"Analysis of Dispersion Properties of Photonic Crystal Slabs"

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DECLARATION

I Aayushi Wadhwa, hereby certify that the work which is being presented in dissertation entitled "Analysis of Dispersion Properties of Photonic Crystal Slabs" is an authentic record of my study carried out as requirement for the award of degree of ME (Electronics and Communication Engineering) at Thapar University, Patiala, under the supervision of "Dr. Mukesh Kumar".

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

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ABSTRACT

Line-defect waveguides in photonic crystals are receiving considerable attention because their waveguiding mechanism is fundamentally different from that of conventional dielectric waveguides, such as optical fibres, which rely on total internal reflection. It has various unique properties which cannot be provided by conventional waveguides such as realization of sharp bends and group velocity dispersion characteristics that differ greatly from conventional waveguides. This structure is based on silicon photonics which allow different optical components to connect each other using silicon waveguide to establish very fast communication between circuit boards, between chips on a board, or even within single chips.

The present work aims at the designing, simulation and analysis of a structure on SOI based on hexagonal lattice of two dimensional photonic crystal with flat dispersion over a large wavelength band, low propagation loss and polarization dependent single mode photonic crystal waveguide. By varying various parameters such as diameter of air holes *(d)*, lattice constant *(a)* analysis has been done for an optimum profile and low propagation loss is realized. At photonic waveguide parameters, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes *(d)* is 0.44 µm, and lattice constant *(a)* is 0.9 µm at the wavelength of 1.55 µm. The low propagation loss is estimated to be of 3.6 dB/ mm. Although the largest negative dispersion value of $19.9x10^4$ ps/nm km is calculated for *d*= 0.44 µm and *a*= 0.5 µm but desired structure has been achieved at *d*= .44 µm and *a*= 1 µm of flat dispersion in a range of $1.375x10^4$ ps/nm km to $0.913x10^4$ ps/nm km with the wavelength range of 1.55 µm to 1.65 µm. The characteristics of both the TE and TM like polarization exhibit periodicity at *a*= 0.8 µm and *a*= 1.0 µm of lattice constant the effective group index for both polarizations coincide at the wavelength of 1.55 µm. Polarization dependent loss and polarization dependent dispersion characteristics are also analysed with proposed structure. Such waveguides can also find applications in generation of slow light which is a promising solution for buffering and time-domain processing of optical signals and also offers the possibility for spatial compression of optical energy and the enhancement of linear and nonlinear optical effects.

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Introduction to Photonic Crystals

1.1 Motivation

In the last few decades, tremendous changes have been brought to our society and the life of people with the new advancement of semiconductor technology. The diminishing to the intense for electronic devices was assaulted by setting the trend of higher denseness of integration and fastest processors. The large resistance and consequently long delay time correlated with the small feature size, and the synchronization problems become more and more serious issue for electronic devices that emerging due to the high speed of transmission of data [1].

At this present century, there is a probability that the role which electronic devices nowadays have in our lives may have been replaced by highly potential photonic devices soon. As it is matter of fact that light can propagates faster than anything. The bandwidth can be provide by photonic devices is much higher than that can be provide by conventional electronic devices due to the high frequency nature of the light. Photons are not restricted by the Pauli Exclusion Principle as photons are bosons. And hence, readily high density of photon field can be achieved. It specifies that the energy density of electronic devices can be much lesser than the energy density of light. Lasers are the standard citation. At room temperature high losses are exhibit by electrons in solids as they are frequently scattered by phonons and impurities. In general it is not possible to build coherent electronic devices due to the far reaching effect of scattering which changes de Broglie wavelength, by changing the energy of the electrons. In case of photonic devices, by doing proper choices of medium the losses of power can be scale down to minimum. Whereas, for most of medium the light loses a small portion of its power while traveling, but the inflexible scattering of light is negligibly small. That is the reason behind the maintenance of the coherence of light throughout its propagation. The cohesiveness of light is important to its role in the information age.

Encouragement for using optical communication includes:

1. Optical communication links have a wider bandwidth than copper or microwave links, so more information can be carried on a given link. The effective bandwidth of current optical fibers is approximately 25 THz.

2. Attenuation in glass fibers is less than experienced in copper or microwave systems. Fewer repeaters are required, and longer distances can be spanned more cost effectively.

3. Optical systems are smaller and lighter, giving them an advantage in crowded ducts or aircraft.

4. Optical waveguides are difficult (but not impossible) to tap or monitor, so data security is higher.

5. Optical waveguides are immune from electromagnetic interference, ground loops, induced cross talk, etc.

6. Finally, and perhaps most important, semiconductor technology has developed a family of lasers, detectors, and other integrated optical devices that are compatible with optical fibers in power, wavelength, and size.

1.2 Photonic Crystals- Fundamentals and Applications

1.2.1 Photonic Crystals Fundamentals

To open up new expansions of encourage for the development of all optical integrated circuits, photonic crystals are entirely exploit the coherent nature of the light. The first photonic bandgap materials or photonic crystal was proposed and fabricated by Yablonovitch [2], which was initially suggested by Sanjeev John. He added to his study the anomalous absorption of light in a disordered medium [3], therefore the basic idea of photonic crystals can be traced back to early works done by him first, where he observed the characteristics of localization in anomalous absorption. While continuing with his work on anomalous absorption he realize that even when the disorder in medium is only moderate still there is always strong localization due to the existence of band gap in the spectrum of photons. The size of unit cells of the crystal lattice is almost comparable to the wavelength of the light which is the basic feature of photonic crystal. On considering the Bragg reflectors or mirrors, the Bragg reflected waves interfere with the original beam when light travels inside the crystal. The reflected waves either interfere constructively or destructively and resulted coherence would fully change the dispersion relationship of the propagating waves and the homogeneous distribution of the light field inside the crystal. In other words we can conclude, the situation is almost the same in which scattering of periodic lattice would fully change the electron energy spectrum as an electron travelling inside a solid. The electron spectrum found from purely periodic ionic lattice is not exact because many body effects in the solid like the thermal motion of the atoms, the presence of defects and the presence of impurities. And these results lead to the strong determination of the true spectrum which is a very difficult problem. The Maxwell equations which is linear if no nonlinear constitutive relation of the materials is involved, is basically used to govern the scattering of light which exhibit purely electromagnetic in nature. Therefore, the problem can be resolved easily. Thus the high accuracy has been achieved by the people in designing of materials. The problems of thermal scattering and many body effects are generally not present in photonic crystal. The thermal expansion of the materials is largely controllable and leads to a small shift of the operating wavelength (about a few nm for particular electronic devices under particular operating environment the temperature deviates), which is restricted by the Thermal effects only.

In the near future, the whole scenario of light guiding has been change by the usage of photonic bandgap materials which has potential of doing the same. In case of classical waveguides which are operated at optical range can guide the light by the total internal reflection which occurs at the boundary of the waveguide. Whereas the waveguide operated at microwave range has quite different scenario like if the metallic waveguides are used. Thus it shows that there are no constraints on the reflection angle but internal reflections can be limited when we consider the propagation of microwave in such as metallic waveguides. At optical frequencies for waveguiding the dielectric waveguides are the obvious choice because metallic waveguides resulting in tremendous losses. Whereas, with respect to the waveguide surfaces the reflection is confine to small incident angles only. A new “convolution” on guiding of light has been put with the development of photonic crystals. The light does not able to propagate inside the crystal when the frequency of the light falls in the bandgap of the photonic crystal or photonic bandgap. For any incident angle such light will be reflected completely whenever light is incident onto the surface of the crystal. A great deal of flexibility for guiding the light is provided by it. A well suitable example is for guiding the light via a sharp bend gives very large efficiency [4]. Many of the groups conduct the experimental studies and calculate efficiency numerically for various photonic waveguides [1, 5]. Hence, analytical studies lag afterwards. A detailed analysis is a difficult task in comparison to the analysis of the traditional dielectric waveguide because of the existence of complication of the field patterns inside the crystal [6].

1.2.2 Photonic Crystals Applications

The belief of photonic crystal is really appealing, but the actual implementation is not easy. A thumb rule is that generally the lattice constant of the photonic crystal that is a constant distance between centre of two nearest neighboring air-holes is about one half to one third of the operating wavelength. Even if the operating wavelength chosen is at the infrared range, of about 1.55 μm, this means a lattice constant of about 0.7 to 1.3 μm. And the rest of parameters inside the cell should also be smaller in dimensions. This happens as per the technological limitations of the best microlithography techniques. For improvement in fabrication of such small featured devices X-ray lithography and electron beam lithography are two possible choices.

However, for the continuous study in the various areas photonic crystals have such capabilities to become a strong dynamic force. The one of the most promising application in photonic crystals is high quality factor Q cavity [1]. Mainly laser generation desire this type of high Qcavity. The density of states per unit volume for free photon is proportional to

$$\frac{1}{w\lambda^3} \tag{1.1}$$

The density of state simply falls to zero if the frequency of operation falls within the bandgap of photonic crystal. The density of states close to the frequency of the localized state get fully changes by introducing localized states with frequency in the gap. The density of states per unit volume for the resonant frequency proportional to

$$\frac{1}{\Delta w \Omega} \tag{1.2}$$

Where, Δw represent the frequency width of the resonance and Ω represent the effective spatial volume. The improvement factor is then roughly given by

$$\frac{w}{\Delta w}\frac{\lambda^3}{\Omega} = \frac{Q}{\Omega/\lambda^3} \tag{1.3}$$

is nothing but the quality factor of the cavity. Important improvement of spontaneous emission occurs which is resulting from small spatial volumes and high Q quality factor. The largest improvement available is almost Q when the smallest volume Ω have an order of the λ^3. It is crucial to fabricate cavities with spatial dimensions which are comparable to the wavelength of light in order to achieve such largest improvement factors. Though the fabrication of cavities requires lithographic techniques but for the realization of such microcavities, single defect photonic crystals are one of the simplest techniques. But the surface disorder which will surely be present due to the small feature size will not be able to effect upon the quality of the microcavities. This insensitiveness of surface disorder on the quality of microcavity gives the hope to fabricate it of practical use.

Another notable application of the photonic crystal is concern to the channel drop filters. This is basically an essential component of wavelength division multiplexing devices. It is not practicable to replace all of the telecommunication optical fibers installed with new fibers of multiple channels. The capabilities of telecommunication channels presently in use are readily being reached to its limits because of the exceptional advancement of Internet. Within two or three years the uncertain advancement may lead these new fibers to go extinct. The wavelength division multiplexing scheme acquire more popularity for multiplication of the communication capacity of currently installed fibers in order to enhance the handling of the currently installed optical fibers. One way is to simply break the complete information to be transmitted, and convert it into some codes, put those codes into optical channels of different wavelength and then transference of information occurs. However, this wavelength says 1.55 μm of infrared range lying in the attenuation windows of the fibers. To limit crosstalk and interference between different channels it is require maintaining a minimum separation between channels for these reason available wavelengths are closely limited. With wavelength division multiplexing technology the bandwidth of every individual channel must not be less than 0.5 nm and the distance between two channels is about 1.6 nm. In order to achieve these compelling requirements, the practical challenges are face by optical device designing.

Specifically the present optical filter technology gives challenge to the add-drop process in the wavelength division multiplexing scenario. Now days it is require having ultra-narrow passband width, low insertion losses and flat-top transfer function for sharp edges. It was first proposed by Fan *et. al.* [7] that the bandgap in photonic material provide a recent resolution to wavelength division multiplexing filters. A resonator system is used which provide side coupling between the two waveguides. Microcavities that create by introducing defects inside the photonic crystals thus form resonator systems. When any signal having pre-defined frequency paired up with the resonator system is fully transferred from one waveguide to the another waveguide the optimized channel get achieve by keeping rest of other signals unaltered.

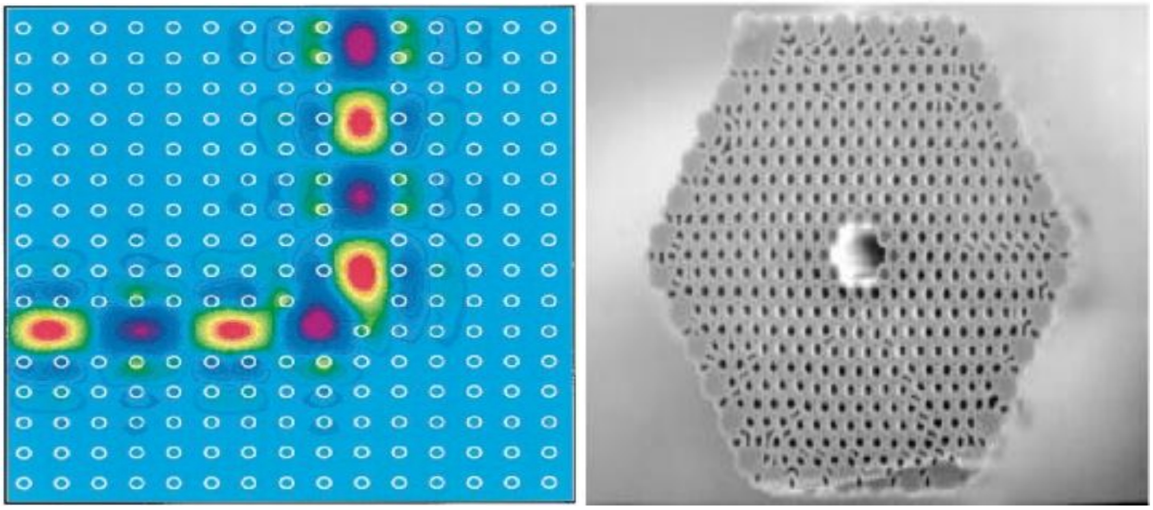

Figure 1.1: A two dimensional integrated photonic crystal circuit [1] and photonic crystal fiber [8] respectively.

Among all optical materials photonic crystals are always attraction for manipulation and controlling the flow of electromagnetic waves. One dimensional photonic crystal are already in comprehensive usage in the form of thin film optics applications ranging from low reflections to high reflection coatings on mirrors as well as on lenses to color changing paints and inks.

For both traditional and practiced research the high dimensional photonic crystals are always of great interest and the two dimensional ones are being generally have commercial applications. Photonic crystal fiber and waveguides are the most common available commercial products that involve two dimensional periodic photonic crystals both are using a micro-scale structure to confine light with radically different characteristics compared to conventional optical fiber and waveguides for potential applications in guiding extraordinary wavelengths and non-aligned devices.

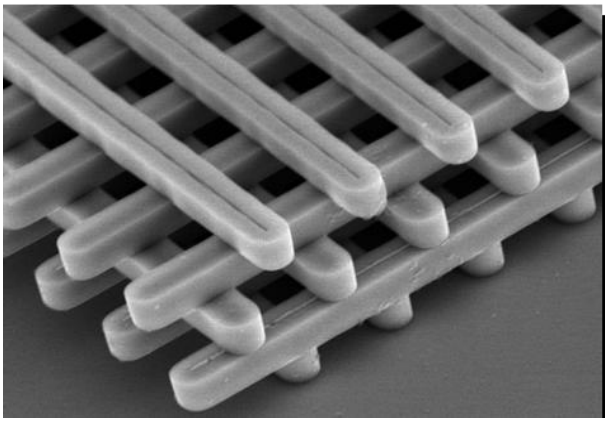

Figure 1.2: A woodpile structure in three dimensional photonic crystals [9].

The three-dimensional photonic crystals are still difficult to implement and away from the make business but still suggest significant features example optical nonlinearity which is required for the operation of optical transistors and used now days in optical computers, when manufacturability and principal difficulties like technological aspects and other discontinuities remains under control.

Tremendous applications of photonic crystal will come out as the study of photonic crystal progress. In this information age the range of application of photonic crystal is only limited by the acuteness of human minds.

1.3 Photonic Crystal Waveguide

Although the direct disruption in the photon density states near a photonic bandgap leads to the analysis of diverse interesting physical phenomena, with implementation of various feasible applications in mind, as now focus is on the experimentation of functional passive photonic crystal devices, especially, the photonic crystal waveguide [10]. A two dimensional photonic crystal waveguide was well analyzed. A straight slab air waveguide is the simplest structure that can be obtained by the introducing an air line defect inside the photonic crystal [11, 12]. Finite two dimensional photonic crystals with index confinement in the three dimensions are more practiced to the variations such as waveguides in photonic crystal slabs, the holey fiber, and slab dielectric waveguides [13, 14]. Exploration in two dimensional waveguides has been done theoretically, prime focus lend on novel mathematical formalisms and numerical modeling like Wannier function expansions and analytical solutions [15-17]. Application-based problems, such as the existence of non-propagating bound states and multimode versus single-mode design in waveguide are easily managed by using above discussed approaches.

An assured benefit of photonic crystal waveguides which make it different from conventional dielectric waveguides is its capability of confinement of light even at sharp curves. As there is computational requirements for three dimensional structures so analysis on bent waveguides has been mostly bounded to two dimensional structures only. Analytical approaches have not been extensively explored because the entire attempt in the theoretical development of bent waveguides has mainly concentrated on numerical methods [18]. More than 95 percent of transference is estimated at around 90 degree bends [12]. To study the characteristics of propagation at the waveguide bends numerical modeling has been initiated. In photonic integrated systems these crystal waveguides generally experiences certain important problems, which make them inappropriate choice for various experimental applications. Nowadays it is possible to realize the compact bends with two dimensional waveguide that can support multimode operations [19].

1.4 Silicon-on-Insulator (SOI): An on-chip Platform of Silicon Photonics

Silicon photonics is application of photonic systems make use of silicon as an optical medium. The silicon is usually patterned with sub-micrometer precision, into micro photonic components [20]. These operate in the infrared, most commonly at the 1.55 µm wavelength used by fiber optic telecommunication systems [21]. The silicon typically lies on top of a layer of silica are known as Silicon on insulator [20]. A technology which makes use of a layered silicon-insulator silicon substrate instead of conventional silicon-built substrates in semiconductor manufacturing, exclusively in microelectronics devices in order to reduce parasitic device capacitance which results in improving performance. Silicon on insulator based devices distinguished from conventional silicon devices because the silicon junction is above an electrical insulator, typically silicon dioxide. These kinds of devices are called silicon on sapphire. The choice of insulator largely depends upon promised application, with silicon on sapphire being used for high-performance radio frequencies and also for radiation-sensitive applications whereas silicon dioxide (SiO_2) is used for diminished short channel effects in microelectronics devices.

Integrated nanophotonics, especially on silicon on insulator (SOI) platform, has recently allowed the successful realization of various nonlinear optical devices on chip itself. This development may realize the tight confinement of light within sub micrometer-sized silicon nanowires to enhance the optical energy density and allows optical nonlinear effects to occur at lessened input powers.

1.5 Purpose and Outline of Work

The purpose of our research is to design and analyze simplified photonic crystal waveguide on Silicon-on-insulator (SOI) wafer. Prime focus of the work will be on Silicon-on- Insulator (SOI) photonic crystal waveguide. In this dissertation, low-loss and flat dispersion line-defect photonic crystal waveguide is proposed based on hexagonal lattice of two dimensional photonic crystals. The simulation is done using finite difference time domain method. This dissertation present a fully three dimensional finite difference time domain simulation model to estimate propagation loss and effective group index characteristics for both the TE like polarization and TM like polarization in photonic crystal slab waveguides.

Chapter 2 provides an introduction to two dimensional photonic crystal based waveguide including defects in waveguide and their types, dispersion in waveguide and their types.

Chapter 3 discussed about the research work done in the photonic crystal waveguide.

Chapter 4 discussed the design and simulation of line defect photonic crystal waveguide structure with controlling of dispersion and propagation losses.

CHAPTER 2

Two Dimensional Photonic Crystal Based Waveguide

2.1 Two Dimensional Slab Photonic Crystal

The photonic crystal slab, which has two dimensional in-plane periodicity is one of the most rising and attractive category of photonic crystal structure having finite height and is comparable to the wavelength of light. The photonic slab is interesting because it is easy to fabricate in comparison to three dimensional photonic crystals and also have manageable chip-level integration [22]. PC slab made up of two dimensional periodic dielectric materials as core which is encompassed by lower refractive index material act as cladding it may be either air or of any low index material. This allows confinement of light in the z-direction through index guiding. Photonic slabs have few similar properties as of true two dimensional photonic crystals having infinite height and also at same moment they are manageable to be implemented at sub micron scales and gain prominent for many photonic crystal applications.

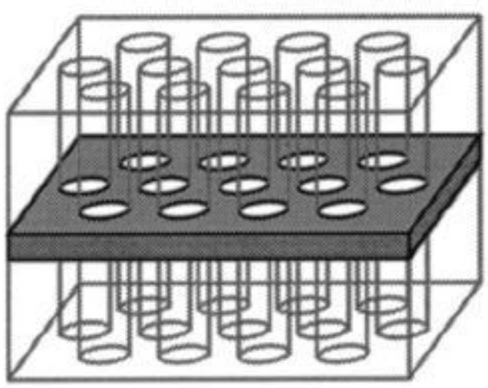

Figure 2.1: Two dimensional photonic crystal high index slab having finite-height surrounded by low index region [23].

In the true two dimensional photonic crystals the eigenmodes are into pure TE and TM modes but same is not the case with two dimensional photonic slabs because of the finite height property associated with it. When both the claddings are identical to each other and the middle of the slab offers symmetry the eigenmodes of the slab can be categorized into even and odd modes. Field distribution pattern of magnetic component in z-direction become symmetrical for even modes and asymmetrical for odd modes. In the case of first order modes polarization mixing is very acute and can be taken as odd TM-like polarized and even TE-like polarized. Aside from the polarization mixing effect, another significant difference between photonic slabs and two dimensional photonic crystals having infinite height is the behavior of the light line that consists of states or radiation modes extending infinitely in the areas outside the slab. Localization of the guided modes to the slab may only exist within the regions of the band diagram which are out of the light cone. The modes lie inside the region of leaky modes of the planar waveguide specifically for above the light line of the cladding material. These modes have intrinsic radiation losses associated to out-of-plane diffraction and so called quasi-guided modes. Below the light cone the discrete bands are the guided modes. Within the plane of the slab these states are infinitely extended, but decrease exponentially in the background region [23]. In two dimensional slab with finite height a bandgap is defined by the range of frequencies in which guided mode does not exist. At those frequencies the radiation modes exist so these are not actual bandgap. In infinite two dimensional photonic crystals the depletion of guided modes is comparable to the bandgap. The condition of a slab having finite height results in certain issues like index contrast with the substrate, slab thickness and mirror symmetry which always play a significant role in deciding the features of photonic crystal slab so in many cases photonic crystal slab is comparable to infinite two dimensional photonic crystal.

There are in general two ways to simulate two dimensional photonic crystal slabs. The first method is by doing a complete three dimensional analysis of photonic slab by taking its height into consideration. This way can figure out the scattering in the vertical direction but very high computational resources are required for it. The second way is by functioning two dimensional calculations using the effective index of the slab at the operating wavelength. This way does not need much computation resources but the scattering in the vertical direction cannot be predicted.

2.1.1Rod and Hole Slabs

Two types of photonic-crystal slabs are shown in Fig.2.2 As per study there are two basic topologies one is a triangular lattice of air holes in dielectric and a square lattice of dielectric rods in air. These structures are refers to as the rod slab and the hole slab respectively.

a) b)

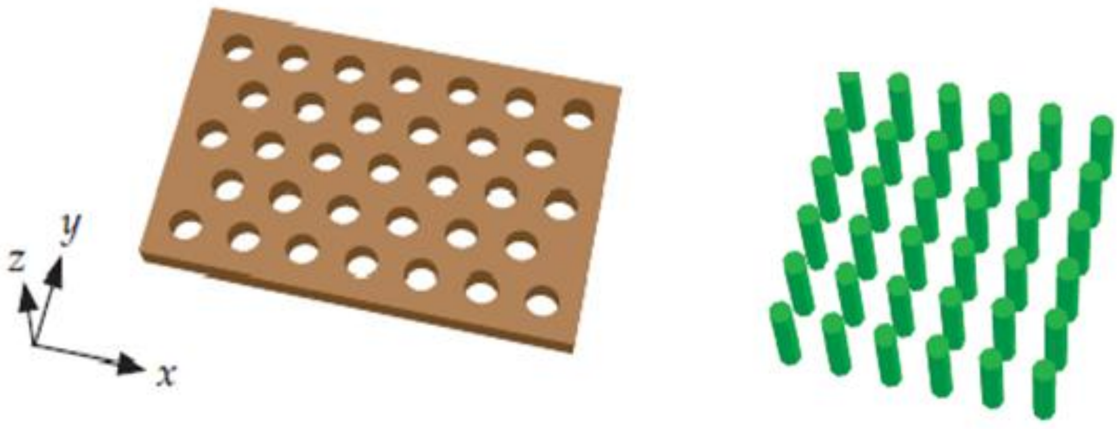

Figure 2.2: Photonic-crystal slabs that combine two-dimensional periodicity in the xy directions and index-guiding in the vertical z-direction. (a) A triangular lattice of air holes in a dielectric slab, hole slab. (b) A square lattice of dielectric rods in air, rod slab [11].

In the rod slab let us consider the rods have a radius r = 0.2a and the slab has a thickness 2a, whereas in case of air-hole slab let us consider, the holes have a radius r= 0.3a and the slab has a thickness 0.6a. These parameters are require to be optimized and in the beginning it is consider as suspended membrane structures that are enclosed completely by air having deictic constant 1 and later on explain the effect of a substrate.

With individual translational symmetry in two directions, the vertical wave vector kz is not conserved whereas the in-plane wave vector k = (kx, ky) is conserved. Therefore, it is advantageous to draw the projected band diagram specifically in this case it is a plot of ω versus k in the exclusive Brillouin zone of the two-dimensional lattice. Most of the characteristics of these diagrams are found to be familiar. For $\omega \geq c\,|k|$, the propagation of extended modes in air patterns a light cone. The higher dielectric constant of the slab has pulled down individual guided bands below to the light cone. In these bands the eigenstates degenerate in the vertical direction away from the slab. Therefore regarding symmetry and polarization the system is consistent under reflections through plane the z=0 which allows us to categories the modes as even and odd modes. However in general there are no x or y mirror symmetries these are broken by the k vector. One may predict from our knowledge of the analogous to two-dimensional photonic crystals the hole slab support a TE-like gap whereas rod slab support a TM-like gap. However the gaps in photonic-crystal slabs are deficient they associate only to the guided modes not the light cone.

2.2 Defects in Photonic Crystal

The most attractive property of photonic crystal is its ability to confine the light. It can be attained by employing defects which introduce discontinuity in the periodic structure. With the appropriate introduction of point or line defect into perfect photonic crystal structure may set up resonant states within the bandgap. A defect design in the photonic crystal could be of any shape, size or other form and it could be select from wide variety of dielectric constants. Thus, in the gap defect state could be adjusted in spatial extent of design consequence and frequency [11, 24]. Along with adjustment in frequency, it should be restrained over the symmetry of the localizing photonic state. All of these capabilities allow an extensive ability to control or module the characteristics of light. In the below section we look forward into the different types of defects that can be formed in photonic crystal and their features.

2.2.1 Line Defect Waveguide

Waveguides are one of the most important elements of photonic integrated circuits. Various working elements like detector, multiplier, modulator and sources can be associated with it. In a simple photonic crystal slab structure a line defect can be created by removing a row of holes along one of its main crystalline directions. Due to this defect either waveguide allow single or multiple modes to exist. These modes can be categorized into standing or traveling modes and evanescent modes. In an integrated system, the traveling modes can be used to carry optical signals between various components, which thereby changes linear defects into true legitimate waveguides. A light have specific range of wavelength can be trap by the line defect within the waveguide with minimal losses even near to the tight bends as well. For dense optical integrated circuits line defect waveguide has the practicability of extreme compact components of waveguide such as acute branches, short directional couplers and sharp bends [25]. Through sharp bend high transmittance for the guided modes can be achieved. Bragg reflection has been used in transverse directions to confine the wave in the waveguide. The field distribution related with the mode is highly confined in the environment of the defect and decreases exponentially in the extent crystal regions. A plane wave expansion method is commonly used to calculate the dispersion property of the photonic crystal, which also give provision to solve Maxwell’s equations in the frequency domain for a given configuration of photonic crystal. How many modes can be supported by photonic crystal structure can also be determined from plane wave expansion method. In other terms we can say the band structure which describes the operational dependence of frequency on the wave vector can be calculated by above discussed method.

2.2.2 Point Defects In Slabs

A localized mode can be trap by introducing a point defect in a photonic-crystal slab, which is similar to the analogous point-defect mode in an infinite two-dimensional crystal. However, it is found in case of point defects in periodic dielectric waveguides, the light cone existence shows that localized modes in the slab are leaky in resonance with intrinsic vertical radiation losses. Let us consider an example, assume that in the rod slab we want to introduce a monopole state. In the two-dimensional or three-dimensional photonic crystal, the simple method to generate a monopole state is done by removal of a single rod, but the same will not work in this case. Fact is the vertical confinement is too weak. Thus we could reduce its radius or dielectric constant by a any amount in spite of completely removal a rod. Fig.2.3 shows the defect mode's field pattern that can be results from reducing the relative permittivity of a single rod and its four nearest neighbors from $\varepsilon = 12$ to $\varepsilon = 9$. Here we chose to modify the neighboring rods. It is a monopole-pattern TM-like mode with a radiative lifetime $Q_r \approx 13000$.

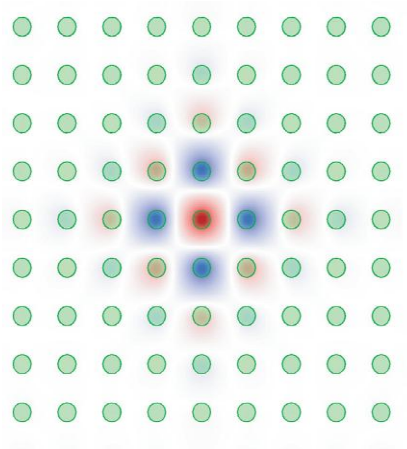

Figure.2.3: Ez cross sections for resonant "monopole" mode of a point defect in the rod slab (dielectric material shown as translucent green), formed by reducing the dielectric constant of the center rod and its four nearest neighbours from ε=12 to ε=9. The mode decays exponentially in the plane of the slab, but slowly radiates away vertically [11].

The lifetime of a resonant mode in a slab is strongly affected by the presence of a substrate as it is known in case quality factors of lossy cavities. Various comparisons of the radiative lifetime Qr of the monopole state, for various different choices of the substrate had been made. When the substrate has the same cross section as that of slab, losses of substrate get reduce. There is one more choice whether to place a layer of the substrate material on top of the slab or not thereby restoring the *z* symmetry. The benefits of this idea are that it counteracts the associated in-plane radiative losses and polarization mixing. The disadvantage it exhibit that, the local density of radiative states is upgrade by growing the mean dielectric constant of the structure. In this specific case when there is no fascinating reason to symmetries the system both of above discussed effects does not support one another.

2.3 Dispersion in Optical Waveguide

In optics, dispersion is the phenomenon in which the phase velocity of a wave depends upon its frequency, or alternatively when the group velocity depends upon the frequency. Media that have such characteristics are termed as dispersive media. Dispersion is frequently called chromatic dispersion to stress upon its wavelength-dependent nature, or group-velocity dispersion (GVD) to indicate the performance of the group velocity.

The well known example of dispersion is apparently a rainbow, in which dispersion causes the spatial separation of a white light into different components of different wavelengths indicated by different colors. Thus, dispersion also has consequences in many other circumstances: such as, group velocity dispersion causes pulses to spread in optical domain, there by degrading of signals occurs over long distances and cancellation take place between group-velocity dispersion and nonlinear effects results in occurrence soliton waves propagation. Dispersion is most frequently characterize for light waves, but it may occur for any type of wave that interacts with a medium or passes through an inhomogeneous geometry like waveguide such as sound waves [26].

There are generally two sources of dispersion: material dispersion and waveguide dispersion. Material dispersion comes from a frequency-dependent response of a material to waves. For example, material dispersion leads to undesired chromatic aberration in a lens or the separation of colors in a prism. In material dispersion different wavelengths of light travel with different velocities a given medium. Consider a pulse that has a finite spectral bandwidth, if the pulse is launched in a dispersive material, each wavelength component of the pulse will travel at a different velocity. The pulse adequately disperses out in time domain and space. It will show that all finite temporal pulses must also have a finite frequency bandwidth. Dispersion is a basic issue within systems. Waveguide dispersion occurs when the speed of a wave in a waveguide (such as two dimensional photonic crystal slab) depends upon its frequency for certain geometric reasons but independent of any frequency dependence of the materials from which it is constructed. Most commonly waveguide dispersion may occur for waves propagating through any inhomogeneous structure such as photonic crystal whether or not the waves are confined to some region. In general, both types of dispersion may be present but they are not strictly accumulative in nature. Their combination strictly resulting in degradation of signal in optical fibers and waveguides for telecommunications, because the each signal component have different delay at reaches on destination at different arrival time thus "smears out" the signal in time domain.

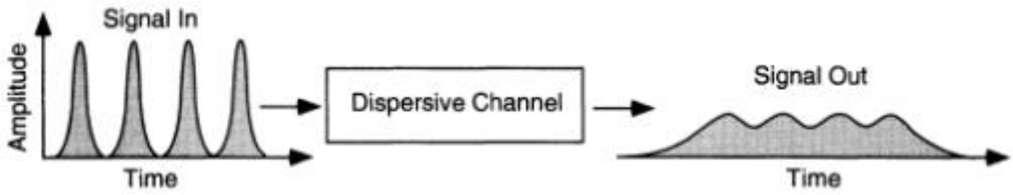

Figure.2.4: Short optical pulses enter the dispersive waveguide. Due to dispersion, they exit with much longer temporal distributions. If adjacent pulses are too close, it will become impossible to distinguish one from another [27].

2.3.1 Chromatic Dispersion (CD)

Chromatic dispersion is a broadening of the input signal as it travels over the length of the waveguide. The concept to understand when we talk about chromatic dispersion (CD) it should be related to optical phase. It is essential to mention the optical phase before any description of CD or group delay because of their mathematical relationship. Group delay can be defined as the first derivative of optical phase with respect to optical frequency [28]. In other words a useful term is the group delay that can also be defined as the time it takes for a pulse of light to travel a unit distance. Chromatic dispersion is the second derivative of optical phase with respect to optical frequency. These quantities are represented as follows:

Group Delay, $\tau_g = \frac{dk}{d\omega}$ this is related to index of refraction, $n(\omega)$ where $k = \frac{n\omega}{c}$

Chromatic Dispersion = $\frac{d^2k}{d\omega^2}$

Where k = optical phase and ω = optical frequency.

$$\tau_g = \frac{d\,((n\omega)/c)}{d\omega} \tag{2.1}$$

$$\frac{dn}{d\omega}\frac{\omega}{c} + \frac{n}{c}\frac{d\omega}{d\omega} \tag{2.2}$$

$$\frac{(n + \omega\frac{dn}{d\omega})}{c} \tag{2.3}$$

The group delay, τ_g, depends on the index of refraction and the first derivative of the index with respect to frequency. Inverting τ_g, we obtain an expression for v_g that has similar form as of the phase velocity, $v_p = c\,/\,n$,

$$v_g = c/(n + \omega\frac{dn}{d\omega}) \tag{2.4}$$

$$v_g = \frac{c}{n_g} \tag{2.5}$$

Where the term n_g is called the group index and is defined to be

$$n_g = n + \omega\frac{dn}{d\omega} \tag{2.6}$$

We will find the group index more useful when defined in terms of wavelength. Simple calculation leads to

$$n_g = n - \omega\frac{dn}{d\omega} \tag{2.7}$$

It is to be kept in mind that the $dn\ /d\lambda$ is negative for most regions. The group index n_g , is always larger than the regular index of refraction, n, except in regions of anomalous dispersion [27].

Chromatic dispersion occurs because of both material dispersion and waveguide dispersion. Both of these processes occur because all the optical signals have a finite spectral width, and each individual spectral component will propagate with different velocity along the length of the waveguide and thus reach on destination at different time. One of the main reasons for this velocity difference is that the index of refraction of the slab core is different for different wavelength which represents material dispersion and so chromatic dispersion is the dominant source of dispersion specifically in single-mode waveguide. Another cause of dispersion is that the cross-sectional distribution of light within the waveguide also changes for different wavelengths. Shorter wavelengths are more completely confined to the waveguide core, whereas a larger wavelength occupies more portion of the optical power while propagating in the waveguide cladding. Since the index of the core is greater than the index of the cladding this difference in spatial distribution resulting a change in propagation velocity. This process is popularly known as waveguide dispersion. Waveguide dispersion is relatively small as compared to material dispersion.

Chromatic dispersion in a component is significantly different than chromatic dispersion in long length optical waveguide. Chromatic dispersion remains constant over the bandwidth of a communications channel for long lengths of single mode waveguides. As a result, chromatic dispersion is a poor predictor of component performance in a communications system. Chromatic dispersion can result in distortion or bit errors in digital communications and a large noisy base in analog communications, and can impose a serious problem in high-bit-rate systems if it is not measured precisely and some form of dispersion compensation is not employed.

2.3.2 Group Velocity Dispersion (GVD)

Another outcome of dispersion exhibit itself as a temporal effect. The formula $v_p = c\ /\ n$ find out the phase velocity of a wave, this is the velocity at which the phase of any one frequency component of the wave will propagate. This is not the same as the group velocity of the wave that is the rate at which changes in amplitude (known as the envelope of the wave) will propagate. In case of a homogeneous medium, the group velocity v_g is related to the phase velocity of a wave.

The group velocity vg is often thought of as it is the velocity at which information and energy is transmitted along the wave. In most cases it is true, and the group velocity can be thought of as the signal velocity of the waveform. In some strange prospects, called cases of anomalous dispersion, the rate of change of the index of refraction with respect to the wavelength changes sign, in which case it is possible for the group velocity to exceed the speed of light ($v_g > c$). Anomalous dispersion happens, for situation, where the wavelength of the light is near to an absorption resonance of the medium. When the dispersion is anomalous, however, group velocity is no longer examined of signal velocity. Instead, a signal travels at the speed of the wave front, which is c without considering of the index of refraction. Recently, it has become possible to create gases in which the group velocity is not only larger than the speed of light, but even negative. In these cases, a pulse can appear to exit a medium before it enters. As demonstrated by Stenner [26] there are certain cases in which basically a signal travels at, or less than, the speed of light. The group velocity itself is usually a function of the wave's frequency. This results in group velocity dispersion (GVD), which causes a short pulse of light to spread in time as a result of different frequency components of the pulse travelling at different velocities. These components will reach the receiver at different times; effectively stretching out the time it takes for a signal to arrive. This effect is called group velocity dispersion (GVD).

Let us consider an optical pulse attain a finite spectral bandwidth $\Delta\lambda$ while traveling through a dispersive medium. The time which is required to travel a distance L is called the latency, and is the product of the group delay (τ_g) along the propagation distance L [27].

$$\tau = \frac{L}{c} n_g(\lambda) \tag{2.8}$$

The spectral width of the pulse ranges from λ 1 to λ 2 (where $\Delta\lambda = |\lambda 1 - \lambda 2|$).

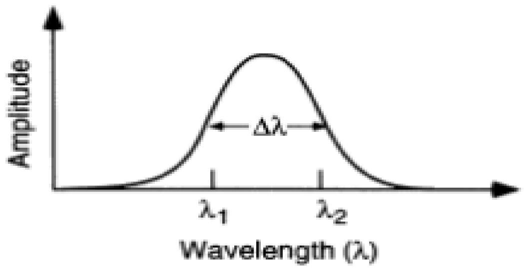

Figure.2.5: An optical pulse will have a finite spread in wavelength [27].

Every signal component will propagate at a slightly different velocity. In the time domain, the pulse spread will be given as

$$\Delta\tau = \frac{L}{c}(n_g(\lambda 1) - n_g(\lambda 2)) \tag{2.9}$$

$$= \frac{L}{c}\Delta n_g \tag{2.10}$$

$$= \frac{L}{c}\frac{dn_g}{d\lambda}\Delta\lambda \tag{2.11}$$

On taking first derivative of equation (2.7) we can obtain $\frac{dn_g}{d\lambda}$, on putting the value of it back in equation (2.11) we can obtain pulse arrival time as below

$$\Delta\tau = -\frac{L}{c}\lambda\frac{d^2n}{d\lambda^2}\Delta\lambda \tag{2.12}$$

The pulse spreading depends upon second derivative of material dispersion thus GVD given by:

$$D = -\frac{\lambda}{c}\frac{d^2n}{d\lambda^2} \tag{2.13}$$

If D is less than zero, the medium is said to have positive dispersion. If D is greater than zero, the medium is said to have negative dispersion. If a light pulse is propagated through a normally dispersive medium, the result is that the components have higher frequency components travel slower in comparison to the lower frequency components. The pulse therefore becomes positively chirped, or up-chirped, increasing in frequency with time. Contrarily, if a pulse travels through an anomalously dispersive medium, high frequency components travel faster in comparison to lower frequency components, and the pulse becomes negatively chirped, or down-chirped, decreasing in frequency with time.

The result of GVD, whether negative or positive, is ultimately spreading of the pulse in time domain. This makes dispersion management extremely important in optical communication systems based on optical waveguides and optical fibers too. Since if dispersion is too high, a group of pulses representing a bit stream will spread in time and merge together, interpreted the bit-stream unknowingly. This limits the length of systems that a signal cannot be sent on optical communication systems without regeneration. One possible solution to this problem is to send signals through waveguides and fibers at a wavelength where the GVD is zero (such as wavelength range of 1.3 μm –1.5 μm in silica), so pulses at this wavelength experiences minimum spreading from dispersion in usual but this approach causes more problems instead it provide solution because zero GVD undesirably give rise to other nonlinear effects such as four wave mixing. Another possible solution is to make use of soliton pulses in the regime of anomalous dispersion. This is form of optical pulse which uses a nonlinear optical effect to self-maintain its shape. Solitons have the certain practical problems that they require a sufficient power level to be maintained in the pulse for the nonlinear effect to be occurring of the exact strength. Instead, the solution that is currently used practically is to perform dispersion compensation, specifically by matching the waveguide with another waveguide of opposite-sign dispersion so that the dispersion effects cancel out in each other, such compensation is basically limited by nonlinear effects such as self-phase modulation, which interact with dispersion to make it very difficult to alter.

Dispersion control is also very important in case of lasers which produce short pulses. The overall dispersion in case of the optical resonator is a major factor in determining the duration of the pulses emitted by the laser. A pair of prisms can be arranged to generate overall negative dispersion, which can be used to compensate the usual positive dispersion of the laser medium. The diffraction gratings can also be used to produce dispersive effects. These are frequently used in high-power laser amplifier systems. Recently, an alternative to prisms and gratings has been developed that is chirped mirrors. These dielectric mirrors are coated so that different wavelengths have different penetration lengths, and therefore experiences different group delays. The coating layer on chirped mirrors can be tailored to achieve overall negative dispersion.

2.2.3 Waveguides Dispersion

Waveguide dispersion has generally the smallest magnitude of the all the dispersion mechanisms. Waveguide dispersion becomes significant in single-mode systems operating near λ0, the zero material dispersion point. Dispersion in the waveguides is one of the limiting factors to determine how much information or energy can be transported on a single mode waveguide. The transverse modes for waves confined laterally within a waveguide generally have different velocity and field patterns depending upon their frequency of operation compared to the size of the waveguide.

In general, for a waveguide mode with an angular frequency $\omega(\beta)$ at a propagation constant β, such that the electromagnetic fields in the propagation direction (z) oscillate proportional to $e^{i(\beta z - \omega t)}$ and resulting the group-velocity dispersion parameter D is as:

$$D = -\frac{2\pi c}{\lambda^2}\frac{d^2\beta}{d\omega^2} = \frac{2\pi c}{{v_g}^2\lambda^2}\frac{dv_g}{d\omega} \tag{2.14}$$

Where $\lambda = 2\pi c\ /\ \omega$ is the vacuum wavelength and $v_g = (d\omega\ /d\beta)$ is the group velocity. This formula generalizes the one in the previous section for homogeneous media, and includes both waveguide dispersion and material dispersion. A similar effect due to a somewhat different phenomenon is modal dispersion, caused by a waveguide having multiple modes at a given frequency, each with propagate with different speed. A special case of this is polarization mode dispersion (PMD), which comes into existence due to superposition of two modes that travel at different speeds because of random imperfections that break the symmetry of the waveguide.

2.2.4 Polarization Modal Dispersion

Polarization mode dispersion (PMD) is a form of modal dispersion where two different polarizations of light in a waveguide normally travel at the same speed start travel at different velocities due to random imperfections and asymmetries [11], causing random spreading of optical pulses. Unless it is compensated, which is difficult, this ultimately limits the rate at which data can be transmitted over a media. Any imperfection or stress in the transmitting media, however, can break the symmetry and split these two polarizations into modes that travel at different speeds. The same thing can happen in a photonic-crystal fiber and waveguide if we operate in a doubly degenerate mode. The differential losses of a hollow refractive index region, however, allow one to operate in a low-loss higher-order mode like TE01 that is non degenerate and hence immune to PMD therefore no perturbation can break the symmetry and split the modes into two polarizations. Alternatively, one can design a high index waveguide that is so asymmetric that it supports only a single non degenerate mode. In recent days a polarization independent photonic-crystal waveguide realized that is capable enough to generate slow light [28].

In other terms, polarization mode dispersion occurs when optical signal is transmitted through a waveguide of a communications system is compensated by separating the dispersed signal into components corresponding to principal polarization states. The components are delayed by respective delays differing by a delay increment which is restrained to correspond to the dispersion delay and the delayed components get recombined to provide dispersion compensated output optical signal. Each of the delays is provided by a chirped Bragg reflector which is a part of delay line, the Bragg reflectors constitute of optical fibers with chirped intra-core index gratings. Transducers or temperature controllers acting on any of the fibers allows dimensional control of the grating periodicity such that the position of Bragg reflection is variable. Wavelength division multiplexed optical signals are compensated using sampled gratings which allow a common Bragg reflection position for each wavelength.

CHAPTER 3

Literature Survey

The simplest possible photonic crystal consists of alternating layers of material with different dielectric constants. This arrangement is not a new idea. Lord Rayleigh (1887) published one of the first analyses of the optical properties of multilayer films. As we will see, this type of photonic crystal can act as a mirror (a Bragg mirror) for light with a frequency within a specified range, and it can localize light modes if there are any defects in its structure. These concepts are commonly used in dielectric mirrors and optical filters (as in, e.g., Hecht and Zajac, 1997). The traditional way to analyze this system, pioneered by Lord Rayleigh (1917), is to imagine that a plane wave propagates through the material and to consider the sum of the multiple reflections and refractions that occur at each interface. Research methodologies developed within the last decade in the field of photonic crystal waveguides are presented below:

Steven G. Johnson, *et al.* in September 2000 [23] present the various families of waveguides in two dimensional photonic crystals and it was found that these structures could be implanted in three dimensions without any fabrication complexities. It has been indicated that how these linear waveguides in photonic crystal slab having finite height is basically different from waveguides which are vertically confined.

M. Notomi, *et al.* in 2001 [29] present the photonic crystal waveguide with line defects (LDWG) which has waveguide characteristics and group velocity dispersion characteristics different from conventional waveguides these characteristics can be tuned by controlling the defect width which results in control of light transmission through light path. An extraordinarily large group velocity is reported in interference transmission window which is achieved by tailoring the various parameters of slab such as defect width, length of slab, thickness of slab thus achieve slow light that allow the waveguiding modes to travel with slower than that of light in vacuum.

Susumu Noda, *et al.* in 2002 [30] efficiently design of single defect cavity which effects the control o photons in both two dimensional and three dimensional photonic slabs with the introduction of a light emitter into 3-D photonic crystal, the small number of stacking structures control the enhancement and suppression of spontaneous emission well and along with single defect cavity high quality factor has been successfully achieved by proper tenability of device. The main focus remains on characteristics of surface emitting-type single-defect channel-drop filtering devices strong enhancement of spontaneous emission is successfully obtained.

Mehmet Bayindir and Ekmel Ozbay in 2002 [31] proposed a design of two dimensional dielectric photonic crystals and the drop of electromagnetic waves at particular band of frequency has been observed. Single cavity has been made and by change in its properties tenability of its demultiplexing modes was achieved favorably.

E. Lidorikis, M. L. Povinelli, S.G. Johnson, and J. D. Joannopoulos in July 2003 [32] present a design of polarization independent three dimensional waveguide and waveguide bends. The transmission coefficients of sharp bends for wide frequency range had been investigated and afterwards transmission spectra for certain frequency range had been achieved successfully. Various phenomenon processes has been discussed that how band dropping can be attained and how it can be tuned. Also the transmission spectra and field pattern for the structure were also presented well.

Binglin Miao, *et al.* in November 2004 [33] proposed and fabricated two designs on silicon-on-insulator substrate; reduction in bend loss of conventional double 60 degree bend is achieved. The improvement in transmission of single line defect planar photonic crystal waveguide is done for realization of PIC based on planar photonic crystal by optimizing the structure with modification in shape and size in photonic crystal lattice to reduce the scattering losses.

Virginie Lousse, *et al.* in 2004 [34] present a design of photonic crystal slab that can act as mirror and can be reflect one polarization completely while it allow the fully transmission of another polarization.

Samir K. Mondal and Bethanie J. H. Stadler in January 2005 [35] designed successfully two photonic crystal waveguides for integrated polarized applications under controlled circumstances without any use of external polarizer. It is shown this optimized structure possesses the bandgap of TE like modes and discussed how based on the orientation and proper designing TE like modes and TM like modes are isolated from each other.

Y. Tang, A. M. Mintairov, J. L. Merz, V. Tokranov and S. Oktyabrsky in July 2005 [36] introduced cavities in the hexagonal lattice photonic crystal slab based upon GaAs-$Al_xGa_{1-x}As$ and characterized the cavity modes with polarization sensitive photoluminescence. Based on different polarization properties of each mode there is good compatibility shown between simulated and measured mode structure.

Aimin Xing, *et al.* in October 2005 [37] discussed the design, fabrication and characteristics by constructing three types of taper design such as special mode matching, group velocity matched, and combined spatial velocity matched of single line defect photonic crystal waveguide on indium-phosphate based material. Coupling efficiency gets improved successfully by doing proper taper design.

Xiang Li, *et al.* in 2006 [38] present the Planar two dimensional (2-D) photonic crystals combined with a one-dimensional (1-D) Bragg mirror to control the Quality factor and out of plane coupling of optical modes. The enhancement of quality factor can be obtained by controlling the thickness of silicon upper layer in which the 2-D photonic crystal is etched and the air filling factor of the photonic crystal. Numerous optical properties of such structure has been characterize well. A similar enhancement should be obtained by varying the thickness of the oxide layer separating the Bragg mirror and the 2-D photonic crystal slab layer.

Shanhui Fan, *et al.* in 2006 [39] discussed recent advancement in the theory of photonic crystal that exhibits the large optical physics effects and provides new ways to do optical information processing tasks more sophisticatedly and perfectly allow the announce of dynamics into photonic crystals system and also would be very able to create new optical signal processing functionalities far beyond the capabilities of static systems.

Ioannis Neokosmidis, *et al.* in 2007 [40] have designed optical delay lines based on soliton propagation in coupled resonator optical waveguides is performed and the influence of higher order linear and nonlinear dispersion, a continuous wave propagation model incorporating these effects of influence of higher order linear and nonlinear dispersion. Integrated optical buffers are realized well by using soliton based delay line. The performance of a solitons-based Coupled Resonator Optical Waveguides delay line where nonlinearity is used to compensate for the second order dispersion-induced pulse broadening was analyzed.

Khadijeh Bayat, Sujeet K. Chaudhuri, and Safieddin Safavi-Naeini in 2008 [41] introduced and analyzed the compact silicon based periodic asymmetric loaded photonic crystal polarization rotator for high frequency ranges near THz. Over long propagation length polarization rotation was successfully achieved and for the implementation of photonic crystal slab they developed new processes

Yonghao Cui, *et al.* in April 2008 [42] designed, fabricated and characterized the two dimensional compact silicon based photonic crystal. As it is silicon based structure so successfully integrated in complex photonic integrated circuits.

J. Canning, *et al.* in 2008 [43] demonstrated polarization conversion from TE to TM and vice-versa at quasi-TE transmission band edge of a linear photonic crystal waveguide on SOI.

A two dimensional slab of photonic crystal waveguide on silicon on insulator wafer has been presented by Y. Huang, *et al.* in 2008 [44] various band gap of guided and index guided modes were discussed by measuring the transmission spectra. Imperfection had been considered during the fabrication of structure and all the characteristics were investigated. High coupling efficiency and short coupling length has been realized successfully by using suppressing power reservation technique.

O'Faolain, *et al.* in 2009 [45] designed and demonstrated a low loss slow light photonic crystals with large operating bandwidth and low losses mechanism has been applied and loss of about 1 dB/bit was achieved efficiently. Promising application of the design like an optical buffer has been realized by this design.

Khadijeh Bayat, Sujeet K. Chaudhuri, and Safieddin Safavi-Naeini in December 2009 [46] present various methods to design and simulate novel and compact PC-based periodic asymmetric loaded polarization converter. Power conversion was avoided and synchronization in coupling was achieved by alternating the upper layer on either sides of line defect. To optimize the structure they use plane wave expansion method and which resulted in loss losses achievement for x polarized and y polarized modes of structure.

Jin Hou, Dingshan Gao, Huaming Wu, Zhiping Zhou in 2009 [47] analyzed the relationship between air hole size and self collimation frequency band for both TE and TM like polarizations. It was present that how this relationship is suitable for pillar type photonic crystals. Both the TE and TM self collimation bands are differently sensitive to the structure parameters tuning. Comparison of proposed annular photonic crystal had been made with normal photonic crystals it was notices that proposed structure is better to form polarization insensitive self collimation waveguide. They demonstrated the high dielectric contrast system. Various methods had been discussed that developed various polarization dependent and independent devices successfully such as polarization splitters, polarization insensitive waveguide bends and other dense wavelength division multiplexing devices.

Wu Yang, *et al.* in march 2010 [48] efficiently achieve high transmission by optimizing the design of two dimensional square lattice of photonic crystal waveguide by introducing line defect in Y shape. Strong coupling is achieved between input and output waveguide by the placement of rods in between for the improvement of transmission coefficients over a wide range of frequencies by further adding the rods in the edge of the output waveguide.

Murtaza Askari, *et al.* in 2010 [49] proposed various method for designing of Photonic crystal waveguide bends systematically by matching the dispersion and field profile of guiding region and bend region to achieve high transmission and low dispersion over large bandwidth. With the modification done in parameters of air holes present in guiding region within the bend systematical design have been made. The better characteristics have been shown after comparing the transmission spectra and phase response of proposed design with various designs reported earlier in literature.

A numerical method was proposed by B. Dastmalchi, *et al.* in 2010 [50] for the calculation of local dispersion in arbitrary shaped waveguides. The wave guiding streching effects by changing the lattice constant have been presented well. And a clear feature of dispersion at interfaces and transmission in photonic crystal has been analyzed well.

Nobuyuki Matsuda, *et al.* in 2011 [51] have demonstrated the nonlinearity of significant design of coupled resonator optical waveguide comprised of width-modulated nanocavities in a line defect of a silicon photonic slab. Experimentally it was revealed that it inherent strong nonlinearity with an effective nonlinear constant exceeds 10,000 /W/m with an integrated structure. The remarkably high nonlinearity was obtained because the slow-light mode of the designed waveguide exhibited the small effective modal area due to the wavelength-sized confinement of individual cavities. This proposed waveguide has great potential for integrated waveguide photonics because of its worth nonlinearity.

Yi Zhai, *et al.* in 2012 [52] realized flat-band slow light in ring-shape-hole photonic crystal waveguide by introducing defects in outer and inner radii of holes in Ring-Shape-Hole Photonic Crystal Waveguide, the slow light get effect and with appropriate modifications in outer and inner radii, the slow light property can be optimized. Also by introducing the oblique structure the flat dispersion bandwidth can be obtained and make structure considerably potential for optical buffering and signal transmission applications.

Peter Kaspar, *et al.* in 2012 [53] focused on propagation losses of line defect photonic crystal waveguides if they are implemented on hetrostructure with weak index. They discussed evidences that asymmetry or any imperfection is not the limiting factor in case of propagation losses and it was investigated that losses can only be minimized by proper designing of waveguides rather than optimizing by their fabrication processes.

Zhu kongTao, *et al.* in November 2012 [54] proposed a design of photonic waveguide with hexagonal lattice and discussed different methods for controlling the upper and the lower cut off frequencies of the guided band by changing the various parameters simultaneously. Even many optical properties and band edge were also tuned efficiently by using discussed tuning methods such as band dispersion method.

Pierre Colman, *et al.* in 2012 [55] discussed the dispersion properties of line defect photonic waveguide when even and odd modes are coupled. Coupling was effectively determined by using group analysis theory rather by just optimization of various parameters of designed waveguide.

Roman Kappeler, *et al.* in 2012 [56] presented a design of an active low loss photonic waveguide with a vertical contacting scheme that promises a net gain for an electrically pumped active in-plane photonic waveguide. The electrical performance and the assessment of the waveguides potential for optical gain has been discussed well by analyzing various parameters such as material and free-carrier absorption, heat conduction, gain material and optical propagation losses. And also presented how multimode waveguide design could be operated in single mode operation by the introduction of cavities or confinements. Applications of such multimode waveguides were explained well with examples. Finally it has been deduced that the design presented has a true single mode operation range with low propagation losses.

Victor Liu and Shanhui Fan in 2013 [19] discussed the design of photonic crystal waveguide in multi-mode operation. The structure is easy to implement and allow low loss transmission over relative bandwidth on introduction of bend. It was demonstrated that same design is applicable to both the rod slabs and air-holes slabs.

H. Wu, D. S. Citrin, L. Y. Jiang, X. Y. Li in 2013 [28] present photonic-crystal waveguide which realize polarization independent slow light. By introducing certain variations in design parameters a constant group index and low group-velocity dispersion for both the transverse-electric and transverse-magnetic polarizations successfully achieved.

CHAPTER 4

Design and Simulation of Line Defect Photonic Crystal Waveguide

4.1 Structure of Photonic Crystal Waveguide

Photonic crystal waveguides can be formed by introducing line defects which breaks the symmetry of slab and when operated at the wavelengths within the photonic band gap they are expected to provide low transmission losses and well confinement of light. Photonic crystal waveguide are normally made up by periodically patterning columns of air holes in high index material slabs. Design of photonic crystal waveguide on SOI is shown in Fig.4.1 In this type of design a photonic crystal slab with high refractive index dielectric material (i.e. Si) having two dimensional periodic air-holes arranged in hexagonal array is one of the most attractive photonic crystal structures. Insertion of photonic crystals into SOI opened up new possibilities in the area of silicon photonics. Photonic crystal based SOI is different from conventional photonic crystal slab in the sense that the former has three vertically oriented layers in addition to the in-plane periodic arrangement of the holes in silicon. It is possible to further tailor the properties of the waveguide by the optimization of the thickness of the two layers – top Si and SiO2 under it.

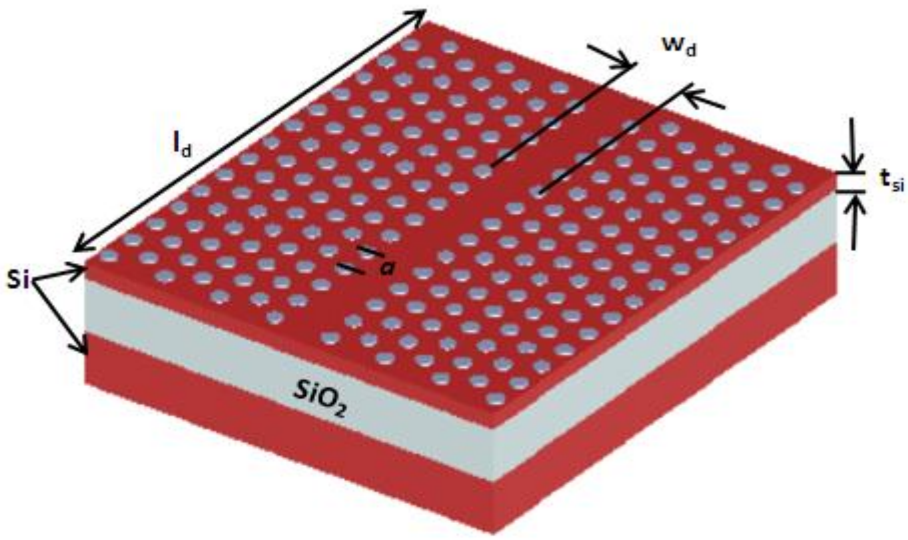

Figure.4.1: Schematic of proposed two dimensional hexagonal air-holes photonic crystal waveguide on

SOI where defect width w_d is the spacing between the centre of the air holes nearest to the defect, l_d represent length of defect and a represent lattice constant which can be defined as constant distance between centre of two nearest neighboring air-holes.

The cross-sectional view of the proposed photonic crystal waveguide design shown above consists of three vertically oriented layers top-Si (refractive index n= 3.5) and SiO2 (refractive index n= 1.44) on Si substrate. The in-plane periodicity is introduced by creating the hexagonal array of air holes in the high refractive index Si layer. Thus line defect waveguide is created by removing single air holes line from hexagonal photonic crystal slab. Where, w_d is the defect width that can be defined as the spacing between the centre of the air holes nearest to the defect, l_d is the length of defect, a is the lattice constant which represent constant distance between centre of two nearest neighbouring air-holes and t_{si} represent the thickness of top Si layer on SOI. These important parameters can be easily changed to effectively control the propagation characteristics without the need of any chirping in the lattice constant or hole-diameter. Specifically the diameter of air holes set to 0.44 µm and lattice constant set to 0.9 µm in order to achieve low loss transmission that confirm the propagation of light at a wavelength of 1.55 µm. The in-plane periodicity (through lattice constant) and vertical index-contrast (through top silicon) will be optimized to achieve low propagation loss and flat dispersion over a large wavelength band. The simulation is performed with finite difference time-domain (FDTD) method.

4.2 Propagation Loss and Electric Field Distribution

4.2.1 Effects of Parameter Variations on Photonic Crystal Waveguide

It is possible to achieve the low losses in waveguide by changing the properties of the waveguide by also optimizing the thickness of the two layers – top Si and SiO_2. In order to reduce the group velocity dispersion, different methods has been proposed, like alteration in the waveguide width w_d, change in size of air-holes, changing the position of air-holes and by employing micro-fluidic infiltration. All these methods may reduce the broadening of waveform but cannot eliminate it. So we propose an optimized structure to achieve low loss and flat group velocity dispersion (GVD) based on single line defect photonic crystal waveguide. The structure was optimized by varying various parameters like diameter of air-holes and lattice constant. Basically the line defect waveguides in photonic crystal slabs need more prudent design than that of two-dimensional photonic crystal having waveguide in dielectric rod.

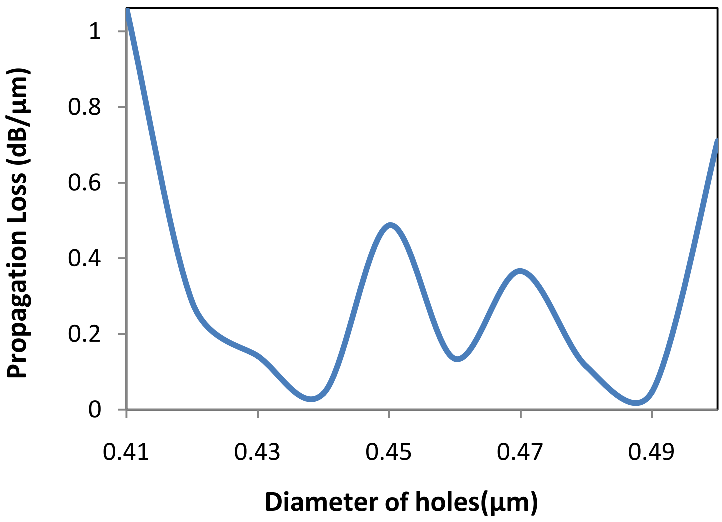

Figure.4.2: Variation of diameter of air-holes with respect to propagation loss. Photonic waveguide parameter, lattice constant is 1.0 µm at the wavelength of 1.55µm.

As shown in Fig.4.2 on varying the diameter of air holes in range of 0.41 µm to 0.50 µm, taking lattice constant 1.0 µm at the wavelength of 1.55µm, low propagation loss is estimated to be 42 dB/ mm at the diameter of 0.44 µm, which is lowest among all the losses measured at other diameter values.

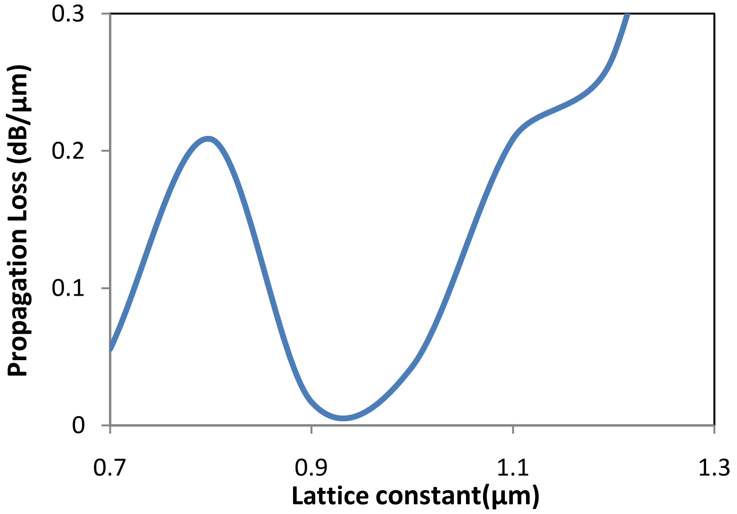

Figure.4.3: Variation of lattice constant with respect to propagation loss. Photonic waveguide parameter, diameter of air-holes is 0.44 µm at the wavelength of 1.55µm.

In Fig.4.3 shows the variation of propagation loss with lattice constant. On varying the lattice constant in range of 0.7 µm to 1.3 µm, taking diameter of air-holes 0.44 µm at the wavelength of 1.55µm, low propagation loss is estimated to be 16 dB/ mm at lattice constant of 0.9 µm, which is lowest loss measured among all other lattice constant values.

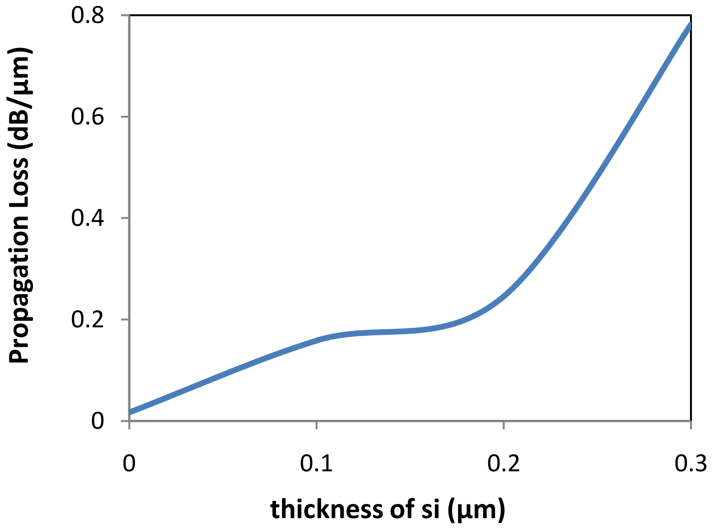

Figure.4.4: Variation of thickness of top Si with respect to propagation loss. Photonic waveguide parameter, diameter of air-holes is 0.44 µm and lattice constant is 0.9 µm at the wavelength of 1.55 µm.

In Fig.4.4 By further increasing the thickness of top Si up to 0.3 µm, taking diameter of air-holes 0.44 µm and lattice constant 0.9 µm at the wavelength of 1.55 µm, propagation loss keep on increasing linearly.

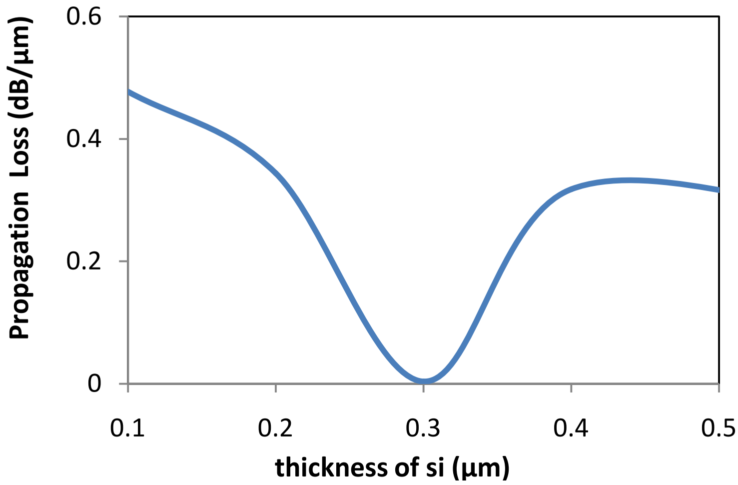

Figure.4.5: Variation of thickness of top Si with respect to propagation loss. Photonic waveguide param-

eters thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm, lattice constant 0.9 µm at the wavelength of 1.55µm.

Further, the effect of vertical refractive index contrast is studied in Fig.4.5 which shows the variation in propagation loss with the thickness of top Si where d = 0.44 µm and a = 0.9 µm at the wavelength of 1.55µm. Whereas, at a Si-thickness of 0.3 µm on SOI the propagation loss is estimated to be 3.6 dB/ mm which is low enough for millimetre-long devices. Here, the propagation characteristics of the waveguide become sensitive to the changes in top silicon layer due to the vertical refractive-index contrast because of presence of SOI.

4.2.2 Electric Field Distribution

Fig.4.6 shows the electric field distribution of optimized structure which is computed using FDTD. The single line defect photonic crystal waveguide can confine light within the narrow region of high refractive index material. As this line defect in the centre acting disturbs the periodicity of air-holes that helps in obtaining strong optical confinement in the narrow region. The periodic structure (air holes) surrounding the defect causes a collective cancellation of scattering of light leading to guiding of light in the defect region. Below figure shows a strong optical confinement in defect region taking photonic waveguide parameters, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm, lattice constant 0.9 µm at the wavelength of 1.55µm.

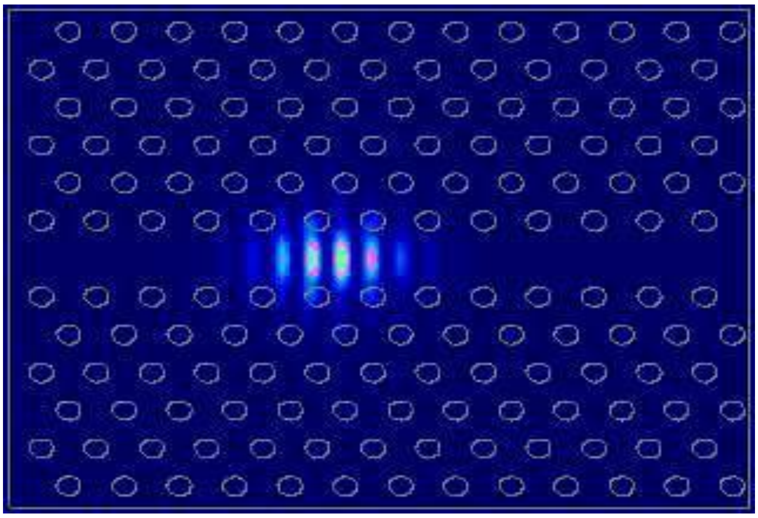

Figure.4.6: Field propagation inside the single line defect photonic crystal waveguide. Photonic waveguide parameters, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm, lattice constant 0.9 µm at the wavelength of 1.55µm.

4.3 Analysis of Dispersion Characteristics

Fig.4.7 shows the effective group index versus wavelength at various values of lattice constant on taking waveguide parameters, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm at the wavelength of 1.55µm.

It is noticed that on increasing the value of lattice constant from 0.5 µm to 1.0 µm, the effective group index curve attain flatness. At 0.5 µm of lattice constant the curve shows great variation in effective group index in range of wavelength 1.4 µm to 1.6 µm. Whereas, It is observed that effective group index has a flat curve for a lattice constant of 1.0 µm but it is low for the lattice constant a = 0.9 µm at the wavelength of 1.55 µm, which shows the effective light-matter interaction become small when n_g is low. In case of conventional waveguides group index is almost an equivalent to the refractive index of the component materials. The consequence of optical processes analysed by light-matter interaction such as wavelength conversion or amplification will be decreased if group velocity inside the surrounding media becomes large. Fig.4.8 shows high order dispersion in the proposed waveguide. The variation in group velocity with wavelength at various lattice constants is shown.

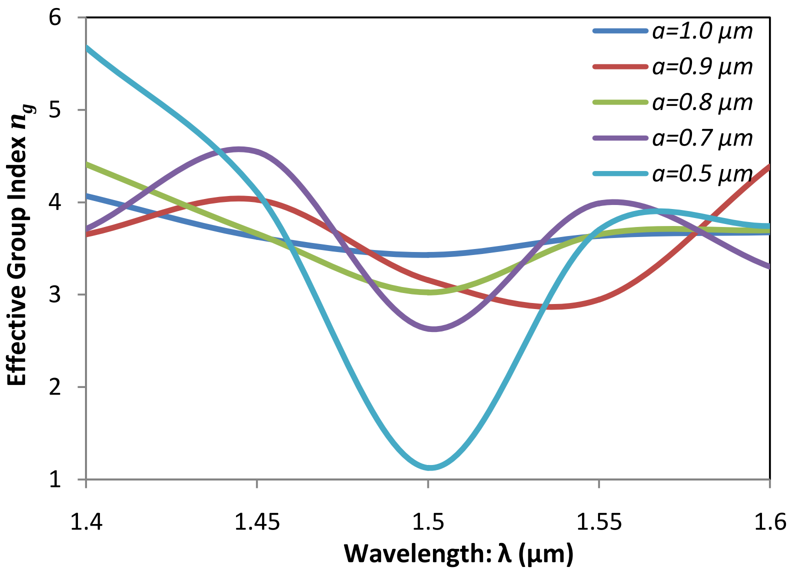

Figure.4.7: Effective group index *ng* vs. wavelength *λ* for different values of lattice constant. Photonic waveguide parameter, thickness of Si is 0.3 µm, thickness of SiO2 is 1.0 µm, diameter of air-holes 0.44 µm at the wavelength of 1.55µm.

The group velocity, v_g can be calculated by using $v_g = c/n_g$ where n_g is the group index. However, there is certain limitation of total-internal reflection confinement that stripe waveguide cannot have group index more than 5, which is not the case applicable with line defect waveguides which has fundamentally different mechanism of confinement. As the group velocity v_g is having inverse of relationship with group index n_g above graph characterise the same relationship at wavelength of 1.55 µm on taking waveguide parameters, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm at the wavelength of 1.55µm.

It is noticed that on increasing the value of lattice constant from 0.5 µm to 1.0 µm, the group velocity curve attain flatness. At 0.5 µm of lattice constant the curve shows great variation in group velocity in range of wavelength 1.4 µm to 1.6 µm. It is investigated that for lattice constant *a*=1.0 µm we have flat curve but on varying the lattice constant to *a*=0.9 µm a high group velocity is achieved as its n_g is low among all the variable values of lattice constant for line-defect waveguide with hexagonal lattice at 1.55 µm.

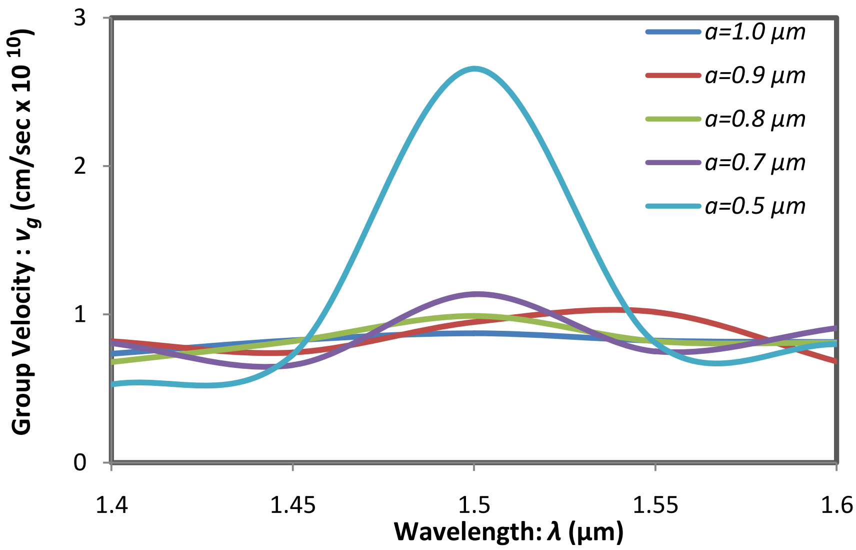

Figure.4.8: Group velocity v_g vs. wavelength λ for different values of lattice constant. Photonic waveguide parameter, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm at the wavelength of 1.55µm.

Generally, the effective group index, $n_g = n - \lambda(dn / d\lambda)$. Therefore if *ng*, effective group index is less than *n*, effective index the structure has anomalous dispersion *(dn/dλ> 0)* which is in general the case of conventional waveguide. But waveguides with large deviation in effective index may exhibit normal dispersion *(dn/dλ< 0)* and thus effective group index n_g is greater than effective index n. Fig.4.9. Show the group velocity dispersion (psec/nm km) vs. wavelength (µm). Photonic waveguide parameter, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm at the wavelength of 1.55µm.

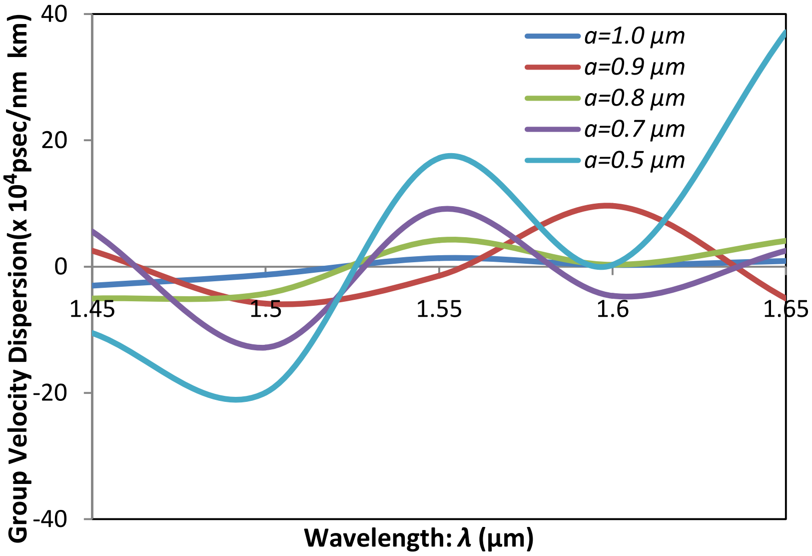

Figure.4.9: Group velocity dispersion vs. wavelength for different values of lattice constant. Photonic waveguide parameter, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes 0.44 µm at the wavelength of 1.55µm.

The group velocity dispersion, GVD = $(-\lambda *(d^2n/d\lambda^2))$. It is noticed that on increasing the value of lattice constant from 0.5 µm to 1.0 µm, the group velocity dispersion curve attain flatness. At 0.5 µm of lattice constant the curve shows great variation in group velocity dispersion in range of wavelength 1.45 µm to 1.65 µm. The group velocity dispersion of n_g at the range of wavelength from 1.55 µm to 1.65 µm has a flat curve for the lattice constant a=1.0 µm whereas, the group velocity dispersion is low for the lattice constant a=0.9 µm at the wavelength of 1.55 µm.

4.4 Analysis of Polarization Characteristics

The proposed line defect photonic crystal waveguide can find applications in polarization insensitive photonic devices for photonic networks. A common drawback, however, to all photonic-crystal waveguide systems proposed until now two dimensional and three dimensional, is that they are highly polarization selective. Given that the polarization state of an input signal may not be known and/or may vary over time, their proper operation would require the use of active polarization preprocessing devices. The ability to control the flow of radiations by varying the radius of air holes, lattice constant and the thickness of the slab in the photonic crystal makes it possible to design reflectors or filters, resonators and waveguides for some specific applications. Straight single-line defect optical waveguides in photonic crystal slabs are designed by the finite difference time-domain into a silicon-on insulator (SOI) wafer.

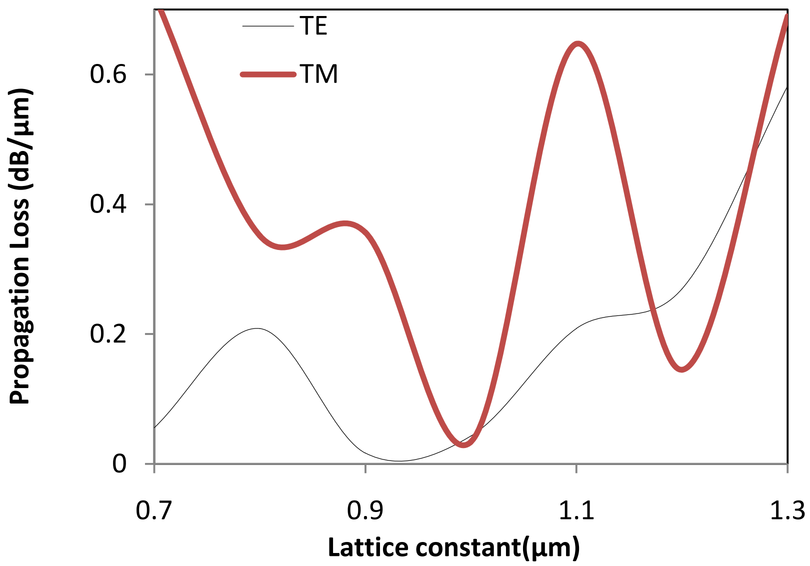

Figure.4.10: Variation of lattice constant with respect to propagation loss. Photonic waveguide parameter, diameter of air-holes is 0.44 µm at a wavelength of 1.55 µm, minimum propagation loss is estimated to be 16 dB/ mm for TE like polarization at lattice constant of 0.9 µm and 33 dB/ mm for TM like polarization at lattice constant of 1.0 µm.

Structure is optimize for low propagation loss by varying the lattice constant *a* at wavelength λ of 1.55 µm and the propagation loss for both the TE polarization, TM polarization have been observed as shown in Fig.4.10, where it has been noticed that TE like polarisation exhibit propagation loss of 16 dB/ mm which is twice less loss measured than that in case of TM like polarization. A clear light propagation for both polarizations is observed with low loss along the waveguide.

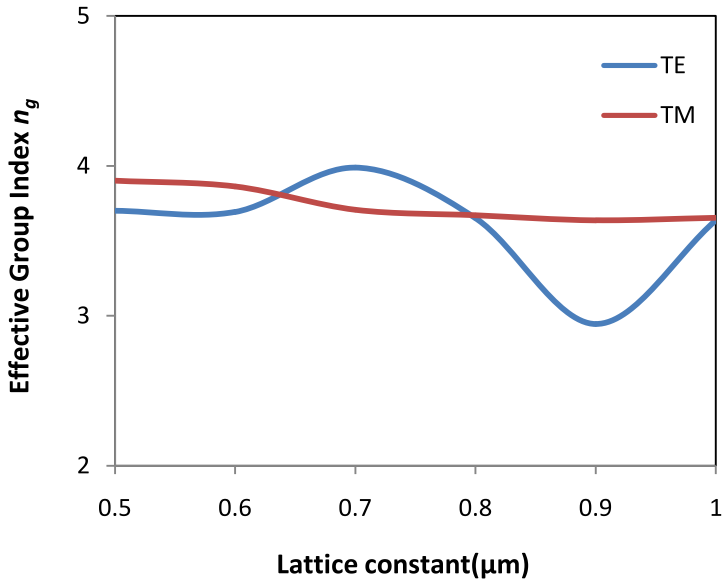

Figure.4.11: Variation of lattice constant vs. effective group index. Photonic waveguide parameter, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, diameter of air-holes is 0.44 µm at a wavelength of 1.55 µm for TE like polarization and TM like polarization.

It is find that the group index more useful when defined in terms of wavelength, $n_g = n \lambda*(dn/d\lambda)$. Keep in mind the $(dn /d\lambda)$ is negative in most regions. The group index, *ng*, is always larger than the regular index of refraction, *n*, except in regions of anomalous dispersion. Fig.4.11 shows the characteristics for both TE and TM like polarization which shows periodicity in nature at wavelength of 1.55 µm. Where at 0.8 µm and 1.0 µm of lattice constant the effective group index for both polarizations coincide.

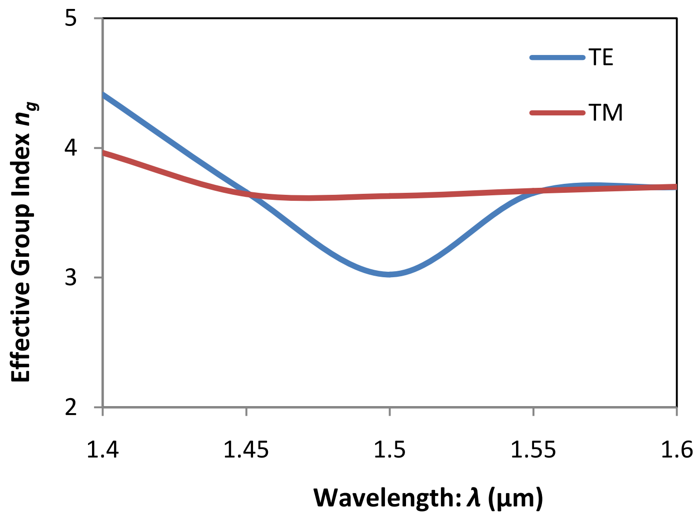

Figure.4.12: Effective group index *ng* vs. wavelength *λ*. Photonic waveguide parameter, thickness of Si is

0.3 µm, thickness of SiO_2 is 1.0 µm, lattice constant 0.8 µm at the wavelength of 1.55µm for both TE and TM like polarizations.

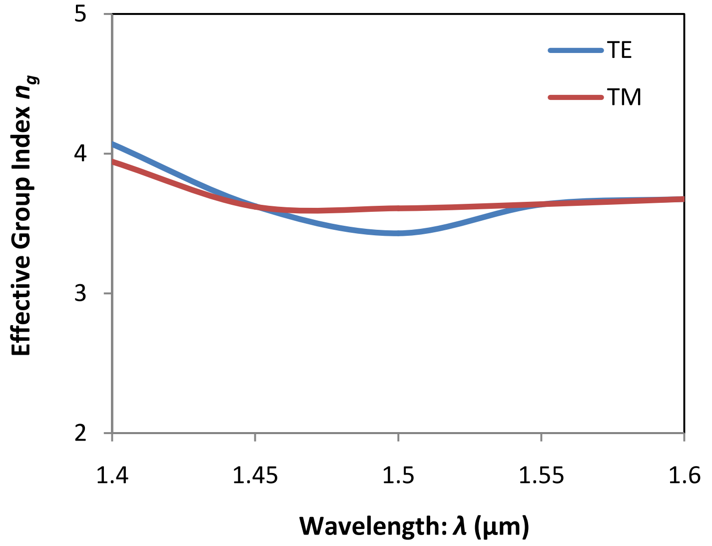

Figure.4.13: Effective group index *ng* vs. wavelength λ. Photonic waveguide parameter, thickness of Si is 0.3 µm, thickness of SiO_2 is 1.0 µm, lattice constant 1.0 µm at the wavelength of 1.55µm for both TE and TM like polarizations.

From Fig.4.12 and Fig.4.13 Notice that n_g decreases monotonically as the wavelength increases up to 1.55 µm (i.e., the frequency decreases); this is normal dispersion. After which TE and TM both shows only slight change in their characteristics.

CHAPTER 5

CONCLUSION

This dissertation targets at the design, simulation and analysis of line defect photonic crystal waveguide on silicon on insulator. A micro / nanophotonics circuit on Silicon-on-Insulator plays a key role in large-scale photonic integration because of the high refractive index contrast of between Si (3.5) and SiO_2 (1.44). A detailed study on the propagation loss, dispersion characteristics and polarization characteristics have been investigated in a simple line-defect waveguide by keeping lattice constant and hole diameter fixed in photonic crystal. Propagation loss and group velocity dispersion values were also calculated to analyses the structure more accurately.

A low-loss and flat dispersion line-defect photonic crystal waveguide is proposed with a simplified waveguide-design on silicon-on-insulator based on hexagonal lattice of two dimensional photonic crystals. Propagation loss and dispersion characteristics have been investigated in a simple line-defect waveguide by keeping lattice constant and hole diameter fixed in photonic crystal. A low propagation loss of 3.6 dB/mm and the largest negative dispersion value of 19.9×10^4 ps/nm km is calculated for d= 0.44 µm and a= 0.5µm but desired structure has been achieved at d= .44 µm and a= 1 µm of flat dispersion in a range of 1.375×10^4 ps/nm km to 0.913×10^4 ps/nm km over a large band of wavelength range of 1.55 µm to 1.65 µm without disturbing the periodicity is achieved. The flat dispersive nature which is one of the most important features in line defect waveguides will bring up new prospects for functional waveguide devices based on photonic crystals. The proposed work suggests that the dispersion and waveguiding properties can be effectively controlled in an easy-to implement way by changing the geometrical configuration in vertical as well as in-plane directions in the photonic crystal slab. The dispersion properties of photonic waveguide are tailored with simple structural variations in photonic waveguide such as air-hole sizes or diameter of air holes and inter-hole spacing or lattice constant. By doing so it is possible to have a photonic crystal platform based on silicon to guide and manipulate the light.

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