, Gallium Indium Arsenide and many others. For better sensing applications, mainly Silicon on insulator substrate is used.

Structure: The structure of sensor can have any one of two possible configurations which may be dielectric rods in a low refractive index material or it may be holes in high refractive index material. The fabrication of the dielectric rods in a low refractive index material configuration is difficult as compared to the configuration having holes in the high refractive index material because it is having high aspect ratio. Light is also not properly guided in such waveguides. Also the structure can be hexagonal and square.

Defects: Photonic crystal waveguides are generated by the introduction of defects in the photonic crystal. Light is passed through these waveguides and then the sensing operation is performed.

Wavelength: For obtaining the sensing operations, 1550nm wavelength is choosen. All the fabrications are done by considering wavelength of 1550nm because at 1310nm water absorption occurs. So, 1550nm is used.

Thickness: Proper thickness of the substrate is maintained so as to obtain better sensing applications. Thickness should be selected with the consideration that there should be minimum radiation losses.

1.11 FINITE DIFFERENCE TIME DOMAIN METHOD

Earlier plane wave expansion method was utilized for predicting properties of photonic band gap by calculating the Eigen–states of an infinite periodic structure and also the field distributions corresponding to those states are also calculated. In order to find the field distributions for complicated structures, plane wave expansion method cannot be used So, in this case Finite Difference Time Domain Method is used [5].

FDTD method is utilized for computation of the distribution of the fields within the photonic crystal based device. These devices are basically optical structures which are having refractive index of non-uniform distribution. In this method space is discretized i.e. discretization of the space is done. This is done by changing the continuous space with a set of discrete nodes. After discretizing, the derivatives of the Maxwell's equation are changed with the finite differences.

This replacement will result in a system of linear algebraic equations. These equations are solved step by step by starting from initial boundary conditions. Thus, the finite difference time domain methods help to find distribution of field by solving Maxwell's equations [5].

1.12 OPTI-FDTD SOFTWARE

Photonic Crystal Waveguides are used for various sensing operations and designing of such waveguides and their simulations are done by using OPTI FDTD software. This software is based on time domain. This software provides a response over wide range of frequencies. In this software, firstly designs of different types of the waveguides are made and then their simulation is done. It is very useful when we actually don't know about the resonant frequencies. Maxwell equations are differentiated and then solved. Various different types of designs can be made by using different types of material having different refractive index. It is very useful software and is user friendly.

1.13 SENSING APPLICATIONS OF PHOTONIC CRYSTAL FIBERS

Photonic crystal fibres are having their applications these days not in communication only but in a various fields and they decline the limitations of the conventional fibres. Due to the advanced technology of the photonic crystal fibres, they are used for the sensing applications. Photonic crystal fibres are used in chemical industry for sensing of different chemicals, toxic and harmful gases. These fibres are used these days for sensing of pressure. Temperature can also be sensed with the help of photonic crystal fibres [9].

Photonic crystal fibres are also various applications in biomedical field as it is used for bio sensing. It is used for detecting various bio components like bacteria, virus etc. Various cells of body like red blood cells, white blood cells, and other cell components like DNA, nucleus, can also be detected with the help of photonic crystal fibres. The sensing mechanism is basically done by the interaction among light and analyte in core region.

Due to this interaction among light and analyte having different refractive index, a shift in resonant wavelength is observed. So, their Sensing applications have drawn much attention towards them. Various Biosensors are designed these days using photonic crystal fibres.

The various sensing applications are defined by measuring the sensitivity of the senor. Sensitivity of the sensor is defined as the ratio of minimum deviation in the resonance wavelength to the variation in refractive index.

1.14 OBJECTIVES OF DISSERTATION

The three main objectives which are achieved in this dissertation based on photonic crystal waveguides are as below:

1. To improve the sensitivity of the sensor by introducing new variations in the design of the waveguide.

2. To design and optimize the performance of photonic crystal based nano-ring resonator.

3. To design a sensor having high sensitivity that is achieved by infiltration of material with different refractive index.

1.15 ORGANIZATION OF DISSERTATION

The dissertation comprises of six main chapters which are explained as follows:

Chapter 1 gives introduction about the photonic crystal waveguides which will be used as a Sensor.

Chapter 2 gives the literature Survey of our topic i.e. photonic crystal Waveguide as Sensor. First step to start any thesis is to study the previous papers and then analyze the work which is already done in this field. It provides vast information about the work which is to be done and gives an idea about future scope of the work.

Chapter 3 deals with the design of a S-shaped waveguide which is generated by introducing line defects in the sensor. This biosensor is used for the detection of various cell components like nucleus, ctyosol and mitochondria. The design is optimized with reflectors of different materials and thus the sensitivity is improved by structural variations.

Chapter 4 deals with the designing of a two dimensional photonic crystal sensor consisting of two C-shaped Curves and a nano-ring resonator. The optimization of the design is done by varying the distance between the curves.

Chapter 5 deals with biosensor design, in which a hexagonal cavity is generated for the detection of different blood cells. Infiltration is done which results in enhancement of the sensitivity.

Chapter 6 gives the conclusion of the whole work and also provides the recommendations and future Scope.

CHAPTER-2

LITERATURE SURVEY

Photonic crystal waveguides are utilized for designing different types of sensors and various researches has been already done in this field. Researchers used different techniques to design sensor depending on the phenomenon of photonic crystal guidance. Various research have been done for designing of various types of sensors like pressure sensor, temperature sensor, chemical sensors and a lot of research is also going on for designing of Biosensors. The literature survey provides a brief idea about the research which is already done in this field. The literature survey of the photonic crystal biosensors is explained below:

H.Y.Fu *et al.* [10] in 2008 proposed an intrinsic fibre optic pressure sensor. This pressure sensor is designed with a sagnac interferometer which is based on a polarization-maintaining photonic crystal fibre (PM-PCF). In this design they have used a 58.4 cm long PM-PCF as a detecting material .using this sensor they have measured a pressure coefficient of 3.42nm/MPa. This sensing device has low bending loss. In sagnac interferometers, polarization maintaining fibres is used because it produces optical path difference thereby causing interference among two counter propagating rays in fibre. This fibre optic pressure sensor has various advantages like greater sensitivity, small size, less temperature sensitivity and less cost.

Debashis Chanda *et al.* [11] in 2008 represented the designing and fabrication of 3-dimensional photonic crystal microstructures. In this design basically a single laser is exposed to the photonic crystal structure and multi-level diffractive optical elements which are phase tuneable are used. In this design they have applied circularly polarised light in order to balance the diffraction order efficiencies and then have improved the uniformity of the structure. Calculation of interference patterns in Finite Difference time Domain provides a smooth transition of symmetry of photonic crystal form tetragonal symmetry to body-centred-tetragonal symmetry. Therefore a 3D diamond –like geometry is generated.

Shota Kita *et al.* [12] in 2008 represented a spectrometer free sensor for refractive index detecting by utilizing photonic crystal point shift nano lasers in an array configuration. These lasers photo pump in a liquid and then it provides a peak intensity of 50-dB and <26 pm spectral line width. By immersing in various different solvents, lasing wavelength shifts. Its sensitivity was 350nm/RIU. They are expected to be integrated with biochips so that they can be employed for label-free single molecule detection. Basically in this sensor light is used in order to control and analyze fluids, colloidal solutions, and any solid in a fluid on micro devices such as labs on a chip. They called this nano laser as HO nano laser because there are no missing holes and comprises of only a shits between two air holes in the photonic crystal. They have obtained refractive index ranging from 1.00 to 1.37 for HO PC nano laser soaked in liquids

Darran K.C.Wu *et al.* [13] in 2009 proposed a micro fluidic refractive index sensor which is depended on a directional coupler and they have used solid-core photonic crystal fibres for designing sensor. A single hole is selectively infiltrated with a fluid (analyte) whose refractive index is required. When solid core fibres are infiltrated with fluid which is having high refractive index than the backdrop are basically guided by the band gap effects. The photonic crystal fibre forms a directional coupler with the analyte channel which itself being a waveguide In this sensor, the core mode is coupled to the mode in adjacent fluid filled waveguide which is beyond modal cut-off and due to this strong field overlapping a very high sensitivity is achieved. Sensitivity of 30,100nm per unit of refractive index is achieved.

WU Jun *et al.* [14] in 2009 represented a photonic crystal waveguide with a slotted single mode which is linearly tapered in order to pass light. There is a change in waveguide's dispersion curve with the change in width of the slot. So, tuning of operating wavelength of light can be done by changing the slot width. The band curve gets shifted in the tapered region whenever there is reduction in the slot width and also the group velocity of light becomes zero at cut off frequency. The design is realized on a silicon slab by forming a triangular lattice of air holes. This single row of air holes is basically detached and then restored by narrow air slot. This structure also allows confinement of slow light-wave in a narrow slot waveguide that causes better synergy among slow light and low index guiding materials which are permeated in the slot.

Min Huang *et al.* [15] in 2009 proposed a sensor in which two technologies i.e. nano-photonics and nano-fluidics are combined together using free-standing photonic crystals and that too on one floor. By utilizing nano-scale openings, manipulation of both light and fluidics is possible at sub-wavelength levels. . In order to implement the sensor, a square lattice of SiNx slab is used and three different media i.e. air (n=1), water (n=1.33), and IPA chloroform mixture (n=1.43) are used. This sensor is basically used for sensing the change in refractive index in an aqueous solution. The sensitivity of sensors is achieved about 510nm/RIU at 850nm in solutions.

Sanja Zlatanovic *et al.* [16] in 2009 proposed a photonic crystal micro cavity sensor for the label free monitoring of the binding of protein in a buffer. The total area of sensor is about 50μm and the effective detection area is $0.272\mu^2$. In this sensor, combining of anti-biotin to biotinylated-biovine serum is observed. This sensor is used for the detection of anti-biotin at various concentrations varying from picomolar to micromolar. Detection lower-limit of anti-biotin is smaller than 20Pm.This sensor can also be used for the measurement of the small molecular species like aromatic rings. The best feature of this design is that the operating area of the sensor can also be recreated and reused again and again in various protein binding experiments.

M.V.Alfimov *et al.* [17] in 2010 proposed Optical Chemo sensors which are depending on photonic crystal. Sensor designing is basically dependent on electrodynamics and quantum-chemical calculations of the first principles. In this method electromagnetic emission sources are taken into consideration by using finite difference time domain method. Here simulation is done from end to end of fluorescence in a whole structure. Then the absorption and emission spectra are calculated for the dye which is present on substrate. The calculation is done by quantum chemistry and then the modifications of the emission spectra of dye are shown in a three dimensional crystal.

Yongqin Yu *et al.* [18] in 2010 represented a photonic crystal fibre temperature sensor. In this sensor, air holes of index guiding PCF are filled with liquid ethanol and then by intensity, temperature variations are sensed. Whenever the thermo optic coefficient of ethanol liquid is greater than silicon dioxide, then in that condition in order to become highly temperature dependent, various factors like mode field, effective refractive index and confinement loss should be found. The temperature dependence is increasing with the increase in input wavelength. Thus, after all experiments and simulations, the temperature sensitivity is obtained.

Christopher Kang *et al.* [19] in 2010 proposed improved silicon slab photonic crystal sensitivity for molecular detection. Sensitivity is improved by multiple hole defects (MHDs) in which label free detection is done by increasing the active area and also quality factor is not affected. By introducing MHDs, detection sensitivity has increased by 44% as compared with the L3 defects for small refractive index and 18% for bulk refractive index changes.

M.G.Scullion *et al.* [20] in 2011 demonstrated slotted photonic crystal cavities which are used for bio sensing and these cavities are integrated with micro fluidics. It is used for the detection of dissolved avidin concentration. The sensing surface area of the cavity is about 2.2μm^2, which can detect surface mass densities of 60pg/mm^2. This design gained a lot of attraction due to its lab-on-chip applications. Because of strong imbrications with analyte, very high sensitivity is achieved over the small area. Very large shifts are obtained in the peak wavelength due to this strong overlap.

Daquan Yang *et al.* [21] in 2011 proposed a nano-scale photonic crystal sensor array which is designed on monolithic substrate. This sensor can be employed for the highly parallel and label free detection in any aqueous medium of the various biological interactions. The proposed sensor design consists of a single Photonic Crystal in which an array of various resonant cavities which are lattice shifted are side-coupled. Due to variations in refractive index, there is a deviation in resonant peak. With the help of three dimensional Finite Difference time domain (3D-FDTD) techniques, 115.60nm/RIU sensitivity of refractive index is achieved.

F.Ouerghi *et al.* [22] in 2012 represented a photonic crystal sensor which is used for chemical sensing. Chemical sensor is dependent on photonic crystal negative refraction (PCNR). Within the PCNR various multi nano cavities which are distributed are embedded. A two dimensional finite difference time domain method is employed for analyzing performance of the device using different parameters and different analytes. If the two analytes are having refractive index greater than water, then it is possible to examine them together. The quality factor obtained is about 105 when radius of external cavity is 0.0215a and that of internal cavity is 0.225a.

Saeed Olyaee *et al.* [23] in 2012 proposed a pressure sensor depending on a two dimensional photonic crystal which is having very high resolution and vast range. In this sensor, there is a square array of silicon rods which is surrounded by air. There is photonic crystal waveguide and a photonic crystal nano cavity and both are coupled with each other. The nano cavity is formed by changing one silicon rod's radius and by deleting few silicon rods, a waveguide is generated. On increasing pressure, the resonant wavelength gets shifted towards larger wavelengths.

Charles Caer *et al.* [24] in 2012 proposed a design of photonic crystal waveguides having wide slot where the slot is structured as a comb. This provided dispersion engineering so as to obtain very less group velocities in range of nanometres bandwidth. This device allowed a very strong interaction between light and the material having low index.

S.padidar *et al.* [25] in 2012 designed a photonic crystal fibre sensor which are used for temperature and pressure sensing. It is necessary to continuously monitor pressure and temperature in reservoir engineering. This designed device is dependent on hollow core photonic crystal fibre. The outputs the sensor is monitored by using three dimensional finite difference time domain (FDTD) method. It is dependent on deviations in the wavelength peaks due to change in temperature of pressure. Sensitivity of 480nm/RIU is obtained.

Y.Liu *et al.* [26] in 2012 proposed an on-chip sensor on the basis of a 2-D photonic crystal cavity. On analyzing the shifts in wavelength according to the variation in refractive index, Sensitivity can be obtained. Solutions of ethanol and water are used and obtained a sensitivity of 400nm/RIU.

Yufei Wang *et al.* [27] in 2012 represented a photonic crystal sensor for sensing refractive index. The sensor is based on Michelson Interferometer. In the sensor, there are two sensing areas, where it is observed that the branch area is used for low index values and reflector area is suitable for bigger index range. No defects and no crosstalk of signal are present in this sensor design and is suitable for real time- parallel sensing.

Hemant Sankar Dutta *et al.* [28] in 2013 proposed a photonic crystal waveguide for bio sensing on the basis of change in refractive index. The analysis of the design is obtained by using 3-D finite difference time domain method (FDTD). With the variations in the refractive index, a considerable amount of change occurs in output spectrum. This is the principle of the sensing. Sensor is examined for different samples having different refractive index. Sensitivity of the sensor is dependent on properties of defects and a sensitivity of about 260nm/RIU is obtained along with 0.001 RIU detection limit. The sensor design is compared with other sensor designs in order to analyze the performance.

Saeed Olyaee *et al.* [29] in 2013 designed a photonic crystal biosensor having label free four channel by using nano cavity resonators. Sensor design consists of four channels which are basically waveguides and are removing group of holes. Nano cavity is achieved by varying radius of the holes. In proposed design, a liquid medium is present in the nano cavity on which the bio materials are suspended. These biomaterials causes change in refractive index which in turn causes change shift in wavelength. This design is best suited for sensing of various bio chemicals like DNA molecule, Protein.

Yi Yang *et al.* [30] in 2013 represented a two orthogonal direction stress sensor which is based on photonic crystal. The designed sensor comprises of an aslant resonant cavity which is lattice shifted and the design is shoulder coupled to T-K waveguides which are terminated. The enforced pressure in two directions is linearly related to the resonant wavelength shift and this relationship is solved by the finite element method and finite difference time domain method. The sensor is having stress sensitivity of about 10nm/μN in vertical direction and in horizontal direction it is about 7.5nm/μN with a stress detection limit of 44nN and 58nN in vertical and horizontal directions respectively.

Sudeshna Pal *et al.* [31] in 2013 proposed a photonic crystal biosensor for the detection of selective virus in complex specimen. The design comprises of W1 photonic crystal waveguide and is paired with point defect. Using lithography and reactive ion etching, it is designed on silicon on insulator substrate. Sensor detects virus on the basis of shifts in resonant wavelength. The simulations are done using FDTD and a detection limit of 1.5nM is obtained.

Kandammathe Valiyaveedu Sreekanth *et al.* [32] in 2013 represented a biosensor designed on one dimensional photonic crystal which is based the incitement of electromagnetic waves on graphene. The design comprises interchanging layers of material having more and less refractive index. This provides angular reflectivity resonance and very big fields in photonic crystal. The obtained sensitivity is 14.8 times more than the conventional biosensors using gold thin films.

Huihui Lu *et al.* [33] in 2013 designed an integrated temperature sensor on the basis of enhanced pyroelectric photonic crystal. Sensor design consists of lithium niobate (LN) on which a cavity is fabricated. Sensing is done by the effect of lithium niobate. The temperature is varied only 32 degrees Celsius and the wavelength is fixed at 11.5nm. The results are analyzed by employing three dimensional finite difference time domain methods. Sensitivity of sensor is 0.359nm/degree Celsius.

Saniya Azeem *et al.* [34] in 2014 designed photonic crystal sensor based on MOEMS for structural health monitoring system. MOEMS technique is combination of MEMS (micro electro mechanical) and optics. Sensor is utilized for pressure sensing, displacement sensing, reverberation sensing and simulations of the sensor are done using FDTD method. Due to change in displacement, the intensity level changes which in turn is altered due to variations in refractive index. By combining both techniques, sensitivity of senor is greatly enhanced.

Krishna Vijaya Shanthi *et al.* [35] in 2014 represented a pressure sensor depending on a two dimensional photonic crystal. The sensor is composed of an array of silicon rods which are arranged in square in which two waveguides and L3 defects are produced. By, changing the radius of silicon rod, L3 defect is generated and it lies in between two waveguides. When the applied pressure is increased, there is a shift in the wavelength towards right. Sensitivity of the sensor is 2nm/GPa and the dynamic range is 7GPa.

Daquan yang *et al.* [36] in 2014 proposed a sensor array based on nano scale photonic crystal and provides very low crosstalk. The sensor array comprises of resonant cavities which are side coupled and obtained a quality factor of $2x10^3$. There is an independent shift in each resonant cavity due to the variations in refractive index. The sensing is analyzed by employing 3D Finite Difference Time Domain method. Sensor provides a sensitivity of about 100nm/RIU.

Yuguang Zhang *et al.* [37] in 2015 represented a photonic crystal cavity sensor which is having a very high value of quality factor and also very high sensitivity and is designed on silicon-on-insulator platform. Due to disturbance of light in region having low index, photonic crystal sensor's sensitivity can be enhanced. The device is dipped in a sodium Chloride Solution having different concentrations and then the transmission spectrum is observed. Sensitivity of about 428nm/RIU is achieved in the sensor.

A.A. Rifat *et al.* [38] in 2015 proposed a Plasmon Resonance Biosensor which is based on photonic crystal fibre designed in a hexagonal lattice having two rings in which the Plasmon resonance occurs. Active Gold Layer and the analyte are kept out of the fibre. The sensor has enhanced sensitivity and show birefringence. The sensor provides maximum sensitivity 4000nm/RIU. The sensor is used for the detection of biological analytes

Rahul Kumar Gangwar *et al.* [39] in 2016 represented a sensor which is depending on surface Plasmon resonance. The design consists of D-Shaped Photonic Crystal fibre. In this D shaped fibre, surface Plasmon effects occur and in turns they help in measuring the refractive index of analytes. The proposed sensor's sensitivity is observed for different analytes having refractive index ranging from 1.43 to 1.46 and sensitivity of about 7700nm/RIU and a resolution of 1.30×10^{-5} are obtained.

S.NO	Name of the author	Title of paper	Year of publish	Content
1.	C. Xiong, W.H.P. Pernice, and H.X. Tang	Low-Loss,Silicon Integrated, Aluminium nitride Photonic Circuits and their use for Electro-optic signal Processing	2012	Proposed integration of AlN films on silicon substrate to get the active functionalities on a small chip.
2.	F. Bagci and B. Akaoglu	Enhancement of Refractive Index Sensitivity in Photonic Crystal Waveguide- Based Sensors by Selective Infiltration	2013	Proposed a refractive index sensor which is based on liquid. Infiltration of first row of holes adjacent to the line defect is done for different hole diameters. Later the holes in line defect are also infiltrated.
3.	Dutta H, Goyal A K and Pal S	Sensitivity enhancement in photonic crystal waveguide platform for refractive index sensing applications	2014	Proposed a photonic crystal waveguide based sensor having circular holes in silicon-on insulator (SOI) Material. Ring shaped holes are introduced in the line defect. A wavelength deviation of 210nm is achieved providing a sensitivity of 420nm/RIU.
4.	Saniya Azeem, Preeta Sharan, srinivas Talabattula	MOEMS based photonic crystal sensor for structural health monitoring system	2014	Designed a senor by combining MEMS and integrated optics to form MOEMS.
5.	Krishnan vijaya shanthi and Savarimuthu	Two-Dimensional Photonic crystal Based Sensor for	2014	Proposed the design of a pressure sensor based on a two

	robinson	Pressure Sensing		dimensional photonic crystal.
6.	Amit Kumar Goyal, Suchandan Pal	Design and simulation of high-sensitive gas sensor using a ring-shaped photonic crystal waveguide	2015	Proposed a photonic crystal gas sensor having a ring shaped structure comprising of holes in photonic crystal waveguides.
7	Amit Kumar Goyal, Suchandan Pal	Design and simulation of high sensitive photonic crystal waveguide sensor	2015	Proposed a PCW based sensor designed on a SOI material with circular holes. Sensitivity is obtained by modifying radius of holes in line defect and by varying etch depth. Average sensitivity achieved is386nm/RIU.
8.	Poonam Sharma	A Photonic Crystal sensor for Analysis and Detection of Cancer cells	2015	Proposed design of a 2D photonic crystal used for detection of basal, cervical and breast cancer cells with help of FDTD software.
9.	Shivam Upadhyay, Vijay Laxmi Kalyani and Chandraprabha Charan	Designing and Optimization of Nano-ring Resonator-Based Photonic Pressure Sensor	2016	Represented a pressure sensor whose structure consists of a linear waveguide with a two dimensional photonic crystal sensor.
10.	Tingyu Li *et al*	High-*Q* and High-Sensitivity One-Dimensional Photonic Crystal Slot Nanobeam Cavity Sensors	2016	Proposed a one dimensional photonic crystal sensor having a nano beam cavity. A quality factor of 174000 is achieved with this sensor.

Table 2.1 Review of work done in the past in field of PCF based applications

CHAPTER 3

PHOTONIC CRYSTAL SENSOR HAVING S-SHAPED WAVEGUIDES INTEGRATED WITH REFLECTORS MICRO-FLUIDICS USED FOR BIOSENSING APPLICATIONS

3.1. INTRODUCTION

A cell is the basic unit of living organism and it is composed of cytoplasm, Nucleus, mitochondria and other components. The detection of these cell components is very important in order to find the other biophysical parameters of the cell [40]. Those biophysical parameters include protein concentration, wet mass; dry mass, elasticity, conductivity and many more. In order to study and analyze about cell division, firstly the detection of cell components is very important. For cell division, it is necessary for the cell components to divide [40].

Photonic crystal sensors are having extensive demands these days because they provide sensing of biological, biochemical agents [41]. Biosensors based on silicon in a silicon-on-insulator wafer provides various a very strong interactions between the analytes and the light thereby resulting in increased sensitivity and provides a feasibility of fabrication with the CMOS technology.

Photonic crystal sensing can be achieved with different structures like micro cavities [42], waveguide [43]. Sudeshna Pal *et al.* [44] designed a photonic crystal biosensor for sensing selective virus in complex specimen. Hemant Sankar Dutta *et al.* [45] designed a photonic crystal waveguide bio sensor and obtain a sensitivity of about 260nm/RIU. A.A. Rifat *et al.* [46] designed a biosensor sensor provides maximum sensitivity 4000nm/RIU.

In this, a biosensor is designed which is used for detection of various cell components like nucleus, cytosol and mitochondria having refractive index 1.35, 1.39 and 1.42 respectively [40]. Sensing is done either by considering the variations in intensity of transmission spectrum or considering the shift in the resonant wavelength which can be towards right or left. This change in intensity or deviation in wavelength occurs due to the variation in refractive index of analytes. The electromagnetic wave equations corresponding to the modes occurring in between are observed by plane wave expansion method or Finite Difference Time Domain methods. Detection of these cell components is very important to analyze processes like cell division in living organisms.

REFRACTIVE INDEX	**ANALYTE**
NUCLEUS	1.35
CYTOSOL	1.39
MITOCHONDRIA	1.42

Table3.1. Refractive index of different analytes

3.2. SENSOR DESIGN

3.2.1 SIMPLE DESIGN

The sensor design comprises of a rectangular array of silicon rods placed in silicon on insulator wafer. The refractive index of silicon is 3.42 and that of air is 1. The design of the sensor is two dimensional. The distance between the centres of the two holes is known as lattice constant and its value is 700nm. Radius of silicon rods is 240nm. The design comprises of a waveguide which contains the sensing region. By introducing line defects within the sensor structure, a waveguide is generated. The line defects are produced by deleting a row of dielectric rods from the design. So, this waveguide is generated in a silicon-on-insulator wafer

Figure 3.1 shows the layout of the design of the sensor. Light is passed through the input of waveguide and then collected at output of the waveguide and in between there is a sensing region. Before simulating further, it is first cleared whether the selected wavelength passes through the design. It is done by plane wave expansion method. The band diagram of the sensor is shown in Figure 3.2. The photonic band gap of the sensor is observed and it is found that it occurs between 0.542308 to 0.651866 (1/) thereby allowing a wavelength of 1530nm to 1800nm to pass through the sensor design.

So, for this design, the input source is set at 1550nm. The sensing region is filled with different analytes like nucleus, cytosol and mitochondria [40] which are having different refractive index. Then the response is observed for different analytes. A change in the transmission intensity is observed variations of refractive index.

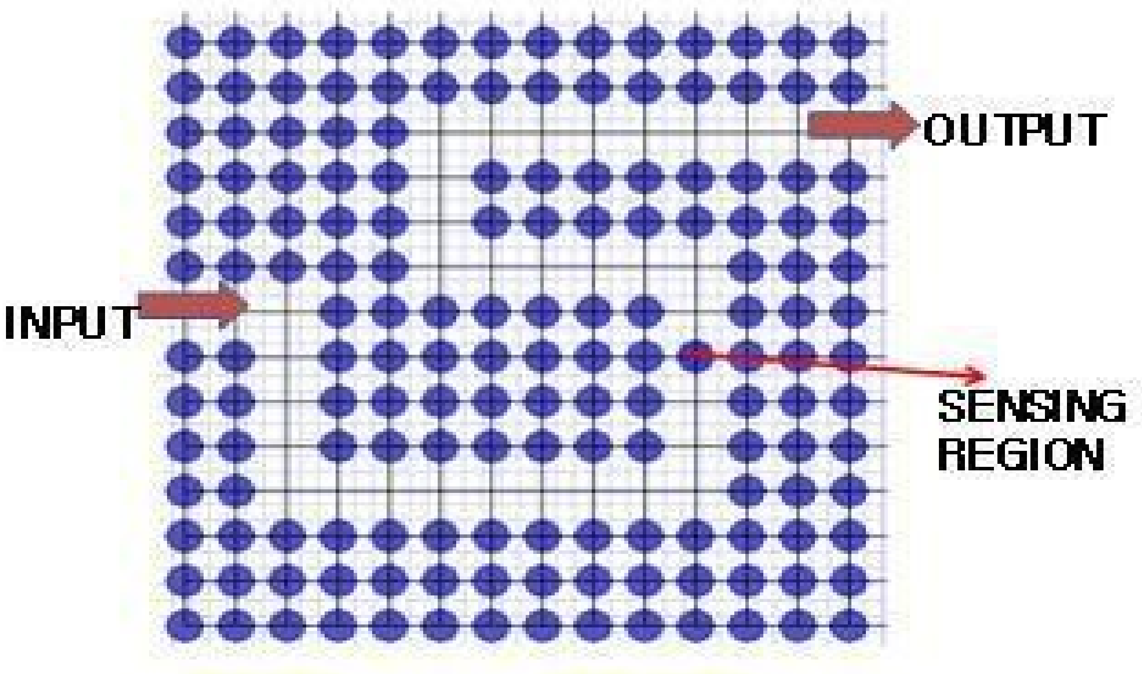


Figure 3.1 S-shaped waveguide Sensor

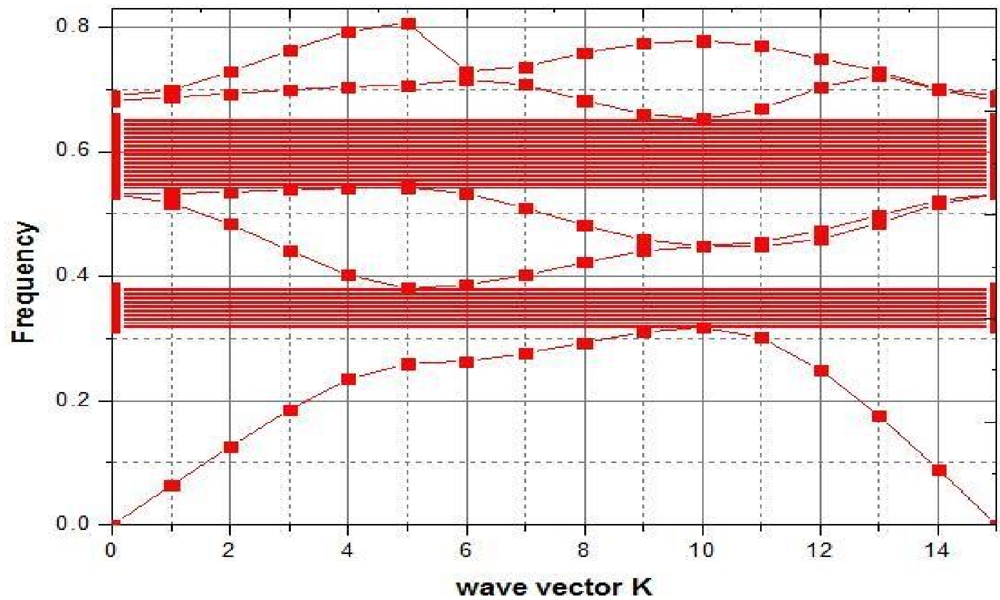


Figure 3.2 Band Diagram of the Sensor

3.2.2 IMPROVED DESIGN WITH SILICON REFLECTORS

In the second part of the design, reflectors are introduced in the sensor. Here the reflectors are made of silicon having refractive index 3.42.The width of the reflectors is altered in order to obtain the perfect sensing properties. So after optimization, the width of the reflector is taken 200nm. These reflectors are placed at every corner in the waveguide.

The reflectors basically reflect the light coming at the corners so as to completely pass the whole input wavelengths through the waveguide. By using the reflectors the sensing performance gets improved. The improved design with reflectors of silicon having width 200nm is shown in Figure 3.3. Light is passed and the results are observed for the selected analytes.

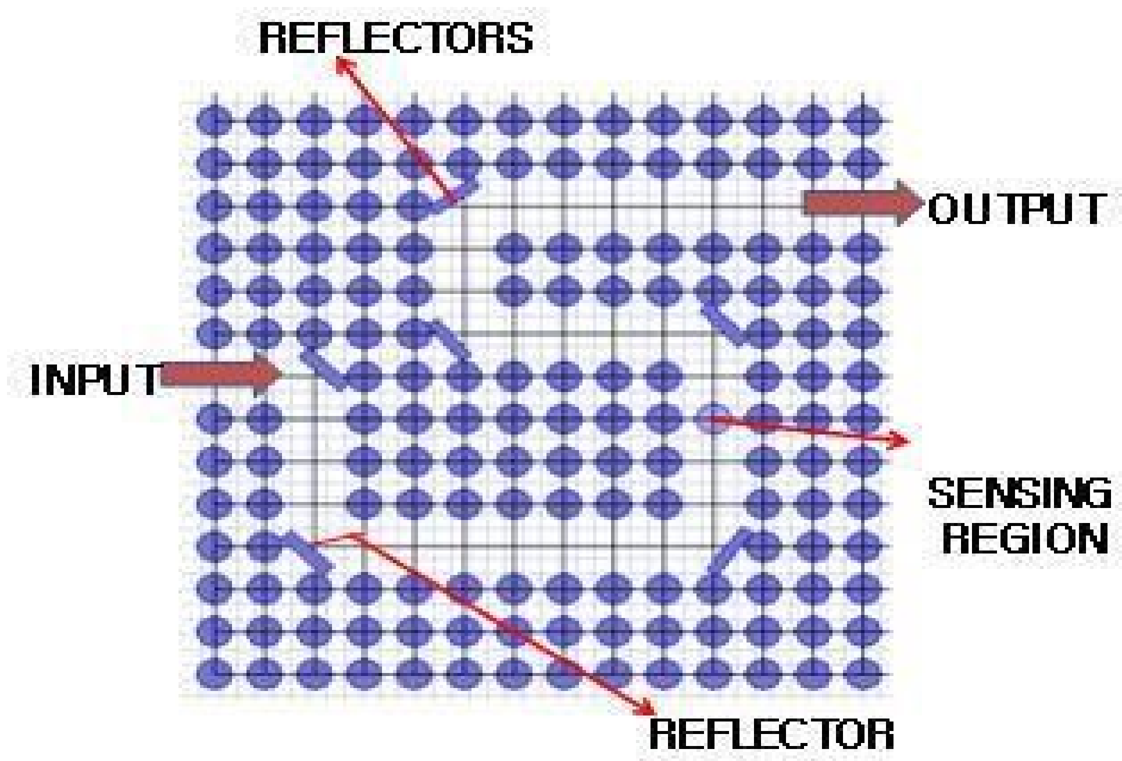


Figure 3.3 Sensor with Reflectors

3.2.3DESIGN WITH INDIUM ARSENIDE REFLECTORS

In order to optimize the sensor design, the material of the reflector is further changed. Here, the Indium arsenide reflectors are used. Further continuously the width of the reflectors is altered in order to optimize the results. Finally the width of the Indium Arsenide reflector is taken as 220nm. The design will be the same as the design with silicon reflectors but only the material will be changed. Here also results are observed for nucleus, cytosol and mitochondria. Sensitivity of the sensor is obtained by the given formula

—

Where Δ denotes change in wavelength and Δr denotes change in refractive index

3.3 SIMUATIONS AND RESULT

Light is entered at the input of waveguide by a light source. The propagation of light through the waveguide containing sensing region is shown in Figure 3.4. After sending through the sensor, light is collected at output of waveguide. The spectrum analyzer is utilized to examine the transmission spectrum through the sensor. The samples should be placed in such a way that maximum interaction between the analytes and the light should occur. In order to pass the maximum light through the sensor, the input source and the spectrum analyzer should be positioned accordingly in the senor structure.

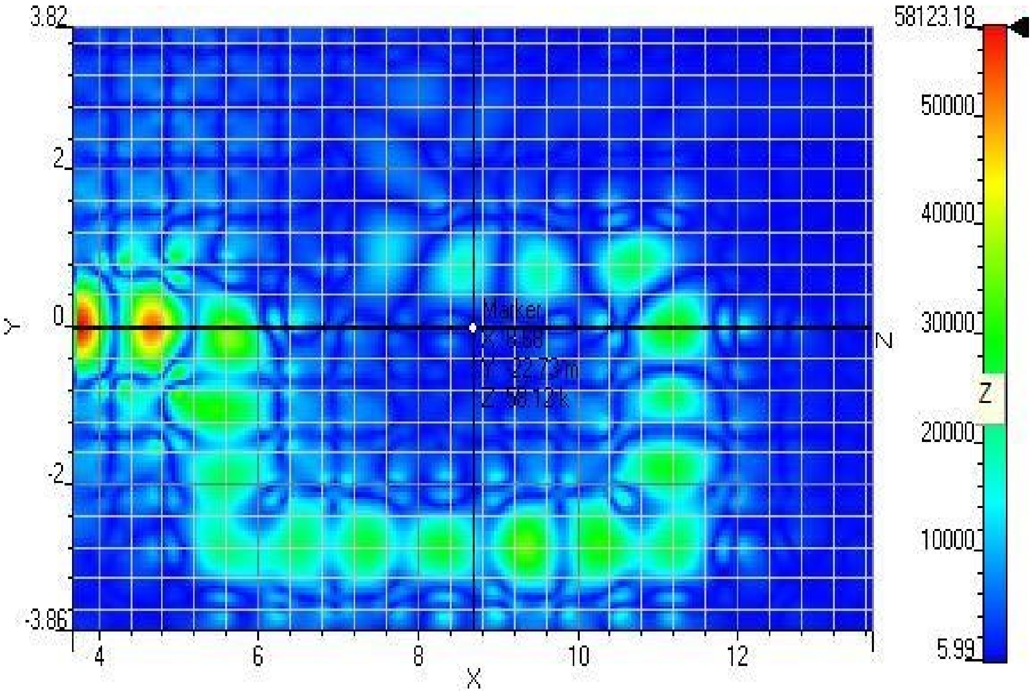


Figure 3.4 Transmission of light through Sensor.

Interaction between light and the different analytes i.e. Nucleus (n=1.35), Cytosol (n=1.39) and Mitochondria (n=1.42) [40] is observed in the simple sensor design which is shown above in Figure 3.1. The response of the light is analyzed by using Finite Difference Time Domain method. As the light passes through the waveguide, variations in the intensity of the light occur along the wavelength. Figure 3.5 shows the Dips in the transmission spectrum of the sensor. Figure 3.6 shows the wavelength shift dependence on the refractive index. It is observed that there is a deviation in the resonant wavelength of the transmission spectrum due to change in the refractive index of the analytes. It is observed that the fall in transmission intensity is observed between wavelengths 1.92µm to 1.94µm with a difference of few micrometres among three analytes.

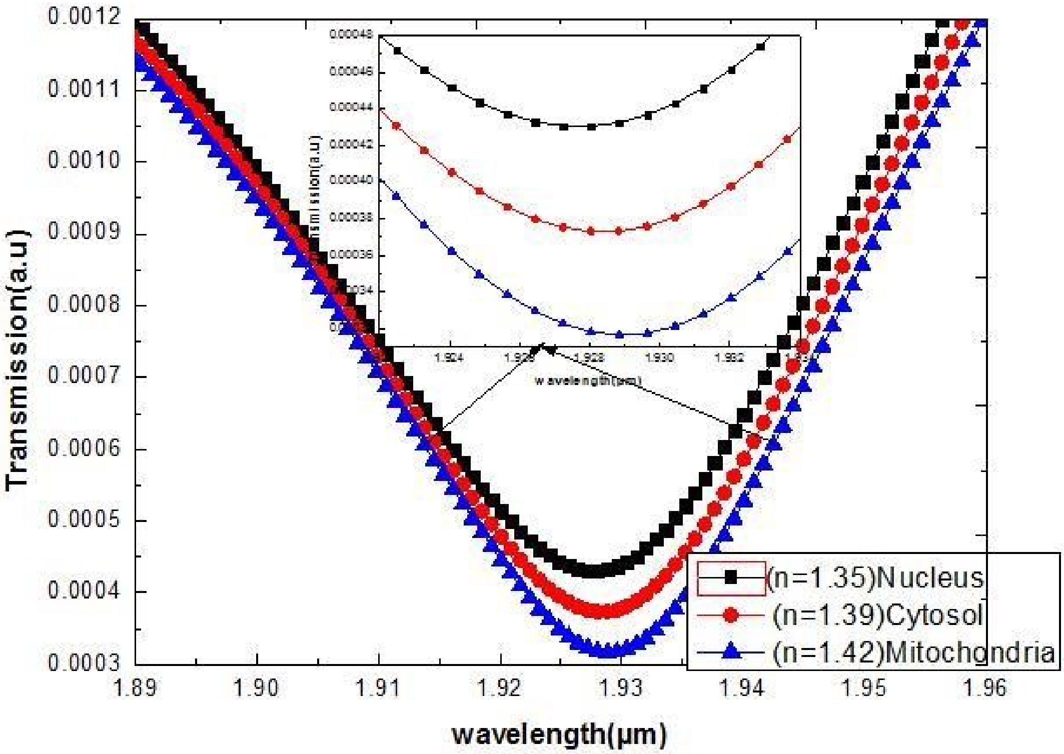


Figure 3.5 Dips in the Transmission Spectrum of the Sensor.

Resonant wavelengths are obtained for the transmission spectrum. Then the change in intensities is obtained. The change in refractive index is also calculated. The sensitivity is obtained for the design and is equal to 43nm/RIU.

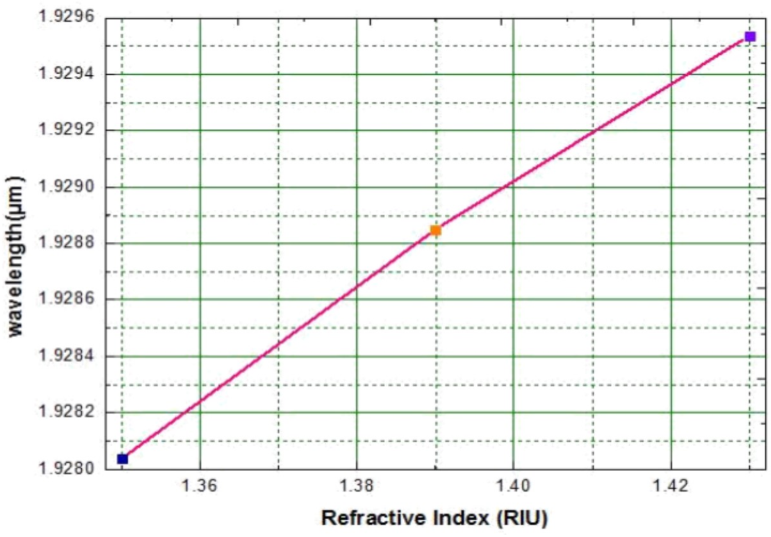


Figure 3.6 Wavelength shift dependence on refractive index

Now, the Simulations and the graphs are obtained for the modified design with Silicon reflectors having width of 200nm. Due to introduction of Silicon reflectors in the design, better interaction occurs between light and analyte because better transmission of light occurs through the design due to reflectors. The transmission spectrum of design with silicon reflectors having width 200nm is shown in Figure 3.7. The wavelength versus refractive index for the modified design with silicon reflectors is shown in Figure 3.8.

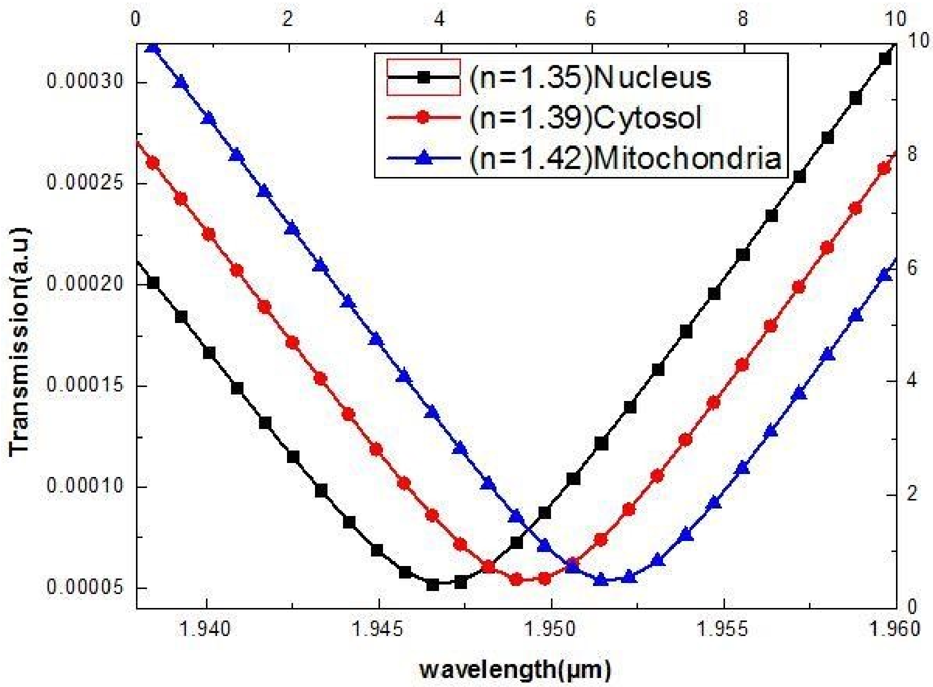


Figure 3.7 Dips in transmission Spectrum of Sensor with Silicon Reflectors

A shift is wavelength is observed in the above transmission spectrum due to change in the refractive index of the analytes. It is analyzed that the fall in intensity for nucleus occurs at 1.947µm, for cytosol, it occurs at 1.949µm and for mitochondria, it occurs at 1.952µm. Also it is realized that a linear relationship exists among wavelength and refractive index of analytes. The transmission intensity of mitochondria is more than that of cytosol and transmission intensity of nucleus is lower than the other two analytes.

It is observed that due to introduction of Silicon reflectors in the sensor design, the sensitivity of the sensor is enhanced and is obtained as equal to 73 nm/ RIU. It is observed that a linear relationship exists between wavelength and refractive index.

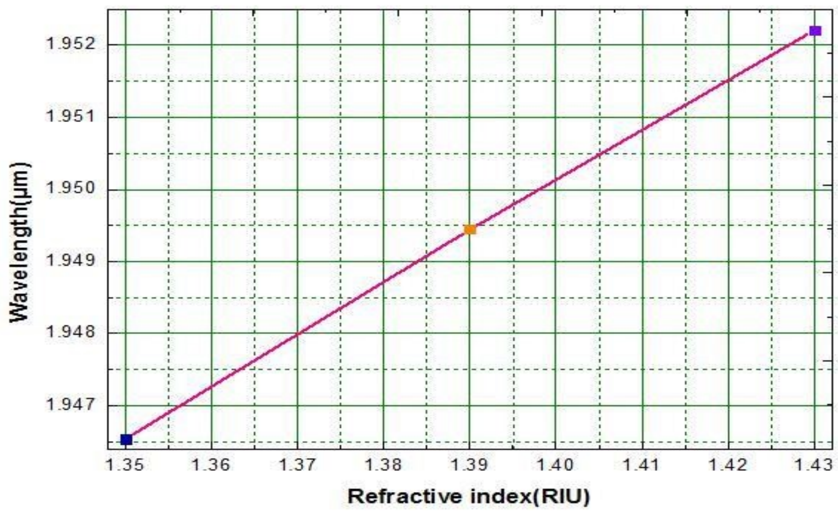


Figure 3.8 Wavelength shift dependence on refractive index of sensor with silicon Reflectors

Further the design is modified by altering the material and the width of the reflector. Now the material of the reflector is Indium Arsenide and the width of the reflector is taken as220nm. Then the transmission spectrum is observed by taken Indium Arsenide reflectors. Figure 3.9 shows the dips in transmission spectrum of the sensor with Indium Arsenide reflectors. The wavelength shift dependence on the refractive index for the modified design with Indium Arsenide reflectors is shown in Figure 3.10. A shift in the resonant wavelength is observed with the change in refractive index of senor.

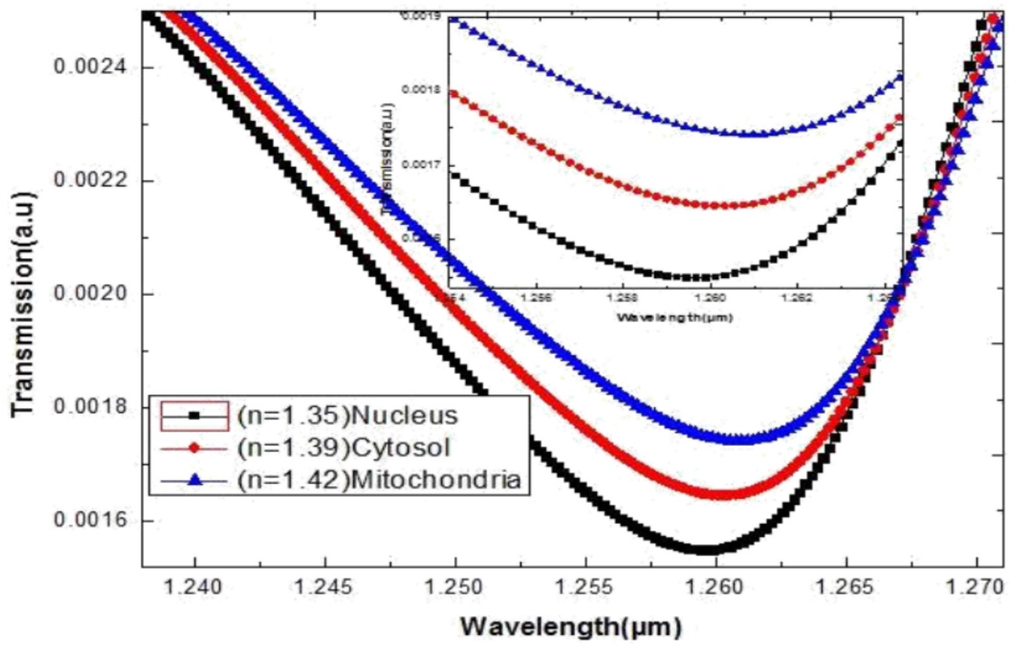


Figure 3.9 Dips in transmission spectrum of the sensor with indium arsenide Reflectors

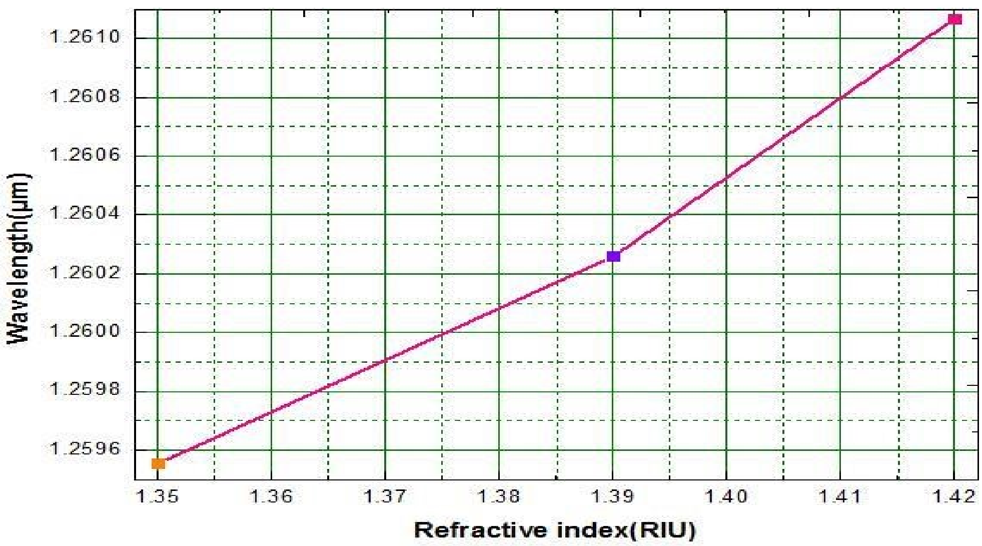


Figure 3.10.Wavelength shift dependence on refractive index of sensor with Indium arsenide Reflectors

From above results, it is observed that sensitivity is reduced by arsenide reflectors than that obtained with silicon reflectors. Thus, it is clear that by introducing silicon reflectors, better interaction has occurred among the light and analytes thereby resulting in better sensitivity in this case.

CHAPTER 4

TWO DIMENSIONAL PHOTONIC CRYSTAL BIOSENSOR SENSOR WITH TWO C-SHAPED CAVITIES COUPLED TO FORM A NANO-RING RESONATOR

4.1. INTRODUCTION

Photonic crystals are periodic dielectric structure which have the ability to guide the light through them and can also manipulate that light [47]. When some defects are produced in the periodic structure by removing some holes, the periodicity gets disturbed which results in the formation of modes due to this electromagnetic field gets confined in the area that is defected [48]. This light is affected by change in refractive index. Biosensors are the sensors which are widely used nowadays in various fields like biomedical research, food storage, drugs production and testing [49].

Chow *et al.* designed a two dimensional photonic crystal biosensor having a micro cavity and obtained quality factor equal to 400[50]. Lee and Fauchet also design a micro cavity photonic crystal biosensor for detection of protein [51]. Quan *et al.* represented a sensor for detection of glucose and its structure is based on nano-beam cavity [52]. Hsiao *et al.* designed a photonic crystal having a structure of nano ring resonator and obtained quality factor of 3200 and sensitivity of 0.5nm/fg [53]. Various sensors having dual nano ring resonators [54] and triple nano ring resonators [55] are also designed.

Bio sensing is done by two methods i.e. either by variations in the intensity of the transmission spectrum or due to the shift in the wavelengths. The shift can be towards right or it can be towards left also. In order to perform simulations and analyze the results of the sensor, plane wave expansion and two dimensional finite difference methods are utilized. These methods are employed for obtaining the photonic band gap and for solving the electromagnetic wave equations.

In this chapter we have designed a biosensor which is depending on photonic crystal whose structure is having a nano ring resonator.

The design consists of a bus waveguide, a drop waveguide and a nano ring resonator. Nano ring resonator is created by two C-shaped curves. The sensing region's refractive index is altered for different ranges 1.32, 1.35, 1.38, 1.41 and 1.44.

4.2. SENSOR DESIGN

The geometry of designed photonic crystal sensor comprises of hexagonal lattice of silicon rods in air in a silicon-on-insulator wafer. The refractive index of silicon rods and the air are 3.42 and 1 respectively. Radius of silicon rods is 200nm and the lattice constant is 850nm. The designed sensor consists of a Bus waveguide, a drop waveguide and a nano-ring resonator. Two C-Shaped cavities are created in the design and these two C-shaped cavities together results in the formation of a ring resonator.

The defects are created by deleting a set of silicon rods so as to form two waveguides and ring resonator. The bus waveguide is placed above ring resonator and drop waveguide is placed below ring resonator and in between bus waveguide and drop waveguide there is a nano-ring resonator cavity. Design of sensor is shown in Figure 4.1.

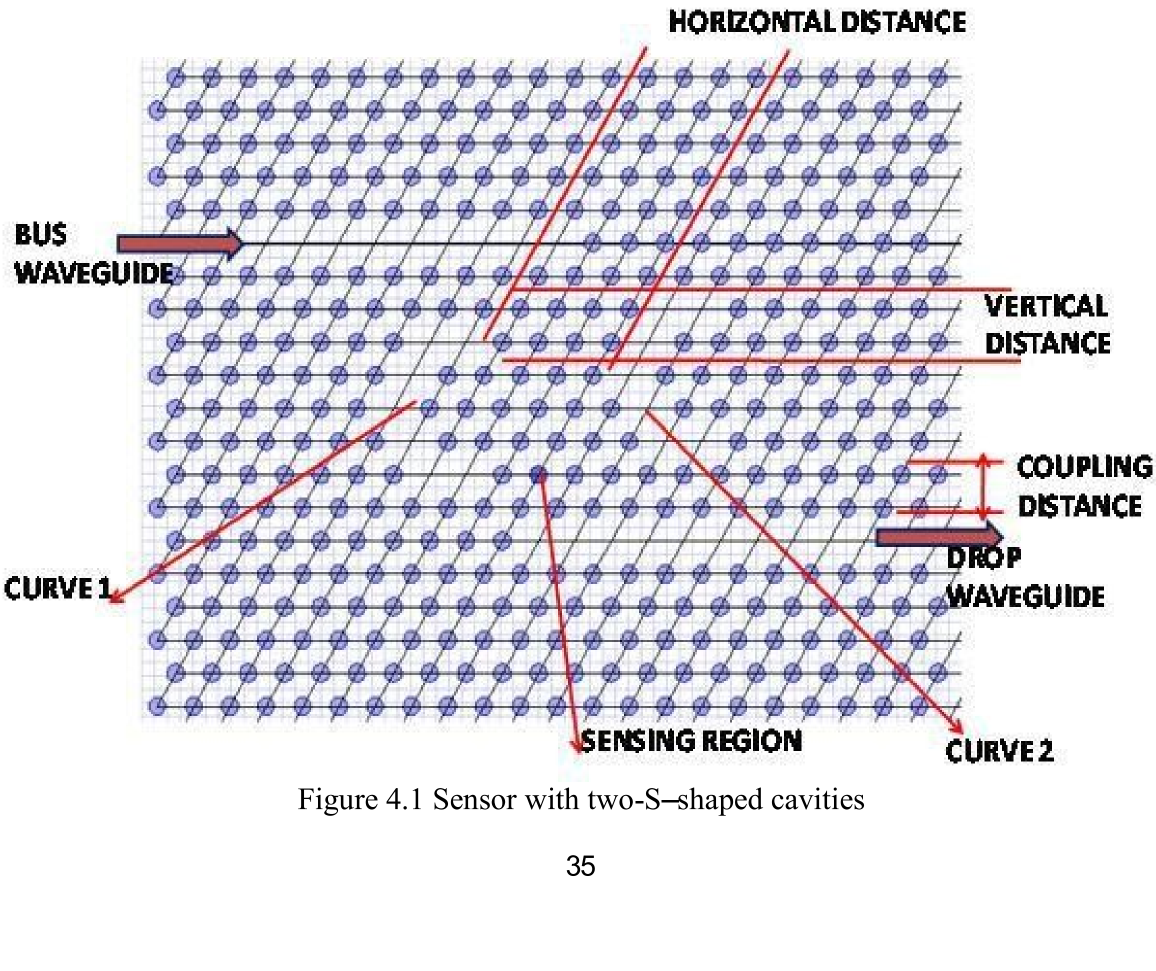


Figure 4.1 Sensor with two-S–shaped cavities

Vertical distance, horizontal distance and the coupling distances are clearly shown in the design structure. A horizontal distance is fixed between two c-shaped curves. Light is input at the bus waveguide and resonance occurs at ring resonator and then after resonance the light comes out through drop waveguide which is present at the bottom of ring resonator. Plane wave expansion method is used in order to verify that whether the selected input wavelength passes through the sensor design.

It is observed that the photonic band gap occurs between 0.58862 to 0.69102 (1/) thereby allowing a wavelength of 1440nm to 1690nm to pass through the photonic crystal. So, the input is fixed at 1550nm. The band structure is shown in Figure 4.2. Sensing region's effective refractive index is altered between the range 1.32 to 1.44. Two Dimensional finite difference time domain (FDTD) and plane wave expansion methods are used for analyzing the sensor

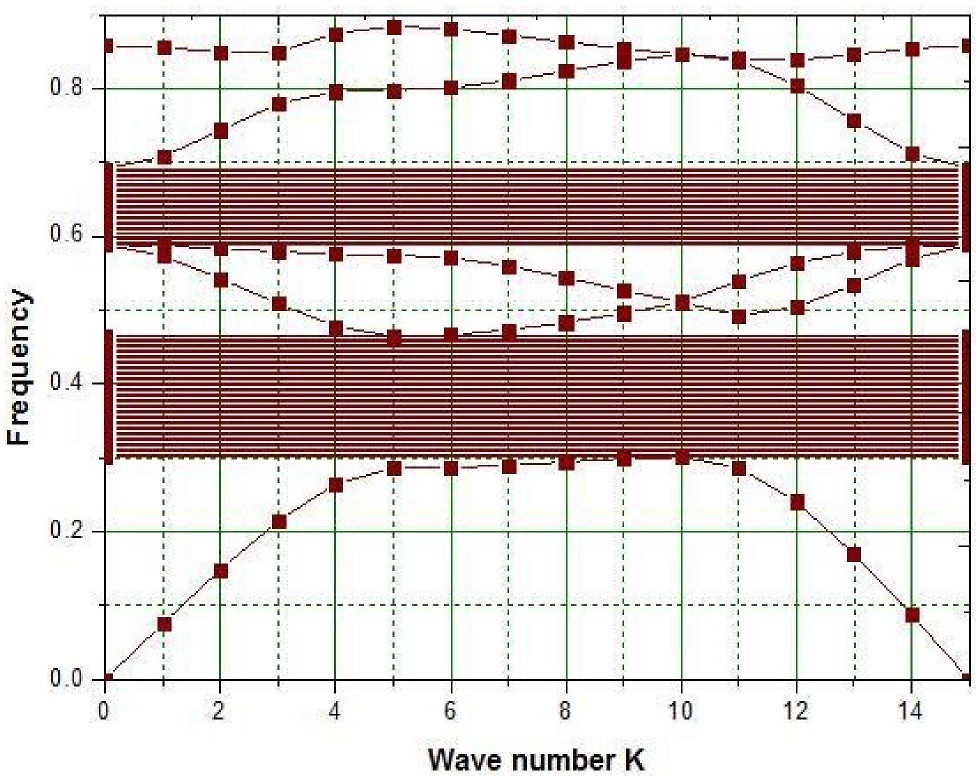


Figure 4.2 Band diagram of the Sensor

4.3. SIMULATIONS AND RESULTS

Various factors like vertical distance, horizontal distance and coupling distance between two curves are very important for this sensor because due to change in these factors, the performance of sensor is greatly affected. Light is input at the bus waveguide in the ring resonator due to which the resonant modes in the ring resonator gets excites. Due to the excitation of the resonant modes, there is a change in the intensity of light. The transmission intensity at the input is shown in Figure 4.3. The propagation of light over design is exhibited in Figure 4.4.

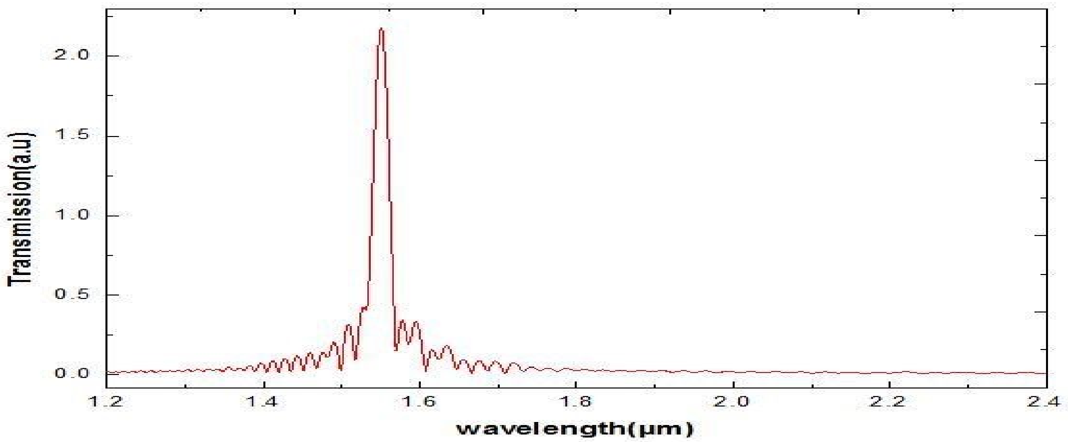


Figure 4.3 Light intensity at the input of the Sensor

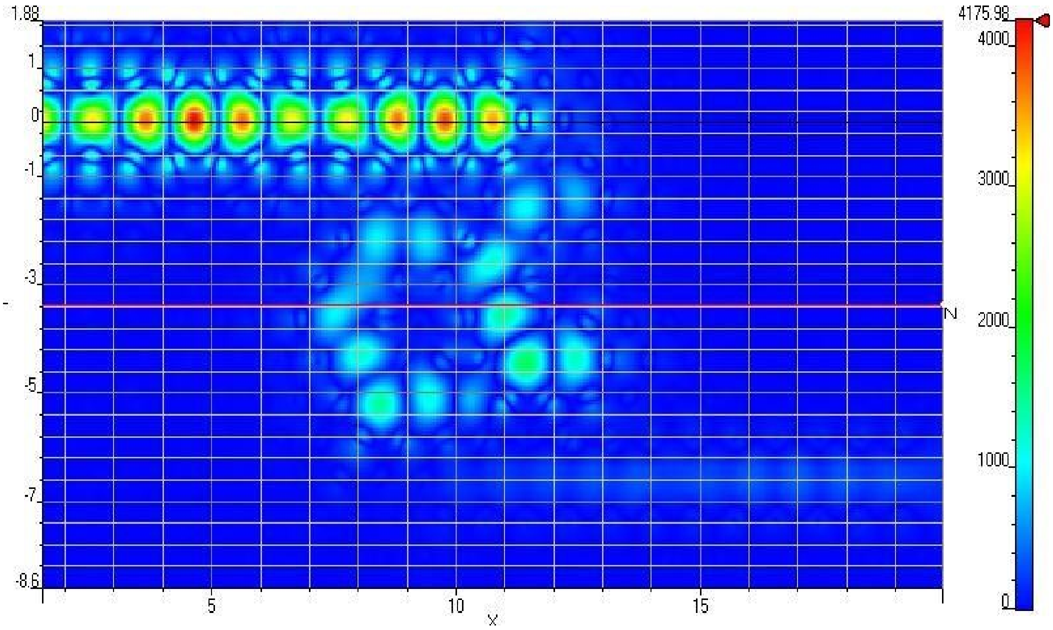


Figure 4.4. Light propagation through the Sensor

From Figure 4.4 it is clearly visible how light has passed through the sensor waveguide by entering through the bus waveguide and after passing through the two curves comes out of the drop waveguide. The defined sensing region is more sensitive than the other regions of the spectrum because in the sensing region, there is a strong interaction between the light and the analyte. The sensor design is analyzed for different refractive index ranging from 1.32 to 1.44. Change in refractive index affects the position of peak intensities. Figure 4.5. shows the peak transmission intensities. There is a considerable change in the peak intensities and also there is a shift in the wavelengths towards right. Figure 4.6 shows the dips in transmission spectrum at different wavelengths due to change in refractive index.

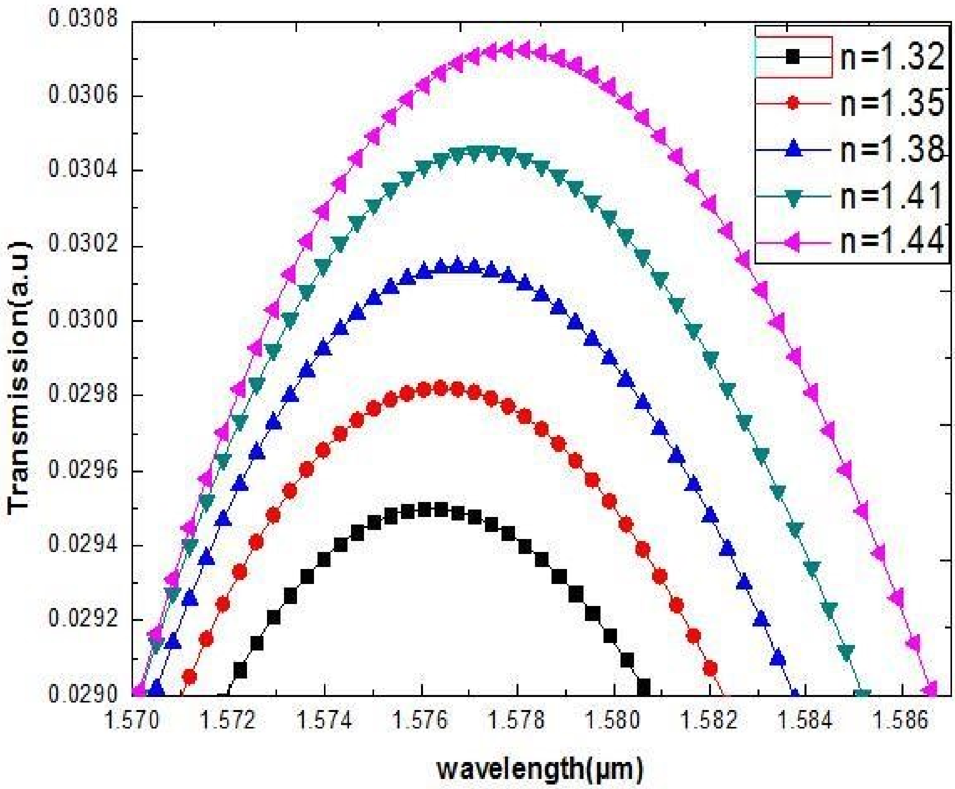


Figure 4.5 Peak intensities in transmission Spectrum

It is determined from the graph that maximum intensity occurs for the analyte having refractive index 1.44 and minimum for the analyte having refractive index 1.32. There is an increase in the transmission intensity of the samples ranging from 1.32 to 1.44. Peaks in the intensity for these samples are observed in the wavelength ranging from 1.574μm to 1.580μm.

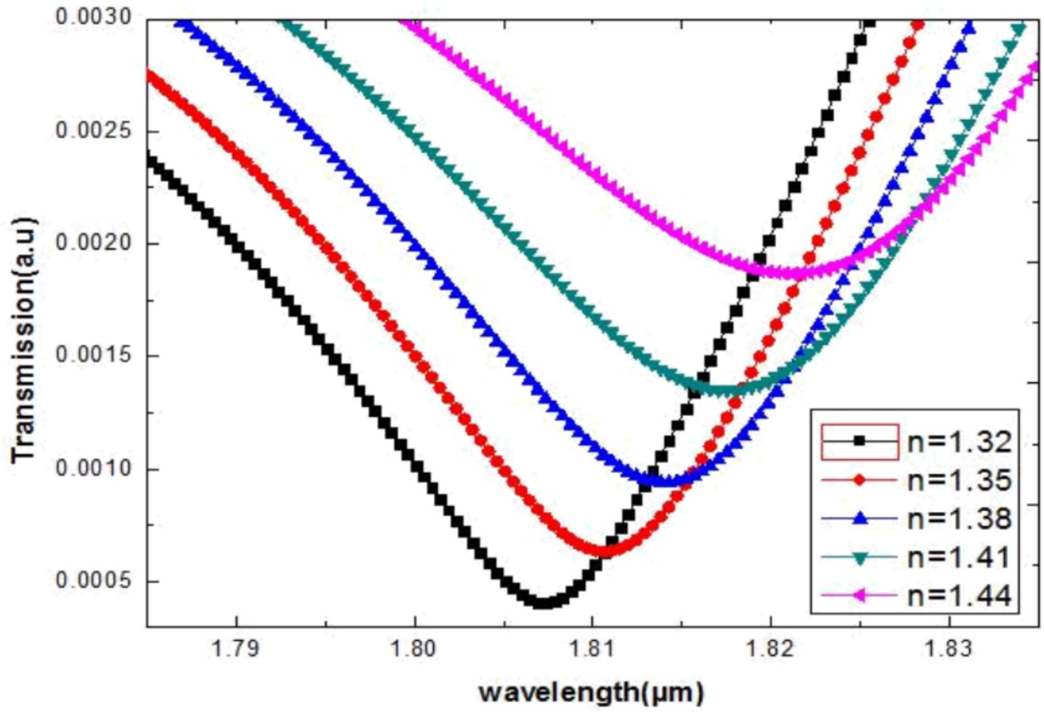


Figure 4.6 Dips in the transmission Spectrum

By comparing the position of these peaks and dips with the refractive index, two calibration graphs can be obtained. A relationship among the peaks and refractive index is shown in Figure 4.7 for peak intensities and Figure 4.8 for Dip intensities. It is observed that a linear behaviour exists between refractive index and the specified intensities.

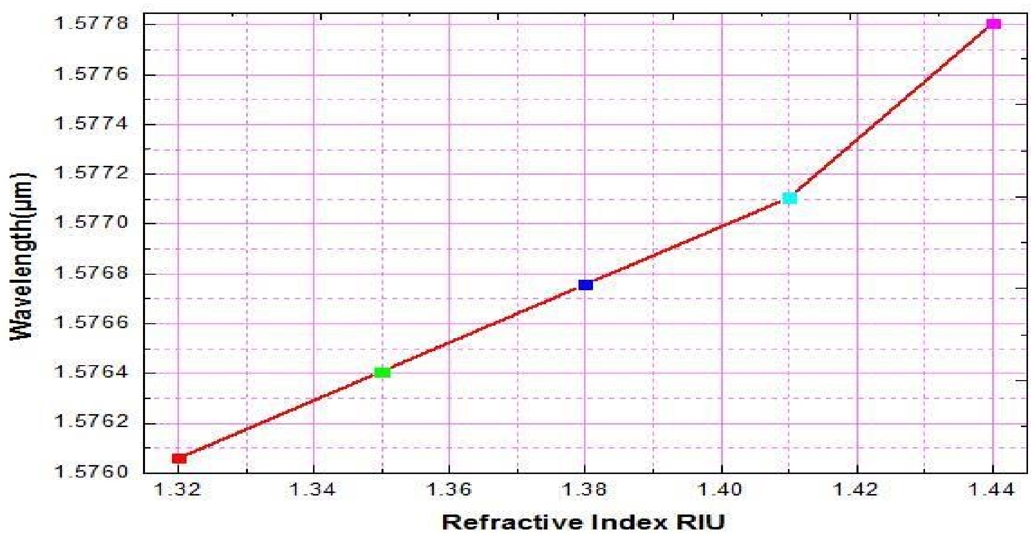


Figure 4.7 Refractive index v/s wavelength graph for peak intensities

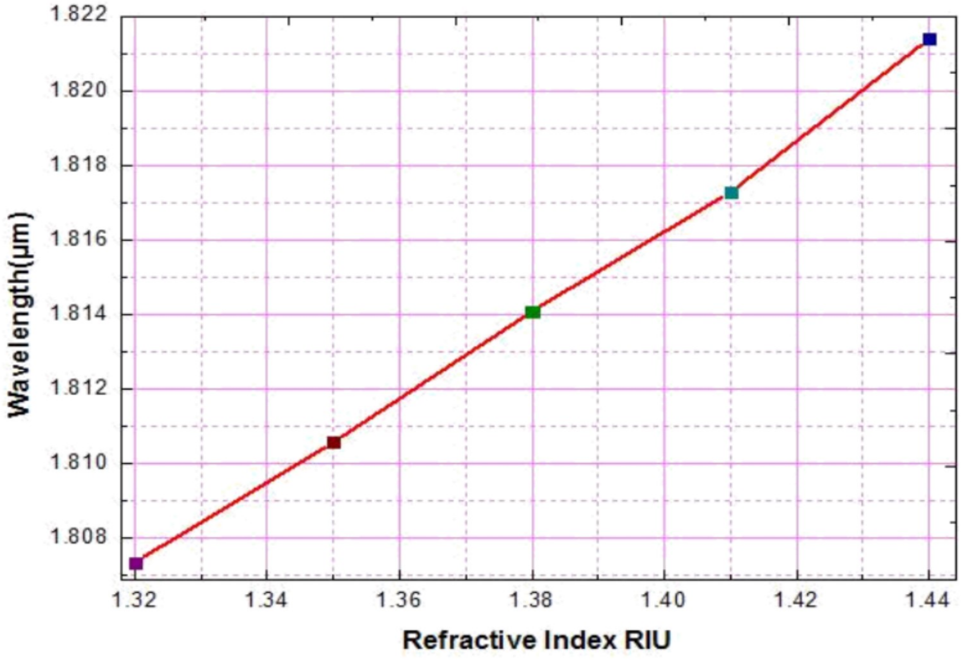


Figure 4.8 Refractive index v/s wavelength graph for dip intensities

From above graphs, it is interpreted that fall in the intensity is occurring in the wavelength ranging from 1.805µm to 1.821µm. for the samples having refractive index varying between 1.32 to 1.44 refractive index values. Also there is a shift in the resonant wavelengths towards right. A linear behaviour is observed for the dip intensities between the wavelength and the refractive index.

4.4. MODIFIED DESIGN HAVING VERY LESS HORIZONTAL DISTANCE BETWEEN TWO C-SHAPED CURVES

The design of the sensor is modified. Horizontal distance among two C-shaped curves is decreased. Vertical distance and coupling distances are kept same as that of the previous design. All other designing parameters like material, radius, and lattice constant are all kept same as the previous design.

The photonic band gap is also same as the previous one and the light is input at the 1550nm. Bus waveguide and drop wave guide are also kept same. Only the horizontal distance is decreased between two curves. The new modified design is shown in Figure 4.9.

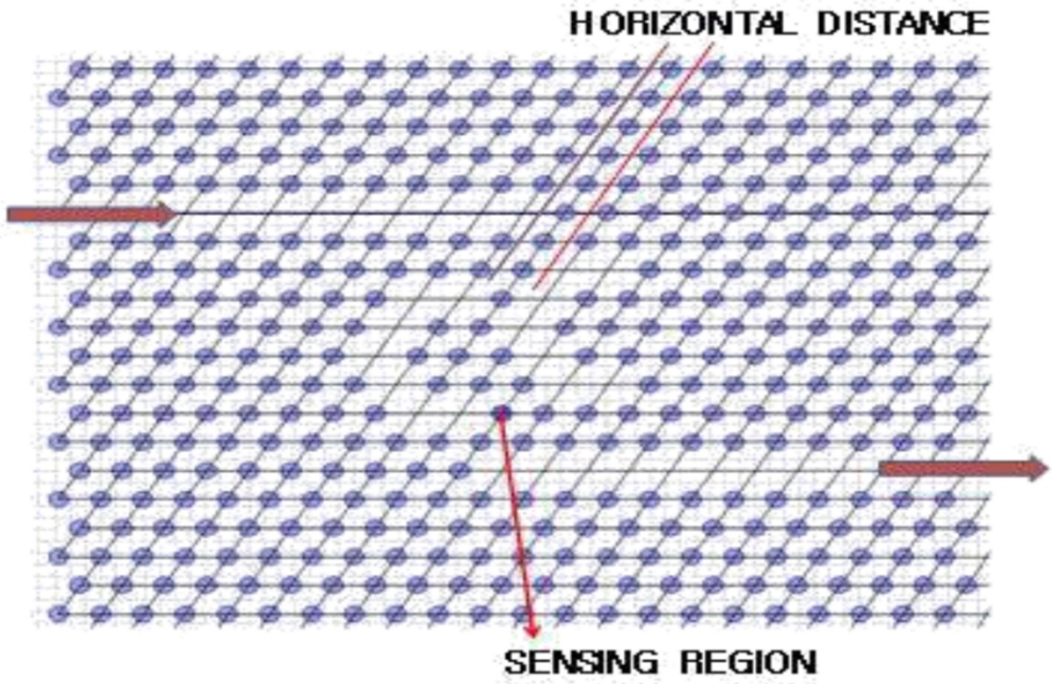


Figure 4.9 Sensor design having less horizontal distance

4.5. SIMULATIONS AND RESULTS

In order to excite the resonant modes inside the ring resonator, a light pulse is input at bus waveguide. Output is obtained at the bus waveguide. The Figure 4.10 shows the peak intensities in the transmission spectrum Figure 4.11 shows the graph between refractive index and wavelength. It is observed that there is a considerable deviation in the wavelength towards right.

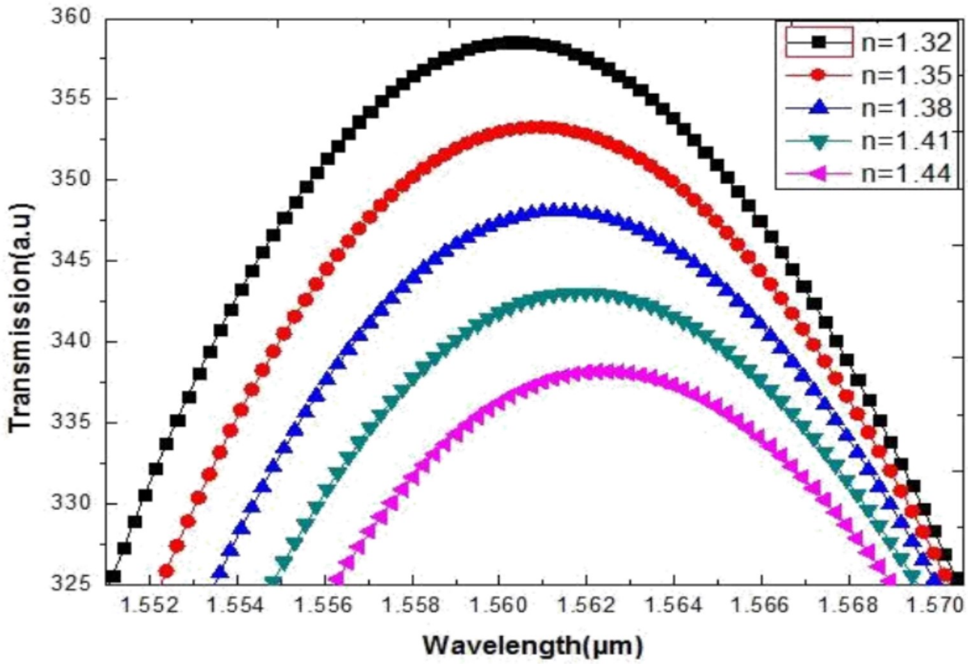


Figure 4.10 Peak intensities in transmission spectrum of modified design

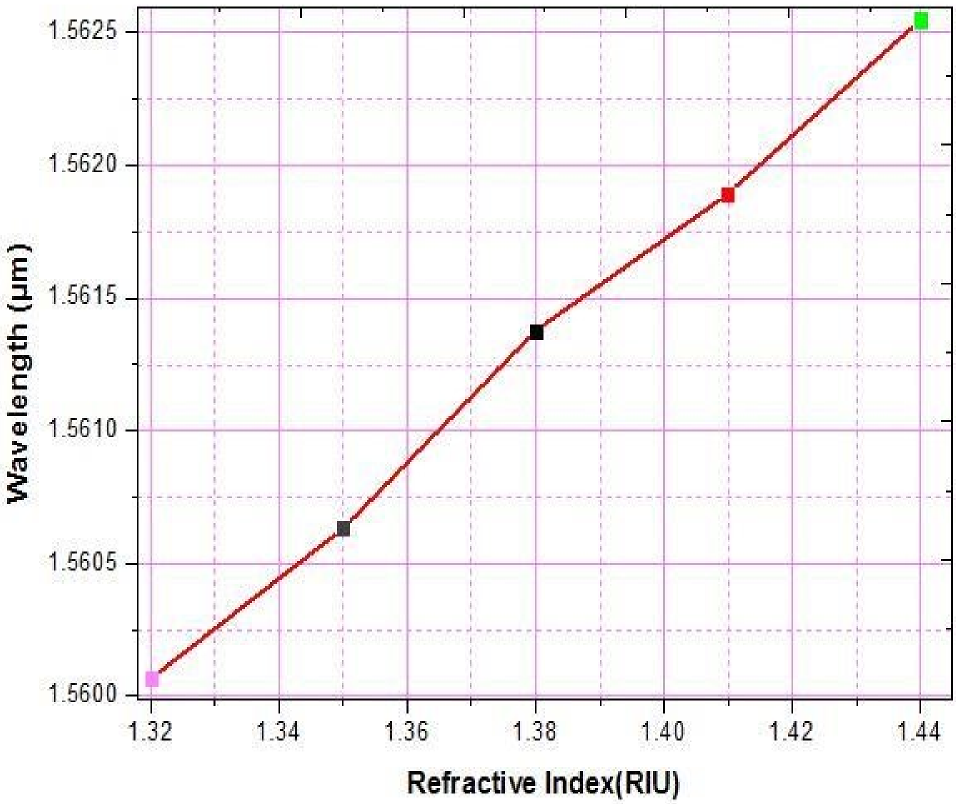


Figure 4.11 Refractive index v/s wavelength graph of modified design

From above graphs, it is seen that there is deviation in the resonant wavelength towards right and the peak intensities is obtained in the wavelength ranging from 1.559µm to 1.564µm for the analytes having refractive index ranging from 1.32 to 1.44. A considerable change in the intensities of the analytes is observed by decreasing the horizontal distance between two C-shaped curves. Thus, by varying the horizontal distance, coupling characteristics gets affected and due to these variations in the intensities is observed for different refractive index. Due to these shifts in the resonant wavelengths and changes in the intensities, sensing mechanism is achieved.

Further the optimizations are done by again varying the horizontal distances, vertical distance but it is observed that best results are obtained with the designs explained above. This is used for different bio sensing applications.

CHAPTER 5

GALLIUM ARSENIDE INFILTRATED HEXAGONAL CAVITY PHOTONIC CRYSTAL SESNOR FOR DETECTION OF VARIOUS BLOOD COMPONENTS.

5.1. INTRODUCTION

Different Blood conditions have become a common problem these days resulting in increase in blood disorders. Various blood disorders are anaemia, infection, haemophilia, blood clots, leukaemia and many more. These disorders are caused due to high values or low values of Red blood cells (RBC), White blood cells (WBC), Haemoglobin, Platelets and also due to different concentrations of blood plasma [56]. These diseases can be cured if their abnormal values are detected earlier. So, there is a need to develop an accurate and fast sensor which will detect various components of blood [56].

Photonic crystal is a periodic structure consisting of air holes in a dielectric slab or some material filled holes in air which maintains its photonic band gap (PBG). The light propagation through the photonic crystal is usually solved by using the Maxwell equations [57]. The light is completely forbidden in the photonic band gap frequency range. So, in order to pass the light through the PBG frequency range, certain defects are introduced in the structure [57].

During last years photonic crystals have been used for gas sensing applications [58], sensing of refractive index [59], sensing of DNA molecule [60], and detection of glucose concentration [61]. Various types of photonic crystal cavity structures such as ring resonators [62], waveguides [63], and hetero structures [64] are used. Dorfner *et al.* [65] represented a drop filter which was based on photonic crystal cavity for sensing of fluid and the quality factor obtained is 3000 and sensitivity 155nm/RIU. Zhou *et al.* [66] obtained refractive index sensitivity of 131.70nm/RIU and quality factor 3000.

The various components of the blood and the various disorders caused due their very high or very low values are explained as follows [56]:

Red Blood Cell: The RBCs carry the deoxygenated blood from all parts of body to the lungs. The blood gets oxygenated in the lungs. Then the RBCs carry oxygenated blood from lungs and supply it to the whole part of body. If the RBC is low, it causes anaemia. The body does not get enough supply of oxygen. Also if the RBC is very high, it causes poly cythemia in which the RBCs join together thereby blocking capillaries [56]. The refractive index of RBC is 1.40 [67].

White Blood Cells: WBCs provides immunity to the body. These cells fight against any disease. Whenever any disease occurs, it generates antibodies to fight against any antigens. The number of different White blood cells gives information about diseases [56]. The refractive index of WBC is 1.36 [67].

Haemoglobin: The haemoglobin carries oxygen to the RBC and it the main reason behind the red colour of the RBC. It is a measure of the ability of the blood to carry oxygen throughout the body [56]. The refractive index of haemoglobin is 1.38 [68].

In this work, a hexagonal cavity photonic crystal sensor is designed for the detection of various blood components. Hexagonal cavity is infiltrated with GaAs rods so as to increase the sensitivity of the sensor.

This sensor provides high value of quality factor and very high sensitivity. In this sensor, the effective refractive index is changed by using different blood components like Blood plasma, WBC, Haemoglobin, RBC which are having different refractive index. The refractive index of plasma is 1.35 [68].

Due to variation in effective refractive index, there is a variation in intensity of transmission and also there is a deviation in resonant wavelength which is observed by using Finite Difference Time Domain (FDTD) and plane wave expansion method. Due to binding with the different blood components, the resonant peaks get shifted.

This change in the refractive index and resonant wavelength shift are used as parameters for the sensing of various blood components. Finite Difference Time domain method is used for the analysis of the sensing variations.

5.2. SENSOR DESIGN AND THEORY

The design of our sensor consists of an array of silicon rods (n=3.42) placed in hexagonal manner in air (n=1) on a silicon-on-insulator wafer. Lattice constant that is distance between centres of two consecutive holes is 800nm. The radius of silicon rods is 220nm.

The design consists of an input waveguide and an output waveguide and in between there is a hexagonal sensing region. Our designed sensor is shown in Figure 5.1. These waveguides are generated by removing set of silicon rods from the hexagonal array. The silicon rods which are present along the waveguides and the hexagonal sensing region are having radius 240nm and specifically these silicon rods (r=240nm) are infiltrated with Gallium Arsenide rods.

The Gallium Arsenide rods which are infiltrated inside silicon rods are having radius of 120nm. A Silicon rod having radius 220nm is present in the sensing region. Light is entered at the input waveguide and then after passing through the hexagonal sensing region, it comes out through the output waveguide.

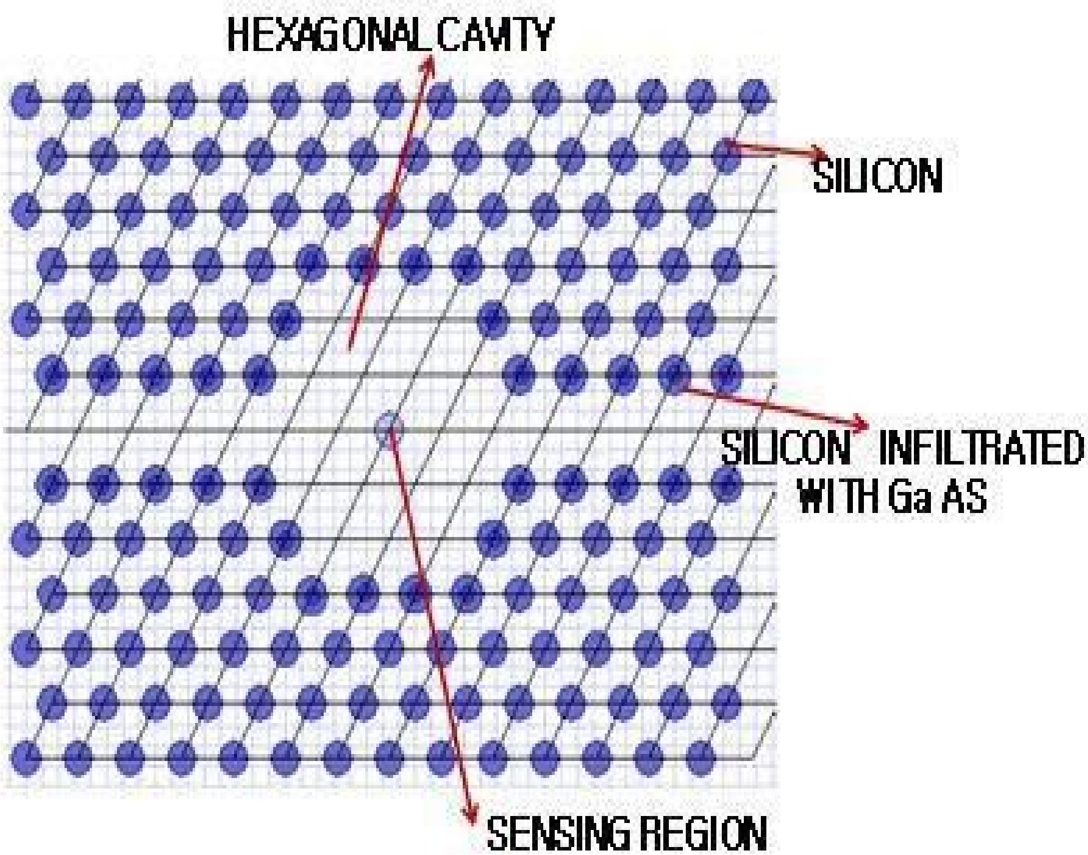


Figure 5.1 Sensor with GaAs infiltrated in silicon rods

Before concluding the parameters of the design of sensor, it is verified that the selected wavelength could pass through the sensor design. This verification is done by using plane wave expansion (PWE) method. The band structure is shown in the Figure 5.2. Sensor's photonic band gap occurs between 0.556437 to 0.698578 (1/) thereby allowing a wavelength of 1431nm-1790nm to pass through the photonic crystal. Therefore the input source is set at 1550nm. The silicon rod which is present in the sensing region is filled with various analytes having different refractive indexes and then after passing light through it, the change in transmission intensities is observed for different refractive indexes.

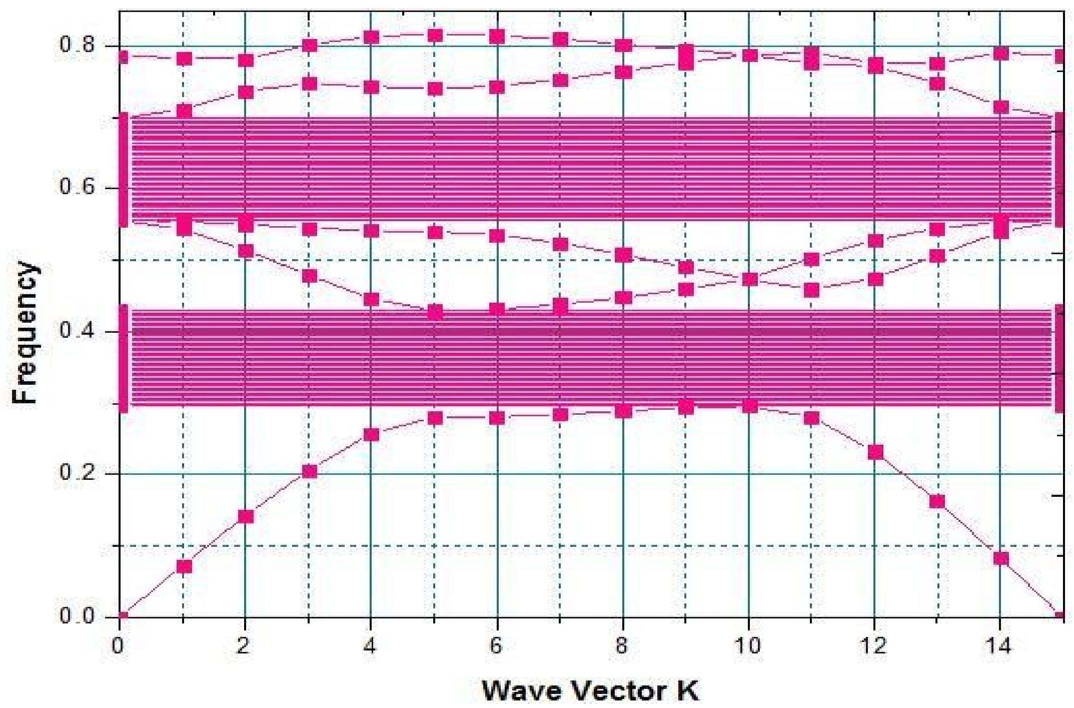


Figure 5.2 Band diagram of the Sensor

5.3. SIMULATIONS AND RESULTS

Light is passed through the input waveguides and after passing through the sensing region containing analyte, it comes out through output waveguide. The output is sensed through the spectrum analyzer. The transmission intensities at the input are shown in Figure 5.3 .Thus the propagation of light through the hexagonal cavity containing analytes is shown in Figure 5.4. It is clearly visible that how the light travels through the sensor design. The refractive indexes of different blood components like Blood Plasma (n=1.35) [68], White -blood cells (n=1.36) [64], Haemoglobin (n=1.38) [65], Red blood cells (n=1.40) [67], and also the design is extended for Biotin Streptavidin which is a biotin complex having refractive index n=1.45 [68].

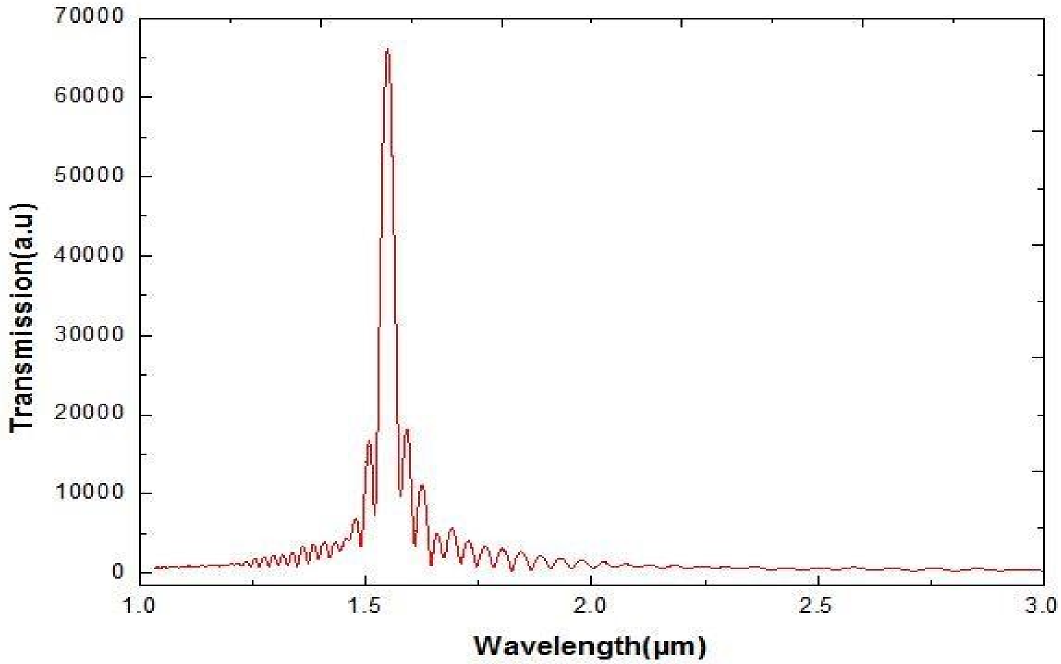


Figure 5.3 Light at the input of the sensor

When the light is passed through the sensing area and analytes are changed, then the response of the light according to different components having different refractive index is shown in Figure 5.5. Light source and detector should be placed in such a manner so that maximum light should pass through the cavity. The response of light is analyzed by utilizing Finite difference Time domain (FDTD) method. The variations of the transmission intensities with the variations in refractive index are observed in the transmission spectrum

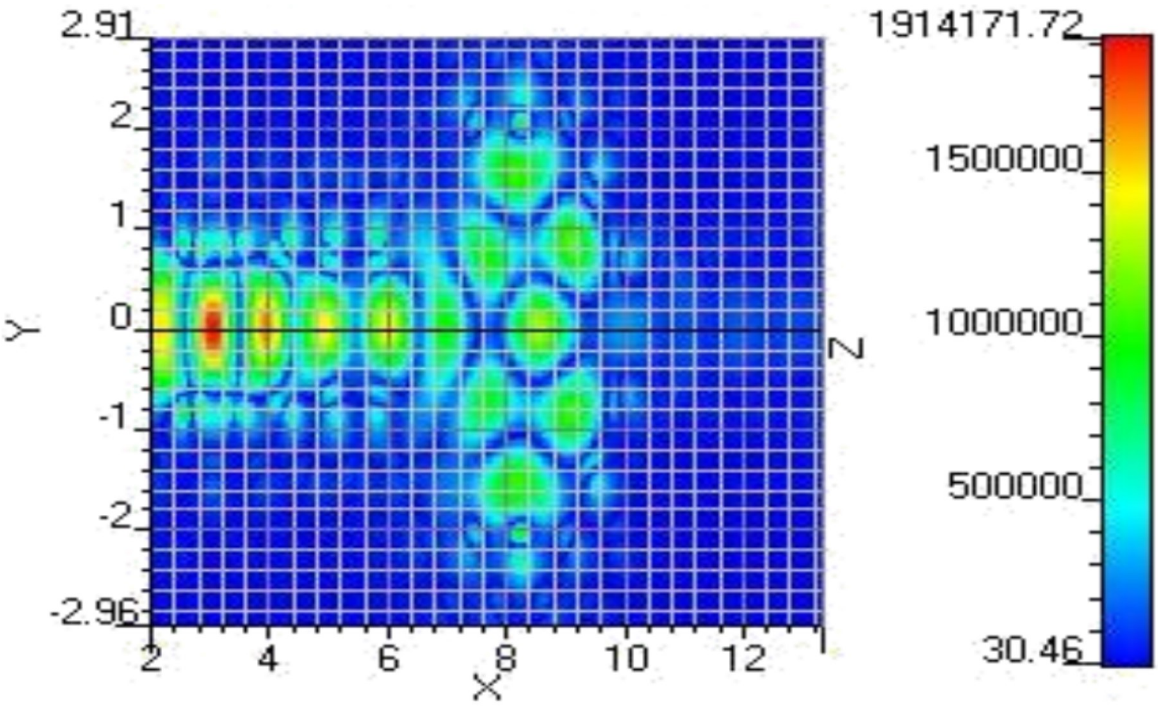


Figure 5.4 Light propagation through sensor

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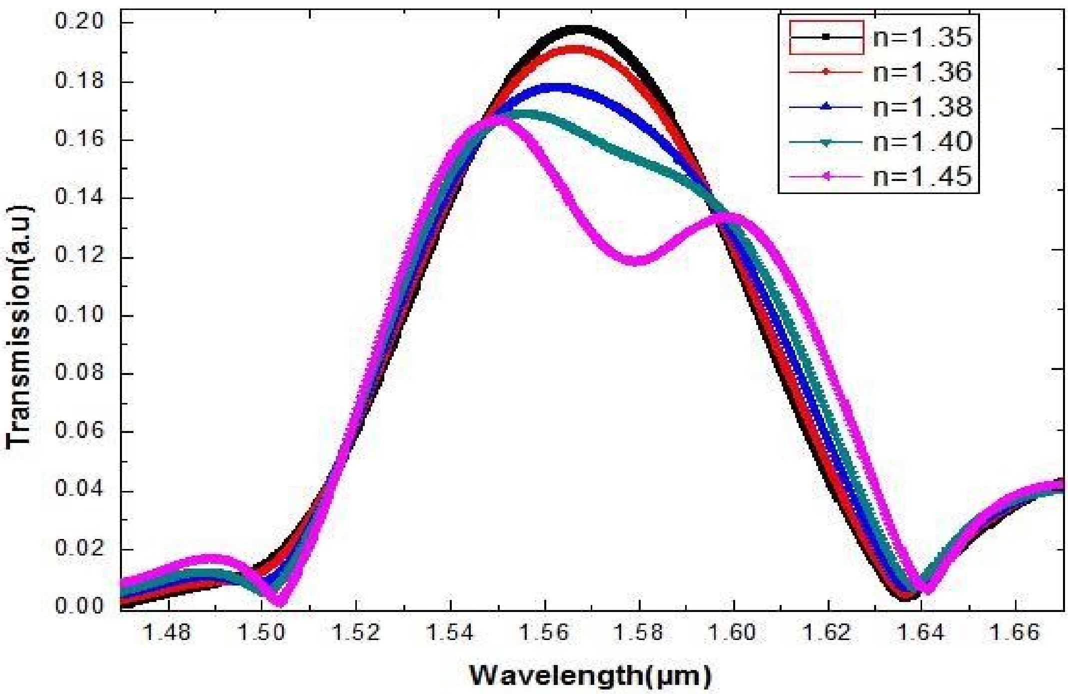

Figure 5.5 Output transmission Spectrum

The rise in intensities with the increase in refractive index of different components is shown in Figure 5.6. It is realized that due to increase in refractive index of different components, there is a shift in the resonance wavelength towards left.

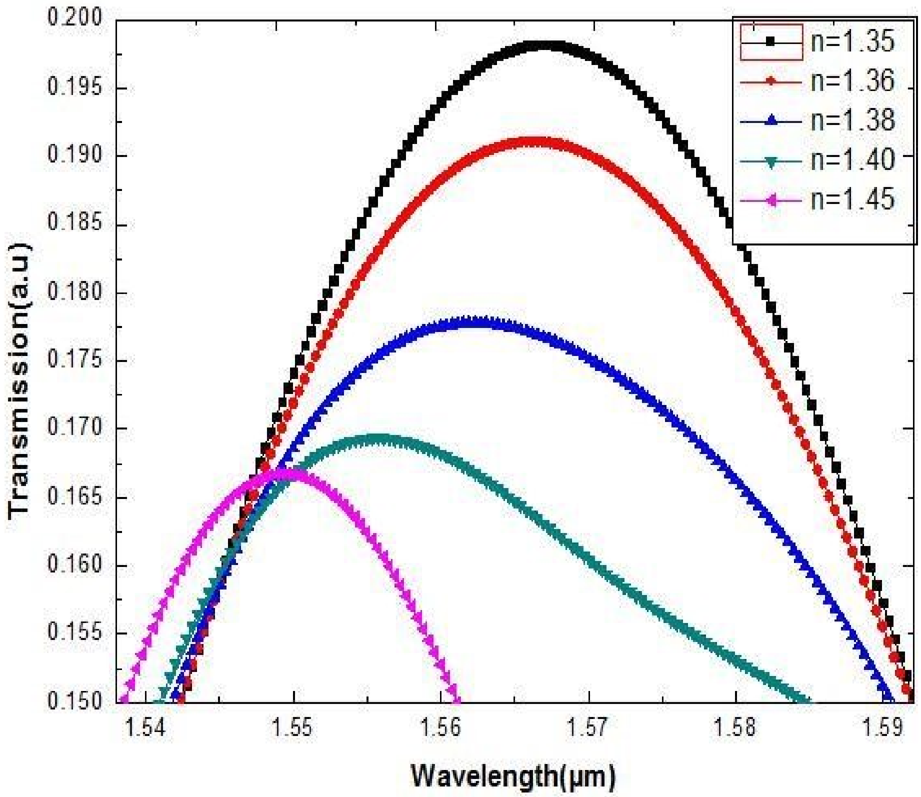

Figure 5.6 Peak intensities in transmission spectrum

From the Figure 5.6, it is examined that peak intensities for the different analytes occurs in between the wavelength ranging from 1.545μm to 1.575μm. Also there is a decrease in the transmission intensities for different analytes having refractive index ranging from 1.35 to 1.45. Since a considerable amount of shift and a change in the intensity is obtained thereby resulting in the realization of sensing mechanism.

Figure 5.7 Shows fall in intensities at some particular wavelengths with the increase in refractive index and also there is a shift in the wavelength. Further Figure 5.8 and Figure 5.9 shows the wavelength shift dependence on the refractive index for peak intensities and for low intensities respectively.

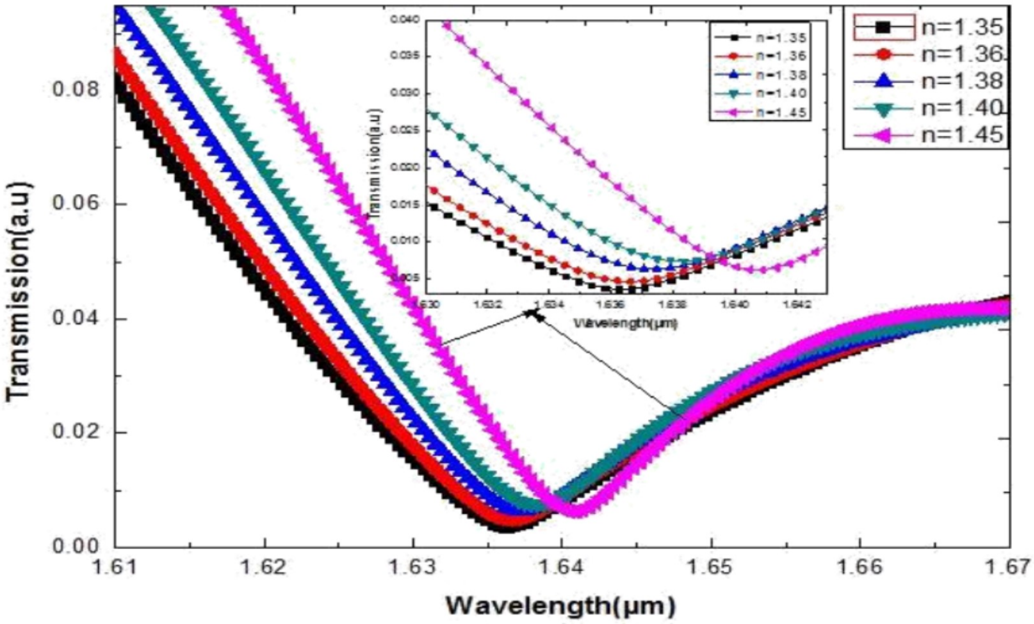

Figure 5.7 Wavelength shift and fall in intensities

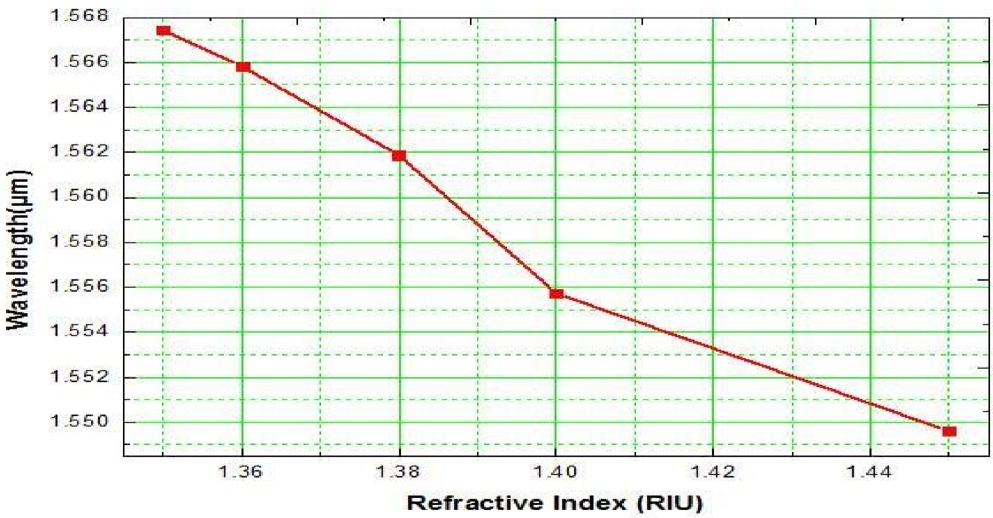

Figure 5.8 Wavelength shift dependence on refractive index for peak intensities

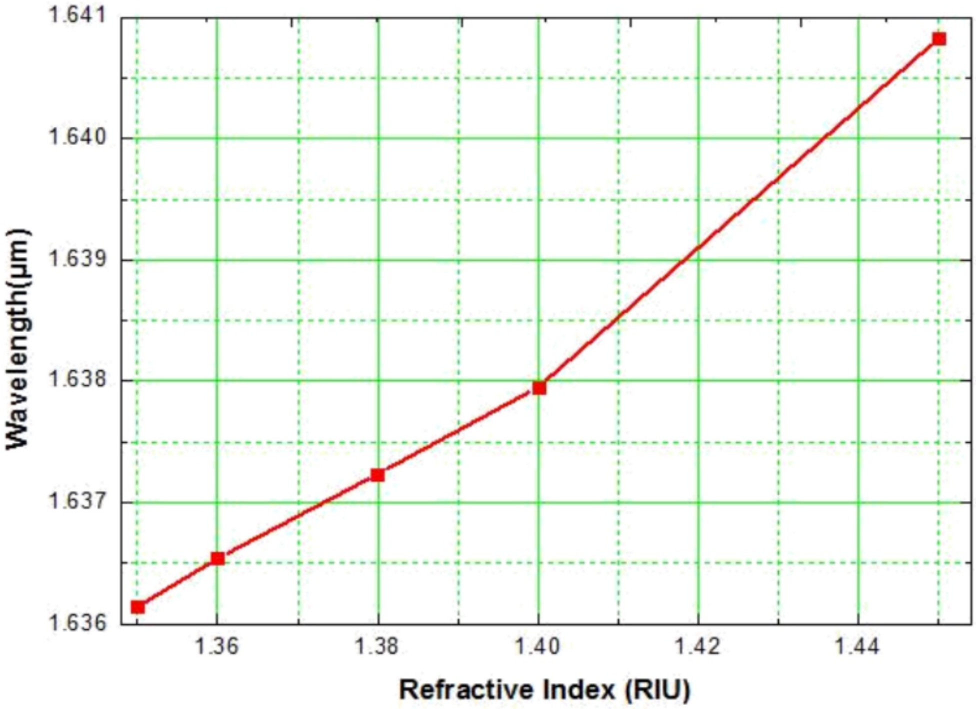

Figure 5.9 Wavelength shift dependence on refractive index for low intensities

It is examined that dips in the intensities of this sensor occurs around the wavelengths ranging from 1.634µm to 1.640µm. Maximum fall in the intensity is achieved for the analyte having refractive index 1.35 and among these analytes minimum fall in intensity is observed for the sample having refractive index 1.45. Maximum sensitivity of about 85nm/RIU is obtained for this sensor design. A relationship is observed between the refractive index of the analytes and the resonant wavelengths. This sensor can be extended for detection of other biomedical samples also.

CHAPTER-6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

A sensor is designed for detection of various analytes on a rectangular array of silicon rods in silicon-on-insulator platform. A S-shaped waveguide is created by removing set of silicon rods to create line defect. The sensitivity of sensor is observed for different analytes i.e nucleus, cytosol, and mitochondria. By introducing silicon reflectors in it having with 200nm, it is observed that the sensitivity has significantly improved. Further, the reflectors are changed and then Indium Arsenide reflectors are used which are having with of 220nm. The transmission spectrums are observed. It is observed that among three designs, a better sensitivity is obtained for the design having Silicon Reflectors of width 200nm.

A biosensor depending on a nano-ring resonator is developed by two consecutive C-shaped curves. It is observed that there is considerable shift towards right. In the spectrum, it is realized that with the increase in refractive index, there is an increase in the intensity. The design is further optimized by decreasing the distance between the two curves and better performance is achieved.

A photonic crystal sensor with a hexagonal cavity is designed. The silicon rods are infiltrated with Gallium arsenide rods. The infiltration is done in order to enhance the sensitivity of the sensor. The sensor is designed for the detection for various blood components like WBC, RBC, plasma, Haemoglobin. The structure is designed in such a way that it provides a good sensitivity.

6.2 FUTURE SCOPE

The work done in this dissertation can be utilized for further improvement of the sensor designs. Optimizations can be done so as to obtain a better design than those designed previously.

The reflectors of different width and different materials can be employed in the design having holes of different shapes. Instead of circular holes, different elliptical, cylindrical or other shaped holes can be used to enhance the sensitivity of the sensor.

Coupling distances can also be modified in ring resonators to achieve a better design. Instead of circular cavities, further S-shaped cavities or J-shaped can also be achieved.

Infiltration can be done with different materials like gold, silver or any other depending upon the requirement. Fabrication of such simple designs can be easily done so as to achieve a realistic sensor for sensing of different analytes.

These designed sensors can be employed in other sensing areas like sensing of chemicals, gas sensing, sensing of different liquids.

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