“Low Dispersion On-Chip Hollow Waveguide for High Data Rate Applications”

Dissertation Submitted towards the partial fulfilment of requirement for the award of degree of

Master of Engineering
In
Electronics and Communication Engineering

Submitted by

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DECLARATION

I **Shruti Sobti,** hereby certify that the work which is presented in this dissertation entitled "Low Dispersion On-chip hollow waveguide for high data rate applications" is an authenticate record of my study carries out ad 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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It is certified that the above statement made by the student is correct to the best of my knowledge and belief

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ACKNOWLEDGEMENT

I would like to express my special thanks to my dissertation Advisor, **Dr. Mukesh Kumar**, Assistant Professor, Electronics & Communication Engineering Department, Thapar University, Patiala for his continuous indefatigable guidance and support. He has been an excellent advisor, as he is a great source not only of knowledge, experience and insight but also of inspiration and encouragement which paved me on to the path to carry this project. I am highly indebted to him for his painstaking efforts and invaluable suggestions during the period of work.

I am also thankful to Head of Department and Professor **(Dr.) Sanjay Sharma**, PG Coordinator **Dr. Amit Kumar Kohli** (Associate Professor) of Electronics & Communication Engineering Department, Thapar University, Patiala for their valuable advice and helped in all possible ways for the completion of my dissertation work.

My greatest thanks are to all who wished me success especially my parents. Above all I render my gratitude to the Almighty who bestowed self-confidence, ability and strength in me to complete this work, for not letting me down at the time of crisis and showing me the silver lining in the dark clouds. I do not find enough words with which I can express my feelings of thanks to my dear friends for their help, inspiration and moral support which went a long way in successful competition of the present study.

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ABSTRACT

Low loss structures for guiding light pulses for on chip communication is the major challenge for the application of high data rate. As time is moving ahead high data rates are becoming the un-escapable for transfer of large data on chip and to overcome the interconnection bottle-neck. In an effort to move this important issue along, the thesis work mainly concentrates on the analysis of engineering of hollow waveguides for being used at higher data rates. Hollow waveguides engineered with high contrast gratings (HCG) have been comprehensively studied over the years due to its diverse application in optoelectronics devices. One of the innovative forms of grating is high-index contrast grating (HCG). It is possible to control the dispersion loss of light in waveguide by optimizing the HCG parameters. Review of the recent advances in HCG grating and its application for high data rate optoelectronic devices is done. From application point of view the dissertation pave the way for realizing low dispersion for high data-rate transmission.

A proficient structure of HCG based hollow waveguide (HWG) on SOI is proposed. The presence of three material i.e. silicon-air-silicon oxide grating on top silicon layer in SOI allows a strong interaction between the guided mode and the grating. The design of high data rate hollow waveguide is presented by optimizing the various grating parameters like grating thickness (t_g), grating period ($\wedge$), waveguide core thickness (d) and refractive index contrast of grating. Optimizing all the parameters the design is then analysed over a wide range of data rates. Design and simulation of waveguide is done in MATLAB using RCWA (Rigorous Coupled wave analysis) and SVFD (Semei-Vectorial Finite Difference) method. Dispersion of 15.14 ps/nm/km is observed at data rate of 40 gbps. The proposed characteristics of the device arise from the engineered structure of hollow waveguide.

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LIST OF ACRONYMS

PLC:	Planner light wave circuits
THz:	Tera-Hertz
OLED:	Organic light emitting diodes
HCG:	High contrast grating
DWDM:	Dense wavelength division multiplexing
DBR:	Distributed Bragg reflectors
HWG:	Hollow waveguide
SOI:	Silicon on insulator
VCSEL:	Vertical cavity surface emitting lasers
Gbps:	Giga bytes per second
RCWA:	Rigorous coupled wave analysis
SVFD:	Semi-Vectorial finite difference method

CHAPTER 1

INTRODUCTION TO GRATING BASED HOLLOW WAVEGUIDES

1.1 Motivation:

Integrated optical systems have played an important role in advancing and modernizing the telecommunications industry, since the origination in the 1960"s. In the last decade the market has invested huge sums of money into high technology companies specializing in technologies that employ the advances in integrated optical systems. Currently, high index contrast waveguides are being actively investigated for their application in on chip optical communication. The aspiration to migrate from electrical components to fibers to high index contrast devices is determined by one critical factor: the high optical confinement of high index contrast devices waveguides. Today"s telecommunications has a tough competition in market for delivering low cost, highly reliable, fast, and high class of telephone, internet, and video service to the office and home is a driving factor in photonic component and PLCs (planer light wave circuits) development. A critical issue associated with their development and implementation is wrapping it up on chip. By far, the most critical aspect of packaging is a precise fiber optic alignment in which PLCs are interfaced with other optical components and devices either by single mode optical fibers or fiber arrays. The struggle, and experiment, is that between the single mode fibers and their interface components, photonic crystals and high index contrast waveguides, there lies in the fact that there is a considerable size differential which results in a poor mode overlap between them.

Inspirations for using optical communication for on chip data transfer take account of:

1. Wider bandwidth of Optical communication links have than existing copper or microwave links, for carrying more information on a given link.

2. Attenuation in hollow waveguides is less than experienced in copper or microwave systems because of its high heat durability. 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 channels or aircraft.

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

5. Due to the immunity of optical waveguide from electromagnetic interference, ground loops, persuaded cross talk, etc.

6. Finally, and conceivably most salient, a family of lasers, detectors, and other integrated optical devices that are compatible with optical waveguides in power, wavelength, and size has been developed by semiconductor technology.

1.2 <u>Hollow waveguides</u>:

A structure that guides an electromagnetic wave inside it is known as a waveguide and when the core is air it is called hollow air core waveguide. A waveguide having air as core has a proposal potential for minimisingthe dependence of light propagationwhich occurs on the air core transparency. Due to lower index of air compared to the cladding material used in waveguide the light can be guided inside the core with the help of the phenomenon of total internal reflections.

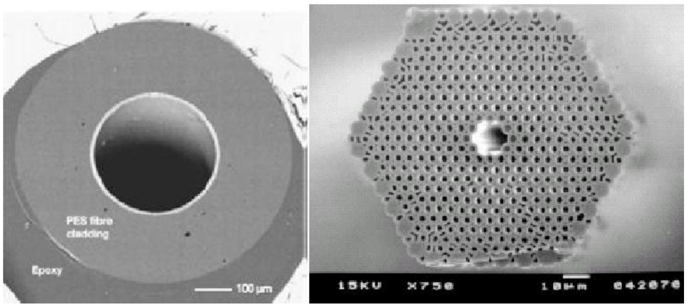

Fig1.1. Schematic diagram of various air core wave guiding structures used in the light pulses propagation[1-2]

Hollow waveguides gives the world a striking alternative for using air core in space of other solid core infrared fibers. Key features of hollow waveguide are the ability to transmit wavelength well beyond 20µm, high power laser delivery and simple structure. Initially they have been developed for industrial and medical applications involving conveyance of CO_2. These waveguides can be grouped in two categories 1) leaky waveguide, the one having the refractive index of the wall greater than one 2) attenuated total reflectance waveguide which have refractive index less than one.

1.2.1 Properties of hollow waveguide

Optical damage is major drawback for using waveguides. Optical damage is perceptible through a diminution of the output light coming out of the waveguide as a function of the time during which the light is coupled in the waveguide. Clarification for this behaviour is the loss of mode coupling, because of the modification in the refractive index induced by the high intensity light inside the guide since the change of refractive index inside the hollow waveguide is constant there is a comparatively low optical damage threshold in hollow waveguide.

Tuning of light inside the waveguide depends on the temperature of the environment inside the waveguide. Since the temperature variation of air core with the power traversing inside the waveguide is very less the hollow core waveguide posses the property of temperature insensitivity

A variety of different integrated optical waveguides are used to confine and guide light on a chip. The most basic optical waveguide is a slab waveguides shown below. The structure is uniform in the y direction. Light is guided privileged of the core region by total internal reflection that occurs at the core-cladding interfaces Confinement is a property of a waveguide structure. It describes how large/wide in space the light mode is (or where the light is confined).Hollow waveguides have a assets of strong optical confinement

Dispersion is spreading of light with change of the velocity of light. In hollow waveguide the refractive index of core does not change or has a very minute effect in refractive index with changing environmental condition thus the velocity does not changes leading to a property of low dispersion in the waveguide.

1.2.2 Applications

1.2.2.1 Optical Interconnects

With the increase of complexity and speed of integrated circuits and computer systems they are meeting with the trade-off between the length of a signal path and the bandwidth sustained by these paths. Optical interconnects do not reveal this trade off and in the forthcoming period are likely replace metal wiring for long interconnects.

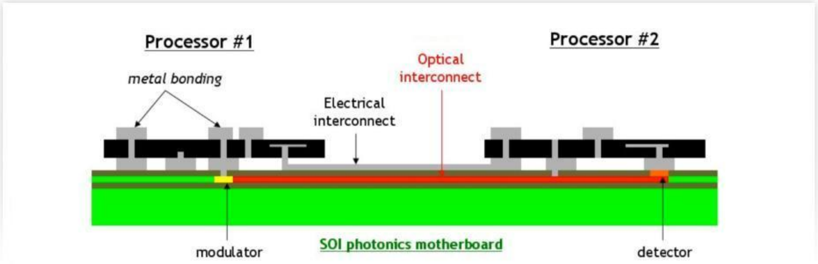

Fig1.2. Schematic diagram showing electrical interconnect and waveguide as optical interconnect [3]

Researchers have also exposed the advantages that optical interconnects offer over electrical interconnects in terms of fan-out, energy conversion, latency, temperature resistant and electromagnetic interference immunity. A number of researchers have realized diffractive grating couplers as the coupling element for optical interconnect systems. Hollow waveguides are desirable because they are more compact than other coupling schemes.

1.2.2.2 Integrated Optical Devices

Hollow waveguides find an application in integrated optical devices as well. On a compact and integrated scale integrated optical devices attempt to accomplish the same task as bulk optics. Beam expanders, polarisation dependant devices, and holographic filters for beam intensity profile reshaping are some of the examples of waveguide integrated optical devices. Other integrated optical devices with applications to computer systems are optical read/write heads, grating coupled surface emitting lasers, optical sensors, and printer heads.

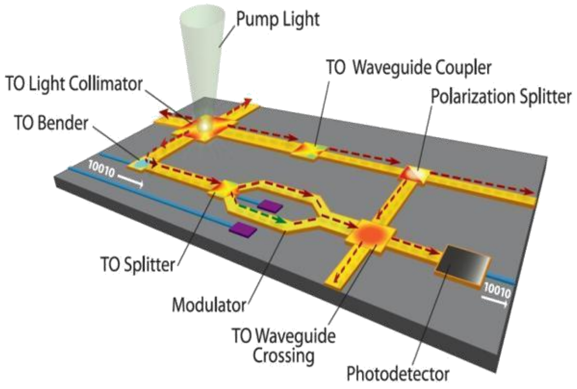

Fig1.3. Diagram showing the application of hollow waveguide integrated optical devices on a circuit[4]

1.2.2.3 Optical Communications

Another area in which Hollow waveguides have found application is in fiber optical communications. Optical communications over fiber optic links have potentially large bandwidths and experience low loss for long distances. One of the advantagesof the bandwidth of optical communications is wavelength division multiplexing. Wavelength division multiplexing and dense wavelength division multiplexing require devices that are highly sensitive to wavelength for interacting with narrow wavelength communication channels. Hollow waveguides have the potential to play an important role in this arena. Some Hollow waveguide based devices have been demonstrated by researchers such as Bragg gratings that are used for wavelength division multiplexing and optical filters.

1.2.2.4 Organic light-emitting diodes (OLED’s)

OLED does have fascinated significant attention due to their impending for flat panel display application. Nonetheless, the low light withdrawal proficiency of OLED‟s [5] is a solemn problematic when seeking to realise high brightness for a long lifetime. In the typical OLED structure, a guileless ray optics theory prophesies that the percentage of surrounded by the light in the high refractive index of an indium-tin-oxide (ITO) anode and organic layers is as high as 50%.It is established that the total energy of the restrained mode is as high as 40-50% by using a more dependable method of that combines the finite difference time-domain simulation and mode expansion analysis.

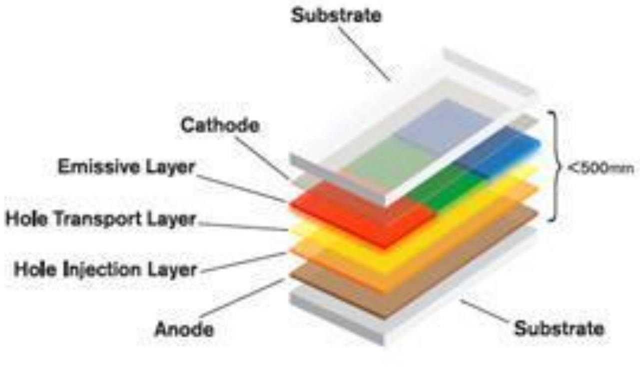

Fig 1.4 Schematic diagram of an OLEDwith a core of 500nm mounted on a silicon substrate [6]

These results recommend that the most nominal method for an improvement of light extraction efficiency is conversion from the confined mode to the output mode in the air.

1.3 Optical gratings

Optical gratings have been a research topic from a very long time now. Because of its wide applications in holography, into spectroscopy, in lasers, and many other optoelectronic devices, it has been comprehensively studied over the years. A Scottish mathematician and astronomer James Gregory (1638-1675) discovered diffraction gratings by spotting the diffraction patterns from passing sunlight through a bird feather. However, the first man-made diffraction gratings were made in 1786 by an American astronomer, David Rittenhouse but, Rittenhouse didn‟t develop this prototype further, so the credit for the invention of diffraction gratings is well deserved by German physicist Joseph Von Fraunhofer. Independently of Rittenhouse, Fraunhofer used a similar method to develop a wire diffraction grating [7] in 1821. Fraunhofer built the first ruling engine, and his research resulted in gratings of sufficient quality which permitted him to quantity the captivation lines of the solar range which are now commonly mentioned to as the Fraunhofer lines. He explained the phenomenon of diffracted orders, and derived and verified the grating equation and is thus, recognized for laying the foundation for today‟s modern grating theory of optics [8]. Subsequently the production forbearances which is required for an optical gratings is quite small, usually a miniature segment of the optical wavelength, in the yester years of grating study they were mass-produced by watchmakers, who were the only people with experience in working with such a high precision level and fine scale. In 1882, at Johns Hopkins University, U.S. physicist Henry Augustus Rowland constructed sophisticated ruling engines, which could fabricate gratings with much higher precision than anything available before. Rowland published a famous paper [9] in 1882, which opened up a new era of spectral analysis and recognized grating as the principal optical element of spectroscopic expertise. More than 180 years have passed since Fraunhofer first developed the grating theory. Today, gratings and other periodic structures have been widely used, not only in spectroscopy, but also in many other areas of science and engineering, such as: solid state physics, optoelectronics, acoustics, nonlinear optics, holography, and x-ray instrumentation.

1.3.1 Role of grating

Gratings are preferred when light of different wavelengths are to be separated with high resolution. Gratings are made up of large number of narrowly spaced parallel slits which provide a very sharp and narrow intensity peak , a precise high resolution and a seamless guiding of light useful for several applications like spectroscopy, imaging, micro-chromators, and wavelength division multiplexing devices. These gratings can be either trans-missive or reflective [10].

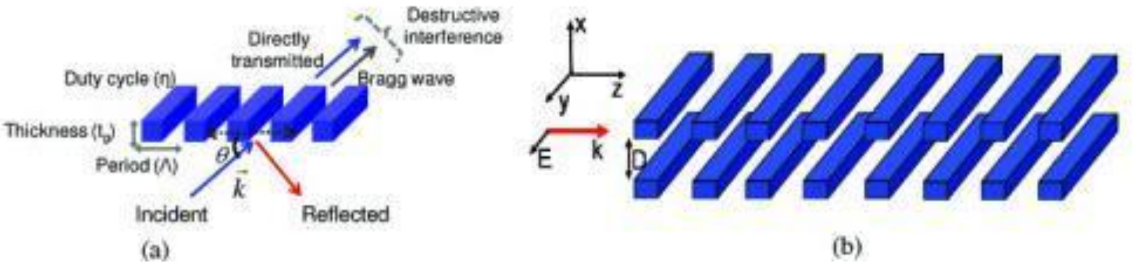

Fig1.5.(a) Schematic diagram of HCG (High contrast grating). High refractive index material surrounded by low refractive index material (b) Schematic of 1 D HCG hollow core waveguide structure consisting of two reflecting HCG‟s [11].

There are appropriatelystated in two regimes: the diffraction regime, in which the grating period (∧) of the grating is bigger than the wavelength (λ) [12-13], and the deep-subwavelength regime, in which the grating period, is much less than the wavelength [14]. Amid these two well-known regimes there is a third, comparatively unmapped regime: the near-wavelength regime, in which the grating period is between the wavelength of the grating material and that of its surrounding media. The gratings behave radically differently at this regime, and demonstrate many distinct properties that are not commonly displayed by the gratings. When there is a large refractive index contrast between the grating bars and their surrounding area these features become more prominent. With an spontaneous top-down design guidelines, broadband ultrahigh reflectivity (>98.5% over a wavelength range of $\Delta\lambda/\lambda>35\%$), broadband high transmission windows, 100% reflection and 100% transmission, as well as high quality factor resonance (quality-factor Q > 107) can be obtained [15-17].

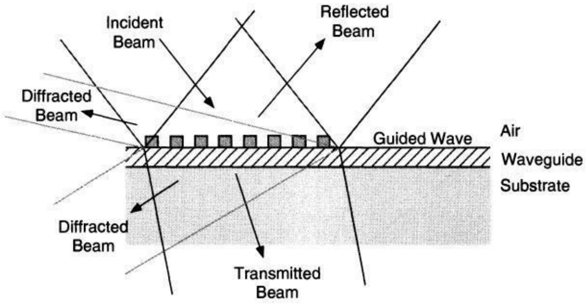

Fig1.6. Schematic diagram demonstrating HCG on hollow waveguide sustrate and the all light beams that get incident diffract transmitted and reflected in the waveguide[18]

This is thus a new class of grating, and is referred as high contrast grating (HCG), schematically shown in Figure 1.1.A key differentiator of it from other near-wavelength gratings is that the high index grating bars which are entirely bounded by low index materials are scratched on a high-index substrate without the additional index contrast at the subsisting plane [19-21]. With numerous astonishing properties, HCG inaugurates a new platform for planar optics and integrated optoelectronics. The principle of HCG lies in its excellent guidance of light, which can be united to its applications within light generation and detection. Whole ranges of aspects in integrated optoelectronics are covered with the extent of functionality of HCG. This recommends that HCG has stretched beyond a single element in integrated optoelectronics and has enabled a new platform for integrated optoelectronics. HCG, since its invention in 2004, has seen prompt improvements in both experimental and theoretical characteristics and has drawn considerations from many researchers around the world, and gradually formed its own research field. Since 2012, a conference named as high contrast meta-structures had been established and is dedicated to this field in SPIE photonic west. It is supposed that HCG will continue to expand its application and play an important role in integrated optics and optoelectronics.

By way of the much expedited growth of information industry in the entire world, the demands for the communication networks for high data rate and larger capacity are also increasing. The optical fiber communication system plays an important role in modern communication networks. The main obstacles faced by the optical fiber communication system are the transmission loss, dispersion, and the nonlinear effects. Consequently, dispersion becomes the major difficulty in refining the optical fiber communication system, but with the advancement in optoelectronic devices, dispersion can also be remunerated to provide high speed optical fiber transmission system. One such method for compensation of dispersion is optical grating that plays a crucial role. By boosting the fabrication process of Chirped Fiber Bragg-Grating[22] many problematic problems i.e. the ripple of the time delay, loss due to cladding mode, fabrication repetition have been solved. Gratings play an attractive role in Dense Wavelength Division Multiplexing (DWDM) optical networks which increases the performance of the system in terms of selectivity and crosstalk between adjacent channels [23].

1.3.2 Grating theory

A distinctive optical grating is a 1D periodic structure which consists of a series of equally spaced grooves as shown in Figure 1.7. The grooves diffract light when it is incidented on the grating surface where each groove behaves like a small source of reflected/transmitted light. [24] At a unique set of angles if light is incidented it scatters from all the grooves and is in phase and also constructively interfere with each other.

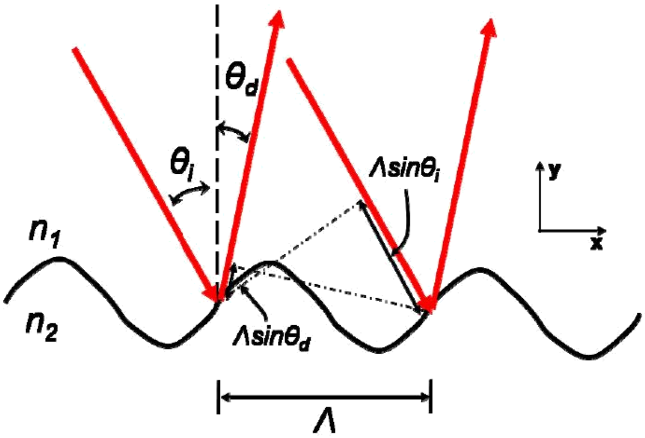

Fig.1.7 Schematic of an optical grating depicting the phase relationship among diffracted rays from the adjacent grooves [24].

In fig with respect to grating surface a plane wave is incident at an angle θ_i. The path difference between two adjacent grooves for a diffracted with an angle θ_d is expressed as

$$\wedge \qquad -\wedge \tag{1.1}$$

Where ^ is the grating period $\theta_i$is the incidented angle and θ_d the angle at which the light is diffracted. For light to be in phase and constructive interference the path difference should be an integral multiple

$$\wedge \qquad -\wedge = \tag{1.2}$$

Where m=0, ±1, ±2… and for all other angles there will be destructive interference between light diffracted from adjacent grooves and will be cancelled out. The above property of grating can be expressed in a simple equation, called as grating equation

$$=+ \qquad \frac{}{\wedge} \tag{1.3}$$

In the above equation is the angle which incident light makes with the grating , is the angle made by mthorder diffracted beam with the grating surface λ is the wavelength of the incident light and ^ is the grating period. The hypothesis made in the above stated equation is that light is monochromatic and collimated (plane wave) [25].The grating acts as a simple reflection mirror when the value of m is zero and the wavelength components are superimposed on each other. To determine the propagation direction of transmission order in the transmission grating similar equation can be derived.

$$= + \frac{}{\Lambda} \qquad (1.4)$$

Where the angle made mth order is transmitted wave with the grating. The grating number or grating vector is defined $= \frac{2}{\Lambda}$ [24-25]. For dealing with all kind of problems accompanying with grating many theories and methods have been proposed which include differential theory, method of Moharam and Gaylord, classical model method, integral method and many more. Rigorous coupled wave analysis (RCWA) is among one of the utmost extensively used methods for precise examination of diffraction of electromagnetic (EM) waves in the periodic structure [24-25].

1.3.3 Applications of gratings

1.3.3.1 Polarization Insensitive Hollow Optical Waveguide

When light interacts with the high refractive index material of the core in conventional dielectric waveguides attenuation and nonlinearities are faced, but this can be avoided when the light propagates in low index core having highly reflective walls [26].Sensing, optical communications, environmental applications, and spectroscopy are a couple of applications of hollow core optical waveguides. The two major characteristics of hollow waveguides (HWGs) are temperature insensitivity and wide tuning range [27] which can be utilized to create widely tuneable photonic devices without the requirement of sensors that control temperature.

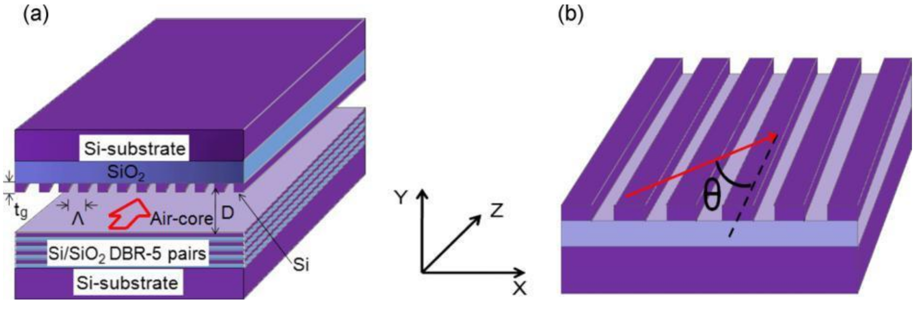

Fig1.8. Schematic of Hollow Optical Waveguide incorporating HCG as top mirror and DBR as bottom mirror with phase matching layer on top of DBR [28].

At narrow air core, the HWGs are polarization dependent because it offers large tuning in propagation constant. For providing lateral periodicity in hollow waveguide and to reduce the dependence on polarization, the HCG mirror can be introduced [28] and figure1.8 shows the design of polarization independent HWG. In these waveguides by announcing a phase-matching stratum in DBR and by adjusting the grating thickness of HCG mirror, the overall polarization dependence of HWG is diminished. This waveguide contains both vertical and lateral periodicity. It comprises of a high index contrast grating acting as a top reflective mirror and DBR as bottom mirror of HWG. Due to the high reflectivity"s of DBR and HCG, light can be restricted in a vertically in air-core. Now, for controlling the orthogonal polarizations a phase matching layer made of Si at the top of DBR is used [28]. The upper side of waveguide comprises of a high refractive index contrast (between air and silicon) grating. The net refractive index of the mode guided in the core below the HCG is higher compared to that in the other two lateral parts of core where HCG is absent. Lateral optical confinement originates from a great phase change under HCG the high index below HCG provides. To alter the propagation characteristics of the orthogonal polarizations the thickness of the high contrast grating and phase matching layer of DBR is optimized. These hollow waveguide are attractive for applications in polarization insensitive photonic devices [29] for photonic networks.

1.3.3.2Terahertz Absorber

Conventional Gratings offer small coupling strength therefore larger size gratings are to be used but they provides an out coupled beam which is much larger than the fiber mode. As a result, an additional lens is needed to couple to a fiber or, alternatively, a curved grating can be utilized that efficiently couples the light into a fiber. Due to large dimensions and low refractive index contrast, integrated optical devices allow a few functions to be incorporated on a chip. A crucial role is played by Nano-photonic circuits on silicon-on-insulator (SOI) in across-the-board photonic integration the reason is the high refractive index contrast between Silicon and Silicon dioxide [30].

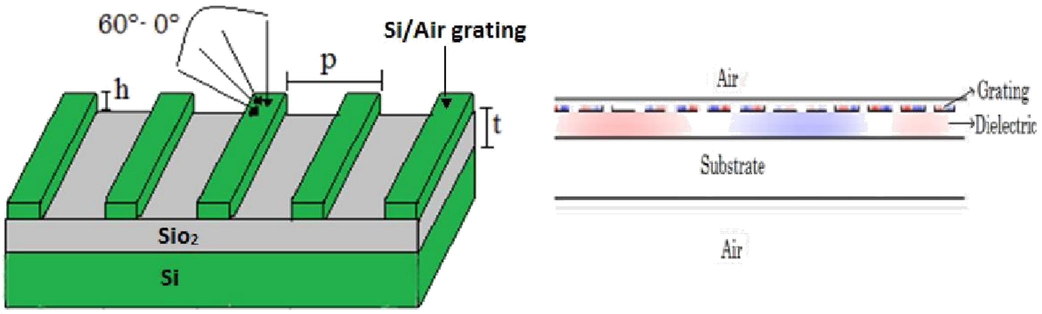

Fig 1.9 a) Schematic of the broadband and wide-angle terahertz absorber with high-index contrast grating. A thin dielectric separates a silicon substrate and a silicon/air high-index contrast grating. The incident light isTM polarized at different angle of incidence from 0˚ to 60˚ (b) Field propagation in grating region of theterahertz absorber simulated using CAMFR simulation tool when TM polarized light is normally incident on it. [31]

One of the other characteristic of SOI photonic circuits is the strong optical confinement. For many applications, there is a strong requirement of integrating electronic and photonic devices on a single SOI chip. Easily coupling light into and out of SOI waveguides is one of the challenges for a photonic device. Allowing optical Inputs/outputs to populate any area of a planar light wave circuits instead of being restricted to just one edge of a chip, grating plays a great role in coupling light into an optical fiber when positioned out of the plane of the waveguide. Optical gratings are the prime candidates to interact with on-chip optical components for coupling the light into the optical fibers or on/off chip devices for further optical processing [32]. High index contrast grating coupler maximizes the interaction of such gratings with the optical modes of the integrated optical devices. The schematic drawing of the out-coupler on SOI chip is shown in Figure 1.9 (a). The SOI waveguide comprises of silicon layer mounted on the top of the layer of silicon dioxide on a silicon substrate. Now, a high-index contrast grating which is also known as HCG is etched onto the top of the silicon layer. The thickness of SiO2 has a major impact on the guiding characteristics of the grating [31]. The radiated wave coming downwards reflects partially at the dielectric-substrate interface. Figure 1.9 (b) shows the field propagation of light wave when incident from sideways in the z direction. The oxide thickness should be so chosen that the reflected wave interferes positively with the one which isdirected directly upward and radiated waves so as to enhance the coupling strength. The device can find applications in broadband high-Q resonator to effectively couple a wide band of wavelength of light.

1.3.3.3 HCG VCSELS

Semiconductor diode lasers play a crucial role in wide range of applications which include telecommunication, sensing, solid-state lighting, display and printing. Among various structures, vertical cavity surface emitting lasers (VCSELs) [33-36] are most encouraging, which provides efficient light extraction. The VCSEL has its output light emission perpendicular to the wafer surface and to the plane of the active layers, in which the optical feedback provided by distributed Bragg reflectors

(DBR‟s) comprising of many layers of alternating high and low refractive indices. VCSEL‟s have very small gain length, so very high reflectivity (>99%) is required in the DBR‟s [35]. Due to small index contrast, numerous pair of DBRs is desirable to provide very high reflectivity. The most critical bottleneck for the realization of VCSELs in large wavelength regions is the availability of materials for making such highly reflective DBRs. With the advancement of optoelectronic devices DBRs are being succeeded by a mirror, , known as high-contrast grating (HCG) that consists of a single layer of 1-D subwavelength grating made of materials with a high refractive index contrast. This mirror provides many uncharted and unanticipated properties that were not found earlier in nature [36].

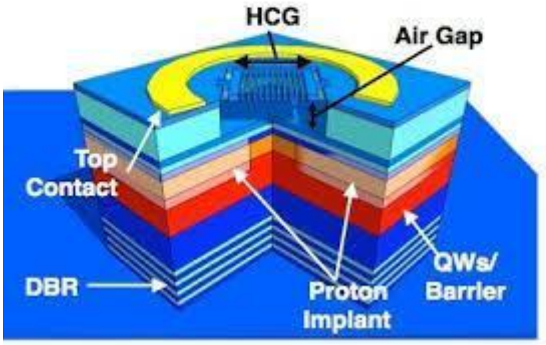

Figure 1.10 shows the schematic of a typical HCG-VCSEL. The device encompasses n-DBR [37]

Semiconductor based mirrors, an operating wavelength cavity layer with the active region, and an HCG acting as a top mirror. A p-doped DBR and a HCG which is freely suspended are the two sections of the top mirror. Spreading of current into the active region and preservation of the cavity layer during the fabrication process in done by n DBRs. These p-DBR pairs can be abridged or expelled out because a single-layer HCG alone is proficient for providing a very high reflectivity (R >99.9%) as the VCSEL top mirror. Electric current is injected through the top and bottom contact. An aluminium oxide aperture lies on the upper side of the cavity layer which provides both optical and current confinement [38].

1.4 Optical Waveguide Theory

Waveguide modelling is done to calculate the modes of electric field traversing inside the waveguide. There are many method of doing so like finite difference method, Fourier analysis, numerical solutions etc. In the presented work the solution of modes travelling inside the mode is done by using SemeiVectorial method. A simple and accurate method which solves automatically and takes in account all the discontinuities in the normal electric field components. Based on split step fast Fourier transform 3 D Semeivectorial wave equations for the quasi TE field with x polarization component

$$\frac{{}^{2}}{{}_{2}} + \frac{\left(\frac{1}{{}_{2}}\ {}^{2}\right)}{} + \frac{{}^{2}}{{}_{2}} + {}^{22}_{0} ,= 0 \qquad (1.5)$$

In the above equation E is the electric field n is the refractive index and k is the wave number. Each of the four semeivectorial polarized modes contain five non zero components of the electric field, which satisfies the zero divergence constraints and is determined by solving

$$\nabla^{2} + {}^{2} = {}^{2} \qquad (1.6)$$

Propagation constant is calculated by

$$({}^{2})^{2} = \frac{\nabla^{2} + {}^{2}}{{}_{2}} \qquad (1.7)$$

And field profile is updated from the iterative solution of linear algebraic equation

$$- {}^{2} = ({}^{2} - {}^{2}) \qquad (1.8)$$

1.5Purpose and Outline of work

The purpose of the work is to design and analyse a versatile Hollow waveguide based interconnect replica using high index contrast grating on Silicon-on-Insulator (SOI) Chip. Prime focus of the work will be on Silicon-on- Insulator (SOI) based on-chip photonics devices. In this dissertation, design of a hollow waveguide engineered with high contrast grating for the transmission of high data rate which goes from 40 gbps to 50 gbps with a low dispersion of 15.14ps/nm/km by optimizing the grating and waveguide parameters. The simulation is done on MATLAB using RCWA (Rigorous Coupled wave analysis) and SVFD (Semei-Vectorial Finite Difference) and this dissertation is divided into following sections.

Chapter 2 has a brief description on dispersion and limitations of dispersion on high data rates

Chapter 3 discusses survey on the research work done in the High Index Contrast Grating for various practical applications.

Chapter 4 discusses our results on the proposal and analysis of the High Index Contrast Grating based hollow waveguide. Usefulness of air core and dispersion in waveguide at different data rates.

Chapter 5 summarizes the whole dissertation with some closing remarks and presents the scope of HCG- Hollow waveguide for high data rate communication in near future.

CHAPTER 2

DISPERSION IN HOLLOW WAVEGUIDE

2.1 Dispersion

When the phase velocity of a wave depends upon its frequency, or otherwise when the group velocity depends upon the frequency the phenomenon in optics is called dispersion and the media with such characteristics are termed as dispersive media. To specify the wavelength-dependent environment or group-velocity dispersion (GVD) to indicate the performance of the group velocity the dispersion is often called chromatic dispersion. Pulses spreading in optical domain are caused by group-velocity dispersion, and this spreading is the reason which degrades the signals over elongated distances. On wave propagation, elimination also takes place among group-velocity dispersion and nonlinear effects which results in manifestation so it. Dispersion is most frequently described for the light waves, but it has a potential to occur for any kind of wave that can interact with the medium or can traverse through an inhomogeneous geometry like waveguides for example sound waves [39]. Normally there are two sources of dispersion which are waveguide dispersion and material dispersion. Frequency-dependent reaction of a substantial to waves causes material dispersion. Now for siting an example for, material dispersion which leads to not desired chromatic abnormality in a lens. In case of material dispersion different wavelengths of light travels with different velocities. If we consider a pulse that has a finite spectral bandwidth and this pulse is launched in a dispersive material then each wavelength component of the pulse will move at a different velocity. The pulse effectively disperses out in time domain and space. It will confirm that all finite temporal pulses should also have a finite frequency bandwidth. The minute the speed of a wave in a waveguide (for example as two dimensional photonic crystal slab) is dependent upon its frequency but independent of frequency of the resources from which it is fabricated then we can say that waveguide dispersion has occurred. Mostly waveguide dispersion occurs for waves propagating all the way through any inhomogeneous structure such as photonic crystal. Generally, both types of dispersion might be there but they are not strictly accumulative in nature. Their combination results in degradation of signal in waveguides and optical fibers for telecommunications, as each signal component will have different delay and they reaches on destination at different time [39].

$$= - \frac{\quad}{\quad}\frac{2}{22} = \frac{2}{2\;2}\frac{\quad}{\quad} \tag{2.1}$$

2.2 Need of high data rate

With the advancement of technologies the high data rates have become a necessity to transfer data on-chip so that the bottle-neck of low data rate can be broken and data can be moved on chip at high rates. IBM‟s Dr Solomon Assefa, in the IEEE International Electron Devices Meeting in Washington DC in December, presented a major advance in the how to usage light as an alternative of electrical signals for transmitting data for computing. In order to deal with the mounting dimensions of data being produced and transmitted a breakthrough technology, called „silicon Nano-photonics‟ is introduced which is able to transport information via pulses of light through optical fibres over innovativeness of networks [40].

Now, businesses are incoming the new epoch of computing due to an outburst of new applications and services which require high data rate transmission. The systems are required to process enormous capacities of information known as Big Data. In coming future Silicon Nano-photonics by allowing the integration of different optical components with electrical circuits on single silicon chip using; on a sub-100nm semiconductor technology provides answers to Big Data challenges. This will faultlessly connect various parts of large systems, which whether are a few centimetres or few kilometres apart from each other, and will enable terabytes of data to be transmitted via pulses of light through optical fibres.

Improving the limitations of overcrowded data traffic and high-cost traditional interconnects, these new technologies will provide a marvellous highway which is used for enormous amount of data to move at reasonably high speeds in between computer chips in servers, huge data centres, and supercomputers, and thus building on its preliminary evidence of the concept in the year 2010, it has explained the major challenges of transporting on the silicon Nano-photonics technology and into the commercial foundry for making it. It was made by accumulation a few processing modules that mad about a high-performance of 90nm complementary metal–oxide–semiconductor (CMOS) fabrication line, a diversity of silicon Nano-photonics workings for example wavelength division multiplexers (WDM), modulators and also the detectors are assimilated on side-by-side through a CMOS electrical circuitry. Now, as a consequence, single-chip optical communications transceivers which can be mass-produced in a conventional semiconductor foundry, which provide a significant and cost reduction which is done over old-fashioned approaches.

The capability to multiplex the large data streams of high data rates and will allow future scaling of the optical communications and are capable for transporting terabytes of data between unsociable parts of the computer systems [40].

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.

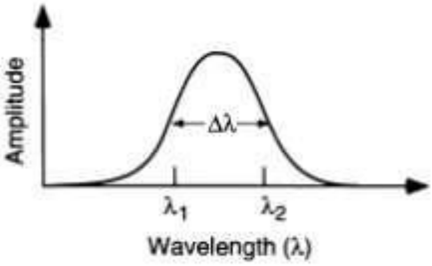

Fig 2.1. An optical pulse with a finite spread in wavelength [41]

Waveguide dispersion and material dispersion are normally two sources of dispersion. The dependence of response on frequency of a material to waves causes material dispersion. For example, undesired chromatic aberration in a lens is due to material dispersion. When different wavelengths of light travels with different velocities it is known as material dispersion. If we consider a pulse that has a finite spectral bandwidth and this pulse is launched in a dispersive material then each wavelength component of the pulse will move at a different velocity. The pulse effectively disperses out in time domain and space. It will confirm that all finite temporal pulses should also have a finite frequency bandwidth. When the speed of a wave in a waveguide (such as two dimensional photonic crystal slab) is dependent upon its frequency but independent of frequency of the materials from which it is constructed then we can say that waveguide dispersion has occurred.

2.4 Dispersion and bit rate

In digital communication employing light pulses, pulse broadening would result in an overlap of pulses, resulting in loss of resolution and leading to error in detection. Pulse broadening is one of the factor that limits bit rate because larger the pulse broadening, the smaller will be the number of pulses that could be transmitted per second that could be sent through the link.

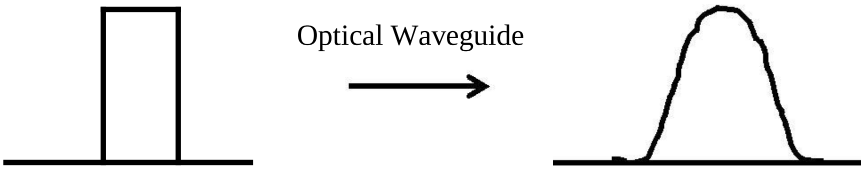

Fig 2.2 Spreading of light pulse in time domain

The dispersion of bits is mainly in time domain. The relation between maximum bit rate and pulse dispersion can be given as

$$= 0.7 \qquad \text{—} \qquad (2.2)$$

Where is the pulse dispersion. When many bits are transmitted together at a higher data rate the bits will interfere with each other leading to inter symbol interference.

[redacted]

Fig.2.3 Spreading of light pulses when transmitted at higher data rates

In case of strong dispersion the pulses invade the bit slot of another pulse which is known as inter symbol interference (ISI). Every signal component propagates at different velocity pulse spreading in time domain which will be given as

$$\Delta = (\; 1 \,\underline{=}\, 2 \;)$$

$$=\_ \quad \Delta = \quad \_\_\_ \quad \Delta \qquad (2.3)$$

Where L is the length of the waveguide is the refractive index of the core material

λ_1 and λ_2 are the wavelength of different waves inside the waveguide c is the velocity of light. Group index inside the waveguide can be defined in terms of wavelength as [41]

$$= - \qquad \_\_ \qquad (2.4)$$

Pulse broadening is caused due to the presence of different wavelength in the optical spectrum of the light source. Each wavelength had different index of refraction (IOR) which leads to a different phase delay and group delay in the waveguide.

Spatial capacity is denotes the "data intensity" in a propagating medium. It is usually used in combination with the transport mechanisms in wireless as well as optical media. It defines the limitation of the bit rate that has to be induced for dispersion less transportation of the data in the particular media. Channel spacing therefore refersto the gap in the wavelength that has to kept in control for loss less transfer as the media will lead to the spreading of the bits which can therefore get overlapped and cause of the dispersion.The bit rate of waveguide is limited by

$$b < \frac{c}{4L \quad d(^{2})} \qquad \frac{d_2 \quad \beta}{} \qquad (2.5)$$

in the above equation b is the bit rate inside the waveguide. C is the velocity of light L is the length of the waveguide and d is the thickness of the waveguide core.

CHAPTER 3

LITERATURE SURVEY

The progressing telecommunication networks and need of transfer of high data rates are increasingly concentrating on configurability and flexibility of hollow waveguide for on chip data transport usage. The fabrication of high speed active waveguides devices led to the birth of optical communication and miniaturising of devices is paving its way for on-chip optical communication. Optical waveguides have materialized as an influential way for transmitting high data rates due to their properties of high heat durability and low losses.

Hennery F. Taylor *et al.* in 1974 [42] presented the phenomenon associated with the propagation and manipulation of light in thin dielectric waveguides. It reviewed the theory of dielectric waveguide, directional coupling, input-output coupling, modulation and distributed feedback laser sources on the basis of coupled-mode theory.

H.A.Haus*et al.* in 1987 [43] proposed coupled mode theory for parallel waveguides and derived from variation principle. Its application was initially to microwaves which gradually developed over years. Later the theory was employed for treating parametric amplifiers, oscillators and frequency converters.

Rowland in 1982 [44] opened a new era by establishing grating as the primary optical element of spectroscopic technology by doing spectral analysis. Today, gratings and other periodic structures have been widely used, not only in spectroscopy, but also in many other areas of science and engineering. Many grating theories and methods have been developed over the years to deal with all kinds of grating problems. Among these theories Rigorous Coupled-Wave Analysis (RCWA) is one of the widely used methods for accurate analysis of the diffraction of electromagnetic waves by periodic structures. Research methodologies developed within the last decade in the field of grating couplers are presented below.

Norman R. Landry *et al.* in 1984 [45] proposed a waveguide dimensioned for operating on fundamental mode over given frequency range and rendering it dimensionless by including a thin dielectric slab within a waveguide which extends parallel to the electric field of fundamental mode where thickness of field ranges between 0.01 and 0.25. Thickness of dielectric member having a nearby dielectric constant can be selected to provide over-compensation. The over-compensated waveguide and uncompensated waveguide can be connected for an appropriate length which yielded an overall waveguide having a substantially dispersion less characteristics.

James A. Harrington in 2000 [46] presented an eye-catching substitute for IR (infrared) transmitting fibers in form of IR transmitting waveguides made from plastic, metal or glass coating on inside of waveguide which had losses low as 0.1dB/m at 10.6 µm bent at radii less than 5 cm which were capable to transmitting power up to 3kW of CO_2 laser power. This paper highlighted on the advancement of hollow waveguides with best waveguides available at that time.

Ahmed Louri*et al.* in 1994 [47] proposed the usage of silicon devices to meet up the data transmission prerequisite future due to ever rising need of high data conveyance.

Damil B. Schwattz in 1996 [48] came up with optical interconnect made of fiber that had a data transferring capability of at minimum output of 1.5 gbps and power dissipation of 1.6W.

David A.B. Miller in 2000 [49] gave summary of development of optical interconnects to silicon integrated circuits. Starting from optical switching it proceeds through novel semiconductors quantum well, optoelectronic physics and first ever proposal of optical interconnect which than leads to hybrid integration of optoelectronic devices and silicon circuits which according to them would have solved the problem of interconnection and information processing theory. It also presented various arguments for introducing optical interconnection was also presented in the same year. Optics might discharge a broad range of design problems, for examplefirstly crosstalk, secondly voltage isolation, thirdly wave reflection, fourthly impedance matching, and pin inductance. It mightalso allowed sustained clambering of prevailing architectures and also enablesa novel highly interconnected or may also sustain high-bandwidth architecture. None of the physical step forward is required for implementing dense optical interconnects to the silicon chips, and though extensive technological work will remain. The cost is a noteworthy blockade to practical overview, though the revolutionary methodologies exist that strength will achieve economies of the scale. An appendage analyses on the scaling of on-chip global electrical interconnects which also includes line inductance and also the skin effect, which impose significant additional constraints on future interconnects.

Dirk Taillaert*et.al.* In 2002 [50] efficiently premeditated and was also fabricated an out-of-plane couplerwhich was also used for butt-coupling which was from fiber to squashed planar waveguides. This coupler is founded on a small second-order grating or photonic crystal, which was engraved on a waveguide with a lower-index oxide protective coating. Optimization of the coupler was done by consuming mode expansion-based on the simulations. Simulations were done using a 2-D model that showed that was up to 74% of the coupling capability between a single-mode fiber and a 240-nm-thick GaAs–AlO waveguide and had a possible 19% coupling competence on the trial structures that have been premeditated.

B.G.Lee*et al.* in 2007 [51]deliberated the power drawbacks of the silicon photonic crystal slow-light waveguides, that can also be used as for buffering of the optical pulses, which was done experimentally and the results were satisfied by the simulations done. It also explains the distortion which is caused by the dispersion in near the mode onset, which imposes a performance compromise between the attainable delay and the unobjectionable degradation.

T. F. Krauss in 2007 [52] discussed about the physical principles and practical limitation of slow light propagation in photonic crystal waveguides. He also illustrated the use of slow light effects in photonic crystal waveguides to increase linear effects, and most advantageously deploying such as for thermo-optic and electro-optic tuning and as well as for gain and nonlinear effects such as Raman amplification, Kerr-based switching and which lead to parametric effects such as wavelength conversion, delay lines that are also possible. He also studied switches and modulators which use broadband and slow light enhanced all-optical functions and can be realized by careful device design which will overcome the dispersion limitation by creating a broadband linear response, to avoid the backscattering losses encountered at the band-edge and to inject light efficiently.

Mukesh Kumar *et al.* in 2008 [53] anticipated a high-contrast-grating (HCG) which was grounded hollow-waveguide and also presented the results which were based on full-vector-replication that had been presented, which exhibited the optical-quarantine, propagation-loss and polarization-characteristics of the given HCG-hollow waveguides and also presented that temperature and polarization sensitivities of hollow-waveguides can be decreased by using a HCG-mirror.

Ye Zohu*et al.* in 2009 [54] recommended an innovative extreme-low loss single-mode hollow-core waveguide which was made by using subwavelength high-contrast grating (HCG). Evaluation and counterfeits of the propagation loss of the waveguide was done and was showed that the losses can be as low as 0.006dB/m, which were of the three orders of lower magnitude in comparison with the lowest loss of the chip-scale hollow waveguides till that time. This HCG hollow-core waveguide proposal was to serve as a elementary structure block in coming many chip-scale assimilated photonic circuits and which will enable system-level applications which include optical interconnects, optical delay lines, and optical sensors.

Mukeshkumar*et al.* in 2009 [29] proposed a hollow optical waveguide for confining light in an air gap that was placedbetween a high-index-contrast grating (HCG) mirror and a distributed Bragg reflecting (DBR) mirror. The collective effect of the lateral (HCG) periodicityand also vertical (DBR), that led to the hollow waveguide showing a comparatively small modal birefringence in the order of 10^{-4}. In accumulation with this, a patterned HCG was also shown to that provided 2-D optical confinement, which is a significant requirement for useful compact photonic devices. The fabrication of the given hollow waveguide was done which reportedly had a low birefringence of 5×10^{-4}.

Ye Zohu et al. in 2009 [11] discussed high contrast grating and its application in optoelectronic devices. It reviewed the current progress in subwavelength high index contrast gratings (HCGs) and also its variability of solicitations in optoelectronic devices, which included the vertical-cavity surface-emitting lasers (VCSELs), the tuneable VCSELs, the high-Q optical resonators, and thirdly for the low-loss hollow-core waveguides (HWs). The properties of HCGs such as broadband ($\Delta\lambda/\lambda \sim 35\%$), and high-reflectivity (>99%) mirrors for that is used for surface-normal incident light, makes it useful to replace predictable distributed Bragg reflectors in optical devices. High-Q resonators can also be made by HCGs with the output coupling in the surface-normal direction. And ultimately it discussed an innovative design made up for HCG as shallow angle reflectors and HWs.

David A.B. Miller in 2010 [55] examined the current presentation and future hassles of interconnects to and on silicon chips. It compared electrical with optical interconnects and it concluded with the requirements of optoelectronic and optical devices for solving the major problems of interconnects for future high performance silicon chips by optics. The possible benefits of optics are inter-connect compactness, energy, and the timing. The requirement for low interconnect vitality enforces the lower limits predominantly on the energy of the optical output campaigns, with a 10 fJ/bit device energy target is emerging. It showed that some of the optical modulators and radical laser approaches have an ability to achieve this requirement. Low photo-detector capacitance is of for most important. For connecting the information to fibers very compact wavelength splitters are essential. Dense waveguides were necessarily made for on chip or on the boards and for guided wave optical methodologies, particularly when the clock rates are very high or dense wavelength-division multiplexing (WDM) that is to be circumvented. Free-space optics hypothetically could be handled the indispensable bandwidths even deprived of fast clocks or the WDM. Now, with such aequipment, nevertheless, optics that might also qualify the sustained scaling of the interconnects dimensions that is mandatory for the future chips. Optics might also permit interconnects now to carry on to the scale for matching the dispensation capacity for the future electronic chips, though a very-low-on energy optoelectronic devices and novel compressed optics will be needed.

AyumiFuchida et al. in 2010 [56] showed zero-dispersion slow light that could be achieved in a hollow waveguide by using high-contrast grating with the waveguide in wide spectral range. At 15nm-optical bandwidth a zero dispersion group index of 7 was obtained with propagation losses of 1 dB/mm.

VadimKaragodsky et al. in 2010 [57] presented exceptional dispersion features of the high-contrast grating (HCG) hollow-core waveguides and also established that slow light can be simplified by using the internal resonances that were emerging inside the waveguide walls. In addition to this, it also showed a fast and accurate technique of finishing the dispersion evidence from the waveguide angular reflectivity spectrum.

VadimKaragodsky et al. in 2010 [58] analysed one of the ultra-high reflectivity characteristics of one of the subwavelength dielectric gratings that were introduced at the time. The phenomenon of ultra-high reflectivity was explained to be because of the destructive interference effect that occurs amongst the two grating methods. Based on this singularity and design an algorithm for the broadband grating mirrors that were also recommended.

Connie J Chang-Hasnain in 2010 [59] presented an idea of high contrast grating as which could be the emerging platform for integrated optoelectronics. A new perception of dielectric subwavelength grating was also emerged at that time. These gratings im-powers a high contrast in the refractive indices of the grating medium and its surroundings. It discussed high-index-contrast grating (HCG) and how it can influence light and its propagation properties to achieve various extraordinary properties. It discussed various designs which were proposed for resilient broadband, high-reflectivity mirrors that were used for light that was incidental on surface-normal to the direction and at an oblique angle, very high-Q resonators having surface-normal to the output, planar high concentrating control reflectors and lenses, and extreme-low loss hollow-core waveguides. The HCGswere to remain a novel and aencouraging platform for the incorporated optics with having many applications such as for lasers, in filters, in form of waveguides, as in sensors and detectors.

Connie J Chang-Hasnain et al. in 2011 [60] proposed a program to progressed a chip-scale, that was integrated on the photonic platform cumulative with "fiber-like" losses for many optical delay solicitations. The capability to engender long optical delays with minimal intrinsic lossesthat were useful for an extensive range of high accuracy military presentations and systems that included: a high time-bandwidth merchandise ofanalog optical signal wave processors and that of delay lines for wideband RF systems, like in optical buffers that are used for all the optical routing in the networks, and highly competent and stable optical interferometers which were used for sensing applications for an instant that, e.g. rotation sensors. They reporteda absolutely new concept for the chip-scale hollow-core waveguide (HCW) which eliminated losses caused due to dispersion and the nonlinearity in emblematic waveguide core. They also established a classic new wave guiding strategy that consisted of two of the parallel silicon-on-insulator wafers, which each contained a solitary layer made up of the high-contrast subwavelength grating (HCG) which is used to reflect light in-between the wafer. The optical confinement which was found without any of the physical boundary that was created by distinction of HCG dimensions and established for the paramount time as in a planar HCW that by means of a recorded a low loss of 0.37 dB/m. Two-dimensional light limitation in are demonstrated for individually in the straight and curved waveguides. The exceptional waveguide‟s geometry that not only adds new elements into the wave guiding theory, but also that would make a conceivable cost-effective used for manufacturing of the integrated optics for on the chip-scale gas/fluidic sensor, at thermal photonic delays lines, and also on the lab-on-a-chip presentations.

Connie J Chang-Hasnain et al. in 2012 [11] proposed a new tutorial of the planar optics that has developed by means of subwavelength gratings through a large refractive index contrast, in this also referred to as high-contrast gratings (HCGs). This apparently simple structure that lends itself to an extraordinary properties, which can be considered top-down grounded on the basis of the spontaneous guidelines. The HCG is that a solitary layer of the high-index specimen that could be as thin as that 15% of one the wavelength used. It could be premeditated to reflect or for transmitting nearly and absolutely and with unambiguous optical phase over a broad spectral range and numerous incident beam angles. They presented an unpretentious theory as long as an inherent phase selection and on instruction and for amplificationand the astonishing topographies. The investigative results and agreed well not only with the numerical simulations nonetheless also experimental data. The HCG has made an easy construction of the surface-normal optical campaigns possible, including the vertical-cavity surface-emitting lasers (VCSELs), one with the tuneable VCSELs, and also the tuneable filters. HCGs can also be premeditated to the consequence in high-quality-factor (Q) resonators and with surface-normal output, which was encouraging for the wafer-scale lasers and also the optical sensors. Spatially chirped HCGs were shown to be outstanding focusing reflectors and lenses with identical high numerical apertures. This is the field that has been seen as prompt the advances in the experimental demonstrations and the theoretical consequences.

They provide an impression of the underlying new physics and the latest results of devices.

Weijian Yang et al. in 2012 [62] presented optical-fiber-constructed, hollow-core waveguides (HCWs) that had unfastened up numerous innovative applications in laser surgery, and in gas sensors, and also in the non-linear optics. The chip-scale HCWs were anticipated for the reason that they are compressed, light-weight and could also be incorporated with additional devices that addicted to systems-on-a-chip. Nevertheless, their advancement had been slowed down by the deficiency of the low loss waveguide architecture. Now here, a absolutely a novel wave guiding perception is established using twofold planar, and parallel, silicon-on-insulator wafers through the high-contrast subwavelength gratings used for reflectingthe light in-between. They reported a record low optical loss that goes lowas of 0.37 dB/cm which was for a 9 μ m waveguide, which was mode-matched to a single mode fiber. Multi-dimensional light internment was experimentally comprehended that deprived of the sidewalls in the HCWs, which is encouraging for extremely fast sensing comeback with nearly on the spot flow of the gases or fluids. The exceptional waveguide geometry that inaugurates an completely the novel scheme for less costingon-chip-scale sensor arrays and all the lab-on-a-chip applications.

H. Huang et al. in 2012 [63] analysed; the presentation of an on-chip hollow-core-waveguide (HW) that was usedwas made from the high-contrast gratings (HCG) for analog signal communication was analysed numerically. After propagating 100 m in a HCG-HW thesimulation consequences that indicated that with optimally designed parameters, there wasa very little dilapidation of whichever third-order intermodulation misrepresentation for spur-free dynamic range (IM3 SFDR) or third-order harmonic distortion (THD) SFDR. Outstanding to the chromatic dispersion of the HCG-HW, the highest second-order harmonic distortion (SHD) SFDR was restricted to 107.3 dB Hz. In addition to these, >100 dB Hz IM3 SFDR could be accomplished above a radio frequency (RF) that to in the range of 80 GHz and an optical wavelength bandwidth of 50 nm afterwards the promulgation 100 m concluded a HCG-HW. The restriction that was dependent of the waveguide performance was correspondingly investigated. With a tolerance of ±20 nm discrepancy on all parameters, the dissemination length in an HCG-HW is incomplete to m in order to conserve an IM3 SFDR >100 of dB Hz.

Yuri A Valsaov et al. in 2012 [64] gave the five standards that are frequently considered by many IEEE standards committees for developing of following generation standards are broad market impending, divergent individuality, and compatibility, as well as technical and economic practicability. It considered these benchmarks separated and showed that the new unindustrialized large-volume markets insecurely demarcated as the computer com that would ultimatum for a novel standards and new-fangled technologies. And it likewise discussed how to sense of balance amongst the single-channel bit rate, and the quantity of wavelength multiplexed and was spatially multiplexed visual channels that can help to satisfy the requirement for massive aggregate bandwidth, while keeping it to lower cost and higher power efficiency. Silicon CMOS-combined photonics holds potential to be developed knowledge of the high-quality for the wide positioning of a low-power and cost-effective optical interconnects aimed at these novel markets, and also used to become a single clarification

Christoforouskachris et al. in 2012 [65] Reviewed that the data centres are undergoing an exponential intensification in the quantity of the complex traffic that they have to withstand due to cloud computing and for numerous developing web applications. Now for facing this network load, large data centres were required with thousands of servers thatwere interconnected through high bandwidth switches. Now a days, data centre networks, are based on electronic packet switches, devour excessive power which was to switch the increased communication bandwidth of developing applications. Optical interconnects have extended consideration in recent times as a talented solution for contribution to the high throughput, low latency and concentrated energy consumption in comparisons to the current networks based on commodity and switches. This paper presented a underlining investigation on optical interconnects for coming generation data centre networks. In addition to, the paper make available a qualitative categorization in addition to association with the proposed schemes that were based on their foremost features for example connectivity and scalability. Finally, this paper discussed the cost and the power consumption of these schemes that are of primary prominence in the future data centre networks.

VadimKaragodsky et al. in 2012[66] presented an unpretentious theory amplification of the astonishing features of the high-contrast optical gratings in the near-wavelength regime, predominantly the broadband high reflectivity (>99%) and the vast-high quality factor resonances (Q>10). They presented, for the very leading time, a spontaneous description for both of theproperties by means of a simple phase assortment rule, and discloses the anti-crossing and crossing effects between the grating modes. Their investigative results agreed well with the simulations and the experimental data was obtained from a vertical cavity surface emitting lasers combining a high contrast grating as a top reflector.

Wejian yang et al. in 2012 [67] proposed the optical-fiber-grounded, hollow-core waveguides (HCWs) that had unfastened up numerous new applications as in laser surgery, and in gas sensors, and also in non-linear optics. The chip-scale HCWs are looked-for since they are compacted, light-weighted and could be assimilated with supplementary devices hooked on systems-on-a-chip. Though, their advancement that had been slowed down by the non-existence of the low loss waveguide architecture. At this time, a absolutelya innovative wave guiding perception was established using the two planar, and parallel, silicon-on-insulator wafers by means of the high-contrast subwavelength gratings to reflect light in-between. They reported a best ever low optical forfeiture of 0.37 dB/cm for a 9- μ m waveguide that was matched with the mode to a single mode fiber. The two-dimensional light confinement was experimentally was comprehended deprived of the sidewalls in the HCWs, which is favourable for an ultrafast sensing rejoinder with approximately on the spot flow of gases or fluids. This exceptional waveguide geometry established a completely new arrangement for the low-cost chip-scale sensor arrays and for the lab-on-a-chip solicitations.

Er'nelGranout in 2013 [68] determined the thoroughgoing the bit-rate of the slab waveguide and its definitive relation with the waveguide dispersion. He also exhibited that while the maximum bit rate inside a waveguide was inversely proportional to the waveguide‟s width, and bit rate apiece unit width (i.e., spatial capacity) diminutions, and in the boundary of a zero-width waveguide and it congregates to (where L is the length and ω and λ are the beam‟s frequency and wavelength respectively). That resulted, which was self-determining of the waveguide‟s refractive indices, was qualitatively corresponding to the communication proportion per unit of width in free space. He correspondingly also demonstrated that in a 3D waveguide (e.g., fibers), unlike free space, the spatial capacity is wiped out in the same frontier.

Min Gu el al. in 2014 [69] reviewed the advances of Nano photonics and has provided a assortment of opportunities for light–matter interaction at the Nano meter scale concluded the supplemented mechanisms for physical and the chemical reactions encouraged by Nano meter-narrowed by the optical probes in Nano amalgamated materials. These emerged Nano photonic devices and materials had empowered researchers to progress troublesome methods of enormously increasing the tidying away capacity of contemporary optical memory. In that paper, they presented an evaluation of the recent improvements in Nano photonics-empowered optical packing techniques. Predominantly, they offered their standpoint of by means of them as optical storage arrays for subsequent-generation hex- byte data centres.

Harish Subbraman et al. in 2015 [70] gave the short-lived description of the developments of that silicon photonics that had knowledgeable extraordinary transformations over the previous years. In that paper, they presented some of the noteworthy developments in silicon-based passive and active optical interconnect components, and highpoint some of theirnoticeable assistances. Light is also dramatis personae on insufficient other parallel technologies that are working in these tandem with silicon-based constructions, and provided that unique functions not attainable with any single system acting alone. By means of a cumulative consumption of CMOS foundries for silicon photonics construction, a worthwhile alleyway for understanding a tremendously low-cost integrated optoelectronics has been cemented. These early payment are predictable to the advantage numerous submission domains in the coming years, which includesall the communication networks, and the sensing, and all the nonlinear systems.

CHAPTER-4

HOLLOW OPTICAL WAVEGUIDE WITH LOW DISPERSION FOR HIGH DATA-RATE APPLICATIONS

High data rate for on chip communication is the need of the hour. As the amount of data is increasing there is a need of transportation of data from one point to another at high rate. Grating based hollow waveguide gives a classic advance in this particular area as its interference with the bits is the least. In the proposed work advancement is made in direction of hollow waveguide for on chip communication. The work is done by the modelling of waveguide using SVFD method and modelling grating by RCWA method and combining the effect of both the time delay in the light pulses is premeditated and hence the dispersion is calculated.

4.1. Structure of grating based hollow waveguide

High contrast gratings having a large refractive index contrast give rise to a new class of planar optics. These High Contrast Grating (HCG) are also known as sub wavelength gratings. The schematic of the subwavelength high index contrast grating based on SOI is shown in Figure. The structure consists a tri structure grating of silicon oxide/air/silicon (a high index media surrounded by low index media) on top of SOI chip. The three important design parameters are: grating thickness, grating period and core size which are denoted as t_g, $\wedge$ and d respectively. The TE/TM polarized light is incident onto the silicon oxide/air/silicon grating at different angle of incidence. Simulations are done by using RCWA (Rigorous Coupled Wave Analysis) and Semei-Vectorial Finite Difference (SVFD) method.This structure provides exotic properties and it is as thin as 15% of operating wavelength. It is fabricated to reflect or transmit partially or completely depending on the application with specific optical phase over various incident angles. Spatially chirped HCGs serve as an excellent focusing reflectors and high numerical aperture lenses.

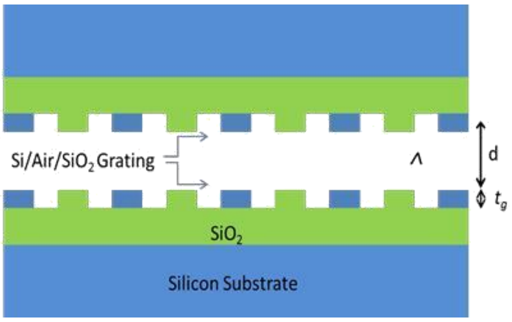

Fig4.1 Side-view of proposed SOI based hollow waveguide with three-material grating. Waveguide core (d) = 1.0, grating period (∧)= 0.51µm grating thickness(t_g)= 0.14µm refractive index contrast in grating= 2.1.

Not only at surface normal direction but also at oblique angles of incidence, HCG shows remarkable properties. HCG resembles DBR and 1D photonic crystals by its physical structure. But the uniqueness of HCG comes from the interaction of waveguide array modes. HCG Reflectivity matrix *R* can be obtained from Eq.4.1 which is common in transmission line theory: [53]

$$= (\quad +)^{-1} (\; -) \qquad (4.1)$$

where is the normalized input impedance matrix similar to constant in transmission line theory:

$$= \; + - \; ^{-1} \qquad {}^{-1} \qquad (4.2)$$

is the reflection matrix which relates the two coefficient vectors of *E* or *H* field and is the HCG propagation matrix which contains the accumulated phases of HCG mode.

E and *H* are the electric and magnetic field profiles respectively. The HCG reflectivity and transmission, and the relation between the two in the subwavelength regime, are given by Eq. 4.2

HCG Reflectivity = $|R|^2$

HCG Transitivity = $|T|^2$

For Subwavelength Gratings where $\wedge < \lambda$

$$|R|^2 + |T|^2 = 1 \qquad (4.3)$$

4.2 Waveguide Model

We choose the TE mode to describe wave propagation in the waveguide [67] i.e.

$$E\ x, z = \hat{y}\varphi(x, z)e^{-i\omega t} \qquad (4.4)$$

Where $\varphi(x, z)$ satisfies wave equation

$$\nabla^2\varphi + k^2{}_g\varphi = 0 \qquad (4.5)$$

And k_g (wave number), ω (angular frequency) and λ (wavelength) are related according to

$$k_g = \frac{n\omega}{c} = \frac{2\pi n}{\lambda} \qquad (4.6)$$

If we use β to represent the wave propagation constant along the waveguide, then

$$\varphi\ x, z \ = \varphi\ x\ e^{i\beta z} \qquad (4.7)$$

With the simple 1-D equation for φ

$$\frac{d^2\varphi(x)}{dx^2} + k_g{}^2 - \beta^2\ \varphi\ x = 0 \qquad (4.8)$$

The stationary solution is equivalent to single Eigen value problem. Inside the waveguide the traversal solution is oscillatory and is given by

$$(\qquad \overline{\quad {}^2 - {}^2 \quad} \qquad) \qquad (4.9)$$

Matching the solution at the boundary condition we obtain

$$\tan \overline{\quad 2 - 2 \quad} = \frac{\overline{\quad 2 - 2}}{2 \quad -2} \ {}_1 \qquad (4.10)$$

The guided modes satisfy the transverse resonance condition as shown below:

$$D.\ \overline{\frac{}{2}\qquad -2} \quad + \qquad (,) = m\pi \qquad (4.11)$$

And (,) is the phase change upon reflection from the HCG which depends on frequency and k_g (wave number).

In a 3D situation, the source-field relationships for electric and magnetic current sources J(z), K(z) in homogeneous background medium are in general described in Maxwell‟s equations and can be rewritten in a wave equation [18] [19]

$$\nabla^2 E\ z \quad + \omega 2 \mu \epsilon E\ z = i \varphi \mu \epsilon J\ z + \nabla \times K(z) \qquad (4.12)$$

The electric field inside the core and the grating is given by [20]

$$= \quad \cos(\ )^{(+)} \qquad (4.13)$$

$$= \cos(\quad + \emptyset \quad)^{( )} \qquad (4.14)$$

The attenuation in the waveguide can be approximated by[18]

$$= \frac{\quad}{(2)} \qquad (4.15)$$

The difference in the propagation delay between the incident light and received light is given by [18]

$$\Delta T = \frac{\quad}{\quad} \left(\frac{1}{\quad} - 1 \right) \qquad (4.16)$$

The bit rate of waveguide is limited by [67]

$$b < \frac{c}{4L \quad \frac{\quad}{\frac{^2 \quad \beta}{d(^2)}}} \qquad (4.17)$$

Where $k_x$and k_z are the lateral and axial wave number and $\emptyset$ is the angle at which light is indented on the grating. Fig 4.2 gives the refractive index map of the proposed waveguide with respect to the direction of propagation of light.

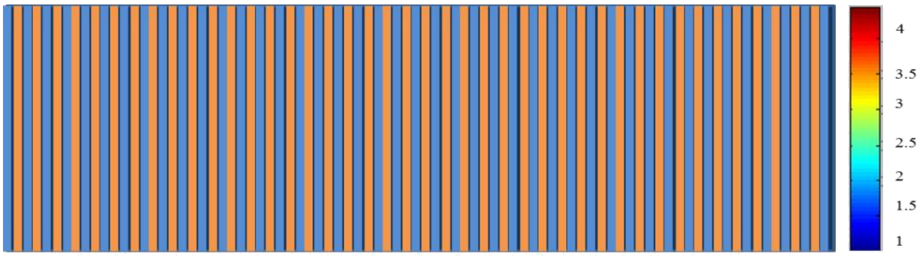

Fig4.2. Refractive index Structure index map of the proposed waveguide. Showing variation of refractive index in the direction of propagation

4.3 <u>Variation in Dispersion at different grating contrast:</u>

The main focus in the waveguide is decreasing dispersion which depends on the grating index and can be controlled by varying the grating index of the HCG"s used on both sides of the hollow core. Higher refractive index of grating helps in the tight guiding of light inside the core as reflections inside is there on the apt angles. Gratings are arranged perpendicular to the direction of propagation of light which provide lateral confinement to the glancing reflections of the incident light. Refractive index contrast is the difference in the refractive index of the materials used in grating. In the proposed grating structure a tri layer of silicon, air and silicon dioxide layers are alternatively used which provide a great optical transparency in the operating wavelength range of 1.5µm. Fig.4.3 shows the decrease in dispersion when grating contrast of the waveguide is increased. Increasing the grating contrast leads to more amount of light being guided and is reflected inside the core leading to less dispersion. The grating contrast is adjusted in accordance with the grating parameters. Grating thickness is kept constant to be 140nm and the grating period of 510nm is used at different data rates.

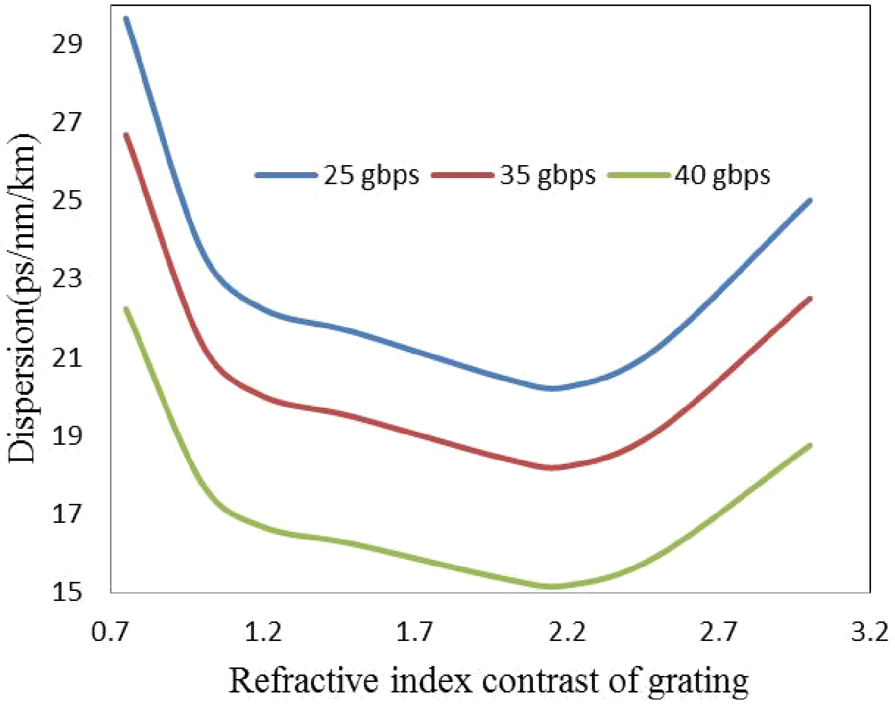

Fig4.3.Dispersion v/s refractive index contrast in grating at constant wavelength of 1.55μm at grating period (^) 0.51μm grating thickness (t_g) = 0.14μm and varying data rates.

4.4. Dependence of dispersion on refractive index of waveguide core:

Dispersion occurs in the medium when the light pulses are absorbed or there occurs a delay in the light pulses leading to spreading of the pulses with respect to the time. When the medium is other than air its refractive index is more leading to the varring velocity of light inside the core which than again leads to higher amount of dispersion. Hollow air core has an inherited property of low dispersion which is verified by changing the index of the core. When a material other than air core is used inside the waveguide it tends to absorb the light pulses traversing inside the waveguide. Fig 4.3 shows that the dispersion at 40 gbps data rate increases when the refractive index of the core material increases

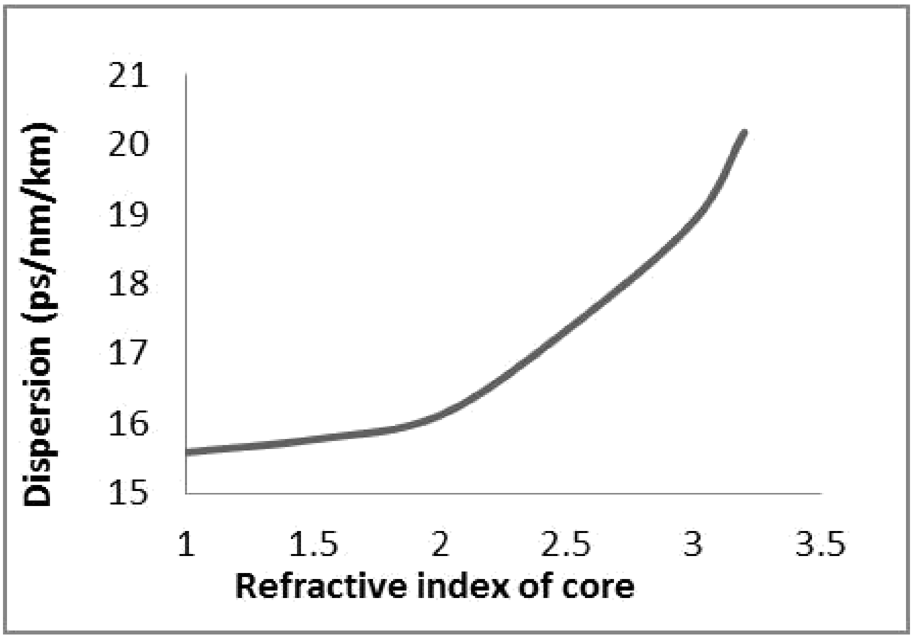

Fig 4.4 Effect of refractive index of the core on the dispersion in the waveguide at 40 gbps data rate core size of 800nm grating period of 510 nm and grating thickness of 140 nm

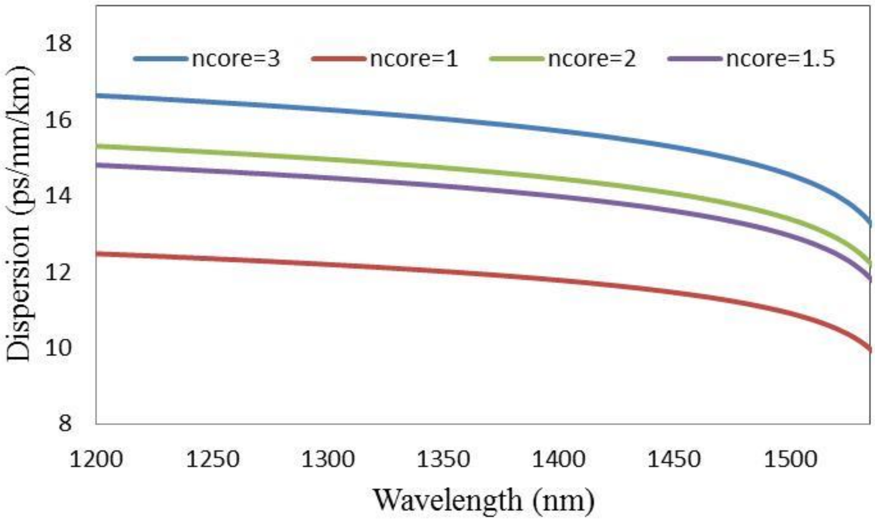

Fig 4.5 Dispersion v/s wavelength graph at different refractive index of core (ncore) at 40gbps data rate core size of 800nm grating period of 510 nm and grating thickness of 140 nm

4.5 Dependence of dispersion on waveguide core thickness:

Dispersion also depends on the core size of the waveguide. As the core size of the waveguide decreases the light waves inside the waveguide start interfering with each other and thus causing delay of the bit which is being transmitted and on increasing core size time for the interaction of light and the waveguide increases which leads to the absorption of light inside the core because the time taken by light to reach the grating and reflect back inside increases thus creating losses at the receiving end. Equation 4.17 gives the dependence of the bit rate on the core size of the waveguide. In the equation L is the core size decreasing the core size leads to more of the bits to traverse along the waveguide but there is a limitation to that we can to go on decreasing the core size as the manufacturing will become harder and in practical word it hinders the wave and thus leads to the dissemination of the pulses leading to the dispersion.Fig 4.6 illustrates the dependence of dispersion on the waveguide core at 40gbps data rate using optimized grating contrast of 2.1 and grating period of 510 nm.

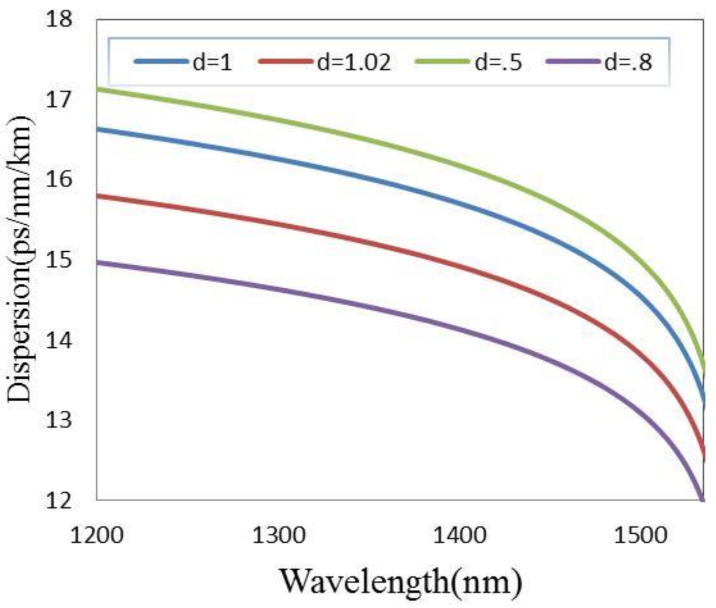

Fig 4.6. Effect of Dispersion v/s wavelength at different waveguide core size (d) with grating period= 0.51µm, grating thickness (t_g) = 0.14µm grating refractive index contrast 2.1 and operated at 40gbps.

4.6Dependence of dispersion on grating period:

Hollow optical waveguide is a potential candidate to realize the high data rate transfer requirements due to its low dispersion properties [23]. The waveguide suggested is based on guiding the light inside the waveguide by using HCG and changing the refractive index contrast of the grating which provides a promising platform for higher data rates. In the proposed waveguide the HCG‟s are periodically placed and then grating period is varied to get an optimized value for low dispersion.

It is perceived that as the grating period increases from 2 the spacing between the grating increases and thus giving space for the light wave to escape as the boundation will be loose for the guiding the light so the grating period should be less than 2

which on simulating and optimizing comes out to be 510nm. Fig 3 shows the variation of dispersion with respect to the grating period with grating thickness 140nm at wavelength of 1500nm and data rate of 40gbps.

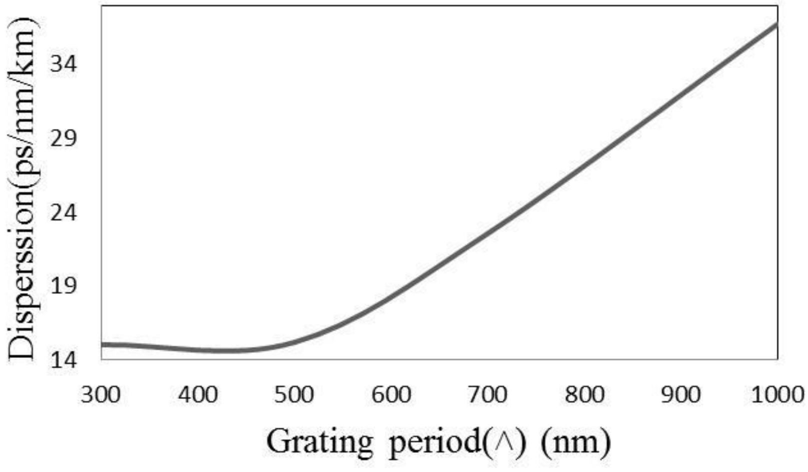

Fig4.7. Dispersion dependence on the grating period with waveguide core thickness =0.8 µm grating thickness of 0.14 µm at λ=1.50 µm and data rate of 40gbps

4.7 Analysis of waveguide at different data rates:

After optimization of all the parameters the waveguide designed with grating thickness of 140nm grating period of 510 nm grating refractive index contrast of 2.1 waveguide core of 1000nm is now analysed over various data rates.

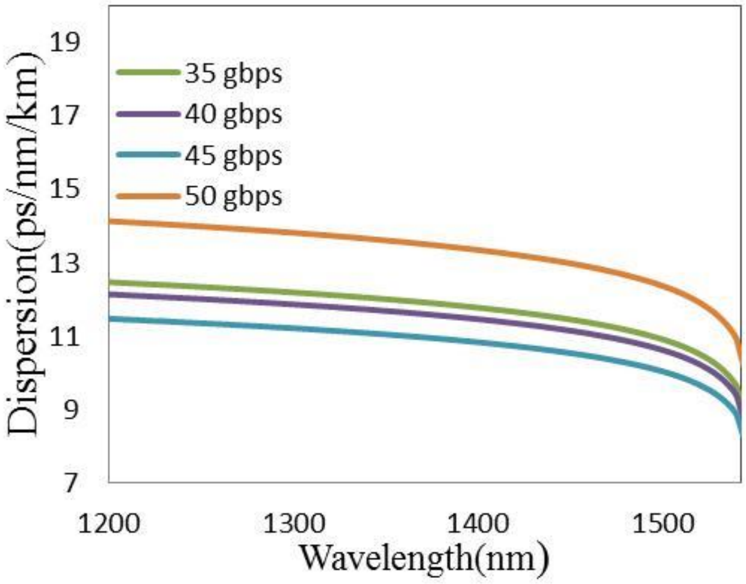

Fig 4.8 Dispersion v/s wavelength graph at different data rates with optimised waveguide parameters.

In the above graph it is seen that the dispersion is high for data rates less than 40 gbps. And as the data rate increases the dispersion decreases because the waveguide is optimised to work at data rates from 40 to 50 gbps.

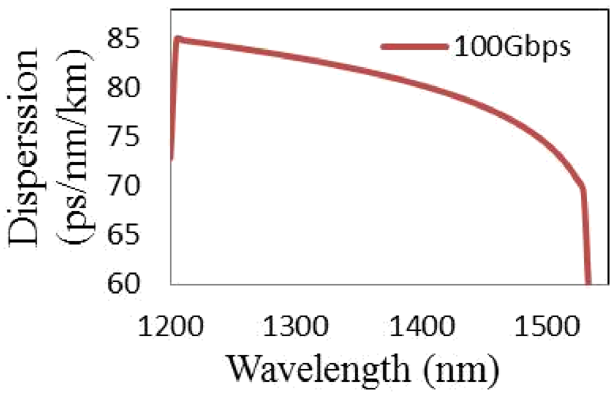

Fig 4.9 Dispersion v/s wavelength graph for extremely high data rates

Now, when the proposed waveguide is analysed over extremely high data rates the dispersion seen is too high. So, that is also a future prospective to optimize the designed waveguide for an extremely high data rate.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

The focus of the dissertation is on the design and modelling of three-material SiO_2/air/Si grating based hollow waveguide on silicon on insulator chip. In the proposed work it has been shown that by modifying the basic parameters such as grating period, refractive index contrast of the grating, refractive index of waveguide core and thickness of waveguide core a practically low dispersion of 15.14 ps/nm/km can be obtained for data rate transmission of 40 gbps. The main hindrance in transmission of high data rates is dispersion. In the proposed design dispersion is controlled by introducing air-core and by inserting a three-material based grating made up of Si/SiO_2/air. The presented design-analysis is based on grating-embedded waveguide model comprises of RCWA and SVFD.

The dependence of dispersion on core-material and on data-rate is analyzed. The effectiveness of presence of air as core material is studied by changing the core material and analyzing that the dispersion is least when air is used as core material. The grating parameters are optimized in accordance to work at a comparably high data rate of 40 gbps to 50 gbps. Dispersion inside the waveguide decreases as the grating period reduces from the half of wavelength which leads to tight bounding of light inside the core. The optimized grating period is found out to be 510 nm. Core size of the waveguide limits the number of bits travelling inside the waveguide thus an optimum core size for the required data rate is computed out to 800 nm. The main criterion for controlling the dispersion in proposed work is the index contrast between the grating materials. A three material grating of SiO_2/air/Si provide good guidance of light inside the waveguide which gives a comparably less delay and hence less dispersion.

The reported results can be useful in realizing on chip data communication. The inherited property of hollow waveguide of low dispersion can be used for designing the elements paving way for high data rate transfer. Optical interconnects are the future of on chip communication as they have high heat durability and can work at much higher bit rates. The projected work is a step toward the on chip optical communication. The next projected work is to focus on decreasing the dispersion at additionally high data rate by using a bi-material grating and engineering waveguide according to that for high data rates for using it as a probable optical interconnects and in big data nano photonics and thus giving out the spatial capacity of on chip HCG hollow waveguides.

List of Publications

- ShrutiSobti ,Harpinderkang and Dr.Mukeshkumar "Nanostructured Hollow Optical Waveguide with Low Dispersion for High Data-rate Applications" submitted to *IEEE Photonics Technology Letters*, 2015.

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