

**NANOCVITY-COUPLED PHOTONIC CRYSTAL WAVEGUIDE AS A
BIOSENSING PLATFORM**

A dissertation submitted in partial fulfillment
of the requirement for the award of degree of

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IN
ELECTRONICS & COMMUNICATION ENGINEERING**

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DECLARATION

I hereby state that the work done in this dissertation entitled as “Nanocavity-coupled photonic crystal waveguide as a bio-sensing Platform” is an unquestionable confirmation of my study approved as requirement for the award of degree of ME (Electronics and Communication Engineering) at Thapar University, Patiala. My big gratitude goes to my dissertation supervisor **Dr. Mukesh Kumar** for his assistance.

The work presented in this dissertation is not traced from any other previous matter submitted in any other university. It is exclusively authors own exercise, apart from where references have been specified in text.

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ABSTRACT

A multi-dimensional artificially designed periodic dielectric media known as Photonic Crystal (PC) brings the opportunity of a revolution in communications and sensing much closer because of the special property of PC such as the potential of boost field-matter interaction. As a result, PC sensors present the probability of multi-analyte and highly compact sensing methods as well as the capability of the detecting a small quantity of analyte (Nano-liters) and low-concentrated samples (Pico-moles), which may be beneficial approach over conventional approaches like fiber optic and slab waveguide sensors.

In this dissertation, a Bio-sensing platform based on nanocavity-coupled photonic crystal waveguide (PCW) is proposed for diseased cell detection. Proposed label-free waveguide-cavity coupled nanostructure with high-Q is designed and analyzed to exhibit high sensitivity and high selectivity against five different cancer cells. The research work is performed using a thin two dimensional PC slab having dielectric in air configuration where silicon rods are arranged in hexagonal array. A PCW is induced by missing a row of dielectric rods which gives a wide Photonic Band Gap (PBG) in transmission spectra. The introduction of a nanocavity in the PCW leads to a sharp resonance which makes it useful for detection of infected cells. A pair of dielectric holes on each side of cavity is acting as reflector. Presented nanocavity-coupled waveguide structure is optimized by shifting and by changing the radii of adjacent rods around cavity.

Sensing principle is observed change in the refractive index (RI) due to presence of analyte. It is observed through 2-D Finite Difference Time Domain (FDTD) method in the transmission spectra that the resonant wavelength of biosensor is red shifted on increasing the RI of the cavity imposed by the presence of cancer cell in blood sample. The change observed in RI is positive because of presence of more content of protein in cancer cell as compared to normal cell. The reported sensitivity and quality factor of the proposed platform are acceptable for cell-level detection of various diseases. The proposed design also shows sufficiently separated resonant peaks for different cancer cells which offer us a possibility of highly selective label-free cancer detection.

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GLOSSARY OF ACRONYMS

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
DBR	Distributed Bragg Reflector
DOS	Density of State
ERI	Effective Refractive Index
FDTD	Finite Difference Time Domain
FWHM	Full Width Half Maximum
IV	Intensity Variation
PBG	Photonic Band Gap
PC	Photonic Crystal
PCW	Photonic Crystal Waveguide
PWE	Plane Wave Expansion
Q	Quality factor
RI	Refractive Index
RWS	Resonant Wavelength Shift
S	sensitivity
TE	Transverse Electric
TM	Transverse Magnetic
TIR	Total Internal Reflection
VCSEL	Vertical Cavity Surface Emitting Lasers

CHAPTER 1

PHOTONIC CRYSTALS BASED BIO-SENSORS

1.1 Introduction to Photonic Crystals

Semiconductors played a significant role in almost every aspect of our daily life. All around the world the drive of compact size and high speed performance of integrated electronic circuits has speed up the considerable research efforts [1,2]. Unluckily, miniaturization of electronic circuits results in high resistance which leads to higher level of power dissipation and higher speed leads to a requirement of more sensitivity. For these reasons, scientists are now turning towards light as the information carrier instead of electrons as light has numerous advantages over the electron [2]. Light travels at much higher speed in a dielectric material rather than an electron travels in a metallic wire. It also transmits more amount of information per second. In spite of these, bandwidth provided by dielectric materials is significantly larger than that of metals. In fiber-optic communication systems, bandwidth available is generally of the order of terahertz whereas in electronic systems it is of the order of few hundred kilo hertz only [1,5]. Furthermore, energy losses are reduced using light particles as information carrier because they don't interact strongly as electrons do. There is only one difficulty in optoelectronic circuits is that design fabrication of optical device similar to the electronic device is difficult [2]. In 1987, Yablonovitch [3] and John [4] firstly proposed artificially periodic structures known as photonic crystals and suggested that periodic structure of dielectric with varying dielectric constant could influence the nature of photonic modes. Engineering of electromagnetic (EM) waves has done at various optical frequencies in photonic crystals (PC's). The very first successful PC structure was presented in 1991 [6]. The idea of Yablonovitch and John was to design a material which can affect the properties of light in a same way as semi-conductor affect the properties of electrons. This new class of optical material generally known as PC holds the key of evolution towards all-optical integrated circuits. Photonic crystals are so called photonic because it acts on light and crystal because of its periodically repeating structure. PC is a periodically arranged material of different dielectric constants exhibiting a property of

photonic band gap (PBG) i.e. a range of frequencies is completely forbidden for light propagation [1]. Yablonovitch's initial idea was to organize the spontaneous emission property of material which was the major cause of degrading the efficiency of many semi-conductor devices like lasers, hetero-junction bipolar transistors and solar cells. During experiments he observed that periodic dielectric arrangement in one dimensional (1D) give rise to bandgap for EM waves propagating in perpendicular direction to the arranged periodic layers. Inspired by this observation he said increasing the periodicity in three dimensions could provide PBG in all directions. It will make possible to inhibit the spontaneous emission as the emission rate is proportional to the density of states (DOS) and DOS is zero within PBG because of the evanescent wave vector k . Meanwhile, John said that photon localization can be achieved by introducing an unsystematic refractive-index variation in three-dimensional photonic lattice. As verified later, light can be prohibited and manipulated by PC's periodic structure. Photons whose energy lies in the range of PBG are not able to propagate through the photonic crystal. This exclusive property opens the chance to figure and mould the flow of light for the required application. This periodicity makes its study analogous to semi-conductors in solid-state physics as depicted in **Fig. 1.1**

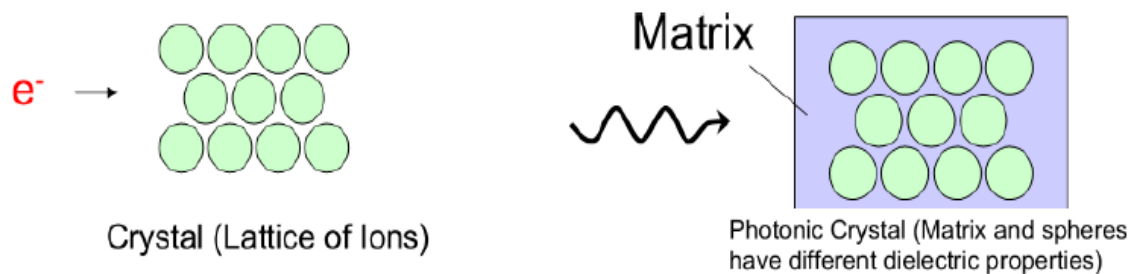


Fig. 1.1: Analogy of atomic lattice in a semiconductor and photonic crystal lattice [5]

In case of semiconductor, the atomic lattice of electronic crystal presents a periodic potential to an electron propagating through it. The crystalline structure of atomic lattice modulates the propagation of electron through it as shown in **Fig. 1.2**. A gap exists in between the valence band and conduction band which defines forbidden states for propagating electrons and known as Electronic Band Gap [1,7]. Similarly in case of photonic crystal, the periodic potential is provided by lattice of dielectric media

in place of atoms. The frequency bands in the dispersion diagram of $[\omega(k) \text{ vs } k]$ for which EM waves are not able to propagate through the structure give birth to PBG. If the dielectric constants of the essential media are unlike enough, Bragg distribution off the dielectric interfaces can produce many of the similar phenomena for photons as the atomic potential does for electrons. As a consequence a PC could be designed to possess a complete PBG i.e. a range of frequencies for which light is not allowed to propagate within the interior of the perfect crystal. Periodic arrangement of atoms arranged in semi-conductors exists naturally but PC's are needed to be fabricated artificially. To fully understand the challenge of fabricating PC's, size of the fundamental unit cell of the photonic crystal i.e. the lattice constant must be comparable to the wavelength of the input light.

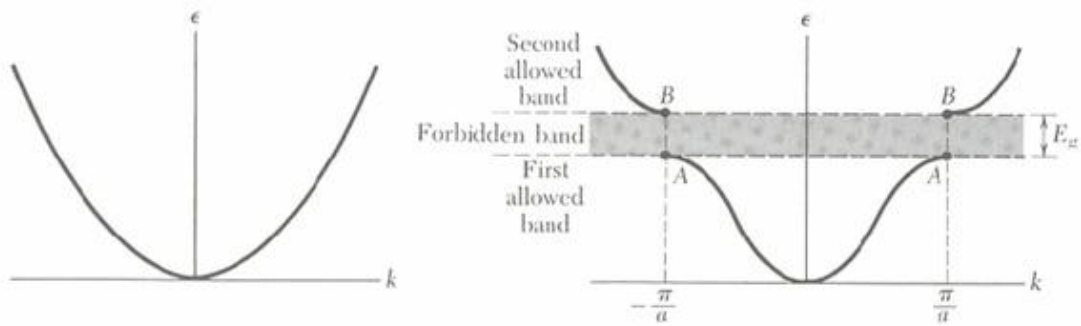


Fig 1.2: Energy diagrams (a) for a free electron, and (b) for an electron propagating through an atomic lattice [5]

Even these simplest of PC structures can have unexpected properties. It is seen that the incident light from any angle can be reflect by the design of layered media. If a PC prohibits the propagation of electromagnetic waves coming from any source with any polarization traveling in any direction, we can say that PC has a complete PBG. A crystal with complete PBG will surely act as an Omni-directional reflector but its converse may or may not be true [1]. In order to generate a complete PBG, periodicity must be maintained along all three axes; means a three-dimensional PC will exhibit this property only. A small amount of disorder created in periodic medium will not destroy all range of band gap but localization of light will occur which gives an existence to new photonic mode in a range lying between photonic band gap. The electronic world has grown up

tremendously compared to the photonic world due to the impact of semiconductor materials and their mature processing and fabrication technologies. The proposal photonic crystals may bring the possibility to cultivate photons efficiently at the micro or nano-scale and a similar revolution as electronic world in many areas including communication as well as sensing.

1.1.1 Maxwell Equations in Photonic Crystals.

The basic of propagation of light in the periodic dielectric media of photonic crystal can be explained by four standard Maxwell's curl equations [1,2].

$$\begin{aligned}
 \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= 0 \\
 \nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} &= \mathbf{J} \\
 \nabla \cdot \mathbf{B} &= 0 \\
 \nabla \cdot \mathbf{D} &= \rho
 \end{aligned}
 \tag{1.1}$$

Where, \mathbf{E} is the Electric field (Volts/m)

\mathbf{H} is the magnetic field (Ampere/m)

\mathbf{D} is the Electric Displacement

\mathbf{B} is the magnetic induction field

ρ is the free charge density

\mathbf{J} is the free current density

In linear, isotropic and non dispersive medium, the electric and magnetic flux are related to the electric and magnetic field as:

$$\begin{aligned}
 \mathbf{D} &= \epsilon \mathbf{E} = \epsilon_0 \epsilon_r \mathbf{E} \\
 \mathbf{B} &= \mu \mathbf{H} = \mu_0 \mu_r \mathbf{H}
 \end{aligned}
 \tag{1.2}$$

Where, ϵ is the permittivity of material

μ is the permeability of material

The medium considered is assumed to be non-magnetic means $\mu = \mu_0$ and $\epsilon = \epsilon_0$ is source free and it is also assumed that medium is source free means there is neither current flow nor charge density exists. That's why by putting $\mathbf{J}=0$, $\rho=0$ and equation 1.2 in equation 1.1 we get:

$$\nabla \times \mathbf{E} = - \frac{\partial \mathbf{B}}{\partial t} = - \mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

$$\begin{aligned}
\nabla \times \mathbf{H} &= \frac{\partial \mathbf{D}}{\partial t} = \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \cdot \mathbf{D} &= 0
\end{aligned} \tag{1.3}$$

The time dependence of fields can be made free from spatial dependence by expanding E and H fields into harmonic modes:

$$\begin{aligned}
\mathbf{E}(\mathbf{r}, t) &= \mathbf{E}(\mathbf{r})e^{-j\omega t} \\
\mathbf{H}(\mathbf{r}, t) &= \mathbf{H}(\mathbf{r})e^{-j\omega t}
\end{aligned} \tag{1.4}$$

On substitution of 1.4 in equation 1.3, the curl and divergence equation can be written as:

$$\begin{aligned}
\nabla \times \mathbf{E}(\mathbf{r}) &= -j\omega \mu(\mathbf{r}) \mathbf{H}(\mathbf{r}) \\
\nabla \times \mathbf{H}(\mathbf{r}) &= -j\omega \epsilon(\mathbf{r}) \mathbf{E}(\mathbf{r}) \\
\nabla \cdot \mathbf{E}(\mathbf{r}) &= 0 \\
\nabla \cdot \mathbf{H}(\mathbf{r}) &= 0
\end{aligned} \tag{1.5}$$

By elimination of E and rearranging in terms of H we get Master Equation as:

$$\nabla \times \left[\frac{1}{\epsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right] = \frac{\omega^2}{c^2} \mathbf{H}(\mathbf{r}) \tag{1.6}$$

Equation 1.6 is an Eigen value equation which is generally known as master equation. It has real Eigen value which is lossless i.e. $\left[\frac{\omega^2}{c^2} \right]$ and Eigen operator $\left[\nabla \times \frac{1}{\epsilon(\mathbf{r})} \nabla \times \right]$ is the Hermetian operator. The field $\mathbf{h}(\mathbf{r})$ is representing Eigen state which are generally orthogonal in nature. The kinetic energy is provided by two curls and $\frac{1}{\epsilon(\mathbf{r})}$ is providing potential energy [1].

1.1.2 Photonic Crystal Types

Depending on the number of dimensions in which periodicity is maintained that the photonic bandgap must exist in photonic crystals, different types of PC's can be categorized into one-dimensional (1D), two-dimensional (2D) and three dimensional (3D) photonic crystals as depicted in **Fig. 1.3**. During propagation of light in photonic crystal band gap is faced by photons only in the direction where periodicity is maintained [1,2,8]. One-dimensional (1D) photonic crystals, which are also called as the Distributed Bragg reflectors (DBR), have been used generally as mirrors particularly in vertical cavity surface emitting laser (VCSEL) even from the time when PC's were not known.

VCSEL consists of periodically arranged dielectric layers of varying refractive indices [2]. After the identification of PBG in one-dimensional PC, it took a complete century to put in a second dimension. The two-dimensional PC's have maintained periodicity in two directions and they are assumed to be extended infinitely in third direction. Photonic crystal fibers are currently the most practical use of 2D photonic crystals.

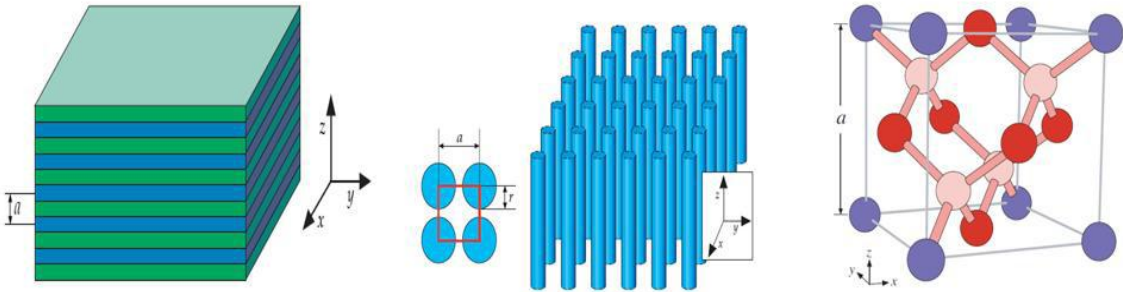


Fig. 1.3: Demonstration of one-dimensional, two-dimensional and three-dimensional photonic crystals. The different colors are representing different materials with different refractive indices. The defining characteristic of photonic crystal is number of directions in which periodicity of dielectric material is maintained [1]

Actually 3D photonic crystals are known as pure photonic crystals because they have maintained periodicity in all three directions and results into a complete photonic band gap [2]. The feature of 3D- PC's makes it able to control the light propagation in all directions, only disadvantage of 3D structure is its complicity. Although so many years have passed away still their fabrication is extensively challenging [5]. In this dissertation we go for 2D structure of photonic crystal because of its simple fabrication as compared to 3D structure [9].

1.1.3 Photonic Crystal Slabs

To overcome the problem of complication in fabrication of 3D structure, we go for the concept of 2D structure of PC. The 2D photonic crystal structure is generally known as photonic crystal slab. The design of 2D-PC seems to be easy theoretically however practically fabrication procedure is not so simple because of its infinitely extended assumption in the third dimension. In recent years, this 2D structure has received a

noteworthy consideration. The 2D structure is generally used over 3D structure because 2D structure retains most of the important characteristics of 3D photonic crystal with simple fabrication [1,9,10,11,12,13,14]. The basic design of two dimensional photonic PC is shown in **Fig.1.4** where distance between centers of two holes is represented by **a** known as lattice constant, radius of a single hole is represented by **r** and **d** is representing the thickness of slab.

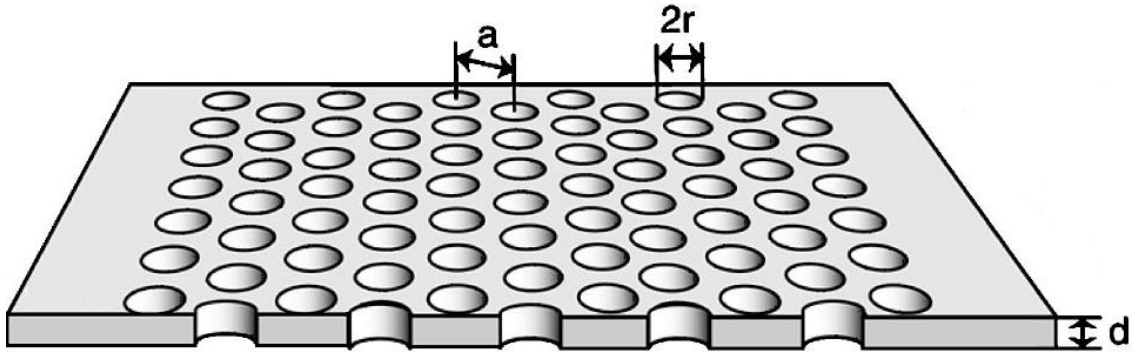


Fig. 1.4: Structure of Photonic crystal slab configured with a hexagonal lattice with its basic parameters [15]

The photonic crystal slab is formed by 2D- photonic crystal lattice placed on a thin semiconductor slab with thickness of the order of one half of the input optical wavelength i.e. $\lambda/2n$, surrounded by air [9]. In vertical direction of both sides of photonic crystal slab when air medium acts as cladding layer, then it is known as 2D air-bridge photonic crystal [6]. The localization of light in all three dimensions of 2D photonic crystal is based on combination of two mechanisms. In vertical direction confinement of light is controlled by the mechanism of the Total Internal Reflection (TIR) and in the lateral direction is controlled by mechanism of Distributed Bragg Reflection (DBR).

As confinement of light is depending on TIR in third dimension, there are chances of not proper confinement. That's why both modes leaky as well as guided modes come into existence. The modes that will satisfy TIR condition will be guided in slab otherwise they will act as leaky modes. The condition for TIR is $(k_{\parallel} > \omega/c)$ where k is in plane wave number, ω is the angular frequency and c is representing speed of light in vacuum. The condition for confinement of light is well defined by **Fig. 1.5** as shown below. On

satisfying condition, light can't be leaked out of the photonic crystal slab since the in-plane wave number (k_{\parallel}) is greater than the available wave number in air (ω/c). The modes that don't satisfy TIR condition will lie inside the light cone. Light cone can be represented as ($k_{\parallel} < \omega/c$) in the k representation [13].

The photonic band gap possessed by PC is possible to control by altering the radius of holes and their periodicity. In 2D PC, guided modes can be classified on the basis of polarization in two totally different classes because of the existing property of mirror reflection symmetry in the direction normal to the plane of periodicity. These two classes of polarizations are TE and TM where electric field and magnetic field is in the plane of periodicity respectively [1,2]. Guided modes in 2D PC are not purely polarized modes because PC slab extends for finite length in the vertical direction. As PBD depends upon radius of holes, filling factor, thickness of substrate etc but it is found that a wider band gap is usually obtained by hexagonal structure of lattice rather than a square array [1,9]. For this reason in this dissertation we go for hexagonal array of dielectric arranged in air medium.

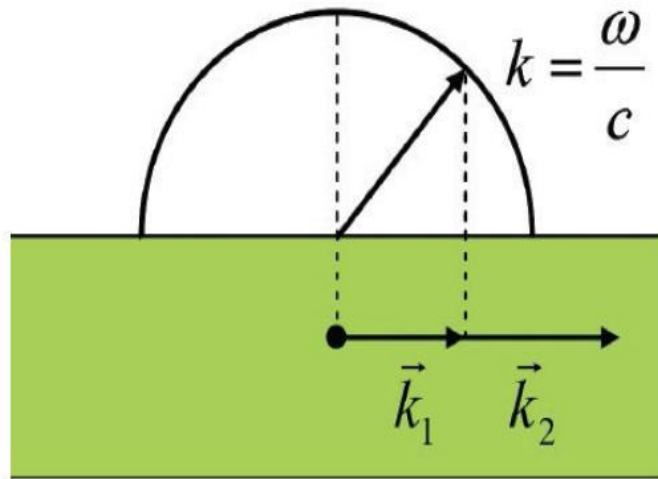


Fig. 1.5: The Explanation of the light cone concept for light guiding in the slab. A mode with a wave-vector length ($k_{\parallel} > \omega/c$) is not guided and can couple out in the air around the slab. A mode with ($k_{\parallel} < \omega/c$) is guided and the total internal reflection condition is fulfilled because no corresponding wave vector with the same tangential component exists in air [13]

1.1.4 Photonic Crystal Defects

As previously said in PC with proper periodicity no wavelength is allowed to propagate in the range of photonic bandgap. The localization of light can be obtained in the range of PBG by inducing defect or a disturbance in the periodicity. It happens due to the disturbance in the symmetry of structure at the defect site and violation of Bloch theorem [1,14]. The dimensions or nature of defect determines the shape and properties of localized photonic states. Defect introduced could be point defect or a line defect. A point defect will result into micro-cavity and line defect will result into a linear waveguide and a planar defect will result into a perfect mirror [1]. This facility to control a photon provides us with a new opportunity to mould or control the characteristics of light. This provides the exciting feature of photonic crystals. Many applications come into existence because of these defects like narrow-band filter [1], PCW [16], directional coupler [56], resonator [18], waveguide splitter, channel drop filter [25], switching circuits etc. The localized photonic states can be explained in 1D, 2D and 3D photonic crystals as:

1.1.4.1 Localized States for a 1D Photonic Crystals

As mentioned, the periodicity of the crystal results into a photonic band gap in its transmission band structure. No electromagnetic mode of frequency lying in the gap is allowed to exist without defect. A defect introduced in a perfect crystal allows light wave to propagate with a frequency lying in the photonic band gap [8]. A localized mode within the PBG can be excite if any mode is well-matched with the structure and the symmetry of a given crystal defect. Generally tight localization of states is possible near the middle of gap than the states lying near the gap's boundary. The limitation of 1D- PC is that localization of states is possible only in one dimension. **Fig 1.6** is showing a state confinement to a given plane [1].

No doubt, defects allow localized modes to exist with frequencies lying inside PBG. But a mode having frequency in the gap has to decay exponentially once it enters into the crystal. The multilayer films lies on both sides of the defect which will act as frequency-specific mirrors for any z -propagating light and will be trapped between. The trapped light will bounce back and forth in between these two mirrors and modes will be

quantized into discrete frequencies.

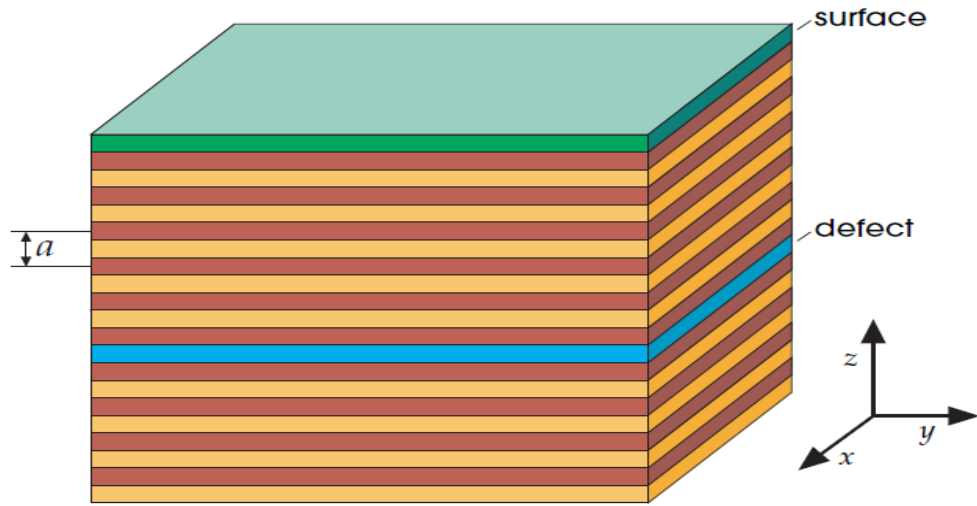


Fig. 1.6: Schematic demonstration of possible sites of localized states in 1D photonic crystal. A localized mode at the edge of the crystal (green) will give surface state and a mode in between the bulk of the crystal (blue) will give a defect state [1]

1.1.4.2 Localized States for a 2D Photonic Crystals

In 2D photonic crystals, band gaps exist for in-plane propagation. Density of states is zero within the photonic band gap as no modes are allowed here. By disturbing a single lattice location, a single localized mode or a set of closely lined up modes can be found that have frequencies lying in between the PBG. In two dimensional photonic crystals more options exist. As shown in the **Fig. 1.7**, a single column can be removed from the crystal, or can be change with new one whose properties differ from the original like size, shape or dielectric constant [17]. Disturbing a single lattice site will result into a line defect in the z direction. However, as propagation is considered only in the plane of periodicity and the disturbance is confined to a particular point in that plane only, we consider this disturbance as point defect. Removing of one column will result into a peak which must be evanescent because it is not able to penetrate into the rest of the crystal as it has a frequency in the band gap [8].

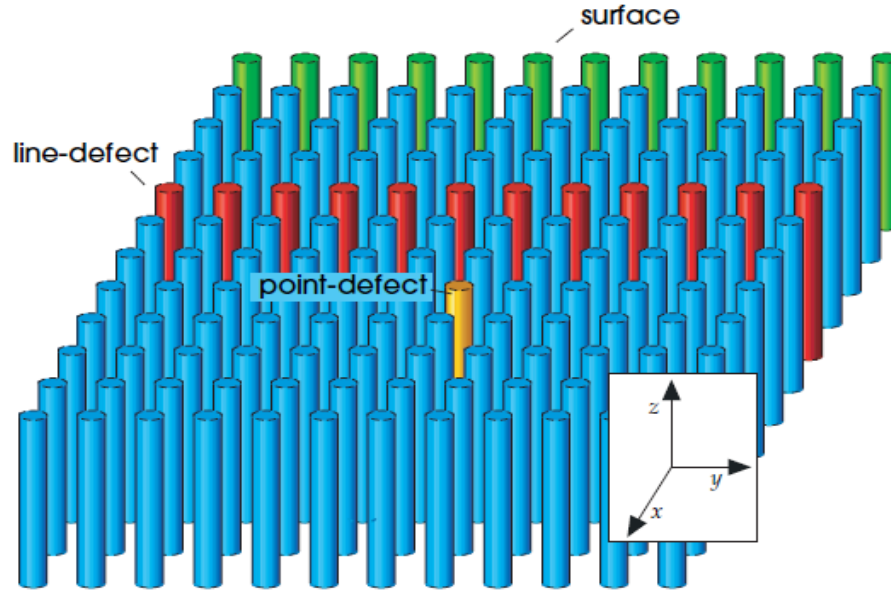


Fig. 1.7: Possible sites demonstration of point, line and surface defects in two-dimensional crystal [1]

Disturbance in one column in the bulk of the crystal (yellow) will allow a defect state to be localized in both x and y directions. This will induce point defect, depending on its size it would be called as micro-cavity if it is in the range of micro-meter [15,57,58,59] and would be called as nano-cavity if it is in nanometer range [9,59,71]. Perturbing one row in the bulk of the crystal (red) or truncating the crystal at a surface (green) will allow a state to be localized in one direction(x). Disturbance in hole row in photonic crystal will induce line defects known as photonic crystal waveguide (PCW) [19,20,21].The rods are assumed to extend indefinitely in the third direction [1].

1.1.4.1 Localized States for a 3D Photonic Crystals

In 3D photonic crystal, a single lattice site can be disturbed and therefore light will localize into a single point in the crystal which will be trapped in all three dimensions. To induce a point defect, there is need to adjust a mono layer of holes in just the same way as defects are created in 2D photonic crystals. There are two simple methods to introduce a point defect as shown in **Fig. 1.8**

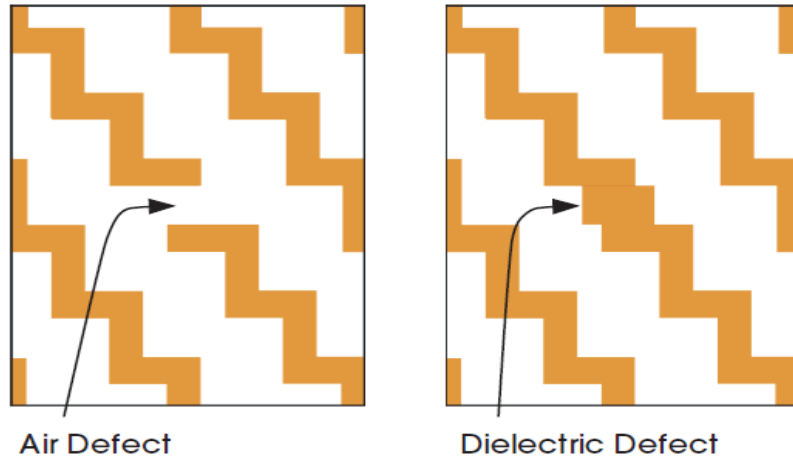


Fig. 1.8: Vertical cross-section of the layered structure is showing how a defect can be created by modification of a single rod: a rod can be removed (left) to form an air defect, or the radius of the rod can be increased (right) to form a dielectric defect [1]

A point defect can be induced by either add additional dielectric material where it doesn't belong in actual or take out some of the dielectric material that should be there in actual. The first case will be known as **dielectric defect** and second one is known as **air defect**. With insertion of point defect, discrete translational symmetry of the lattice structure is ruined means modes of the system can't be classify the with a wave vector k . Examples of both defects are shown in the above figure which is created by removal of a single rod in a rod layer to create an air defect (left), and radius is increased to create a dielectric defect (right) [1].

1.1.5 Photonic Crystal Applications

Long ago, engineers use metallic components to control the light propagation, to guide, reflect and to trap light. These electronic devices rely on the high conductivity of metals which depends strongly on frequency. Unfortunately at higher frequencies metallic devices suffer from high dissipative losses. In contrast, the dielectric materials of photonic crystals can provide a much simpler behavior, with low frequency dependence. Thus a photonic crystal provides us new gear for the treatment of photons and has received a great attention in a variety of fields. PCs have received attention in number of fields as these provide ability to manipulate photons by modulating its structure

accordingly. There are numerous applications as band gap or defect engineering is one of the best design criteria of photonic crystals that make use of photonic band gap [17]. The other way of engineering in PCs is band engineering which focuses on the propagation of light in transmission spectrum. By controlling the dispersion relation in transmission spectrum light can be controlled in many ways. It is recommended that a number of applications and photonic devices can be developed for imaging by significantly slow down the speed of propagation of light and by changing its direction in a photonic crystal [8].

- (a) **Resonator** A single cavity in a photonic crystal will act as resonator. As already explained, point defect on perfect crystal breaks the symmetry and light will localize in this point defect. Once the light entered the photonic crystal will go back and forth but will not be able to escape out. This phenomenon gives the basic of resonator [13,18]. Using photonic crystal nano-cavity a resonator of high quality-factor with small mode-volume can be realized.
- (b) **Perfect Dielectric Mirror:** The property of reflectivity in photonic crystals arises from their geometry and periodicity, not a complicated atomic-scale structure (unlike metallic components). The only demand for the required material is to be essentially lossless for the interested frequency range. Such materials are widely available all the way from the ultraviolet regime to the microwave [1].
- (c) **Waveguide:** A waveguide is generally used for the transportation of waves of a particular frequency from one place to another place along a path. Waveguides that confine light via photonic band gaps are a newer development. By the formation of linear defect in two-dimensional photonic crystal will allows us to design a waveguide. By removing a single row of rods from the crystal light is made to travel along the path of waveguide only. With this light is guided primarily within the *air*, much like a hollow metallic waveguide, but very unlike a traditional index-guiding structure [1,16,19,20,21].
- (d) **Non-Linear effects:** A number of novel nonlinear optical mechanisms can also be realized with band-edge engineering. Using of the materials with non-linear properties (like stimulated Raman scattering) for construction of photonic crystal

lattices open new possibilities for molding the flow of light. In this case the dielectric constant is additionally depend on intensity of incident electromagnetic radiation and any non-linear optics phenomena can appeared [22,23].

- (e) **Narrow Band Filter:** A narrow band filter can be realized using a nano-cavity structure. A cavity can be formed by the absence of a single rod, adjacent to two waveguides, each of which is formed by the absence of a row of rods. Means a nano-cavity coupled waveguide is created. Previously when excitation of cavity is done directly by a current source or atomic transition within the cavity then the energy in the cavity leaked out slowly. However, something more interesting happened when excitation of the cavity is done from one of the coupled waveguide and a sharp peak is obtained in the range of photonic band gap. This sharp peak means that the device acts as a narrow-band filter. The light is transmitted for frequencies near the resonant frequency of the cavity, and is reflected for somewhat lower or higher frequencies. The existence of the resonance peak conforms that near the resonant frequency, light from the input waveguide can couple into the cavity, and the cavity in turn can couple into the output waveguide [1,24].
- (f) **Waveguide splitter:** Waveguide splitter divides the power in an input waveguide equally between output waveguides. Using photonic crystal it can be realized by use of waveguides i.e. by missing air holes in a row if air in dielectric configuration s used or by missing dielectric holes if dielectric in air configuration is used. Photonic band gap obtained in PC eliminates radiation loss means we need only to deal with the possibility of reflection losses to realize waveguide splitter. Reflection losses can be minimized by proper chosen of structure [1].
- (g) **Channel Drop Filter:** A channel-drop filter is a device which redirects 100% of light from the input port to the output port, but only for a single resonant frequency. For all other frequencies, no light is allowed to propagate from one port to other port. This structure can be realized using photonic crystal. Frequencies other than resonant frequency will propagate along the top waveguide unimpeded [1,8,25,26].

- (h) Lasers:** for proper operation of lasers spontaneous emission rate should be controlled as possible and this can be done using cavity structure of photonic crystal as PBG helps to restrain spontaneous emission. In a cavity structure, the spontaneous emission rate can be greatly enhanced compared with that in free space which is known as Purcell effect which can increase laser modulation speeds. That's why Photonic crystal lasers can be realized with small mode volumes (V) and high Quality (Q) factors, having enhanced photon emission and can operate with high modulation speeds. Defect can be formed in the 2D photonic crystal by removing a single hole means photon energy can be localize similar to that for electrons in a quantum wire structure. At air-slab interface localization of Photons is done by TIR in vertical direction. The combination of Bragg reflection from the 2D photonic crystal and TIR from the low-index cladding (air) results in a three-dimensionally confined optical mode [27,28]. Using photonic crystal nano-cavities various lasers has been designed with lower threshold which a noticeable achievement [10,28,29,60].
- (i) Optical Sensors:** Photonic crystals (PCs) is an even more attractive sensing platform as silicon based PCs comprise a group of holes in a silicon slab or vice-versa to form a periodic dielectric structure which is compliant with photonic band gap (PBG). The propagation of light within PBG frequency range is forbidden in PCs structure. The light within the PBG frequency range is enabled to be guided or localized by introducing certain defects in the PCs structure. Therefore the local electromagnetic field is modified by surface state of holes as by the various concentration of solution on top of PCs sensors.

With the aid of defects, micro-cavity or nanocavity based PC based resonators are demonstrated as PC sensors of high sensitivity in terms of resonant wavelength detection. Resonant wavelength of PCs resonator sensors are extremely sensitive to a small refractive index change attributed to medium around hole (rod) surface. In present days, optical sensing mechanisms receive attention in chemical sensors as well as biochemical sensors. These optical sensors hold long lasting interests due to their close relation with human life. Examples include bacteria and virus detection, medical diagnostics, screening

of chemical compounds in drug discovery, food safety, and environment monitoring. The general use of optical sensors for real time applications is prevented by the problems of stability, sensitivity and size. But silicon technology based integrated photonic biosensors could solve such drawbacks and could improve the effectiveness of in-vivo and in-vitro diagnostics [30]. In some last years, PC's have been presented as sensing platform in numerous fields like chemical detection[31], fluid detection[32], gas sensing[33], detection of bio-molecule in aqueous solution[34], bio-chemical sensing[35,36,37], pressure sensing[39,41,42], protein detection[18], temperature sensing[40] and others [18,42]. Optical sensing is the base providing mechanism of this dissertation.

1.2 Sensing Principle

For an efficient optical sensor, we need to study various parameters which are affecting the sensor. In presented design, early detection of cancerous cell is done using nanocavity coupled waveguide structure in 2D photonic crystal. The presence of analyte brings the physical changes at the interface between sensor and analyte which makes the basic principle of sensor. These physical changes results a change into effective refractive index of cavity where analyte is placed which shifts the resonant wavelength at output transmission spectra. Hence by monitoring the resonant wavelength change one can determine the amount of analytes present. After discussion of these parameters, these will provide knowledge about which mode and mechanism of sensing can be used. Various affecting parameters are discussed as:

1.2.1 Types of Sensing Modes

There are two frequently used sensing modes homogenous sensing and surface sensing which have commercial use [43,44]. The **homogenous sensing** is a mechanism whose principle is refractive index modification of covered medium and **surface sensing** is influenced by change in thickness of bio-molecular layer placed on a particular surface. In homogeneous sensing, the device is covered with a medium that serves as top cladding in which analytes are suspended. The analyte homogeneously distributed in the solution can modify the bulk refractive index of the solution and in turn change the effective index of the guided mode. But in this scheme, any materials in the solution (including the

analyte to be detected) can contribute to the resonant wavelength shift, which means the sensor is not specific to a particular type of analyte. To solve this problem, the surface can be treated to have binding or receptor sites that can selectively bind specific bio-molecules. The unbound molecules can be washed off by a simple rinsing step. Using this method, only the bound bio-molecules on the sensor surfaces contribute to the effective index change. Hence, surface sensing solves the problem of selectivity which is generally faced in homogenous sensing.

1.2.2 Types of Sensing Mechanisms

There are two main sensing mechanisms with which calibration of sensor can be done. These two sensing mechanisms are resonant wavelength shift and intensity variation [43,44,45]. In **Resonant Wavelength Shift (RWS)** scheme amount of change in resonant wavelength $\Delta\lambda$ is measured due to the presence of analytes. The change in the resonant wavelength of optical sensor is due to change in effective refractive index (ERI) which is the signature of presence of the analyte. Precision of RWS based sensors can be improved by narrow full width half maximum (FWHM), hence higher quality factor will be obtained. To measure a very minute change in ERI of cavity, a highly sensitive sensor is required. Many devices have been demonstrated where this functionality is used to detect gas, pressure, DNA molecule, temperature, pressure etc [38,46,47,48]. In **Intensity Variation Scheme (IV)** amount of change in the intensity at resonant wavelength at the output port is measured. In comparison with RWS scheme, the IV scheme is more accurate, precise and apparatus required is also simple. This scheme is highly accurate and precise because a steep slope observed at output port will help in detection of change in intensity. Only disadvantage of this scheme is narrow range of wavelength shift can be used whereas RWS scheme is used for wider wavelength shift. Accordingly, this surface sensing method enables specific and label-free detection [22,47,54,65,68,72]. To transduce the amount of analyte into a detectable signal, two sensing schemes can be used: monitoring the resonant wavelength shift or the intensity variation at a selected wavelength. The former scheme provides a wide detection range. Surface sensing requires binding sites on the sensor surfaces.

1.3 Photonic Crystal Bio-sensors

Increasing demand for the fast and accurate detection of any type of infection has speed up the progress of a large range of biosensors. It is always desirable to have a small sized portable biosensor with reasonable high sensitivity, small response time and it should be able to perform real-time measurement for most of all applications. The idea of bio-sensing envelops a wide collection of medical instruments. In last some years, PC's receive attention for chemical as well as bio-chemical sensing. Optical sensing provides an attentive platform because these can meet the present demand of fast response and precise real time detection of any type of substances. Generally, these instruments convert information from a physical biological procedure to a measurable signal. Measurements can be made straightly on living subjects (in vivo) or on biological samples which was taken from an organism such as cells, tissue and blood (in vitro). The analyte could be cells, proteins, bacteria and microorganisms, DNA and various other submicron particles. Today much focus of the research is on miniaturization in the field of in vitro diagnostics, where there is the possibility to defeat the disadvantages of already existing systems, such as their high costs, need of large sample and more response time. In general the existence of the specie to be detected (analyte) is sensed by a biological recognition element in bio-sensor and produces a response whose conversion is done by a transducer to a signal. The general block diagram shown in **Fig. 1.9** represents the basic flow of a bio-sensor.

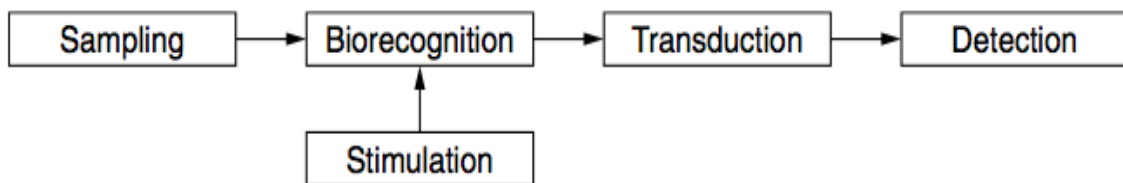


Fig. 1.9: General block diagram representing the basic flow of bio-sensing [49].

Process of Bio-sensing can be explained by combination of five parts as shown in above figure. In whole process, combination of whole biological element is done with a physiochemical detector. The **Sampling unit** introduces sample fluid (analyte) into sensing apparatus. The **Bio-recognition** element binds the antigens with immobilized antibodies and provides specific bio-detection. **Stimulation** can be provided by either

optical source or electrical or other that extracts response at output as a consequence of bio-recognition. The **Transduction** unit converts of antigen binding events to detectable optical signal and **Detection** unit studies this optical signal on data acquisition platform to identify analyte.

A number of PC based structures has been presented as bio-sensing platform. Some of the presented optical sensors utilize evanescent wave to probe the presence of analytes at the sensor surface or in the surrounding medium by detecting the effective index change. In order to detect low concentrations or minute amounts of analytes, a long interaction length is often required. Consequently in past devices were typically large (in the range of centimeters) and needed a significant amount of analytes, which might not be available in many applications. The sensitivity of the evanescent-field based sensor remains very low because penetration of exponentially decaying electromagnetic field to the sensing region is low. To overcome this disadvantage, various other structures have been presented. A brief description of these structures is discussed as:

1.3.1 Photonic Crystal Fiber based sensing

The Photonic Crystal Fiber (PCF) based on evanescent field provided the new potential for exploiting the interaction of light with analytes (gases or liquids). PCF consists of a cladding region made by holes which runs along the full length of the fiber which made the base of evanescent field. The various parameters determines the performance of PCF based sensors such as sensitivity, mode area and confinement loss. These parameters are affected by a number of factors which includes operating wavelength, diameter of hole and pitch (separation between two neighboring holes) in the clad region. The relative high sensitivity is always desirable which comes at the cost of a reduced mode area. There is trade-off between relative sensitivity and mode area as it is well known that small mode area is a shortcoming for coupling of light from source to fiber. Therefore, it is important to look into the way of enhancing both parameters i.e. relative sensitivity and mode area of the index guiding PCF simultaneously. In general, the sensitivity of the evanescent-field based sensor remains very low because penetration of exponentially decaying electromagnetic field to the sensing region is low. A gas sensor is presented based on photonic crystal fiber and properties of a depressed-index core PCF have been

studied [33]. PCF with long period grating is also presented for bio-chemical sensing. A shift in the resonant wavelength is measured due to immobilization of a layer of bio-molecules [36]. Detection of bio-molecule in aqueous solution is also done by PCF based evanescent-field sensor [34].

1.3.2 Waveguide based sensing

A photonic crystal waveguide can be created by inducing linear defect in perfect photonic crystal. It has achieved a lot of research importance due to its exclusive property of light confinement [50]. As it provides a compact and lossless platform it is used in many applications like directional coupler, waveguide splitter including sensing also. The PCW allows the propagation of a small range of wavelengths lies within the range of photonic band gap (PBG). The transmission in the PCW depends entirely on the effective refractive index (ERI) of photonic crystal slab. Thus photonic crystal slab can be used as a sensing device by changing effective index of slab and corresponding change can be measured in output transmission spectrum. The presence of analyte makes the change in ERI and causes a change in the cut-off wavelength in output spectrum. PCW has been presented as bio-sensing platform based on refractive index sensing. Optimization of structure is done to increase its sensitivity and achieved sensitivity is 260nm/RIU [51]. Detection of different analytes from aqueous solution is also done with achievable sensitivity of 386nm/RIU. Here effect of over etching of oxide layer under silicon substrate is studied and it gave positive results to enhance sensitivity [73].

1.3.3 Micro-cavity based sensing

Photonic crystal micro-cavities formed by introduction of point defect in range of micrometer have shown great challenging structure for sensing. Its feature of showing strong localization of light and efficient light-matter interaction makes it important as high electric field can be concentrated with a very small mode volume within PC micro-cavities. Such compact devices are useful for bio-sensing purpose as it will reduce amount of blood sample required to a great extent. Moreover, the miniaturization of device gives the possibility of lab-on-chip application [30]. It provides a better sensing platform as compared to other sensing platforms that make use of the interaction between

the analyte and evanescent tail of the EM field. It is possible to localize the Electric field in a region of low refractive index which makes sensitivity extremely high. Air bridged micro-cavity structure is presented for bio-sensing with high quality-factor and acceptable high sensitivity. Sensitivity of 320nm/RIU and quality factor of 120 has been presented [52]. A highly compact bio-chemical sensor has been presented using two-dimensional PC micro-cavity [35].

1.3.4 Ring Resonator based sensing

Ring resonators are formed by two or more waveguides, out of them one should be in a ring shaped which generally interact with each other at particular points, may be horizontally or vertically at some frequencies. These frequencies are resolute by effective refractive index, length of the waveguides and the respective distance between the waveguides. In comparison to micro-ring resonators, nano-ring resonators provide well confinement due to their highly small size and low bending loss. A ring waveguide sandwiched by bus and drop waveguides can be used as sensors with good sensitivity and quality factor. Bio-chemical sensor has been reported with quality-factor of 3000 using ring resonator. It brings down the bio-molecule detection to a single cell level [37]. For protein detection, label free optical bio-sensors have been presented using silicon-on-insulator micro-cavity [47]. Bio-chemical sensing has also been presented using nano-ring resonators and amount of analyte required is reduced to a great extent because of its nano structure [53].

1.3.5 Micro-cavity Coupled Waveguide based sensing

Combination of waveguide and micro-cavity realized by inducing line and point defect respectively in photonic crystal used as bio-sensor with high sensitivity. The refractive index in 2D-PC varies with time due to presence of analyte which will cause a variation in transmission spectrum too. Thus properties of analyte can be measured with described mechanism. For sensing purpose, the only need is to alter the structure parameter ERI by presence of analyte. A multi-channel bio-sensor is presented using waveguides and micro-cavities in 2D crystal [42]. Extremely sensitive torsion free pressure sensor is also presented using PC micro-cavity designed in PC waveguide. Side-coupled piston is used

with micro-cavity and pressure sensitivity of 0.50nm/nN was achieved with highly reduced size [42]. A label free optical bio-sensor is presented with high quality-factor using ring slot structure in cavity coupled waveguide structure [54].

1.4 Sensing Parameters

There are two main sensing parameters of our concern i.e. Sensitivity (S) and quality-factor (Q) which are explained as:

1.4.1 Sensitivity

The Sensitivity (S) is the first and ultimately the most important requirement. For optically resonant sensors, the bulk sensitivity metric quoted in units of nm/RIU (i.e., the total shift in resonant wavelength with respect to a change in refractive index unit) subscribes to the internal sensitivity measure [31]. Detection limit or detection sensitivity of a sensor refers to the smallest quantity of interest that can be accurately measured. A minimal detection limit is desired for detecting rare analytes [45]. Sensitivity is the ratio of obtained change in the resonant wavelength due to change in the refractive index. Sensitivity is to be measured in terms of nm/RIU and it should be high as possible.

$$S = \frac{\Delta\lambda}{\Delta n} \quad (1.7)$$

Where, $\Delta\lambda$ is the change in resonant wavelength and Δn is the change in refractive index.

1.4.2 Q-Factor

It has been said earlier that in a photonic crystal slab light confinement is because of Bragg reflection in two dimensions and due to total internal reflection (TIR) in the third dimension. It reveals that photonic band-gap effect is the reason of horizontal confinement and TIR is the reason of vertical confinement of light in cavity. However, in a cavity the defect modes generally suffer from in-plane (horizontal) and out-of-plane (vertical) losses. Q-factor is the widely used parameter for the measurement of light confinement in cavity [1,31].The resonance Q factor is defined as the ratio of stored energy to the energy loss. Therefore, to achieve high Q factors, all the cavity losses need to be minimized. Mainly three types of losses are of primary concern: bending loss,

leakage loss to the substrate, and loss induced by surface-roughness scattering. Bending loss doesn't exist in our linear structure. Leakage loss occurs when higher-index substrates, such as Si, are used because light tends to travel in higher-index materials, so these losses are also eliminated in our structure. Surface-roughness scattering is caused by physical surface roughness, especially on the side walls, produced typically during its fabrication. Thus, surface-roughness scattering is the primary loss and has to be minimized to achieve high Q factor. With better design and improved fabrication techniques, the entire loss can be reduced significantly. Analytically relation is established between quality factor and near field pattern of cavity mode [59]. Numerically, the Quality factor (**Q**) is defined as the ratio of obtained resonant wavelength to change in the wavelength at Full Width Half Maximum (FWHM). Q should be high as possible and it is unit-less parameter.

$$Q = \frac{\lambda(\text{resonant})}{\Delta\lambda(\text{FWHM})} \quad (1.8)$$

Where, $\lambda(\text{resonant})$ is wavelength at resonance and $\Delta\lambda(\text{FWHM})$ is difference of wavelengths obtained at FWHM.

To achieve high Q, resonant peak should be narrow. Q can also be defined as the ratio of stored energy to the energy loss. Therefore, to achieve high Q-factors, all the cavity losses need to be minimized [31].

1.5 Nanocavity-Coupled Waveguide Based Bio-sensors

A very challenging application of photonic crystals is to recognize optical nano-cavities with which light can be trapped in a very small mode volume with high quality factor means for a long period of time. The well confinement of light in PC nano-cavities provides a longer light-matter interaction and the photon-photon interaction which have significance for a broad range of applications even from basic science to engineering. As previously discussed PC nano-cavities can be created by modifying radius or refractive index of a particular hole. This breaks the periodic symmetry and creates new energy levels within PBG which is analogous to energy levels within the semi-conductor energy bandgap due to doping in pure semi-conductor.

In photonic crystal linear defect can be combined with nano-cavity to construct waveguides for input and output to reduce losses because of direct excitation to nano-cavity. The linear waveguides used as bus and drop waveguides minimizes the losses and makes structure so simple where there is no need of extra sources for excitation. The compact waveguides provide very low losses even with sharp bends because no matter in which direction the light is turning as it hasn't any other way to escape out because of the band gap. For the realization of highly compact and wider bandwidth optical integrated circuits waveguides and cavities coupled structure can be used. These photonic structures will provide higher level of functionality because optical devices can also be integrated with electronics as they are fabricated with standard electronic materials. These devices offer a unique advantage of reducing the device size by orders of magnitude, which reduces the amount of analytes needed to an extent. Meanwhile, our aim is to find a bio-sensor whose reduced size doesn't compromise the device sensitivity. The resonant frequency of the cavity is highly sensitive to changes in the refractive index as well as geometry of the crystal. This feature makes this structure feasible for highly sensitive bio-sensing platform.

1.6 Thesis Objective

The objective of report is to design a bio-sensing platform biosensor using nanocavity coupled photonic crystal waveguide for cancer detection with high Q-factor, high sensitivity and high selectivity against five different cancer cells. Other aim is the miniaturization in order to reduce the amount of required blood sample.

1.7 Thesis Organization

The dissertation has been divided into four chapters.

Chapter 1 provides a general information about photonic crystals, Maxwell equations used to study light propagation inside PC, types of PC, concept of photonic crystals slabs, applications of photonic crystals, defects in photonic crystal, principle of sensing, types of sensing modes, types of sensing mechanisms, Bio-sensing by means of photonic crystals, also elaborate the parameters by which PC bio-sensor can be quantized and optimized i.e. sensitivity and quality factor.

Chapter2 discusses the implications of currently existing technologies. It provides the literature of different types of photonic crystals, different types of photonic defects, various applications of photonic crystals, different types of sensors using photonic crystals and optimization of sensitivity and quality factor.

Chapter 3 presents the analysis of proposed design using photonic crystal. it includes the discussion of structure of photonic crystal nano-cavity, PWE and FDTD algorithm description, optimization of proposed structure to enhance sensitivity and quality factor, methodology used, step by step approach of design and Experimental results.

Chapter 4 gives the directions of future work, summarizes the work done and presents a recap of the main conclusions.

CHAPTER 2

LITERATURE SURVEY

C. Xiang Hua *et al.* in 2005 [27] have studied the defect modes in two-dimensional photonic crystal by using distorted triangular lattice. Simulations are done using super-cell method and FDTD method. It is observed that the frequencies of defect modes as well as corresponding magnetic field distributions can be changed by stretching and shrinking of the lattice. Even by doing changes in lattice structure doubly degenerated dipole modes can be separated. Even further separation is possible by both stretching and shrinking of lattice which is even enough to realize single mode emission. The defect modes with higher frequency can be obtained by shrinking of lattice which makes fabrication easy and make localization easy as compared to stretched cavities. It is stated that the single mode operation can be obtained by using shrinking of lattice. The obtained results will be useful to manufacture of lasers using photonic crystal since single mode emission is the basic requirement of lasers.

Yoshie *et al.* in 2001 [57] characterized nano-cavities of donor-mode by using a single defect cavity in photonic crystal thin slab made by air holes in GaAs with triangular array for range of 1.1-1.3 μm . A large hole is replaced by a small hole at the center of thin PC slab. Optimization of the cavity is done with fractional edge dislocation in two steps. First step is the creation of elliptical air-holes instead of circular air-holes in line where cavity with smaller hole is formed. Second step followed is the displacement of holes. The behavior of structure is analyzed with different values of displacement for Q-factor and normalized resonance. They observed that Q-factor increases as resonance energy decreases. It was observed that previously the maximum quality factor of 2800 was found with design parameters as $r=0.29a$, $d=0.65a$. Here, simulations are done using 3D-FDTD which give Q-factor of 4400 with mode-volume of 0.43. It is reported that structure gives higher values of Q-factor than the value of 1500 measured previously without use of fractional edge dislocation.

W. Chiu *et al.* in 2007 [18] demonstrated design and fabrication of a photonic crystal ring resonator formed by linear waveguides and a ring shaped waveguide in PC. The presented structure is comprised of silicon rods arranged in a hexagonal array on an SOI wafer. Structure is optimized by controlling the size of nano-rods. The presented photonic crystal ring resonator filter structure is suitable for the wavelength separation of range 1.31 and 1.55 μm . The fabrication of device is done by e-beam lithography. Device is more compact with diameter of ring resonator 8 μm than conventional ring resonators having diameter of 300 μm means light confinement is proper. Presented structure has low crosstalk of 15dB with small optical loss. That's why it is applicable to use in integrated optics for various applications such as optical fiber communication. To increase coupling efficiency, polishing of Si substrate is done and substrate is cleaved also to make a mirror like facet at the both ends of waveguides.

L. Huang *et al.* in 2006 [61] proposed high-Q and label-free sensor based on a photonic crystal (PC) ring-slot resonator to apply surface bio-molecule detection. The proposed device consists of a line defect acting as an input as well as output waveguide and a ring-slot cavity is coupled to linear waveguide which is made by removing six holes only in hexagon shape. Simulations are done by using 2D finite difference time domain (FDTD) method. Structure shows a high quality factor of magnitude 10^7 when ring slot width (w) is kept at 0.20a and center air hole in inner ring slot has radius of 0.34a. At telecom wavelength range, the refractive index (RI) of water surroundings equals to 1.330, still Q of 11477.3 can be obtained when the width of ring-slot is kept at 0.28a. The sensitivity (S) obtained is 160nm/ RIU (refractive index unit) with the detection limit of 8.75×10^5 RIU. It reveals that the refractive index (RI) based sensor design is a shows potential for label-free bio-sensing in life science, medical diagnosis and environmental monitoring. Results obtained reveal that the proposed sensor structure exhibits high Q factor and is applicable to RI sensing for detection of the surface bio-molecule.

S. H. Kwon *et al.* in 2008 [31] reported high response factor (R) to measure the change in refractive index in the background material by the design of hetero-structure cavities. Simulations are done using 3D Finite Difference Time Domain (FDTD) method. By

rising in the overlapping of field within the background material, through different three methods of reducing the slab thickness, inducing the air holes at the center of the waveguide, and presenting the slot in the waveguide, response factor R is enhanced. For providing better spectral resolution for gas sensing, the Q should be high as much as possible and for the final cavity structure it is kept at larger than 10^5 . Enhancement of the R is done by reducing the thickness of slab. The electric field profile of slot or cavity with central holes, optical losses and allowable mode within PBG are explaining the behaviors of the response factor and the quality factor. Optimization of the presented Photonic Crystal hetero-structure cavities is done by changing four parameters i.e. modulation of the lattice constant, the width, the refractive index, and by the radius of the air holes. Sensitivity of 310nm/RIU in the thinner slab with central air holes was reported previously. The presented hetero-structure made in the slotted waveguide of thin PC slab owes strong confinement of electric field in the low-index region which shows better sensitivity of 512nm/RIU.

X. Liang *et al.* in 2005 [62] reported a method for calculating the effective refractive index (ERI) of a single living cell with help of a small integrated chip. This novel designed chip is able to find out the RI of a living cell in real time domain which can be helpful for early-stage diagnosis of diseases like cancer. It offers high accuracy with low cost as no fluorescence labels and extra chemical treatment is required for diagnosis. It provides a good and easy approach for cell level diseases diagnosis like cancer. The system consists of laser diode, micro-lenses, and micro-fluidic channels within a micro-chip. There are two polystyrene beads with nominal refractive indices are used to regulate the system and ERI of five types of cancerous cells are measured. A living cell is a mixture of various organelles with different refractive index. Normally cancer diseased cells have more concentration of protein in their larger nucleus due to which rapid cell division occurs. It is notified that protein content in living cells has large contribution to the effective RI of the cells. The results indicate that refractive index of five tested cancerous cells ranges from 1.392 to 1.401 whereas RI varies from 1.35 to 1.37 for cytoplasm of normal cells. It indicates that cancer can be detected by the ERI of the cell

before it becomes uncontrolled. This microchip could be a helpful tool in future because of its advantages like early and easy diagnosis in clinical laboratories.

K. Zinoviev *et al* in 2008 [30] presented a remarkable growth in the development of various integrated optical biosensor platforms using silicon technologies and their application in different areas such as surrounding environmental observation, food safety, biotechnology, drug screening, medical diagnostics, and security etc. The possibility of the various different platforms for bio-sensing has been presented. Among all platforms, the optical biosensors platform has achieved a high level of maturity and several products are on the edge to come into market. But there are some limitations like problem of stability, size and reasonable sensitivity which have prevented the broad use of optical bio-sensors for real field applications in our daily life. Presented integrated photonic bio-sensors using silicon technology could resolve all drawbacks and offers a easy to use, early detection devices with better reliability, high sensitivity and specific to use. These features could improve the usefulness of both diagnostics i.e. in-vivo and in-vitro. Our developments using silicon technology is mainly related to the present a portable and highly sensitive integrated multi analyte photonic bio-sensor for the diagnosis of numerous biological molecules of attention in situ and in real-time. All the described configurations open the feasibility of lab-on-a chip micro-system for the integration of different fields like optic, fluidic, and electrical functions on one single platform.

K. De Vos *et al.* in 2007 [47] demonstrated a very small sized label-free biosensor which fits in an area below $10 \times 10 \mu\text{m}^2$ in Silicon-on-Insulator (SOI) material using micro-ring cavities. Input source of 1550nm is used for simulations. Label-free biosensors provides better stability and reliability than labeled biosensors because generally a problem is faced in labeled bio-sensors that material used for labeling also get involved in simulations and gives unwanted variation in results. SOI offers a high refractive index contrast in micron-sized as well as submicron sized optical cavities which is suitable for the nano photonic circuit fabrication with minimal fabrication losses means quality factor remains high. The light-matter interaction gets enhancement in the cavity which increases the sensitivity while keeping the dimensions of the sensor small. Use of telecom

wavelengths (1550nm) is suitable for purpose of bio-sensing because minimum absorption losses are observed at this wavelength. They reported that even a very small amount of analyte (even a molecular layer of 0.7 fg) allows the device to sense because of its high quality factor and unbelievable small size. The principle of sensing is shifting of resonance wavelength that occurs due to change in the surroundings of a cavity. Chemical modification is required for bio-sensing using semiconductor materials of the semiconductor surface to facilitate a suitable bio-interface. They did this required modification using avidin/biotin of high affinity to show acceptable detection of small protein concentrations even down to 10ng/ml. Deep UV lithography technique is used for fabrication which makes the device allowable for high throughput and suitable for lab-on-chip device. Two step modification of silicon surface is done for bio-sensing purpose i.e. aminosilanization and biotin covalent binding.

M. Lee and P. Fauchet in 2007 [38] demonstrated a highly sensitive bio-sensor based on two-dimensional 2D photonic crystal micro-cavity theoretically as well as experimentally. A tunable laser source of range 1440 nm to 1590 nm is used. Experimentally calculations are done using a finite domain time difference (FDTD) method and a plane-wave expansion (PWE) with 32 grid points to calculate transmission spectra and PBG respectively. Silicon-on-insulator (SOI) wafer is used in device fabrication and it operates at 1.58 μ m near its resonance. This sensor can measure the protein size. When coating of internal surface of sensor is done with different sized proteins, a different amount of red shift appears in resonance. A red shift is measured in device output spectra due to binding of glutaraldehyde and bovine serum albumin (BSA) which signifies their respective binding. Two important characteristics for a presented bio-sensor are sensitivity and selectivity. The presented device can detect even with a monolayer of molecule with a very small total mass as 2.5fg. The experimental results agree with theoretical results. Q-factor of presented bio-sensor can be further enhanced by controlling the position of the biological analyte in the defect region only.

X. Xiong *et al.* [39] proposed two- dimensional photonic crystal (2D-PC) based pressure sensors. Plane wave expansion (PWE) method is used to study photonic band gap (PBG)

of structure which is varying with variation in amount of pressure. This change can be observed by monitoring transmission spectra which is calculated by finite difference time domain calculations. The principle of 2D-PC based pressure sensor is totally different from PC fiber based sensor. Results show a good relation between the resonance wavelength and the pressure which is varying linearly for a pressure range of 0-40GPa (Giga-Pascal). Sensitivity and the demanded pressure range both can be controlled by changing properties of material, physical structure, shape, and dimension of the crystal. Presented 2D-PC based pressure sensor holds characteristics like high sensitivity for a satisfactory pressure range and most important is its simple design which makes fabrication very easy. That's why presented pressure sensor will be suitable to make a wireless strain gauge. It can be widely used in the many real life applications like bridge inspection, container weight and highway detection and so on.

Hsiao and Lee in 2010 [37] investigated the feasibility of biochemical sensing applications using a PCs-based nano-ring resonator. They propose a novel PCs based nano-ring resonator of hexagonal shape in hexagonal lattice for bio-sensing application and sensitivity is explored upon a basis of a single hole binding mechanism. Due to the well light confinement, the size of hexagonal nano-ring resonator is as small as $3\mu\text{m}^2$. As compared to the micro-cavity based PC sensors, they focus on the sensing phenomena based on a single hole located between waveguide and resonator. The ring resonator comprises of a hexagonal waveguide and two terminal waveguides in 2D silicon PCs substrate of hexagonal lattice and it is considered that the whole resonator is dipped inside a micro-fluidic channel for sensing procedure. The proposed nano-ring resonator reveals high quality factor, small volume required with reasonable sensitivity. The results of optimized resonator configuration show that the quality factor enhances with drop in efficiency on increasing coupling distance. Sensing principle is monitoring of shift in peak of resonant wavelength due to trapping of DNAs molecules in functionalized holes at output terminal. Variation in quality factor is observed with change in coupling distance. Quality factors of 2400 and 3200 are reported by observing the resonant peaks of the demonstrated nano-ring resonator with coupling distance of two and three respectively. Sensitivity is also investigated for the proposed structure by varying

position of sensing holes with coupling distance of two-hole and three-hole. The results obtained reveals that there is strong dependence of resonant wavelength shift on the position of sensing holes and linear relation of resonant wavelength with change in Effective Refractive Index (ERI) is obtained due to placement of DNA's molecule within the sensing hole. The minimum weight of bio-molecule which can be detect in sensing hole for demonstrated nano-ring resonator of two-hole and three-hole coupling distance is reported as 0.23 fg and 0.2 fg respectively where fg (femtogram) is decimal fraction of base unit of mass. It shows a promising structure because of its ability to sense with a single copy of DNA which brings down the need of bio-molecule copies.

J. Ruperez *et al.* in 2010 [63] reported experimental results label-free anti-bovine serum albumin (anti-BSA) antibody detection as well as refractive index sensing using a SOI planar photonic crystal waveguide (PCW). Here complementary BSA antigen probes are used to bio-functionalized the initial structure. Near the edge of the guided band sharp fringes are obtained in the slow-light scheme which is used for the sensing mechanism. Tracking of these sharp fringes is easy than the edge of either the PBG or the guided band, and it ensures the working in the slow-light system of the PCW, which makes the interaction stronger with the target substance for this wavelength range. In fact bandwidth is small for fringes obtained in the band edge which gives easy and more accurate determination of their positions. Modeling of the origin of these band edge fringes is done and sensing is done by performing refractive index variations detection with sensitivity of 174.8nm/RIU. After that, anti-BSA sensing experiments have been done, which results in surface mass density detection limit lower than 2.1 pg/mm² and due to the small size of our PCW a total mass detection limit is lower than 0.2 fg if only active area is responsible.

F. Hsiao and C. Lee in 2010 [53] investigated the sensing action based on photonic crystals (PCs) nano-ring resonators theoretically. This PC nano-ring resonator structure promises the feature of bio-molecular and chemical sensing applications. The nano-ring resonator is formed by removing holes in hexagonal shape from a two-dimensional silicon PC slab having hexagonal array of air holes in silicon. In other words we can say a

hexagonal waveguide is inserted in between two terminal linear waveguide. The size of presented nano-ring resonator is very small approximately equals to $3\mu\text{m}^2$ which is due to well light confinement possessed by structure. Numbers of simulations are done for every hole as sensing hole to characterize sensitivity for a single hole binding mechanism scenario. They trapped DNA bio-molecules in a functionalized hole which allows the shift of peak of resonance wavelength derived at output terminal. The proposed structure combines features of both i.e. ring resonator and as well as 2-D PCs. That's why demonstrated structure has high quality factor, small size of required footprint with high sensitivity. On optimizing its configuration, results show that quality factor can be enhanced by increasing coupling distance but on the cost of drop in efficiency. The quality factors of 2400 and 3200 are reported in the presented nano-ring resonator structure with two-hole and three-hole coupling distances respectively. Observations shows a strong dependence of the resonant wavelength shift on the position of sensing holes and a linear relation to the ERI change is also reported within the sensing hole. The minimized bio-molecule detection limit for presented nano-ring resonator in a sensing hole of coupling distance two-hole and three-hole is reported as 0.23 fg and 0.2 fg, respectively. As single hole level detection is presented, it is better approach than micro-cavity based sensors for bio-chemical sensing purpose.

L. Junhua *et al.* in 2011 [52] focused on design of optimized PC micro-cavity structure to achieve a remarkable resolution with larger sensitivity. Optimization of the structure is done by varying three parameters including slab thickness, radius of defect hole and use of air-bridged structure. They compared the performance silicon-on-insulator (SOI) PC micro-cavity and an air-bridged SOI-PC micro-cavity structure and noted that air-bridged SOI PC micro-cavity is better than SOI PC micro-cavity. The structure simulations are done using three-dimensional (3D) finite-difference time-domain (FDTD) method using a software package named as FDTD Solutions–Numerical which is commercially available. The performance is analyzed by changing the thickness of slab and by varying the defect hole radius. It is observed that for a thinner slab with larger defect hole measured sensitivity is higher with low quality factor. By proper selection of slab thickness and defect hole radius sensitivity of 320nm/RIU can be achieved for air-bridged

PC micro-cavity and sensitivity of 120nm/RIU can be achieved for micro-cavity in PC slab when the refractive index is kept at 1.33. These values are important for bio-sensing with low detection limit.

S.Olyae and Dehghani in 2012 [41] Designed and presented a new photonic crystal pressure sensor of high resolution and wide dynamic range. The geometry of this pressure sensor is 2D PC with configuration of dielectric in air. Silicon rods are arranged in square array fashion. The photonic crystal nanocavity is coupled to a photonic crystal waveguide in the proposed design of sensor. The waveguide is configured by removing one row of Si rods and modification is done in the radius of one Si rod to create nanocavity. The proposed sensor is operating for wavelengths in the range of 1300 nm-1400 nm. This sensor is based on the principle that by changing optical properties of Si, the refractive index changes, and therefore, resonant wavelength of nanocavity shifts. . With emphasis on this point, the sensor can be calibrated to measure applied pressure. Simulation results show that with increase in pressure the resonant wavelength of nanocavity is linearly shifted to longer wavelengths. A linear behavior is obtained between 0.1 GPa to 10 GPa (Giga-Pascal) for the designed sensor and pressure sensitivity of 8 nm/GPa is obtained with quality factor of 1470. The sensor has also shown an excellent resolution of mN range, and wide linearity range between 0 to 10 GPa. Similarly in nanotechnology and nano-electro-mechanical systems (NEMS) industry resolution of sensor can be increased by improving the quality factor of nanocavity.

M. Yuna *et al.* in 2012 [55] presented a sensing application two-dimensional 2D photonic crystal theoretically. Two-dimensional photonic crystal is consisting of air in dielectric configuration where air holes are arranged in triangular fashion. Line defects and point defects are deployed in 2D crystal to induce waveguide and micro-cavities respectively. Simulations are done using Finite Difference Time Domain (FDTD) method to obtain transmission spectra. They allow analytes to flow through the point defects which change the refractive index of defect region means change also occurred in respective PBG and thus transmitted spectra get also changed which can be measured to examine the properties of analyte. The simulation results reveal that presented device is

highly sensitive to the effective refractive index of point defect which is changed due to injection of the analyte into micro-cavity. The demonstrated device can be used for measuring refractive index and detecting protein concentrations. It is concluded that multi-channel biosensor can be made using photonic crystal alterations. Multi-channel structure is a one step forward towards lab on chip.

L. Shiramin *et al.* in 2013 [64] simulated a sensor in 2-D photonic crystal with a triangular lattice of air holes in dielectric based on the refractive index which is called double-hole defect sensor using finite difference time domain FDTD methods. The triangular pattern of PC is utilized as it provides large photonic band gap as compared to square pattern and due to large PBG it is expected to serve a better platform for a very compact optical sensors. The difference between radii of two adjacent holes is 440nm known as lattice constant. The presented structure of sensor consists of two waveguides and two-point defect micro-cavities. Optimum structure has the sensitivity of 500nm/RIU (refractive index unit) with a very small refractive index resolution as well as higher Q factor and higher transmission efficiency in the same refractive index range. Sensitivity of 500nm/RIU means resonance wavelength shifts up by 0.05 nm for a very small change of $\Delta n = 0.0001$ in the refractive index. Sensing function is also investigated for elliptical structure of defect and structure is also compared with double circle hole defect. Optimization of structure is done using by modeling of three air holes around micro-cavity to make sure high transmission efficiency.

F. Bagci and B. Akaoglu in 2013 [45] presented a based liquid refractive index sensor using photonic crystal waveguide slab structure with triangular array of holes. Its sensing mechanism is based on the shift in resonance wavelength due to selective infiltration of the lattice holes. The 3D plane wave expansion (PWE) and Finite Difference Time Domain (FDTD) methods are used to calculate the photonic band gap structure and transmission spectrum respectively. Sensitivity of the device is analyzed for the three different structures. In first case only the adjacent rows of the line-defect are infiltrated and get sensitivity of 53.3nm/RIU. In second case this analysis is repeated by varying hole diameters and sensitivity reached to a value of 60.02 nm/RIU. In third case

investigation is done for the effects of infiltrated holes which are placed in the line-defect and the sensitivity reaches to 282.4nm/RIU which is improved by 5.3 times. They did analysis for water, ethanol, isopropanol and xylene with respect to air for all three structures by monitoring the cut-off wavelength in transmission spectra and a linear relation is too observed for all cases over a RI range of 0.5 in between cut-off wavelength and surrounding RI change. The obtained results reveal that the PCW structures with small infiltrated holes have better sensing properties. So this particular design can be employed in miniaturized sensor with better sensitivity.

H. Dutta & S. Pal in 2013 [51] demonstrated a highly sensitive refractive index based bio-sensing platform using photonic crystal waveguide (PCW) platform on silicon-on-insulator substrate. The proposed structure has air in dielectric configuration where holes are arranged in triangular fashion with a lattice constant of 500nm and radius of hole is 200 nm. The linear waveguide is formed in sensor by reducing the dimension of holes of a row and in order to get better sensitivity modification is done in its surrounding holes. Simulations of the designed structure is done by using the three dimensional Finite Difference Time Domain (FDTD) method. The principle of sensing is based on the measurement of changes in the cut-off wavelength observed in output transmission spectra of waveguide due to change in refractive index. Results reveal that the sensitivity of the sensor mainly depends upon the geometric structure of the defect region and its surroundings. The results are verified for many different samples having refractive index range varying from 1 (air) to 1.57 (BSA, Bovine serum albumin). The value of sensitivity of the sensor is 260nm/RIU with a minimal detection limit of 0.001 RIU means cut-off wavelength get a shift of 148nm when waveguide is infiltrated with BSA (1.57) by replacing air (1.0). This high sensitivity is useful for the analyte detection having a low-concentration. The designed sensor can also be used for detection of samples that are generally limited in quantity, where only the defects can be infiltrated and shows a shift of 96-nm in cut-off wavelength which leads to a sensitivity of 168 nm/RIU. That's why it can be stated that proposed sensor can also be used for selective infiltration detection without much compromise with sensitivity.

S. Olyaei *et al.* in 2013 [65] designed and characterized an ultra small sized multi-channel biosensor based on the 2D photonic crystal having hexagonal lattice of air holes in the silicon slab. Combination of linear waveguides and nano-cavities is used to make highly parallel operation of four channel bio-sensor. Waveguides are created by removing a group of air holes and nano-cavities are made by changing the radius of air holes. The channels of this bio-sensor are able to detect four different analytes in a same time. Parallel operation of this designed biosensor is due to its special architecture. Analysis of the structure is done for each channel as bio-sensing platform which is based on the single hole sensing mechanism within the nano-cavity. By inducing the analyte in selected holes, the ERI of the nano-cavities will change, and the corresponding change will be present in the transmission spectra of the structure from which properties of the analyte can be determine. The biomaterials get trapped inside nano-cavities which cause changes in effective refractive index (ERI) which lead to the shift in resonant wavelength at the output terminal. It is observed that with increasing the ERI inside nano-cavities, resonant wavelengths get shift to higher values. The obtained results conclude that sensitivity and quality factor follows opposite trend. By increasing the radius of the nanocavity the sensitivity was improved where as the quality factor was decreased and vice-versa. That's why, an optimum state is selected. Optimized structure has characteristics of high transmission efficiency with high quality factor, and reasonable high sensitivity with the small amount of mass. This novel design can be used for biochemical sensing, protein detection and for the refractive index sensing.

Y. Zhang *et al.* in 2014 [66] proposed a novel highly compact refractive index based sensor formed by a cavity-based fiber loop ring-down structure in photonic crystal (PC) with high-quality (Q) theoretically. Sensing element is a nano-cavity which is inserted in a cavity ring-down fiber loop. Analysis and simulations of refractive index sensor are done using the finite difference time domain (FDTD) method. In proposed design a linear waveguide is created by missing a row of air holes. A pair of two air holes is inserted into the linear waveguide which are acting as reflectors and a nanocavity is formed by inducing point defect in between the two reflectors. As the output transmission spectra is highly sensitive to a minute refractive index change attributed to the analyte infiltrated in

the holes, parameters like the ring-down time as well as the output radiation intensity are functions of the effective refractive index for input light at certain wavelength in spectra. To improve the parameters sensitivity (S) and the quality-factor (Q) of structure is optimized by adjusting the radius holes inserted and the space in between reflectors situated around each side of nano-cavity. Results obtained shows a linear variation of refractive index is achieved with sensitivity of 20.34ms per refractive index unit (RIU) and Q-factor of 605 with low cost and simple structure which is easy to realize. The sensing range of system can also be broadened to 1.33–1.4 μm by using several operating frequencies. Due to minimized size of the designed sensor, it can be used in some harsh environments. In addition, the demonstrated structure has the ability to make lab-on-chip device for label-free sensing with reasonable high sensitivity and wide wavelength range.

P. Sharan *et al.* in 2014 [67] presented the procedure of early detection of cancer cell by use of photonic band gap PBG method. The detection of System level cancer cell is done with the dielectric constant of different cells taken as the input. The comparison of normal and cancerous cell has been done and accurate frequency shift has been noted at output. The dielectric constant of normal cell (healthy person) lies in the range of 1.8225 to 1.8769 whereas for cancerous cell it varies from 1.9376 to 1.9628. the sensitivity obtained is high as change in dielectric constant values is very minute but at output change in frequency is observed of micron range. The presented PC based bio-sensor is able to differentiate cancerous cells from normal cells. During analysis, light is made to localize in waveguide for particular band. By this procedure they consider these band values for various different cancer cells including normal cell also and plot a graph between obtained resonant frequencies and corresponding wave vectors. On observing the band shift of wavelength and comparing it with reference, they conclude that cell is infected or not. For early stage detection of cancer cells an efficient, sensitive and accurate method is proposed with resolution of the range of 10^{-5} to 10^{-2} .

Goyal and Pal in 2014 [73] represented Photonic crystal waveguide (PCW) based sensor structure with high sensitivity. PCW is created by inducing a local line defect in a perfect periodic PC structure. As sensor is made in silicon-on-insulator (SOI) material it is

suitable for fabrication with minimal losses. Optimization of sensor is done by etching of the circular holes arranged in silicon layer up to a finite depth underneath the oxide layer buried below silicon substrate and it is useful to sense various different aqueous analytes. Sensing mechanism is based on measurement of change in output due to variation in refractive index is used, which is measuring the shift in cut off wavelength by corresponding shift in effective refractive index of waveguide surface due to analytes. Simulations of structure are done by using 3-D finite difference time domain (FDTD) method when wavelength of $1.55\ \mu\text{m}$ is used at input which is mostly used wavelength in telecom industry. Structure is optimized by modeling two parameters, first is variation in defect radius and second is variation in etch depth. Further enhancement in sensitivity is done by over etching in the buried oxide layer while lattice constant and radius of defect hole are kept constant. Enhancement is due to more energy guided which can be explained in PCW that in horizontal direction light is confined by Bragg reflection and in vertical direction light is confined by total internal reflection. A very small amount of light radiates out in surrounding cladding layer, when the light propagation occurs through the PCW. Most of the component of the radiated energy retains near the interface of core and cladding. That's why using etching the hole up to some depth in cladding, radiated light can also be guided. Optimized structure shows sensitivity over a range of refractive index of 1.0 and 1.5 of 386nm/RIU.

CHAPTER 3

DESIGN AND ANALYSIS OF HIGHLY SENSITIVE PLATFORM FOR CANCER DETECTION

A bio-sensing platform based on nanocavity-coupled photonic crystal waveguide (PCW) is proposed for diseased cell detection. Proposed label-free waveguide-cavity coupled nanostructure exhibit high-Q, sensitivity and high selectivity against five different cancer cells. The introduction of a nanocavity in the PCW leads to a sharp resonance in transmission spectra which is used for detection of infected cells.

3.1 Structure of Proposed Design

The proposed design presents a nanocavity coupled waveguide structure as a label-free bio-sensing platform. Label free optical bio-sensing provides an easy way of sensing by eliminating the need of the fluorescent levels on analyte molecules. The dielectric in air configuration of PC is used where dielectric rods are arranged in a hexagonal array in silicon-on-insulator (SOI). SOI offers a high refractive index contrast for micron- and submicron sized optical cavities with high quality factor which is suitable for the fabrication of nano photonic circuits. The structure consists of a nanocavity acting as a resonant cavity which is closely coupled with straight bus waveguides which serve as optical input and output path for the device. The nanocavity coupled structure is providing light-matter interaction with minimal losses which increase sensitivity while keeping the sensor's dimensions small. Input source of wavelength 1550nm is used because telecom wavelength provides a minimum absorption losses. There is a dip in the water absorption spectrum at 1550nm so it is believed that 1550nm is a suitable wavelength for bio-sensing purposes [47]. Sensing approach is measurement of resonant wavelength shift in the transmission spectra because the resonant peak of high quality factor enables high detection resolution. Our main aim of this dissertation is to increase sensing parameters sensitivity and quality factor with minimal modulations in the design. Previously reported Q-factor and sensitivity values are needs to be improved for a better design of sensor. Q-factor of 2400 and 3000 with coupling distance of two and three

respectively in PC resonator biochemical sensor [53], sensitivity of 65.7nm/RIU using nanocavity resonator[65], 160nm/RIU using high-Q PC ring-slot structure has been reported [37] whereas using PCW based sensor, sensitivity of 282.4 nm/RIU [51], 174.8 nm/RIU [54], 260 nm/RIU [63] has been reported. Goal is achieved with optimization of the structure.

A Bio-sensing platform for cancer detection is presented using nano-cavity coupled waveguide structure as shown in **Fig.3.1**. According to the report given by World Health Organization (WHO) **CANCER** has become one of the leading disease worldwide resulting in increased morbidity and mortality. Due to increasing number of cancer cases everyday detection of cancer has been selected. In 2012, 14.1 million cases of cancer were detected and it is expected that within the next 2 decades, annual number of cancer cases will rise from 14 million in 2012 to 2022 [26]. Cancer can be cured if detected early, however the need of the hour is to develop a fast, efficient accurate method of detection and diagnosis in the early stages. Cancer cells show some distinct features from normal blood cells. Cancer cells normally have larger RI's than normal cells have, because of more amount of protein in their larger nucleus those results into the rapid cell division. The refractive index ranges of normal cell and cancerous cells are reported as 1.35-1.37 and 1.39-1.401 respectively [62,68]. The reported difference in the effective Refractive Index (ERI) is the principle of our photonic biosensor.

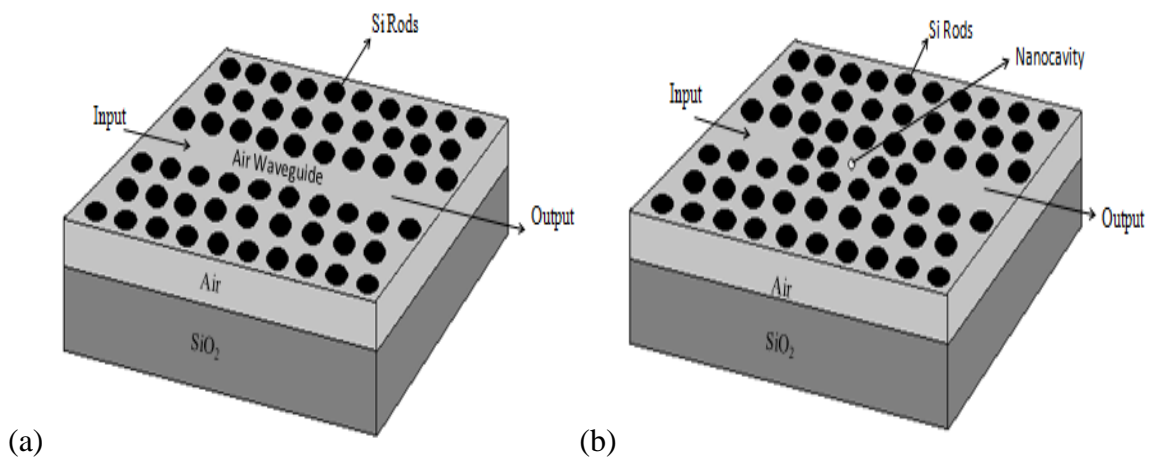


Fig. 3.1: (a) 3D View of dielectric profile a linear waveguide induced by removing a row of dielectric holes. Lattice constant $a=0.8\mu\text{m}$, radii of air-holes $r=0.3a$. (b) 3D View of dielectric profile of nanocavity coupled waveguide structure.

Dielectric rods of $\eta_{si}=3.42$ are arranged in hexagonal fashion in an air background of index 1 in the proposed design of bio-sensing platform. Distance between centers of two adjacent holes is $0.8\mu\text{m}$ known as lattice constant \mathbf{a} , radii of silicon holes is $r=0.3a$ ($0.240\mu\text{m}$). Dimensions of 2D slab are $19 \times 12\mu\text{m}^2$. The input source is set at 1550nm and boundary conditions are applied to reduce scattering losses. Plane Wave Expansion (PWE) method is used to calculate transmission spectra and get a TE PBG for normalized frequency of $0.5240 a/\lambda$ to $0.6698 a/\lambda$ i.e. $1.492\mu\text{m}$ to $1.908\mu\text{m}$ in terms of wavelength. Factors affecting PBG are the dielectric contrast of used materials and other one is dielectric lattice structure. Dielectric contrast of materials is proportional to width of PBG obtained.

The PBG property can be changed by introducing defect as defect introduced in the perfect crystal breaks symmetry and energy gets released. That's why photonic crystal cavity can act as centre for placement of analyte by placing it on top face of sensors. Defect can either be point defect or line defect. On introducing point defect, light can be localized means PC acts as resonator.

In this work we present a simple structure of biosensor, easy to fabricate with minimal transitions. By inducing line defect, a linear waveguide is created as shown in **Fig. 3.1(a)** and its corresponding transmission spectrum is shown in **Fig 3.2**.

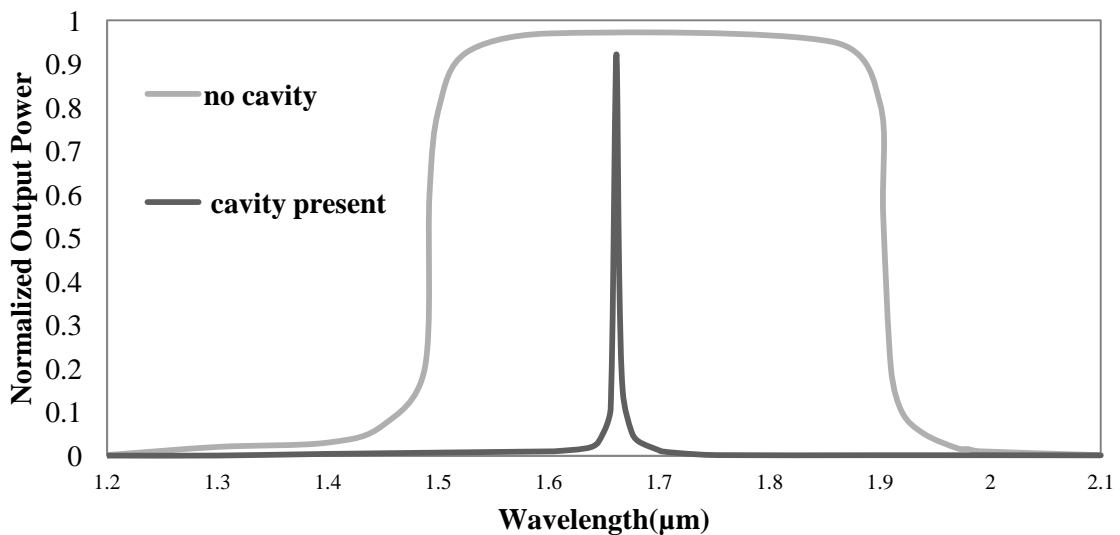


Fig. 3.2: Transmission spectra of Photonic crystal waveguide and cavity coupled waveguide

A broad PBG is obtained which is of no use of sensing. A point defect can be induced either by missing a hole or by changing its dimensions or by changing its material. It will break the periodic symmetry of PC structure and results into a guided mode within PBG which is good for sensing purpose. A point defect is created by missing a centre hole as shown in **Fig. 3.1(b)** which creates a coupled nanocavity within waveguide and for guided optical mode a resonant wavelength obtained at $1.661\ \mu\text{m}$ when no analyte was filled within point defect as shown in **Fig. 3.2**. Optimization of structure is done by changing the surrounding parameters around nanocavity. Optimized is done by changing mainly three design parameters i.e. by changing radius of central nanocavity, by shifting the adjacent holes and by changing the radius of adjacent hole. Our main concern of optimization is to give red-shift in resonant wavelength with increasing RI. Proposed bio-sensor makes use of this resonant wavelength as it shows variation with change in refractive index of cavity or by changing its surrounding structure. Our ultimate goals are high sensitivity and high Q-factor where sensitivity measures how much output of sensor is varying with minute changes in input [42] and quality factor is measuring, how selective it is i.e. desired resonant peak (varying position with different cancer cells) should be sharp and efficient enough so that it can be easily extract from undesired noisy peaks [66].

3.2 Software Description

Various numerical methods can be used for the analysis of PCs. The Plane Wave Expansion (PWE) and Finite Difference Time Domain (FDTD) are two methods which are widely used for the investigation of PCs. For accurate analysis of modified dielectric material full vector nature EM field is need to be studied as scalar wave approximation will not give accurate results. The method PWE is frequency domain formulation whereas FDTD is a time domain formulation. For the calculations of band diagrams and mode field patterns, PWE is a superior technique but dielectric constant imposed by PC material should be lossless and frequency independent. When there is a defect in the periodicity of crystal it results into large number of plane waves used for expansion then super-cell approach has to be used. On the other hand, using FDTD transmission and reflection spectra of finite structures can be calculated without difficulty and propagation

of the wave trough the medium can be observed in time. As frequency dependence and losses are also included in FDTD method. That's why FDTD method is more favorable. In fact calculation of band diagram using FDTD is difficult as the initial selection of the excitation field is important to excite all possible modes. High symmetry points shouldn't be selected as detection points because uniform meshing will not predict the characteristics properly at very sharp edges. Thus, analysis of PC structures is performed the by these two numerical methods which provide insight and great flexibility for the analysis of PCs. The highlights of PWM and FDTD methods are described in the following section. In all simulations, used materials are assumed as lossless. While not exact in reality, but this approximate treatment is good for calculations.

3.2.1 Plane Wave Expansion Method

In this dissertation, Photonic Band Gap (PBG) structures of periodic structure of Photonic Crystal (PC) are obtained in frequency domain. Plane Wave Expansion (PWE) method is doing computations in frequency domain. We can obtain photonic bandgap diagrams of PC and field distribution of incident light in the perturbed design of photonic crystal can also be obtained by using Eigen value equation. In plot of PBG, horizontal axis is representing Bloch's wave vector in reciprocal space of Irreducible Brillouin Zone (IBZ) of photonic lattice i.e. direction and period of Bloch wave and vertical axis is representing the normalized frequency of incident light which have a mode with that Bloch wave vector. We move around the perimeter of IBZ in small steps and at each step computation of the Eigen-value is done. On plotting all these Eigen-values as a function of β , all points are lined up to form continuous "bands". In this approximate computation information about inside of IBZ is missing in band diagram as we are taking points around the perimeter only. For each point in IBZ, an infinite set of Eigen frequencies is associated. The key points of symmetry are acting as Band extremes.

3.2.2 Finite Difference Time Domain Method

FDTD method was introduced by K. Yee in 1966 [69] and basic Yee cell is shown in **Fig. 3.3**. It allows the precise simulation of electrodynamic problems whose analytical solution is not possible. In this dissertation FDTD is used to calculate

transmission spectra exhibited by periodic structure of Photonic Crystal (PC). As Maxwell's equations describe the relation between electric field and magnetic field i.e. they describe that how a temporal change in E field is depending upon H field's spatial variation [69]. FDTD solves these Maxwell's curl equations and gives direct solution to users after calculating time evaluation of electromagnetic (EM) waves using Yee cells. The computational space is collection of Yee cells, which are composed in Cartesian coordinates by orthogonal components of electric and magnetic field. The continuous EM field is sampled in a finite volume of space at discrete points with second order accuracy. In Yee cell, field components are oriented in such a way that "leapfrog" time-stepping approach is possible [70].

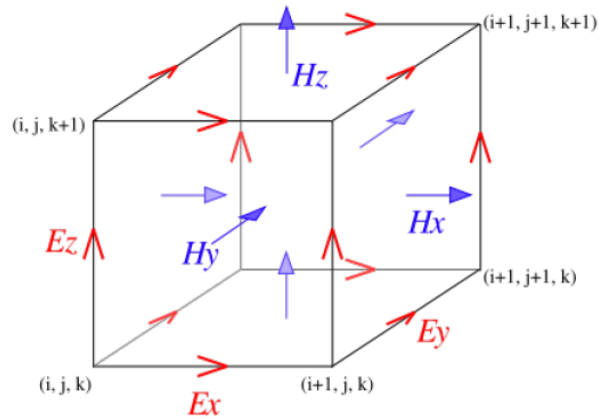


Fig.3.3: Yee cell for a three-dimensional FDTD simulation [69].

FDTD gives direct solutions of the curl equations by using second order difference approximations for space and time derivatives directly to the respective differential operators. Different field components can be obtained at different grid locations. It can be said that Maxwell's differential equations are replaced by finite differences in time domains to connect various EM field points obtained at one time interval to the points of next time interval. Only a single run of simulation is enough to attain response of wide frequency of the stimulated structure because of its time-domain nature. FDTD is a single run powerful and versatile tool which can be used easily to find broad spectral information of non-linear frequency dependent conducting materials. The

performance of FDTD method depends upon proper selection of mesh spacing Δx and time stepping Δt .

$$\Delta t \leq \frac{1}{c\sqrt{\Delta x^{-2} + \Delta y^{-2} + \Delta z^{-2}}}$$

This condition is called as Courant stability condition and it guarantees causality. The convergence of numerical simulation is ensured by the stability criterion. An adequate portion of the minimum wavelength component of the EM field should be sample by the mesh spacing Δx . Generally for accuracy [$\Delta x \leq \lambda_{\min}/20$] condition should be fulfilled. We can say its resolution completely depends on density of the Yee cells. As density of Yee cells increase simulation time also get increased. So it is the main trade off for the resolution of FDTD. Termination of vertical boundaries is done by perfectly matched layers (PML) which absorb incident radiations. The Gaussian wave is used as the excitation source for the calculation reflection and transmission spectra as it is made to span the frequency range of interest.

3.3 Design Methodology

A simple design of bio-sensor is presented using point and line defect using 2D photonic crystal as it shows almost all features of 3D structure and it is also easy to fabricate as compared to 3D crystals. Previously researchers modified the design of PC in numerous ways with an idea to enhance light matter interaction to support sensing parameters with minimal losses. Optimize of structure is done for improvements in parameters like sensitivity, selectivity, quality factor, mode volume, reliability etc. The Q-factor has been improved by modification of single air hole [15]. Deformation of lattice is also done to enhance quality-factor [27]. Some have changed the radii of whole line of air holes to increase quality factor [59]. Other way of modification followed is changing the radius of surrounding holes of cavity [29]. Even optimization is done by some researchers in a very unusual way, they did it by making a ring structure around cavity [54]. The most appropriate method is use of two reflectors each of which is made of two holes placed around cavity. Another researcher optimized structure by shifting adjacent holes of cavity

towards outward direction [9,64]. By taking inspiration from these last two methods, combination of both is followed in this dissertation.

As we discussed 2D crystals shows features almost same as 3D crystals but not exactly same. The 2D structures don't show complete photonic band gap as 3D structures show. For the same reason there are energy losses in 2D photonic crystal slabs as these structures show photonic band gap in the lateral direction only, no band gap in the vertical direction. These energy losses affect quality factor. According to formula energy losses are inversely proportional to quality factor [54].

$$\frac{1}{Q} = \frac{1}{Q_{\parallel}} + \frac{1}{Q_{\perp}}$$

The number of PC layers will determine the leakage in the lateral direction. Here, Q_{\parallel} will describe lateral losses and Q_{\perp} will describe radiation losses. As energy loss in the lateral direction can be controlled by increasing the number of PC layers. Main problem is optimization of vertical Q-factor in 2D crystal. A number of ways have been presented to increase Q by reducing energy losses in the vertical direction [13]. The simplest way proposed is to increase the length of defect. By doing so mode volume became large means reduction in the leaky modes. But, for miniaturization of devices large mode volume is not acceptable. Another method followed to reduce k-vector components inside light cone is the symmetry of filed distribution of cavity. By exact choice of defect size and its field distribution, the defect modes with odd symmetry will be created with respect to the normal plane of dominant contributions. One more method followed is the alteration of filed envelope of cavity mode. The affect of sudden change in cavity edge can be suppressed by choice of Gaussian filed envelope [71].

The approach deployed in this dissertation to get Gaussian field distribution of cavity modes and to minimize leaky wave vector components in the cavity mode is to design the structure by modification of nearest two surrounding dielectric holes of cavity. The structure is designed in a way to decrease losses due to out of plane radiation and in turn, Q factor is increased without an increase in mode volume of cavity. Thus, a cavity is designed which provide strong light matter interaction and results into proper confinement of the light. FDTD simulations are performed for computation of resonant modes in output transmission spectrum. A high Q factor with reasonable sensitivity is achieved.

3.4 Results and discussion

In this section, each step of design is discussed with obtained results.

3.4.1 Optimal radius of nano-cavity

First of all, it is needed to be finding out the area where analyte is to be placed for detection procedure. On simply missing a center hole from perfect photonic crystal, a resonance obtained at wavelength $1.661\mu\text{m}$ in transmission spectra as shown in **Fig.3.2**, it occurred because light get localized in cavity due to induced point defect. A minimum area should be covered with blood sample to reduce amount of blood sample required for efficient detection. To find this essential area, a nanocavity is created which is filled with healthy person's blood having refractive index 1.35 and simulations are observed for different radii $0.12a$ to $0.18a$ with an increment of $0.02a$ to analyze parameters sensitivity and q-factor. A radius is to be selected where both parameters show a significant value. Results obtained for resonant wavelength and both sensing parameters with varying radius are shown in **Table 1**.

Table 1: Values obtained of resonant wavelength, sensitivity and quality-factor for varying radius of center hole.

Center-hole-radius (μm)	Resonant at (μm)	Sensitivity (nm/RIU)	Q-factor (unitless)
$0.12\times a$	1.691	85.82	2818
$0.14\times a$	1.696	102.82	2781
$0.16\times a$	1.712	146.53	2717
$0.18\times a$	1.721	172.74	2495

It is noticed that on increasing radius there is favorable increase in resonant wavelength as well as sensitivity with but q-factor is going downwards and after $0.16a$ there is sudden drop in q-factor. That's why with regard to simulation results, radius $0.16a$ found as the optimized radius of nanocavity, because of its favorable outputs like high sensitivity with reasonable q-factor which could make detection possible. The variation of resonant wavelength, sensitivity and quality factor for every radius is shown in **Fig. 3.4**.

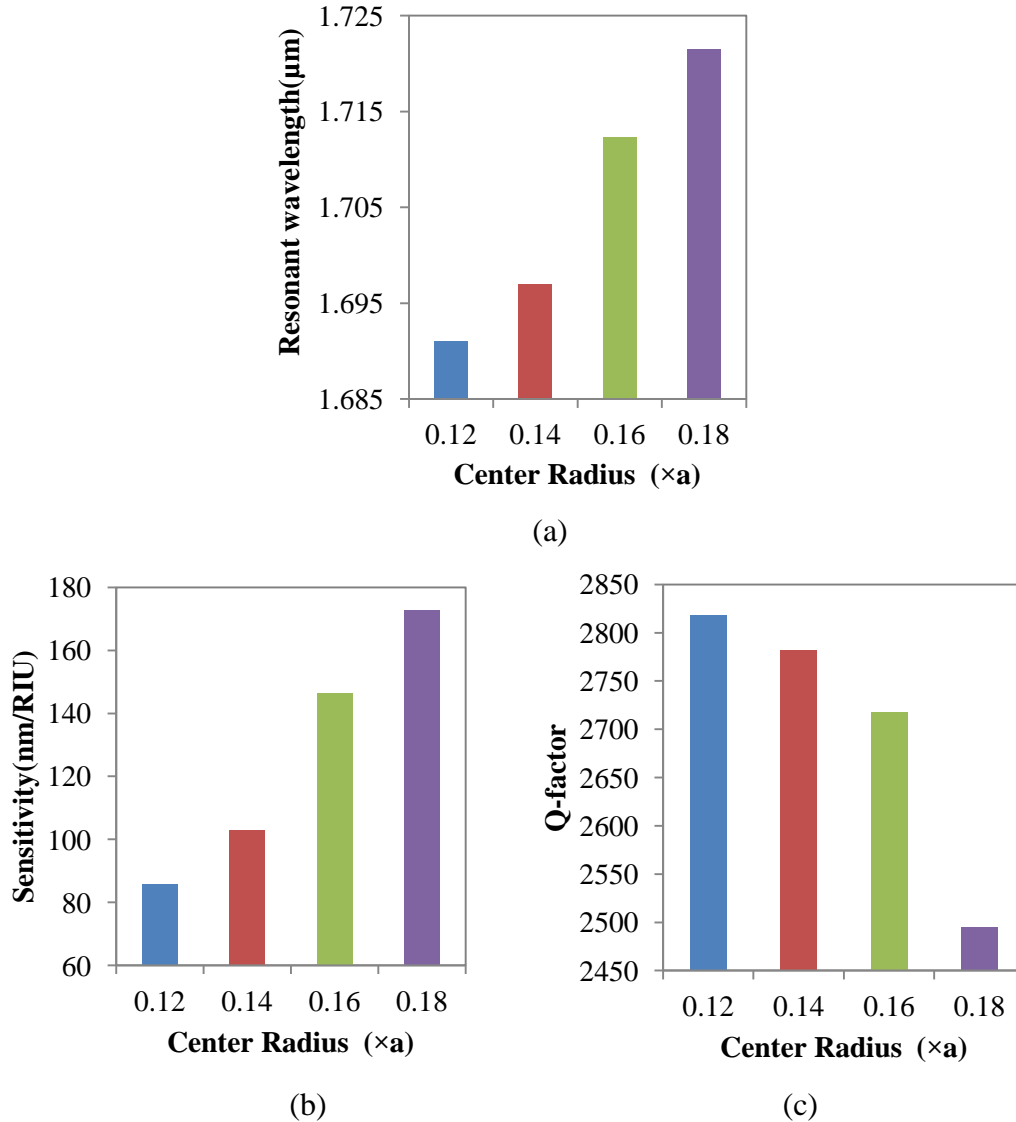


Fig. 3.4: Variation of (a) Resonant wavelength (b) Sensitivity (c) Q-factor with change in radius of point defect. Lattice constant $a=0.8\mu\text{m}$, radii of Si-holes $r=0.3a$, radii of defect varies from $0.12a$ to $0.18a$ with an increment of $0.02a$.

3.4.2 Performance of Unoptimized Bio-sensor

In previous step, radius has been found which is to be essentially covered with blood sample. Here, performance of bio-sensor is checked for five different cancer cells. The propagation velocity of light get reduced when it passes through analytes having more refractive indices than that of air and water and signals results differently due to change in optical properties according to ERI which can be easily detected and measured. Due to

the same reason filling of each sample gives independent shift in the resonant wavelength. It is assumed that RI of nanocavity in PC is varied according to blood samples and corresponding change is appeared at output in transmission spectra. Database for different five cancer cell lines along with healthy person's blood is shown in **Table2** with Values obtained of resonant wavelength and both sensing parameters.

Table 2: Variation of resonant wavelength, sensitivity and quality-factor for five different cancer cell lines with their varying refractive index.

Different cell	Refractive Index	Resonant at (μm)	Sensitivity (nm/RIU)	Q-factor (unitless)
Normal	1.35	1.7122	146.53	2718
Jurkat	1.39	1.7195	150.14	2456
HeLa	1.391998	1.7199	150.31	2356
PC-12	1.395	1.7205	150.81	2263
MDA-MB-231	1.399	1.7213	151.20	2178
MCF-7	1.401	1.7216	151.33	2125

The transmission spectrum of corresponding unoptimized bio-sensor is shown in **Fig.3.5**. The variation in resonant wavelength, sensitivity and Q-factor for different cell lines including normal cell also is shown in **Fig. 3.6** for an un-optimized bio-sensor.

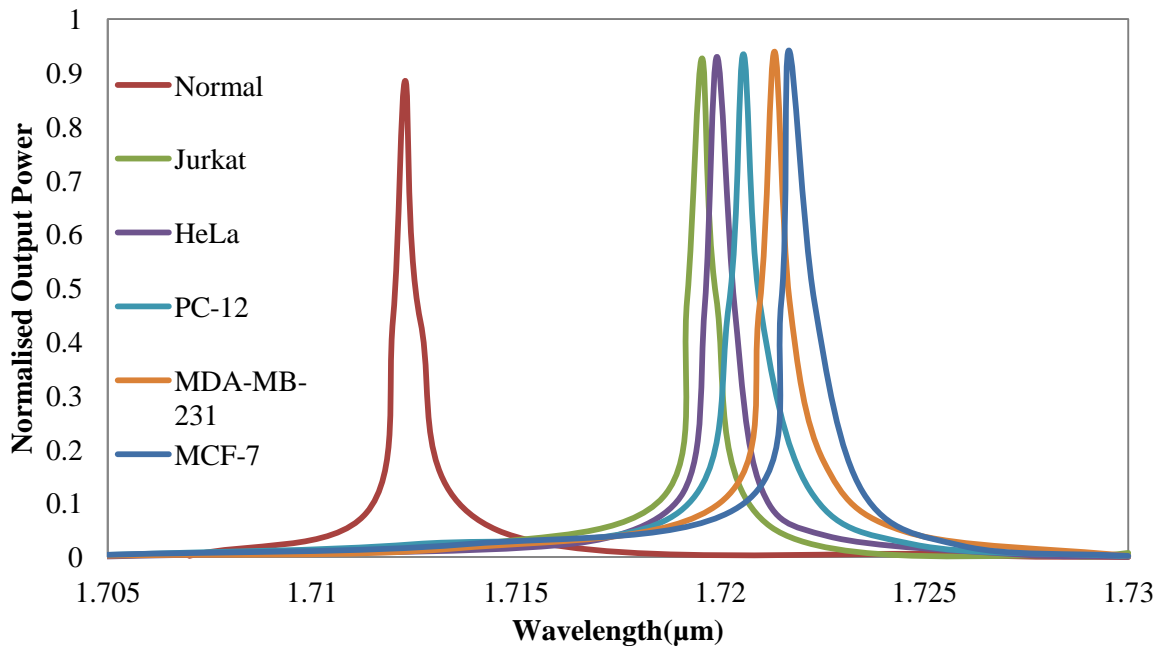


Fig 3.5: Normalized transmission spectra of unoptimized bio-sensor, Lattice constant $a=0.8\mu\text{m}$, radii of Si-holes $r=0.3a$, radius of nanocavity is $0.16a$.

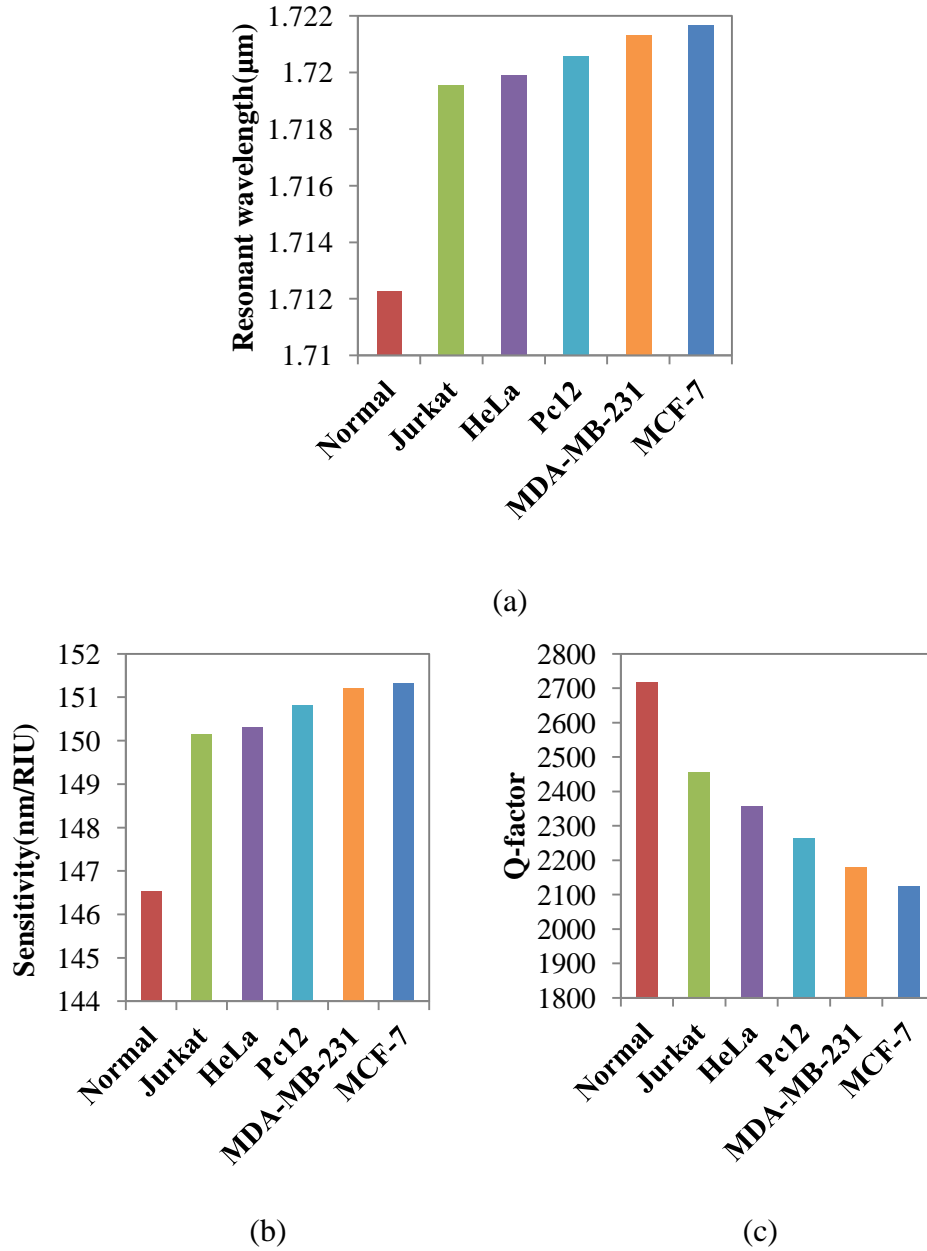


Fig. 3.6: Variation of (a) Resonant wavelength (b) Sensitivity (c) Q-factor for unoptimized bio-sensor by placing different cancer cell lines in nanocavity of radius of $0.16a$. Lattice constant $a=0.8\mu\text{m}$, radii of Si-holes $r=0.3a$, radius of nanocavity is $0.16a$.

It is noticed that structure is able to differentiate cancer cells on observing their respective resonant peaks. Results are shown for five different cancer cell lines including blood sample of healthy person. Normal blood sample can be easily differentiate from infected blood samples but peaks for different cancer lines lies very close to each other and peaks are not so sharp i.e. quality factor is not as high as required for efficient

detection. Next mandatory step is to increase Q-factor without any compromise with sensitivity of sensor. It is observed that different cell lines show different response.

3.4.3 Optimization of Proposed Structure

To make sensor highly accurate, efficient and selective, the structure is needed to be optimized by changing surrounding parameters of nanocavity as discussed in **Table 3**. Optimization is done by shifting the adjacent holes named as A and B towards outside and by increasing the radius of adjacent hole named as A to the cavity.

Table 3: Steps taken to optimize proposed structure.

Step no.	A-shift (μm)	B-shift (μm)	C-shift (μm)	A-radius (μm)	Resonant at (μm)	Sensitivity (nm/RIU)	Q-factor
0	0	0	0	$0.3 \times a$	1.70373	122.08	2542.88
1	0.15	0	0	$0.3 \times a$	1.745	240	3355.76
2	0.19	0	0	$0.3 \times a$	1.75372	264.91	3579.02
3	0.2	0	0	$0.3 \times a$	1.74279	233.68	3288.28
4	0.19	0.15	0	$0.3 \times a$	1.7586	278.85	3908
5	0.19	0.2	0	$0.3 \times a$	1.75961	281.74	4291.73
6	0.19	0.21	0	$0.3 \times a$	1.758	277.14	2930
7	0.19	0.2	0.075	$0.3 \times a$	1.79692	388.34	4549.16
8	0.19	0.2	0.1	$0.3 \times a$	1.80244	404.11	3466.23
9	0.19	0.2	0.075	$0.28 \times a$	1.79171	373.45	4702.65
10	0.19	0.2	0.075	$0.312 \times a$	1.797	388.57	4856.75

The first step for optimization is to shift the adjacent holes away from nanocavity named as A and by shifting step by step we observe the $0.19\mu\text{m}$ is the maximum shift to show red shift in resonant wavelength and $1.75372\mu\text{m}$ is obtained as max value of resonant wavelength. On further shifting A, resonant wavelength get shifted to lower value of $1.74279\mu\text{m}$ and simultaneously S and Q also get reduced as discussed in table. Similarly in next step we shift the holes named as B and find $0.20\mu\text{m}$ as the best with resonant wavelength of $1.75961\mu\text{m}$. For further enhancement, shift the holes named as C

and get $0.075\mu\text{m}$ as the optimized distance and resonant wavelength get reached to $1.79692\mu\text{m}$. On further shifting hole C, as resonant wavelength is getting red-shift means sensitivity is also increasing but Q-factor is going downwards. That's why further shift in C-hole is skipped as we want both parameters high simultaneously. Values obtained after shifts in adjacent holes are A-shift= $0.19\mu\text{m}$, B-shift= $0.20\mu\text{m}$ and C-shift= $0.075\mu\text{m}$. Next enhancement in parameters is done by changing the radius of adjacent holes. It is observed that by decreasing the radius of A-hole to $0.28a$, Q-factor gets incremented but on the cost of reduction in sensitivity which is not acceptable and on increasing the radius of A-hole to $0.312a$, a negative shift in resonant wavelength and increment in Q-factor is obtained without any compromise in sensitivity. In this way, an optimized radius of adjacent holes is obtained. **Fig. 3.7** is showing the optimized structure.

During simulation, it is observed that generally sensitivity and Q-factor follows opposite trend. If sensitivity is increasing then there is decrement in Q-factor and vice-versa but we need both parameters high as possible parallel. In proposed structure both parameters achieved an acceptable value with optimization.

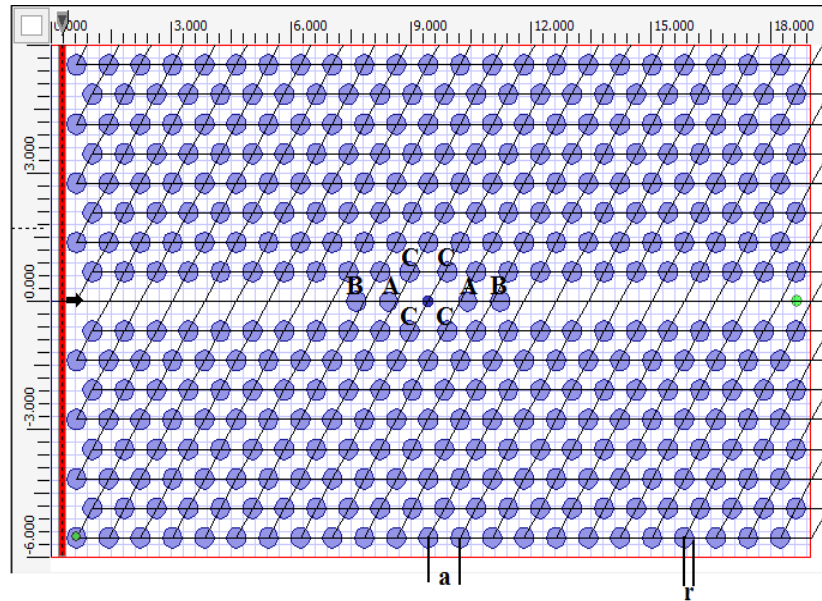


Fig. 3.7: Optimized structure of proposed bio-sensor with Lattice constant $a=0.8\mu\text{m}$, radii of Si-holes $r=0.3a$, radius of nanocavity= $0.16a$. A-shift = $0.19\mu\text{m}$, B-shift = $0.20\mu\text{m}$, C-shift = $0.075\mu\text{m}$, A-radius= $0.312a$.

3.4.4 Performance of Optimized Bio-sensor

Optimized structure is obtained in last step. In this step, transmission spectrum of different cancer cell lines including normal cell for Optimized structure is observed. **Table 4** shows the values of resonant wavelength, sensitivity and quality-factor of all different cells for optimized structure and corresponding transmission spectrum is shown in **Fig. 3.8**. Variations in the resonant wavelength, sensitivity and quality-factor are shown in **Fig. 3.9**.

Table 4: Variation of resonant wavelength, sensitivity and quality-factor for five different cancer cell lines with their varying refractive index for optimized bio-sensor.

Different cell	Refractive Index	Resonant at (μm)	Sensitivity (nm/RIU)	Q-factor (unitless)
Normal	1.35	1.7970	388.57	4856
Jurkat	1.39	1.8132	390.41	4850
HeLa	1.391998	1.8141	390.59	4503
PC-12	1.395	1.8154	390.93	4476
MDA-MB-231	1.399	1.8171	391.37	4442
MCF-7	1.401	1.8180	391.60	4402

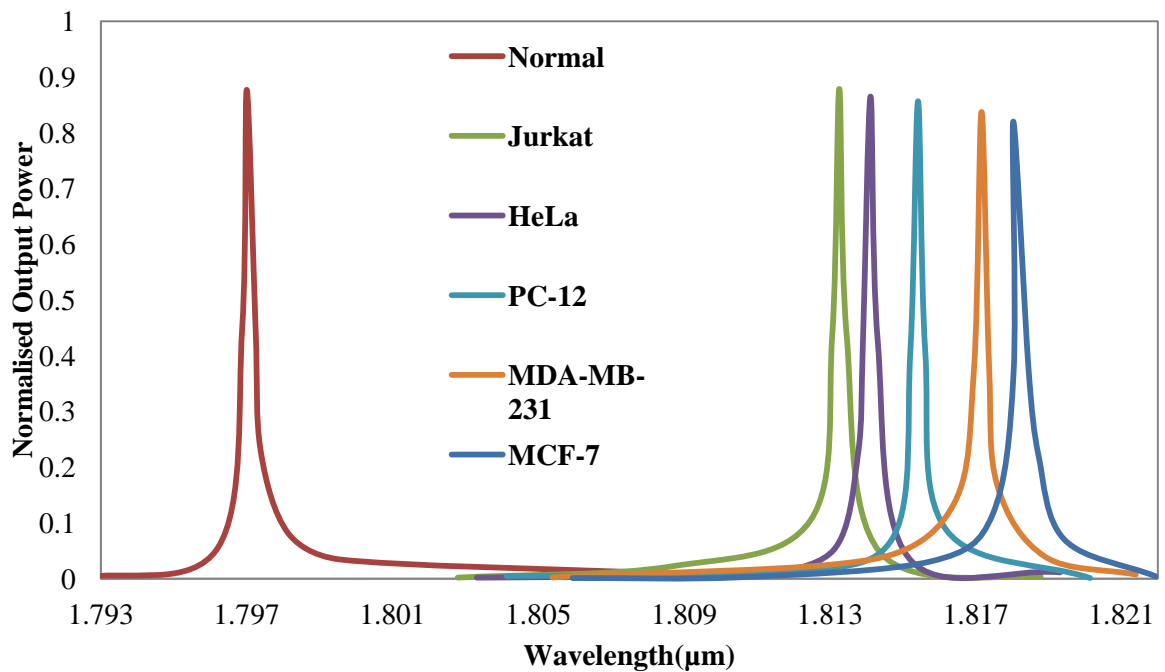
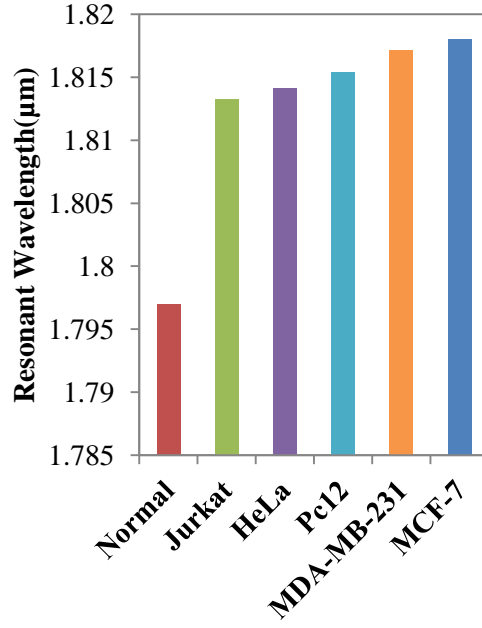
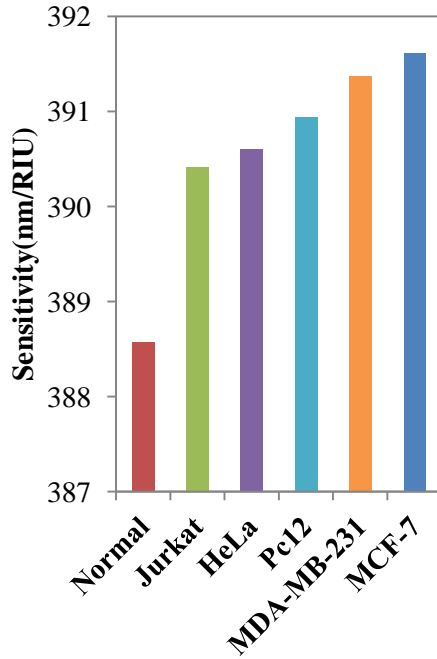


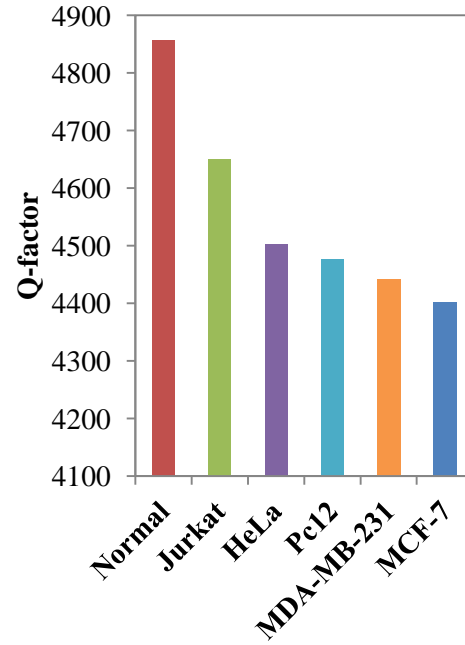
Fig. 3.8: Normalized transmission spectra of optimized bio-sensor. Lattice constant $a=0.8\mu\text{m}$, radii of Si-holes $r=0.3a$, radius of nanocavity is $0.16a$. A-shift = $0.19\mu\text{m}$, B-shift = $0.20\mu\text{m}$, C-shift = $0.075\mu\text{m}$, A-radius = $0.312a$.



(a)



(b)



(c)

Fig. 3.9: Variation of (a) Resonant wavelength (b) Sensitivity (c) Q-factor for optimized bio-sensor by placing different cancer cells in nanocavity of radius of $0.16a$. Lattice constant $a=0.8\mu\text{m}$, radii of Si-holes $r=0.3a$, A-shift = $0.19\mu\text{m}$, B-shift = $0.20\mu\text{m}$, C-shift = $0.075\mu\text{m}$, A-radius = $0.312a$

In comparison to unoptimized bio-sensor, a great change is notified in values of sensitivity and quality-factor which is desirable. It can be seen that there is a very small difference of 0.001998 between ERI of Jurkat and HeLa cell line still our demonstrated structure is able to differentiate this slight change by simple observation of resonant peak in transmission spectra. Even for the minute change in the input RI, the PC based bio-sensor provides distinct change in the output wavelength means giving very sensitive results. Observed resonant peaks are sharp and narrow enough to give efficient and accurate detection for all five different cancer cell lines means giving reasonable high Q-factor. With placement of each blood sample as input changes, its resonant peak in transmission spectra is shifting, hence each transmission spectrum is acting as a signature of the corresponding sample for the designed optimized bio-sensor.

3.4.5 Linear behavior of resonant wavelength and refractive index

A makeable observation is done during simulations that there is a linear relation in between resonant wavelength and refractive index. As effective refractive index (ERI) is increasing due to placement of different blood sample, resonant wavelength is also linearly shifting towards higher wavelengths. This linear relationship of resonant wavelength and refractive index is also shown in **Fig. 3.10**.

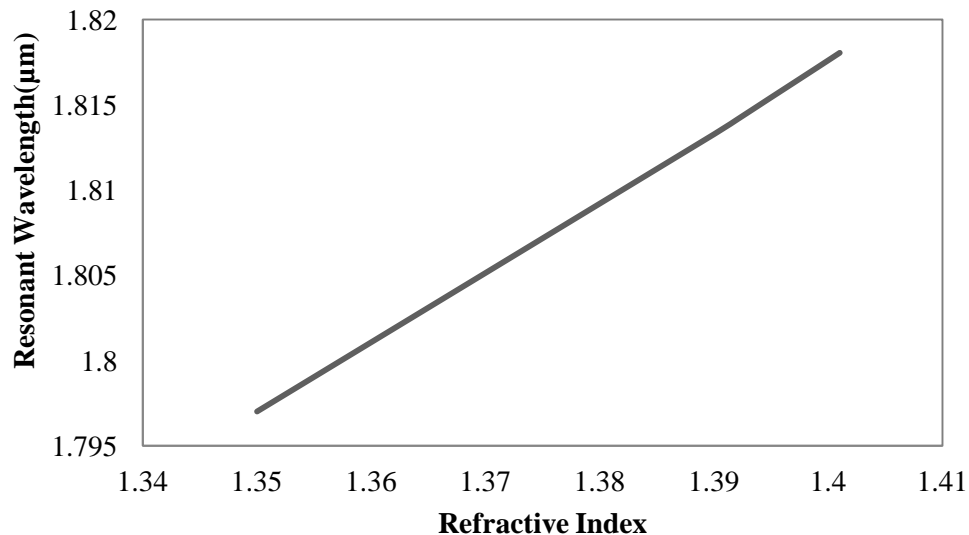


Fig. 3.10: Linear behavior of resonant wavelength with respect to refractive indices of cancer cell lines.

CHAPTER 4

CONCLUSION AND FUTURE SCOPE

Currently less than 0.1% of the world total analytical market is using bio-sensors. Without any doubt bio-sensors have got remarkable applications in case of healthcare. But, the level of reliability, knowledge, cost, superiority, availability and marketing will decide whether bio-sensors will be popular in future or not.

A bio-sensing platform for cancer-cell detection is proposed based on nanocavity coupled photonic crystal waveguide. The mechanism of bio-sensing is change in effective refractive index (ERI) of the sensing hole. Proposed nanostructured platform shows acceptably large values of transmission efficiency, sensitivity, selectivity and Q-factor. The insertion of nanocavity in PCW causes sharp resonance in the transmission spectra which makes it possible to realize cell-level detection of cancer. The analysis is performed on different cancer cell lines using FDTD method. Presence of different cancer cell-lines in blood samples is detected by measuring the resonance shift in transmission spectra of proposed nanocavity coupled PCW. The mechanism of shifting in the resonant wavelength at output terminal is for the reason that of ERI of the cavity gets variation with placement of different bio-molecules. This device needs very small surface to be covered with blood sample which reduced the required amount to a great extent. Reduction in the blood specimen will allow persistent monitoring of blood chemistries and also reduce the chances of infectious contamination from patient blood.

The performance of this sensor is improved by optimization of structure results into high sensitivity and reasonable Q factor with appropriate mass. Optimization is done by changing the radius of nanocavity, shifting of adjacent holes and by changing the radius of adjacent holes which results in a significant improvement in sensitivity as well as Q-factor. The results obtained reveals that sensitivity can be improved by larger radius and Q-factor can be improved by smaller radius. For this reason, an optimum state has been chosen. The reported work is useful as the proposed sensing platform is easy-to-fabricate and has large fabrication tolerance. In future, further reduction in the complexity of structure can be reduced by use of 1D crystal. It would be a challenge for researchers to

do same sensing with 1D crystal. The presence of single nanocavity on a photonic crystal waveguide of linear single defect makes the structure easy-to-fabricate. Proposed on-chip bio-photonic sensor can be a promising platform to detect diseases at cell level.

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LIST OF PUBLICATIONS

Saronika, Mukesh Kumar, Siddharth Sharma, Manoj K. Pal “Nanocavity-coupled Photonic Crystal Waveguide as Highly Sensitive Platform for Cancer Detection” submitted to IEEE sensors journal, 2015.