

Three Dimensional High Contrast Gratings based Hollow Core Waveguide for Chip Scale Integrated Optical Interconnects

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DECLARATION

I **Sandeep**, hereby declare that the work which is presented in this dissertation entitled "**Three Dimensional High Contrast Gratings based Hollow Core Waveguide for Chip Scale Integrated Optical Interconnects**" is an authentic record of my study carried out as requirement for the award of degree of M.Tech. (VLSI Design) at Thapar University, Patiala, under the Guidance of **Dr. Anil Arora** (Assistant Professor), ECED.

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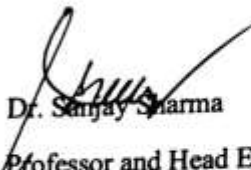
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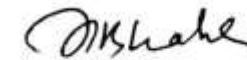

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ABSTRACT

Three dimensional high contrast gratings based hollow core waveguide is a potential candidate for telecommunication systems which provides a promising platform to realize integrated optical interconnects. These have been comprehensively studied over the years due to its diverse applications in the communication systems. With advancement of technology these days as we are doing scaling the size of devices and distance between the devices is reducing which makes interconnects more important in communication system. To maintain such high speed and small size optical interconnects are required which can play crucial role to achieve today's high speed large bandwidth requirements. The high reflectivity, high speed and high bandwidth of HCGs based Hollow waveguide is one of the key component for integrated chip scale optical interconnects. This can be used to guide light and transmit Tb/s data over the communication link and attracted a lot of attention for next generation communication network as well as high performance computing applications. SOI is an ideal platform for the development of passive optical interconnects like Hollow waveguide.

Several key challenges exist in developing the waveguide, including fabrication difficulties, dispersion and non linearity. Using high contrast gratings, the fabrication difficulties can be minimized. Dispersion remains to be the most dominant source in the system of data loss. From the aspects of reflectivity, bandwidth, dispersion and non linearity, using high contrast gratings in waveguide approach is widely popular. Modified approach involves the high contrast gratings with high index material surrounded by a low-index material. The refractive index difference is maintained high that is greater than 2.4 which provides high reflectivity. Parameters on which reflectivity of waveguide mainly depends are grating thickness (t_g), grating period (Λ), and duty cycle (η). Important design attribute is the sub wavelength size of gratings.

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ABBREVIATIONS

ICs	INTEGRATED CIRCUITS
OIs	OPTICAL INTERCONNECTS
CIs	COPPER INTERCONNECTS
HCG	HIGH CONTRAST GRATING
HW	HOLLOW WAVEGUIDE
DBR	DISTRIBUTED BRAGG REFLECTOR
CMOS	COMPLEMENTARY METAL OXIDE SEMICONDUCTOR
PMOS	P CHANNEL METAL OXIDE SEMICONDUCTOR
NMOS	N CHANNEL METAL OXIDE SEMICONDUCTOR
PD	PHOTO DETECTOR
MSM	METAL SEMICONDUCTOR METAL
VCSEL	VERTICAL CAVITY SURFACE EMITTING LASER
SOI	SILICON ON INSULATOR
BR	BIT RATE
VLSI	VERY LARGE SCALE INTEGRATION
MOSFET	METAL OXIDE SEMICONDUCTOR FIELD EFFECT

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Interconnects are the backbone of any electronic system of devices as far as communication of signals and data is concerned. Interconnects are more important when the communication distance is small. These days as we are doing scaling the size of devices and distance between devices is reducing so interconnects are more important as technology advances. If we look at the rate at which scaling is done in last few decades, the chip size reduces rapidly as given by the Moore's law. Even with scaling data rate also doubles in almost two years. To maintain such high speed and small size advancements are required in interconnects. Optical interconnects can play crucial role to achieve today's high speed large bandwidth requirements[1]. Conventional interconnects like copper are facing many problems as size reduces and data rate increases. Dispersion, signal loss, reflection and attenuation are the key problem which conventional interconnects are facing. Copper interconnects facing many problems which affects their performance such as cross talk which hampers parallel communication of data. Limited bandwidth, high power consumption and latency are some other problems. Considering these problems it is very important to make changes at design level and other alternatives need to develop. As mentioned before Optical interconnects are the one of the best alternative to these problems facing by conventional interconnects. Because of the properties of low loss, low dispersion and linearity optical interconnects are the ideal candidates to remove the problems that are facing by copper interconnects. Even on chip integrated applications are also realizable. As we know the on chip applications require low power dissipation and high bandwidth which can provide by optical interconnects.

Recently the silicon on insulator platform has developed which is the base of development of the optical devices of chip level. Large number of researchers attract toward this new platform for chip scale integration from all over the world. Second unique property shown by silicon is its optical transparency when high refractive index contrast is maintained, as in silicon ($n = 3.47$) and SiO_2 ($n = 1.45$) at the wavelength of $1.55\mu\text{m}$ which

make it possible of ultra compact device dimension which in turn suitable for chip scale integration . In all over world the availability of CMOS photonics foundries have make the development work easy so, it lead to low cost development of component libraries with the microelectronic devices. SOI development is cost effective than the development of other materials. [2] The optical interconnects also decrease the energy consumption due to monolithic integration. Utilization of the standard CMOS flow reduce data loss and increase the possibility to integrate more optical functionality in the single component. This also leads to less manufacturing cost, low heating of the components, higher density interconnects and high reliability. From above properties of optical interconnects it is clear that they are capable of providing large bandwidth requirements with consumption of low power. So Optical interconnects will give improved desired results than the traditional copper interconnects in chip scale level.

Fig.1.1 shows block diagram of optical interconnects

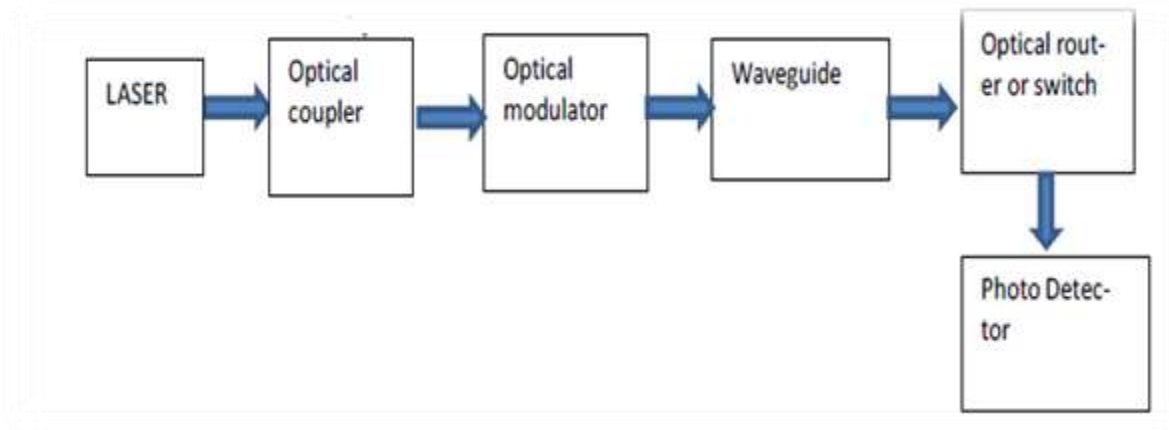


Fig. 1.1 Block diagram of Optical interconnects [3]

1.2 LASER SOURCE

The most efficient and reliable optical source of light for small distance optical interconnects is Vertical Cavity Surface Emitting Laser (VCSEL). This advanced Laser (VCSEL) is a semiconductor laser diode which emits light in the direction perpendicular to the surface of the semiconductor wafers.

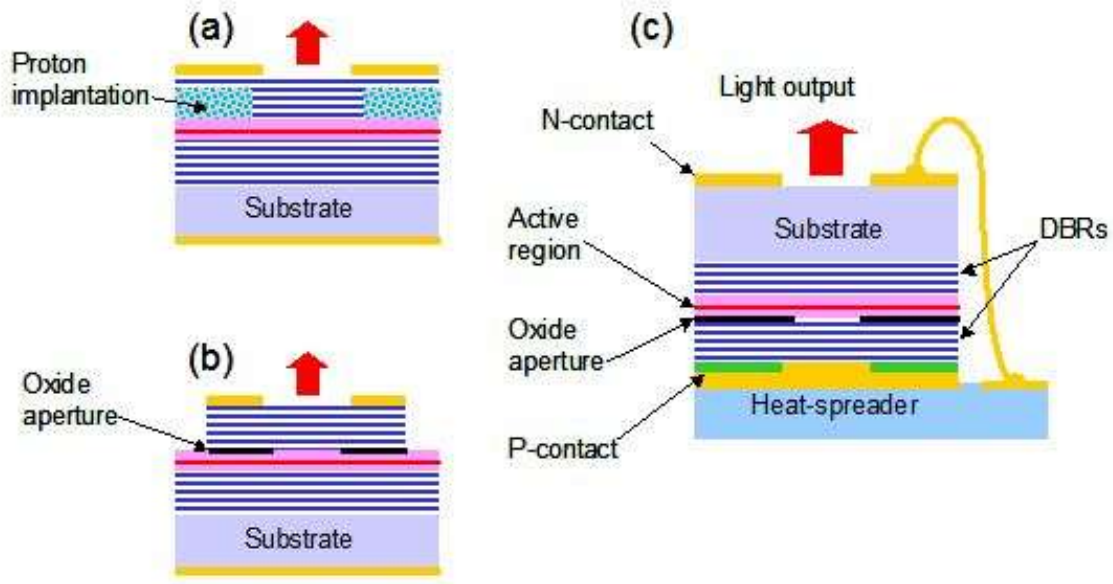


Fig. 1.2 VCSEL Structure [4]

Monolithic array of high density of VCSELs has been developed by various manufacturers which is competitively priced. VCSELs are manufactured for several different wavelengths. Nowadays, devices emitting around 850 nm wavelength represent the most matured high-speed optimized technology for VCSEL and these devices are the top-emitting devices due to large substrate. VCSEL operating with 980 nm technology are based on the GaAs/AlGaAs process technology. They have advantages of emissions through the substrate. GaAs is transparent with 980 nm [4]. This brings added benefit such as integrating of backside micro lens for improved coupling. VCSEL has been the 980 nm wavelength of choice for ultra-dense chip-to-chip level interconnect, operating at Tb/s of data range.

1.3 OPTICAL MODULATOR

It is a device which modulates the beam of light. Through the waveguide the modulated beam propagates in the free space. Depending upon the manipulation of the parameters of the light beam the modulators are divided into different types i.e. Amplitude modulators, the polarization modulators and phase modulators. Modulation intensity is obtained by the modulating of the current light source which drives the light for e.g. Laser diode. This modulation is called the direct modulation. External modulation is inverse of the former and

performed by the light modulators [5]. Due to this the light modulator in optic communication is called external light modulator.

1.4 PHOTO DETECTORS

Receiver section in the optical interconnect comprise of semiconductor Photo Detector which is followed by electronic amplifier. Photo detector performs the operation of optical to electrical signal conversion. Basically it is reversed biased device which absorbs the incident radiations and generate electron-hole pairs which in turn produce photo current in the external circuit. Detector to use in optical interconnects should provides the high bandwidth, easy optical coupling and high sensitivity. It should also amenable with high density fabrication. Many semi conductor photo detectors may fulfill the requirements. These are such as p-i-n photodiode (PIN), metal semiconductor metal photodiode (MSM), and avalanche photodiode (APD). PIN is the most common used photo detector for short-distance optical link. MSM is low-capacitance optical-detector with high speed operations and more active area than the PIN but responsivity of MSM is typically lower than PIN and also APD provides the maximum responsivity due to internal gain. Major drawbacks are the requirements of high-biasing voltages and expensive fabrication processes. GaAs is the suitable material for the photodiode at wavelengths in range of 850 nm and GaAs are more popular in the high-speed applications but they are costly. Silicon is used at wavelength up to 1 μm , for longer wavelengths upto 1.7 μm , InGaAs material systems on InP substrate are commonly in use but for optical interconnect the most important photo detector material is Germanium, because of it has potential of integrating monolithically photo diodes based on Si integrated circuits.

The optical interconnect waveguide is used as a routing device so, instead of being a surface normal, the Photo Diode need to be the waveguide integrated. Recently the Waveguide-integrated Germanium photo diode has becomes topic of high research and development. Small photocurrent generated by Photo Diode must be amplified with minimum amount of the added noise for the further processing. So, a preamplifier used as first stage of the amplification. Three widely used configuration for pre amplifier circuit are of large input impedance, low input impedance, and trans impedance amplifiers. TIA is a

typically selected in optical interconnect because it meets the requirements of large bandwidth having low noise. Photo detectors are always used at the end of optical communication system. They demodulate the coming optical signals into the electrical signals. They convert by the absorbing light and then generate the electrical currents according to input optical signal level. In photonic communication network design, silicon micro resonator filter has used as a demultiplexer. The wavelength which is parallel to optical data used for placing each of wavelength channel on the unique waveguide. When each of the wavelength channel has isolated then detection is performed by the photo-detector.

1.5 COUPLERS

Optical coupler couples light into waveguide or fiber. Photonic devices in their working efficiency coupler are very crucial and used in implementation of their basic functions. These are particularly used in those applications which required the interface between system and the optical interconnects and coupler itself a very important device in many applications . The most common used application in case of couplers is the routing of the optical waves for coupling into the different devices [6].

For on chip applications couplers are important silicon optical devices which plays major role in interfacing with the different off chip components. The high index contrast in silicon and silicon oxide results in the usage of it in many applications that require small optical mode size. This enables the close integration of silicon photonic device, moreover this make it challenging for the coupling between the given optical modes of waveguide (with $0.3\mu\text{m} \times 0.2 \mu\text{m}$ of cross sections) and single mode fibers of small diameter (having nearly $10\mu\text{m}$ diameter), producing about a mismatch of the cross sectional area for the given optical mode. Coupler is also used in the Sophisticated applications which the contains devices like beam splitters, mode converters, as a polarization converters, beam combiner, wavelength filters, directional couplers, multiplexers of the wavelengths etc. There are many problems in developing the coupling methods, which are insertion loss, reflectivity, integration, bandwidth and scalability.

1.6 OPTICAL WAVEGUIDE

It guides the waves which are in optical range. Dielectric waveguides are the waveguides which are worked in the optical frequencies range. The basic principle is the structure in which material having high permittivity and high refractive index is always surrounded by the lower permittivity material with low refractive index. This structure guides optical waves by phenomenon of total internal reflection. For example optical fiber[7].

The most fundamental waveguide having silicon as photonic component is Silicon waveguide, that can carry very high speed optical data. Recently, crystalline silicon waveguide with the sub-micrometer dimensions have worked as photonic waveguide also silicon waveguide is capable of the carrying wavelengths which are parallel to the optical data of speed in terabit per-second range which is data rate of electronic chip. Even, this waveguide can be bent and crossed, can be coupled and create the region where the optical signal can be passed from one waveguide to another. The first demonstration of transmission of the high speed optical data by using crystalline silicon waveguide shows launching 1.30 Tb/s optical data, comprising of the 32 modulated defined channels each with 45 Gb/s, using 6 cm long crystalline waveguides made of silicon.

Optical waveguides which are used in the optical interconnects must have very low attenuation of signal and should have optical properties of high stability in the manufacturing stress involved in the electronics assembly process. The attenuation in these waveguides of silicon arises mainly due to scattering of light from etched sidewalls. The minimization of optical field is overlapped with the etched interface that can effectively reduce the attenuation in waveguides. Increasing the width of waveguide and decreasing the etch depth can minimize this overlap. Hence rigid waveguide structure is generally preferred for the waveguides in the optical interconnects. There are many waveguide manufacturing technologies exists such as printing, photolithography, ion-exchange, laser direct writing, laser ablation etc [8]. The materials that used in fabrication of waveguide include acrylates, polyimides, cyclic olefins, silsesquioxanes and siloxanes. Apart from the waveguide other passive components such as bends, crossings are essential to route signal on the board.

1.6.1 Hollow Waveguides

Structure which guides the electromagnetic wave in it is called a waveguide and when air is used as core then it is called hollow air core waveguide or hollow waveguide. waveguide having air as a core material has potential for minimize the dependence of loss of the light which propagate in the air core . Core material air having low index than cladding can guide the light inside the air core material with the phenomenon total internal reflection.

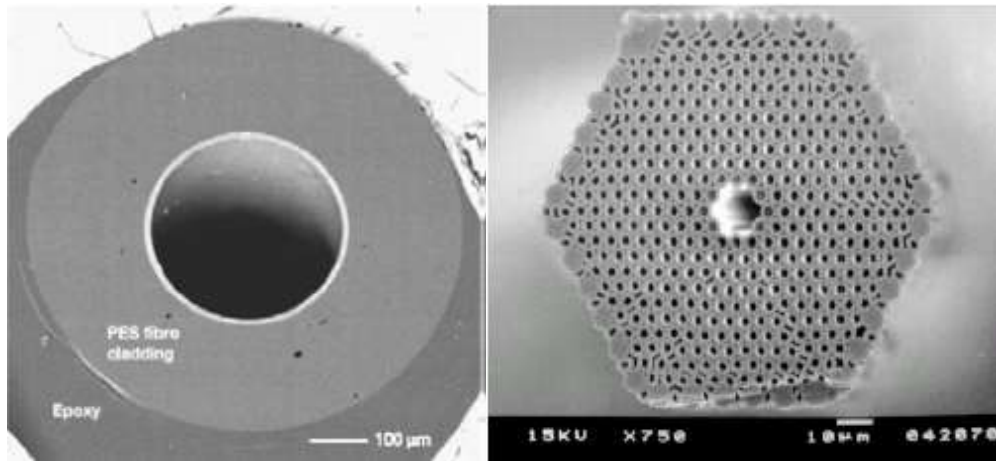


Fig. 1.3 Schematic diagram of various guiding structures having air as core material used in the light propagation[9]

Hollow waveguides gives the world a strong alternative for using air core in place of other solid core fibers. The key features of hollow core waveguide are wavelength at which it can work. It has ability to transmit wavelength beyond $20\mu\text{m}$, including high power laser delivery and the simple structure. Initially its development was for industrial and medical applications which involve conveyance of CO_2 . This waveguide is of two types

- 1) Leaky waveguide which has the refractive index of wall greater than one
- 2) Attenuated total reflectance waveguide having refractive index less than one.

1.6.1.1 Hollow Waveguide Properties

Optical damage is one of the major drawbacks for using waveguides. This damage is perceptible through a minimization of the light coming out of waveguide as a function of time during which the light is coupled inside the waveguide. This behavior can be clarified in terms of loss of mode coupling. Due to the modification in refractive index induced by the high intensity light which is inside the waveguide since change of refractive index inside the waveguide is constant therefore, there is comparatively low optical damage in hollow waveguide.

Inside the waveguide tuning of light depends on the temperature inside the waveguide. Since the temperature variation in air core with the power transmission inside the waveguide is less, so the hollow core waveguide possesses property of temperature insensitivity. The variety of different integrated optical waveguides is reliable to guide and confine light on a chip. The one of basic optical waveguides is a slab waveguide. The structure of waveguide is uniform in the y direction. Light has been guided in the core region by phenomenon of total internal reflection which occurs at the core-cladding interface. Confinement depends on the waveguide structure. It describes how in wide space the light mode is confined. Strong optical confinement is the asset of Hollow waveguides. Spreading of light pulse in waveguide is called Dispersion. In hollow waveguide having air core the refractive index of core is small which does not change or has a small effect in refractive index with change in the environmental conditions, so the velocity does not change the property of the low dispersion in the waveguide.

1.6.1.2 Hollow Waveguide Applications

1.6.1.2.1 Optical Interconnects

With the increase in speed and scalability of integrated circuits high bandwidth and low loss is required. Optical interconnects can fulfill these requirements and they are likely to replace this metal wiring for interconnects.

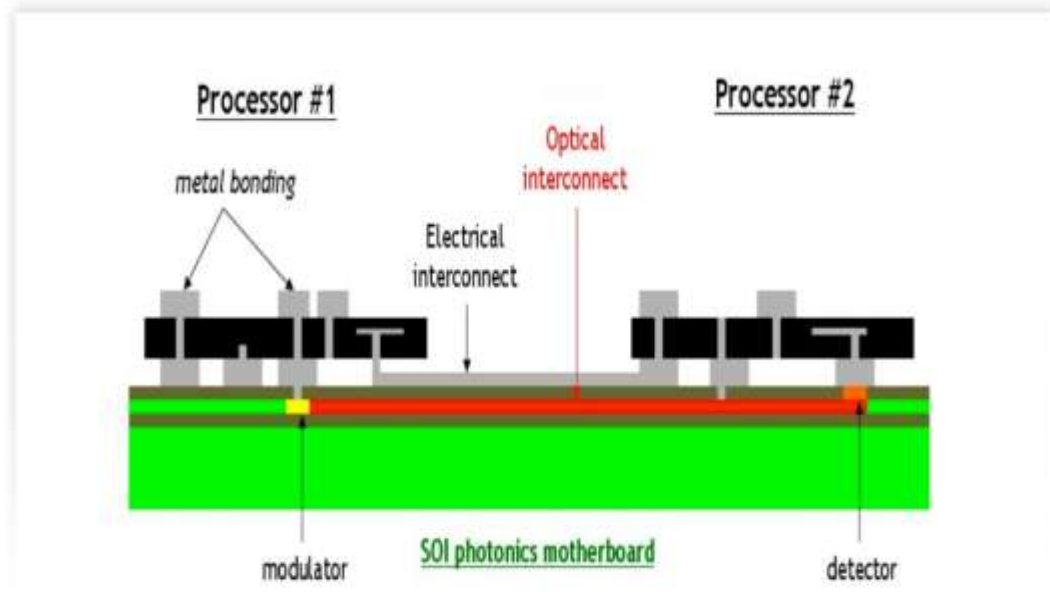


Fig. 1.4 Schematic diagram showing waveguide as optical interconnect [10]

Researchers have exposed various advantages that optical interconnects offer over the electrical interconnects. These are in terms of fan-out, latency, temperature resistant, energy conversion and electromagnetic interference immunity. Many researchers have realized that diffractive grating coupler as the efficient coupling element for optical interconnect systems. Here the hollow waveguides are more desirable due to their more compact size and high fabrication tolerance than other coupling schemes.

1.6.1.2.2 Integrated Optical Devices

Hollow waveguides are reliable in integrated optical devices as well. Compact and chip scale integrated optical devices used to accomplish this task. Beam expanders, holographic filters and polarization dependant devices for intense beam profile reshaping are the some examples of waveguide integrated optical devices.

Other integrated optical devices having applications with computer systems are grating coupled surface emitting lasers, optical read/write heads, optical sensors, and printer heads.

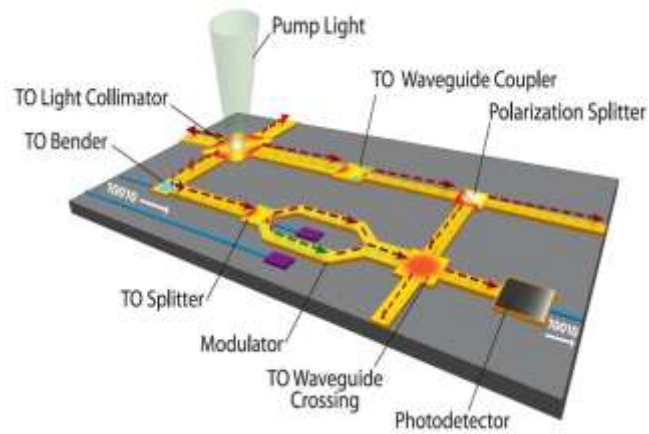


Fig. 1.5 Diagram showing the hollow waveguide as integrated optical devices on a integrated circuit [11]

1.7 HIGH CONTRAST GRATINGS

Gratings are preferred when light of different wavelengths need to separated with high resolution. Gratings consist of large number of narrowly and equally spaced parallel slits which provide sharp and narrow intensity peak with precise high resolution and seamless guiding of light which is useful for several applications like spectroscopy, micro-chromators, imaging and wavelength division multiplexing. These gratings can either transmissive or reflective [12].

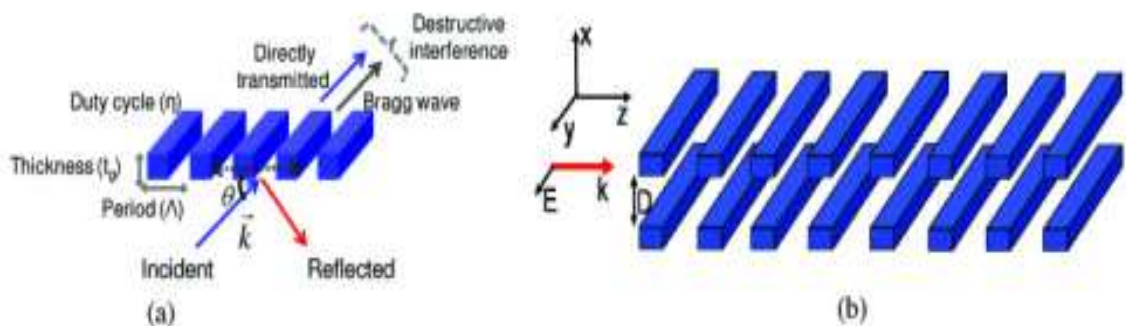


Fig. 1.6 (a) Schematic diagram of High contrast grating (HCG) representing high refractive index material surrounded by the low refractive index material (b) Schematic of HCG hollow core waveguide structure consist of two reflecting HCG's [13].

There are two regimes: one is diffraction regime, in which grating period (Λ) of grating is larger than the wavelength (λ) [14-15] and other is sub wavelength regime in which the

grating period, is less than the wavelength. In spite of these two regimes there is a third regime which is comparatively unmapped regime in which the grating period is between that of its surrounding media and the wavelength of the grating material. The behavior of gratings is different at this regime, and represents many distinct properties that are not common in the gratings. When there is a large refractive index difference between the grating bars and their surrounding they show important properties. These properties become more prominent. With an spontaneous design guidelines, ultrahigh reflectivity ($>99.5\%$ over a wavelength range of $\Delta\lambda/\lambda > 35\%$), high transmission windows, 100% transmission and 100% reflection, as well as high quality resonance (quality-factor $Q > 108$) can be obtained [16-18].

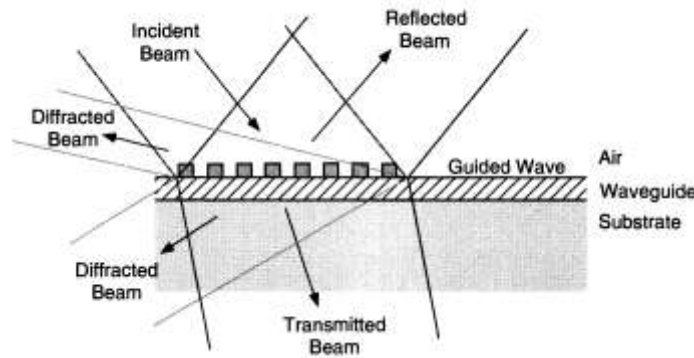


Fig.1.7 Schematic diagram demonstrating hollow waveguide with HCG on substrate and the light beams get incident on gratings get transmitted and reflected in the waveguide[19].

This is thus a new type of gratings, and it is referred as high contrast gratings (HCGS), schematically shown in Fig 7. The fundamental difference of HCGS from other near wavelength gratings is that it has the high index grating bars which entirely bounded by low index materials fabricate on a high-index substrate, so additional index contrast is not required at the subsisting plane [20-22]. With large astonishing properties, HCG gives a new platform for planar and integrated optoelectronics. The basic principle of HCG lies in its ability of excellent guidance of light, this can be utilized its applications of light generation and detection. Integrated optoelectronics based applications are covered with the extent of functionality of HCG. All of these recommend that HCG has potential to use beyond a single element in the integrated optoelectronics and has also enabled a new platform for the integrated optoelectronics applications like optical interconnects. HCG, since the invention in 2004, has been seen prompt improvements in both theoretical and experimental

characteristics and has drawn attention from many researchers around the world, and with the time formed its own research field. From 2012, a conference named high contrast meta-structures had established and dedicated to this field in the SPIE photonic west. It is seen that HCG will continue to play an important role in integrated optics and optoelectronics and expand its applications.

Information industry have shown high growth in the entire world , which increases the demand for the communication networks for high bandwidth and high data rate. To overcome these demands optical fiber communication systems plays an important role in today's communication networks. The prime challenges faced by the optical fiber communication systems are the dispersion, nonlinear effects and transmission loss. Dispersion becomes the major difficulty in the optical fiber communication systems, but with the advancement and new technology in optoelectronic devices, dispersion can be reduced to provide high speed in optical fiber transmission system. One method for compensation of dispersion is the optical grating that plays crucial role. By improving the fabrication process of Chirped Fiber Bragg Grating many problematic problems such as loss due to cladding mode, the ripple of the time delay, fabrication repetition have been solved. Also gratings play an important role in the Dense Wavelength Division Multiplexing (DWDM) used in optical networks which enhance the performance of the system i.e crosstalk and selectivity between adjacent channels [23].

1.7.1 High Contrast Grating Theory

A optical grating is a 1D periodic structure consists of a series of equally spaced grooves that are shown in Fig 1.8. The grooves diffract light when it incident on the grating surface where each of the groove behaves like a small source of reflected or transmitted light. At a unique set of different angles if light is incident it scatters from all the grooves in phase and shows constructively interfere with each other.

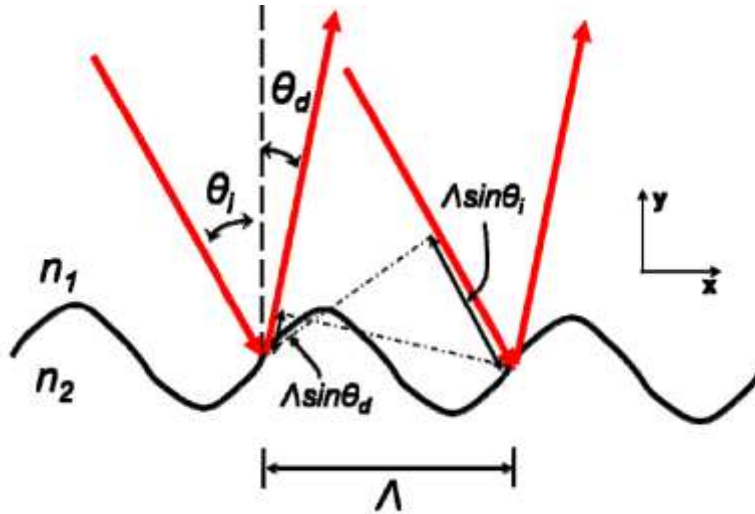


Fig. 1.8 Schematic ray diagram of an optical grating representing the phase relationship among the diffracted rays from adjacent grooves of grating [24].

In fig8 a plane wave is incident at an angle θ_i to grating surface. The path difference between adjacent grooves for a diffracted ray with an angle θ_d is expressed as below

$$\Lambda \sin \theta_i - \Lambda \sin \theta_d \quad (1.1)$$

Where Λ is grating period, θ_i is the incident angle and the angle at which light is diffracted is θ_d . For constructive interference and light to be in phase the path difference should be an integral multiple of wavelength

$$\Lambda \sin \theta_i - \Lambda \sin \theta_d = m\lambda \quad (1.2)$$

Where $m=0, \pm 1, \pm 2, \pm 3 \dots$ and for all other angles except these there will be destructive interference between light rays diffracted from adjacent grooves and they will be cancelled out. This property can be expressed in a simple equation, which is called as grating equation

$$\sin \theta_{d,m} = \sin \theta_i + m \frac{\lambda}{\Lambda} \quad (1.3)$$

In the above equation θ_i is incident angle which light makes with the grating surface and the angle with m^{th} order diffracted beam is $\theta_{d,m}$ which is with the grating surface. Λ is the grating period and λ is the wavelength of incident light. The hypothesis made in the stated equation is that the light is monochromatic and a plane wave. Here grating acts as simple

reflection mirror when value of m is zero and wavelength components superimposed on each other. To determine the direction of propagation transmission order in transmission grating equation can be derived.

$$n_2 \sin \theta_{t,m} = n_1 \sin \theta_i + m \frac{\lambda}{\Lambda} \quad (1.4)$$

Where $\theta_{t,m}$ is the angle made by m^{th} order is transmitted wave with grating. The grating number is defined $K = \frac{2\pi}{\Lambda}$. For all kind of problems with grating many theories and methods had been proposed which include the classical model method, integral method differential theory, method of Moharam and Gaylord and many more. RCWA (Rigorous coupled wave analysis) among one of the most extensively used methods for the precise examination of diffraction of the electromagnetic (EM) waves in the grating structure [25].

1.7.2 Gratings Applications

1.7.2.1 High Contrast Gratings in Hollow Waveguide

When the light interacts with high refractive index material of core in the conventional dielectric waveguides it faced nonlinearities and attenuation, but this can be avoided by using low index core having highly reflecting walls [26]. Optical communications, environmental applications, Sensing, and spectroscopy are some applications of hollow core optical waveguides. Two major characteristics of hollow waveguide (HWG) is wide tuning range and temperature insensitivity which can utilized to create wide tune able photonic devices and it is without the requirement of sensors that controls the temperature. In narrow air core, HWG is polarization dependent because of its large tuning in propagation constant [27].

Lateral periodicity in hollow waveguide also reduces the dependence on polarization. The HCG based mirror is introduced [28] and Fig.1.9 shows the schematic of polarization independent HWG. In this waveguide by announcing a phase matching of stratum in DBR and by adjusting grating thickness of the HCG mirror, overall dependence of polarization of HWG has diminished. This waveguide contains both lateral and vertical periodicity. It consist of a high index contrast (si-air) grating acting as top reflective mirror and bottom

DBR as bottom mirror of HWG. Because of high reflectivity of DBR and HCG incident light can be restricted vertically in air-core.

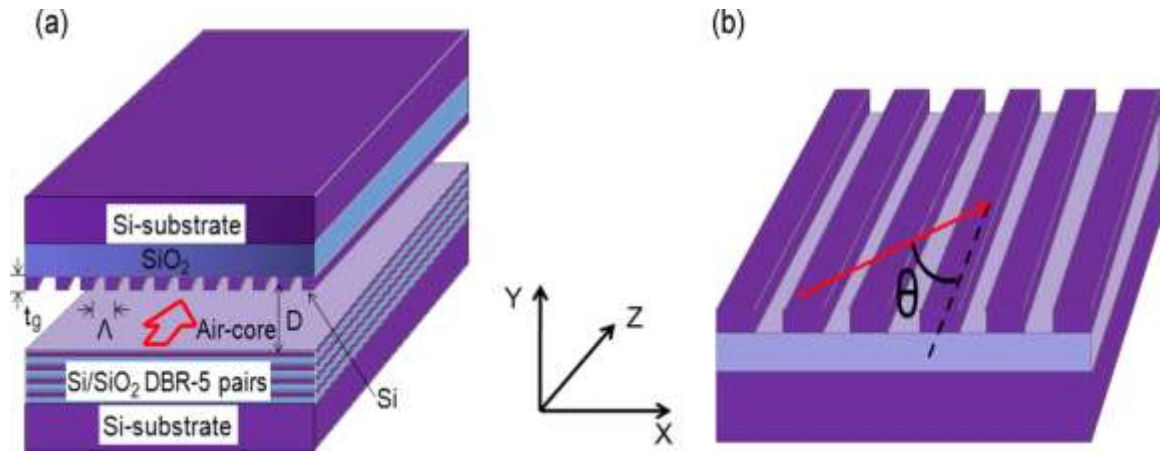


Fig.1.9 Schematic diagram of Hollow Waveguide with HCG as top mirror and DBR as a bottom mirror [28].

Now, to control the orthogonal polarizations a phase matching layer which is made up of Silicon at the top of DBR? The high refractive index difference (between air and silicon) grating is on upper side of waveguide. Therefore net refractive index of mode guided inside the core below HCG is higher as compared to that mode which is in the other two lateral parts of the core where HCG (High contrast grating) is absent. Lateral confinement of light originates from great phase change under the HCG which high index below HCG provides. To change the propagation characteristics of orthogonal polarizations the thickness of high contrast gratings and phase matching layer of DBR is also optimized. These hollow waveguides are important for applications in the polarization insensitive photonic devices used in photonic networks [29].

1.8 PURPOSE AND OUTLINE OF WORK

Motivated by the HCGs based Hollow waveguide's potential in integrated optics and optoelectronics. This dissertation devotes to the development of HCG in optical interconnects, both theoretically and experimentally. There are mainly two tasks. The first one is to further develop the theory and physics of HCG, and the second one is to expand the applications of HCG, i.e. design of novel devices based on HCG, and characterization and application of these devices in chip scale integration on system. The required properties for the defined prospective have studied and various parameters based on these properties have defined and experimentally calculated using RCWA. The analytical formulation of HCG is first studied, for light incidence at an oblique angle, which can be subsequently simplified into the special case of surface normal incidence. This analytical treatment captures the physics of the HCG and is much more elegant and intuitive than the conventional grating analysis like rigorous coupled wave analysis. This analytical formulation outlines a clear physical picture of HCG which provides an understanding of the extraordinary features of the HCG. It is represented that the designing work of HCG can do with RCWA using its methodology and rigorous numerical calculations done through computer software. An HCG band diagram is developed to differentiate HCG from photonic crystals (PhCs) and DBRs. The subsequent chapters explore various applications of HCG.

Chapter 2 Discusses survey on the research work done in the High Index Contrast Grating for Hollow waveguide.

Chapter 3 Gives proposal and analysis of high index contrast gratings. HCGs provides very high reflectivity and discussed about various properties of HCGs which make them suitable for integration with hollow waveguide and used as optical interconnects.

Chapter 4 Reports results of a novel hollow-core waveguide using HCG. The hollow-core waveguide using two parallel HCG layers is designed and simulated. Three dimensional light guiding is experimentally demonstrated though the hollow-core waveguide only has a one-dimension confinement in geometry. Record low propagation loss of 0.31 dB/cm is demonstrated. Another scheme of hollow-core waveguide providing low dispersion would also be discussed. These experimental demonstrations set up a hollow-core waveguide platform for integrated optics where various functionalities such as coupler, slow light, optical switch, gas sensing, etc can be built up. In particular, an optical interconnects has

proposed and discussed. A high speed link between two devices is demonstrated in a single fiber, where one device is functioned as a transmitter and the other as a receiver, or verse vice. Based on this HCG a novel configuration of the device as a novel chip-scale optical integration of optical interconnects would also be presented.

Chapter 5 Summaries the dissertation and discuss the outlook and future work for the further development of HCGs based Hollow Waveguide.

CHAPTER 2

LITERATURE REVIEW

To start the thesis, the beginning step is to study the research papers that have already been published by other researchers. Papers related to my work are chosen and studied. This literature review makes this work easier. It make easy to analyze the work and make work better organize and easy to understand. A review of various aspects of low loss high contrast grating based hollow waveguide for chip scale integrated platform of optical interconnects is presented. It is presented in the paper that how the high contrast grating based hollow waveguide is a potential candidate to overcome the challenges of modern ICs. For the implementation of high contrast grating based hollow waveguide the various requirements are also shown.

2.1 RESEARCH PAPER LITERATURE REVIEW

H. Subbaraman *et al.* in 2015 [6] presented an overall overview of recent progress in silicon based active and passive optical interconnect components and highlighted some of their research contributions. They have also cast light on few other parallel technologies that worked with silicon based structures, and also provides unique functions which are not achievable with any single system. With increase in the utilization of CMOS foundries for fabrication of silicon photonics a reliable path for the realizing very low cost integrated chip scale optoelectronics that has been developed. These recent advances will be beneficial in several applications that will use in the coming years, which will include communication networks, interconnects, nonlinear systems and sensing.

H.Chin Lan *et al.* in 2014 [30] have presented chip-level optical interconnect module which is combined with a photo detector (PD) chip, vertical cavity surface emitting laser (VCSEL) chip, an amplifier IC on silicon on insulator (SOI) substrate and a driver integrated circuit (IC) with 3-D guided wave path which is experimentally demonstrated. Such a optical

interconnect has developed for the signal connection from memory to processor interfaces or multi core processors. The 3 - D guided wave path consist of silicon based 45 degree micro reflectors and a trapezoidal waveguide, that has used to connect optical signal between the transmitter and the receiver. In this demonstration, the VCSEL and PIN-PD chips are the chips which are integrated on a SOI substrate which is an achievement of complete chip level optical interconnects. Due of the unique 3- D guided wave path a higher laser to PD coupling efficiency of 2.19 dB with a larger alignment tolerance of 10 m for the VCSEL and PD assembly has achieved.

Alan E. Willner *et al.* in 2012 [31] studied the fields of optics and photonics that are related to the devices, communications, lasers, materials, bioimaging and displays. They have experienced dramatic technical advances in optics and photonics field over the past decades and have established themselves as the key enabling technologies in many different industries. This paper explored the past achievements, present state of art and the future perspectives of the several different topics which include devices, communications, lasers, materials, bioimaging, displays, industry evolution and manufacturing.

C.Ta Chen *et al.* in 2015 [32] demonstrated the chip scale optical interconnects with the polymer vertical splitter which is developed on a silicon substrate is demonstrated. The vertical splitting configuration has realized using a waveguide of polymer which is terminated by three silicon 45degrees reflectors. The transmission lines of high frequency has combined with the indium has developed solder bumps to flip chip assemble the vertical cavity surface emitting laser chip with the input port and also two photo detector chips at the output ports. In overall setup total transmission loss 3.26 dB has obtained with a splitting ratio of 1 : 1 for splitter is experimentally obtained. The 10-Gbit data transmission with bit error rate better than 10^{-12} for two output ports has achieved. It reveals that chip level optical interconnects using this polymer vertical splitter are much suitable for high speed and error free data transmission with multiple output ports.

Connie J. Chang Hasnain *et al.* in 2010 [33] presents a new concept of subwavelength gratings, with a high contrast in refractive indices with its surrounding to obtain various

extraordinary properties including low loss and ultra broadband reflection in hollow-core waveguides. Recently, they reported some extraordinary properties from one dimensional single layer subwavelength gratings which are fully surrounded by media with large contrast of refractive index. From the high reflectivity it can be understood that when a light beam incident on HCG, the light is reflected into multiple diffraction orders. but, when the grating period is less than the wavelength of light then all higher order modes are evanescent in air and when grating parameters are optimally designed ultra high reflectivity (>99%) is obtained which requires 20-40 pairs of DBRs. Hence, it can easily replace the DBRs which are typically very thick. The HCG with its ultra thin layer result in 10,000 times mass reduction and more than 160 times increase in speed.

W. Yang *et al.* in 2011 [34] demonstrated a novel hollow core waveguide based on high contrast sub wavelength gratings (HCGs) experimentally for the first time. The waveguide formed by the two HCGs planar structures and it is able to confine the light in both ways transverse and laterally. Therefore HCGs based Hollow core waveguides (HWs) have wide range of applications in optical interconnects, gas based nonlinear optics and gas sensing. With the elimination of core material dispersion effects and nonlinearity in traditional Silicon waveguides can be drastically reduced. Moreover Chip scale HWs would open a new range of chip scale applications such as optical signal processors and optical buffers. The oxide is 2 μm thick with a 5 μm waveguide height (d) and wavelength of light is 1.55 μm . The relative effective index difference between cladding and core has calculated which is $\sim 0.25\%$ as confirmed by both finite element method (FEM) and rigorous coupled wave analysis (RCWA). Propagation loss of waveguide is calculated to be 0.12 dB/m

Ye Zhou *et al.* in 2009 [35] proposed a single mode hollow core waveguide providing ultra low loss by using subwavelength high contrast gratings (HCGs). They simulated and analyzed the propagation loss of waveguide and demonstrate that it can be as low 0.006 dB/m, the orders of magnitude which is lower than the lowest loss of chip scale hollow waveguides. This high efficient HCG based hollow core waveguide design will be serve as a building block of many chip scale integrated platforms for photonic circuits that can enable

system level applications including the optical interconnects, optical sensors and optical delay lines.

B. Pesala *et al.* in 2009 [36] presented Hollow core waveguide based on high contrast grating is analyzed using exact analytical formulation (RCWA). They obtain dispersion diagrams and also proposed a planar geometry which is similar to hetero structure for confining the light in these waveguides. Previously, the hollow core waveguide has been demonstrated using distributed Bragg reflector (DBR), metallic shells and photonic crystals. For on chip hollow core waveguide lowest loss reported which is close to 10 dB/m. Now, high-contrast gratings based hollow waveguide has been proposed to achieve very low loss. The hollow core waveguide which has been demonstrated using high contrast gratings shows unique properties for the communication of light in waveguide. They showed that its properties can be varied by proper choice of grating parameters. So, the versatility of this design will make it realizable for many guided wave optical components.

Connie J. Chang-Hasnain *et al.* in 2012 [37] presented three Dimensional high contrast grating based hollow waveguide which provides very low loss and efficient confinement of light in it. This HCGs based hollow waveguide can be implemented in chip scale integrated platform of optical inter connects. They simulated and analyzed the propagation loss in waveguide which is 0.04 db/cm. HCG-HW with 5um core height attains 1.08 ps-(nm/km) chromatic dispersion and ultra low non linear coefficient. For a HCG-HW with a 6 um core height, it exhibits even decrease in loss. The HCG-HW also achieve an ultralow nonlinear coefficient that is of the order of 10^{-5} W/m.

E. Bosman *et al.* in 2013 [38] presented two solutions to obtain efficient coupling between planar optical waveguides and vertical cavity surface emitting lasers by reducing the free space optical path length. One approach based on flip-chip assembly that is using micro bumps and the other approach is based on embedding of optoelectronic chips in polymer layers. The micro bumps are defined by a technique called laser induced forward transfer (LIFT). It is a technique in which the bump material can be transferred from a donor carrier

to substrate that guides the wave. In these cases, out of plane bending of light is achieved by using 45 degree micro mirror interface.

Biao Yang *et al.* in 2013[39]represents a novel high efficient compact optical coupler having curved gratings with non uniform pitches to couple light into silicon photonic chips required for large scale integrated functions. Here the optimized non uniform pitches improve the coupling efficiency of the single mode fiber and the waveguides by reducing mode matching loss between the grating and the coupler fiber. This kind of highly focused grating coupler has reduced the transition length between the gratings and that of single mode waveguide.

Kai Yang *et al.* in 2007 [40] represented Integrated waveguide grating coupled VCSEL and RCEPD arrays with greater than 1.4 mW output power and VCSEL to the photodetector data communication provides speed greater than 1.25 Gbps through integrated waveguide. They have designed and fabricated new heterogeneously integrated 980 nm InGaAs VCSEL array structure in which lower cavity contains an epitaxially grown semiconductor DBR and a active gain region.The upper cavity consists of an dielectric structure which includes the optical waveguide, WGC and the upper distributed Bragg reflector (DBR) mirror. This advanced technology will enable applications using VCSEL based optical integrated circuits.

E. Granout *et al.* in 2013 [41] determined the bit-rate of the slab waveguide and its relation with the waveguide dispersion. He exhibited that the maximum bit rate inside a waveguide is inversely proportional to the waveguide's width and bit rate of a piece unit width (i.e. spatial capacity) and at the boundary of zero width waveguide and it has congregated to $\omega / \lambda L$ (where L is the length and ω and λ are frequency of the beam and wavelength respectively). That results which was self determining of the waveguide's refractive index was corresponding to the communication proportion per unit width in free space. He also demonstrated that in a 3D waveguide (e.g., fibers) unlike the spatial capacity and free space has wiped out in the same frontier.

Y. Yue1 *et al.* in 2010 [42]demonstrates that high contrast grating hollow core waveguide exhibit low chromatic dispersion of 8.6 ps/(nm-km)). With this low dispersion high speed

(>100 Gb/s), low-penalty (<0.2 dB) long-distance (30 m) on-chip can be achieved. Chromatic dispersion affects the quality of high rate data signals. They analyze the variation of chromatic dispersion and its effects on high-speed signals. Low loss, low dispersion and low nonlinearity is the key for high speed (>100 Gb/s), low penalty (<0.2 dB) . Dispersion with different HCGs-HW core having sizes from 5 to 20 mm is analyzed and it is found that CD is stable near 1.525 mm wavelength and third order dispersion or dispersion of slope decreases with increase in core size.

V. Karagodsky *et al.* in 2009 [43] presented analytical solution for reflectivity of sub-wavelength gratings in case of incidence of transverse plane wave and proposed a design guideline which provide maximum reflectivity. Broadband mirrors having high reflectivity (>99%) are very crucial for various applications like communication network. They have proposed highly reflecting, single-layer high contrast subwavelength gratings (HCGs) that provides very broad bandwidth. Even experimentally demonstrated the monolithic integration in VCSEL replacing the conventional DBRs . The large index contrast results in extraordinary large tolerance on HCG dimensions. Most of the designs and calculations were done using either Rigorous Coupled Wave Analysis or FDTD (Finite Difference Time Domain methods).

Y. Zhou *et al.* in 2009 [44] have studied the recent work done in the field of high contrast gratings of range of grating in the sub wavelength and a number of device applications have found in this field such as in photonic devices like hollow waveguides. High contrast gratings provide very high reflectivity (> 99.5 %). This property of HCGs make them different from the other existing technologies and it has replaced distributed brag reflectors as they are difficult to fabricate and require more space. At the end they have presented a design of HCGs which worked as a small angle reflectors in the hollow waveguides. A detailed view on the modern technology based on HCGs has discussed in this paper. After discussing in detail a unique design is implemented which is providing ultra low loss of <0.01 dB/m, and this loss is even low than the lowest loss achieved before for chip scale integrated photonic circuits so this design enables the application of integration on chip of optical interconnects.

H. Huang *et al.* in 2011 [45] have demonstrated the signal performance of analog signal which is transmitted using HCGs based hollow waveguide and get SFDR greater than 100 dB implemented in broad range of 80 GHz and bandwidth of wavelength is obtained 50 nm when it is transmitted over a distance of 100 m. The results which are obtained from the proposed design we can say that HCGs based HWs are much better than the optical fibers. In this design one parameter need to take care that is fabrication. As the size reduces dependency on fabrication increases so at first one grating period is implemented and results are verified by noticing the variations in SFDR curve and compare it with variations in air gap between gratings and grating thickness. From all these observations it is concluded that HCGs based HWs are far better than silicon waveguide.

Y. Yisu *et al.* in 2009 [46] presented a 2 D structure with sub micron gratings which are analyzed and simulated by the most common method of FDTD and RCWA. After analyzing the structure design it is obtained that this structure design can provide reflectivity which is greater than the 99.5 % and can reach upto 99.9 % over the range of wavelength of 1.46 μm to 1.60 μm . This ultra high reflectivity enhances the efficiency and makes it suitable for the mirror used in resonant cavity and also in photo detectors. This design with these remarkable properties has proved itself as a best replacement of DBRs as they have with increase in reflectivity also reduce the size and fabrication steps too. With all these improvement one more addition to the performance by the more symmetric modes that propagates in waveguide.

Vukovic *et al.* in 2015 [47] presented a new type of waveguide having hollow core to guide the wave through it and the guided wave will be guided in core with bigger mode area as compare to those which are used earlier. We propose a hollow core large mode area fiber with a new type of guiding mechanism. The basic principle of waveguide is the zero contrast refractive index with the design parameter are so specified that the grating of waveguide is of sub wavelength (grating size is less than the wavelength used) range. Second design importance is the circular gratings on which when waves incident that provides the resonance which results in ultra high reflectivity and high reflectivity is of prime importance to reduce

loss in waveguide, so the presented waveguide provides very low loss which is required for the today's applications. They have also shown high reflectivity by using self-suspending gratings and with these new gratings low loss is achieved. The proposed design can be used in applications which require THz range.

S.C. Huang *et al.* in 2015[48] have demonstrated HCGs with various fabrication parameters which are important to realize the design for various applications including communication networks, chip-scale integrated platforms and others. The fabrication involved mainly two steps that are electron beam lithography and plasma process which are relatively less steps as compared to fabrication of its contemporary DBRs which required a large number of fabrication steps and can be scaled in nanometer range. The fabrication involved above two steps are easy to fabricate. All the parameters are calculated using FDTD. High reflectivity is achieved with a bandwidth of 200 nm. From these calculations it is said that HCGs are promising candidates of a new era of communications which can be used in integrated circuits and provide large bandwidth with high speed and low propagation loss.

Y. Yue *et al.* in 2010 [49] have demonstrated the HCGs based HW which is a promising candidate for chip-level applications on a system that requires digital data transmission. For digital data transmission non-linearity is one of the most important parameters because it affects the digital system badly and it is found to be very low of order 6×10^{-13} W/m. The low non-linearity is due to the unique design of HCGs. Normally light incident on a material diffracts in many modes which include higher-order modes which cause non-linearity but when gratings of sub-wavelength range are implemented all higher-order modes fade away and provide high reflectivity and low non-linearity as only the zero-order mode exists. For long distance and high power transmission requirements in both analog and digital systems non-linearity degrades system performance but with this novel design this problem will be sought out. After analyzing the design very low loss and dispersion of 8.2 ps/nm-km has been achieved which can provide a high data rate of 40 GB/s.

M. G. Moharam *et al.* in 1981[50] have presented a method to analyze the light in a waveguide by diffraction of light when incident on gratings and proposed a rigorous coupled

wave analysis for calculations. In this approach calculations are based on state variables of matrix, so it can easily implemented on digital system using programs like MATLAB. The calculations done by this method are exact calculations which give accurate results. The matrix formulas and diffraction properties are presented which are based on RCWA methodology. In this method exact values are calculated to attain proper results. This method is compared with previous existing methods like two wave coupled theory and errors of these theories are removed and high accuracy is obtained by using higher order modes in formulation of various parameters.

CHAPTER 3

ANALYSIS OF HIGH CONTRAST GRATINGS

3.1 HIGH CONTRAST GRATINGS

High-Contrast Grating (HCGs) are single-layer subwavelength gratings in which the refractive index difference between gratings of high refractive index region and low index region is relatively high. Due to refractive index difference and of subwavelength high contrast gratings these could be used as high-reflectivity mirror. The HCGs consists of a single layer of periodic grating structure having high refractive index material (e.g. Si) which is completely surrounded by low index material (e.g. air). The HCG design provides extraordinarily high reflectivity over a wide bandwidth for transverse-magnetic (TM) polarized light, with an electric field perpendicular to the grating incident from the surface-normal direction.

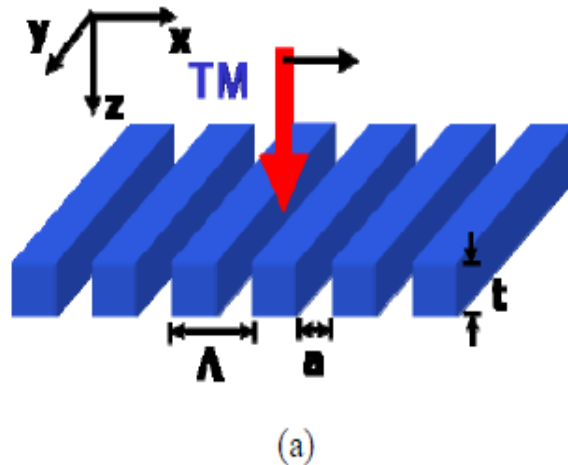
3.1.1 HCGs Layer Works Like Mirror

HCGs work like mirror provides ultra high reflectivity which can be used in many applications such as optoelectronics, semiconductor lasers (VCSEL), optical interconnects, and optical filters. Although the reflection band of metal mirrors is large but high absorption cause large propagation loss in the metals, even most of the metal mirrors are not able to attain reflectivity more than 99%. Due to this they are not providing appropriate results for mirrors which are needed for the transmission applications. The distributed Bragg reflector (DBR), made up of multiple layers of alternating materials having the periodic variation of refractive indexes, had been used as mirror having high reflectivity in most surface emitting lasers. But the small index difference between material layers ultra high reflectivity had not been achieved from DBRs and large DBR pairs are needed to obtain ultra high reflectivity, but with this fabrication becomes costly and difficult even they become bulky. As we will show in this section, HCG structure can be an ideal candidate to work as mirror.

3.1.2 TM-HCG and TE-HCG

Fig. 3.1 represents the schematic of the proposed broadband high-reflectivity HCGs structures. Before we discuss the details in the HCG designs, it is necessary to distinguish between the two cases of polarization for a grating. When linearly polarized light is incident and gratings are at 90 degree to electric field vector (perpendicular to the y direction in this case), both the reflected and transmitted lights have the same polarization. It is called TM polarization. In the other case, when the electric field is parallel to the grating stripe direction (parallel to the y direction), both the reflected and transmitted lights also preserve the polarization direction, and this is called TE polarization. Any other state can be represented as the linear combination of the two fundamental polarizations. Therefore, it is only necessary to investigate the HCG response for these two polarizations.

HCGs as discussed before can work as ultra high reflectivity mirrors and they work like mirror for both the TM polarized light and TE polarized light. HCGs which work as ultra high reflectivity mirrors for the TE polarized light called the TE-HCGs and the HCGs which work as ultra high reflectivity mirrors for the TM polarized light called the TM-HCGs shown in fig. 3.1 (a) and (b), we have show examples of designs of both TE-HCGs and TM-HCGs. These HCGs have designed for the 1550 nm wavelength and they made up of periodic Silicon bars as high index material which is surrounded by air as the low index material. For TM- HCG, the grating parameters are: the period (Λ) = 1050 nm, spacing (a) = 300 nm and thickness(t) =350 nm. Here Silicon is used as grating material with air as other material example of the designing is shown below in Fig. 3.1 (a)



For TE-HCGs, the parameters of designed gratings are: the grating period (Λ) = 1170 nm, spacing (a) = 230 nm and thickness (t) = 340 nm.

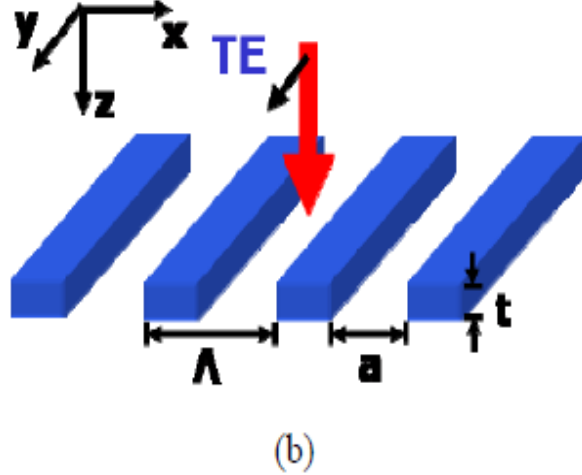


Fig. 3.1 Schematic of (a) TM polarized and (b) TE polarized high contrast grating (HCG). Red arrows show the light propagation directions. The black arrows attached to them show the E-field polarization directions.

3.1.3 Dimension Sensitivity

In a HCG design, important design parameters include grating period (Λ), grating thickness (t), and grating duty cycle (η). In this section, the study the HCG reflectivity spectrum varies when design parameters changes. Here shows the design sensitive analysis by varying one parameter at a time, while keeping the others constant. The dimension sensitivity for both TM-HCG and TE-HCG, whose designs are the same as described in earlier section.

The grating period (Λ) sensitivity study is shown for both TM HCG and TE-HCG. In this study, we fix TM-HCG grating parameters at $\eta = 65\%$ and $t = 350$ nm and scan the grating period (Λ) from 1050 nm to 1170 nm. For TE-HCG, the grating parameters are fixed at $\eta = 65\%$ and $t = 340$ nm, and scan the grating period (Λ) from 1050 nm to 1170 nm. For both HCGs, the high index material is Si, with the refractive index $n=3.7$, and the low index material is air with $n=1$. Reflectivity spectra as a function of grating period (Λ), using RCWA for both TM and TE HCG is calculated. The 99.5% reflectivity contour line is shown in black. Both TM- and TE-HCG can tolerate at least 40 nm variation in a period while still maintaining a high reflectivity $>99.5\%$. Grating period can usually be controlled accurately

in most deep UV lithography or e-beam lithography systems as well as in nano imprint systems. Therefore, a 40 nm fabrication tolerance is more than enough for of the most systems, and high reflectivity can be easily achieved.

3.1.4 Scalability

One of the nice design property of HCG its scalability with the wavelength on which it is worked. The calculated reflectivity for a TM-HCG with grating period (Λ) = 1050 nm, thickness (t_g) =350 nm, and duty cycle (η) =65%. Calculated reflectivity for a TM-HCG with grating period (Λ) = 1170nm, thickness (t) =340 nm, and duty cycle (η) =65%. While keeping the other parameters the same, only multiply the dimensions given here by a particular constant, the reflection band shifts from 0.7-1 μm to a 7-10 μm wavelength range with all features and values being identical. Therefore, we can easily design HCG in other wavelength regimes by scaling wavelength, until the refractive index doesn't change much. Although we used TE-HCG as an example here, this wavelength scalability applies to all other HCG designs.

3.1.5 HCG as Shallow Angle Reflectors

HCGs which are designed are for the surface normal operation if in some applications at any arbitrary angle light need to incident then by changing the dimensions of the HCG structure, we can optimize the HCG structure as a high-reflectivity mirror for almost any incident angle. In this section, HCGs for oblique angle reflection are discussed. This type of HCG is very useful in designing ultra-low loss hollow-core waveguides.

High Contrast Gratings (HCGs) are a single layer sub wavelength gratings in which the difference between refractive index of high index region (silicon) and low index region (air) is high. This has proposed that when HCGs have sub wavelength grating then they can be work like a surface normal mirror due to ultra high-reflectivity. The HCGs having a single grating layer with material of high refractive index (e.g. Silicon in blue) which is completely surrounded by the low index material (e.g. air) as shown in Fig. 3.2 The proposed design attains ultra high reflectivity with desirable large optical bandwidth for the incident light.

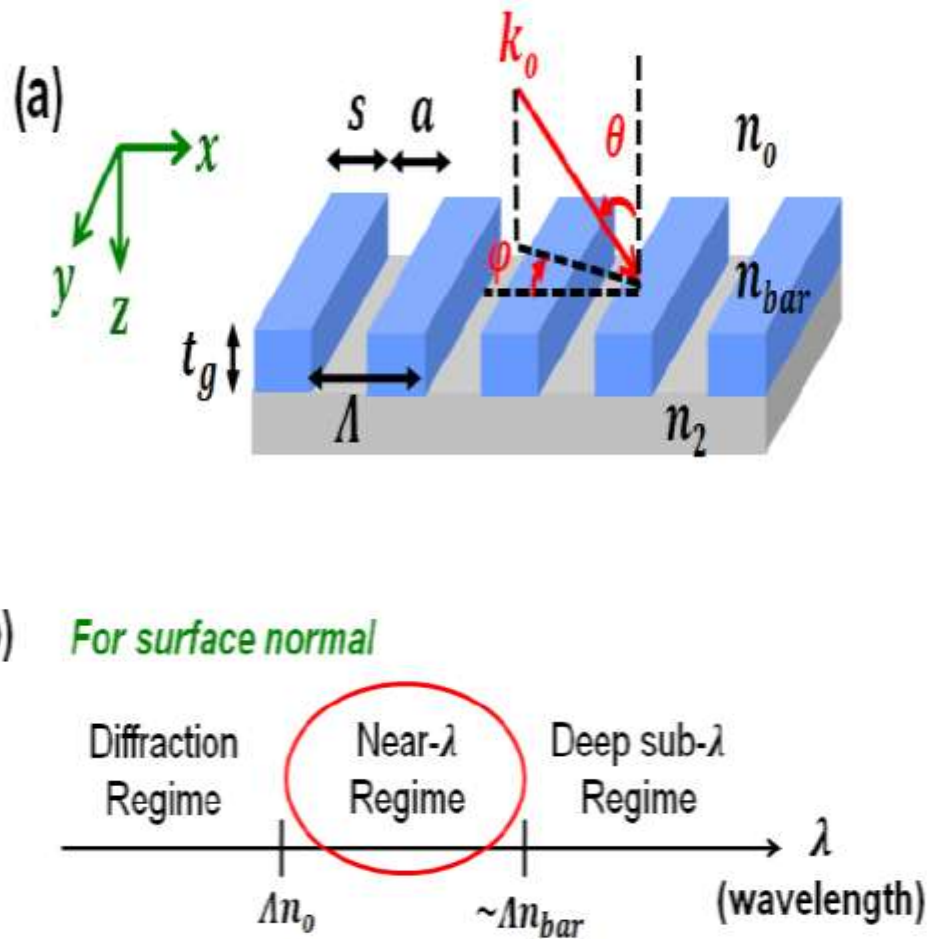


Fig. 3.2 (a) Schematic of HCGs consist of grating of Silicon having high refractive index n_{bar} , air acts like a low index medium .

(b) Three operation region for gratings. High contrast grating operates at the near -wavelength regime.

The proposed structure can fabricate on a silicon on insulator (SOI) substrate. The design parameters for the structure include the grating period (Λ), grating thickness (t_g), grating duty cycle (η : The duty cycle (η) of HCG is ratio of the width of high index material and the grating period). This SOI HCG has designed for $1.55 \mu\text{m}$ center wavelength and the design parameters are $n_{\text{substrate}} = 3.48$ (Si), $n_{\text{superstrate}} = 1$ (air), $n_H = 3.48$ (Si.), $n_L = 1$ (air), $\Lambda = 1.17 \mu\text{m}$, $t_g = 0.34 \mu\text{m}$ and $\eta = 0.65$.

For this HCGs structure rigorous coupled wave analysis (RCWA) method is used for calculations. Reflectivity for a TE polarized incident light from surface normal direction. The results from calculation methods agree very well with theoretical analysis. An

extraordinarily broad bandwidth ($\Delta\lambda/\lambda \sim 65\%$), high-reflectivity ($>99.5\%$), spectrum ranging from $1.2 \mu\text{m}$ to $2.00 \mu\text{m}$ is obtained using RCWA method. For reflectivity requirement of ($R>99.5\%$) the HCGs based mirror provides ultra reflection for given bandwidth as shown in figure.

The reflectivity spectrum of a $5\mu\text{m}$ DBR with 40 pairs of GaAs/Al_{0.9}Ga_{0.1} as alternating layers is similar with the reflectivity spectrum of HCGs. For a fair comparison, the wavelengths of both reflectivity spectra are normalized to 1. The reflectivity obtained by 40 pairs of DBRs is obtained by single grating layer of HCG also with large bandwidth and 10 times reduction in thickness achieved. Moreover, unlike DBR structure HCGs attains this ultra high reflectivity for one polarization which is very desirable for many applications such as VCSEL mirrors.

The reflectivity is calculated using the RCWA. A broadband width, high-reflectivity ($>99.9\%$) is obtained. Although this particular HCG is designed for TE polarized light, we can also design HCG with changed dimensions TM polarize light which provides broadband width, and ultra high-reflectivity spectrum.

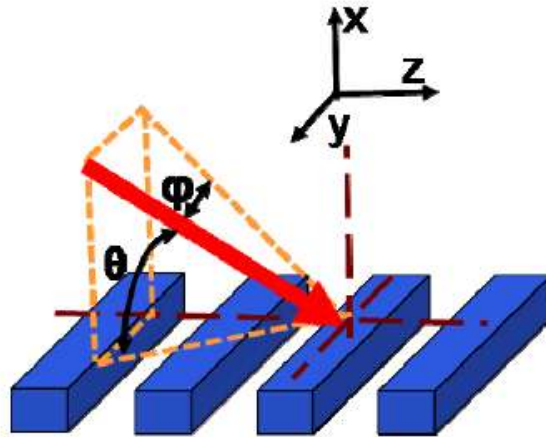


fig. 3.3 Schematic of HCGs with an arbitrary angle of incidence. Here to identify direction of incident light angles θ and ϕ are used between incident beam and yz plane and the angle between incident beam and xz plane.

The proposal of the first HCG broadband mirror opens a new era in subwavelength grating study. We believe the extraordinarily broad band and the high reflectivity from the HCG are the results of their sub wavelength size and high index low-index media's unique arrangements. The HCGs in this section are designed for small value of θ and φ and are designed for 1550 nm. The refractive index of high index material of grating is 3.4. Air is used as low index material having $n=1$. HCGs are designed for TE light for the $\theta < 1^\circ$ and $\varphi=0^\circ$ the design parameters are grating period (Λ) = 1170 nm, thickness (t) =340 nm, and duty cycle (η) =65%.

CHAPTER 4

PROPOSAL AND ANALYSIS OF THREE DIMENSIONAL HIGH CONTRAST GRATINGS BASED HOLLOW CORE WAVEGUIDE

4.1 INTRODUCTION OF HOLLOW WAVEGUIDE

In recent years, the hollow-core waveguide (HCW) has attracted researchers because of their unique properties of wavelengths. These property make HCG based HWs unique while the conventional solid waveguide surfaces problems such as high loss due to absorption in material and challengeable non-linear effects. Conventional designs like DBRs and Photonic crystals are not capable to efficiently confine the light into a hollow core waveguide . The basic fundamental of these hollow core waveguides is the interactions with grooves of gratings of subwavelength range while that of DBRs is many layers, which is difficult to fabricate and bulky in size which make it near to impossible to work as chip scale integrated components. Moreover these waveguides has material which interact with light causes loss and high material dispersion and hollow waveguide provide flexible design and cost effective fabrication which make HCG-HW ideal candidate for realization of chip scale integrated platform of optical interconnects.

HCG based Hollow-core waveguide which guides the light into air core, that is a promising candidate for achieving low propagation loss, small material dispersion because of the elimination of the core material. These features are very significant for chip scale integrated platform. Papers publish recently on high contrast grating based hollow waveguide have shown that high contrast gratings (HCGs) provides ultrahigh reflectivity which is a crucial part in designing of low loss waveguide and can obtain ultra low dispersion and very low nonlinearity in waveguides . Secondly, the HCG-HWs are easy to fabricate due to less process steps as compare to other waveguides. The fundamental principle is to guide the light inside the hollow core waveguide is via reflections using high contrast gratings whose one layer gives reflection that of 40 layers of DBR.

Here we proposed a 3-D HCG based HW which is designed by the two HCGs. Because of ultra high reflectivity in waveguide the two HCGs are able to confine efficiently light in the waveguide. Here, we propose and high contrast gratings to achieve low propagation loss in HWs. We represent that when HCG are placed parallel to propagation of wave it confine light efficiently in the waveguide. As a result, reduction in loss achieved. High contrast gratings give high reflectivity, greater than 99.5% when grating period is of sub wavelength range [5]. When the designed grating period of sub wavelength range (1170 nm) is used then only zero order mode exists and higher modes becomes evanescent and high reflectivity achieved.

High reflectivity is prime reason for ultra low loss in waveguide. We show that propagation loss of 0.031 dB/cm is achieved using Rigorous coupled wave analysis. The loss in waveguide can vary with the width and core height of waveguide. With increase in width loss decreases but on the other hand size increases and these days devices are becoming small so these factors need to be optimized according to present technology and fabrication limits. In hollow core waveguide the core material is air due to which the chromatic dispersion has reduced to large extent as chromatic dispersion is caused by material dispersion and waveguide dispersion. Due to air core material dispersion is almost negligible and non linearity is of range 10^{-5} /w/m which are desired for chip scale integrated platform as distortion in optical signal is prevented. [4]. All these properties make this high contrast grating based hollow waveguide suitable for chip scale integrated chips based on applications that include optical interconnects like connection between micro-processor and memory, multi core micro processors and other integrated chips.

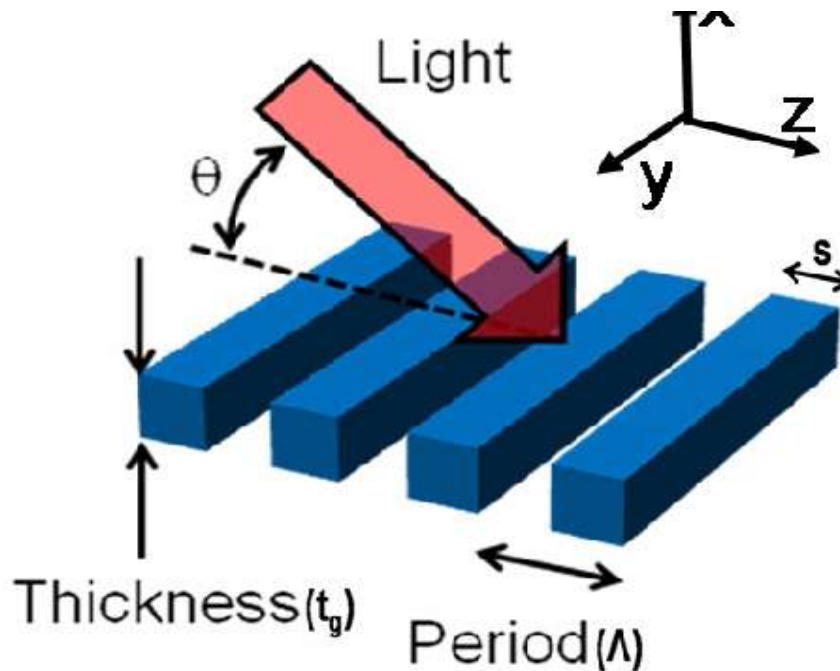
Low loss Integrated chip scale based hollow waveguide using high contrast gratings system faces basically critical technical challenges for implementation in integrated platform for optical interconnects. Technical problem— Low loss Hollow Waveguide based on HCGs facing major Design, Fabrication & Testing problems which include small size, ultra low loss, design for make it working at communication wavelengths and important engineering tools development and their maintenance methods for proper measurement of parameters which define waveguide properties such as signal loss in waveguide and dispersion in waveguide.

4.2 BASIC PRINCIPLE

HCGs structure has shown in the figure. In this structure the high contrast gratings surrounded by air which acts like low index material. The refractive index difference is maintained high that is greater than 2.4. Parameters on which reflectivity of waveguide mainly depends are grating thickness (t_g), grating period (Λ) and duty cycle (η). Important design attribute is the sub wavelength size of gratings. The angle of incidence of light with the surface of gratings is θ . It is already discussed that for high reflectivity angle of incidence on the grating should be small. The unusually high broadband reflectivity arises due to high index difference between the silicon gratings and air. In addition, the period of the grating is sub-wavelength. No diffraction orders other than the zeroth are present in waveguide which provides ultra high reflectivity.

4.3 WAVEGUIDE STRUCTURE DESIGN AND SIMULATION

a)



b)

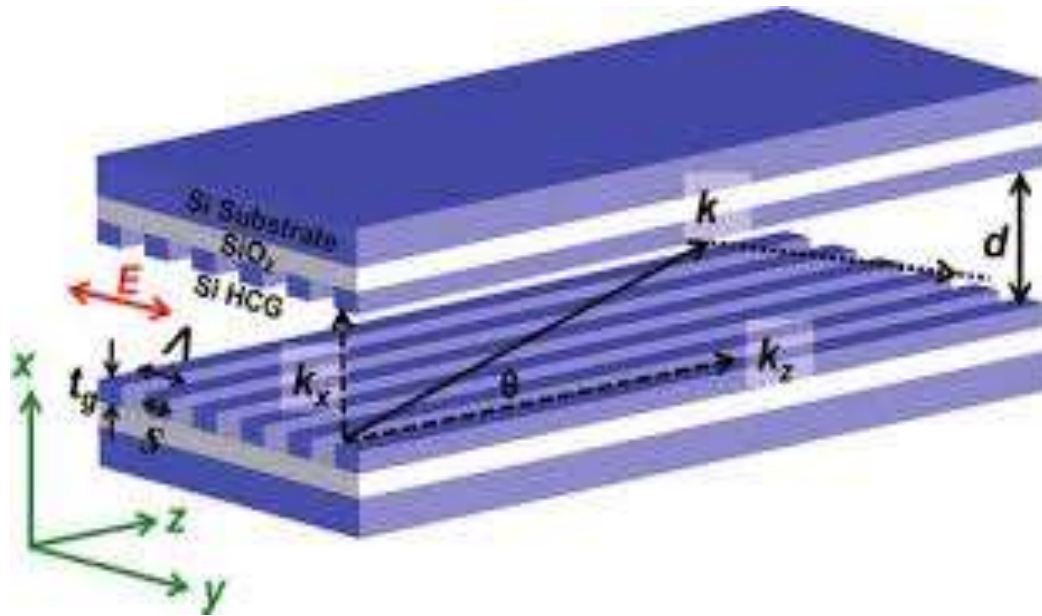


Fig. 4.1a) HCG grating shows grating parameters.

b) Schematic consisting of two reflecting 3-D HCG-HW in the y-direction. High index gratings are on top which made of Silicon and a 2 μm SiO₂ layer and Silicon substrate. The light propagates in waveguide in the z-direction.

The schematic of a 3-D HCG-HW is shown in Fig. 4.1 (b) given above, The light travels along the grooves of gratings and interacts with them. Two silicon on insulator are the substrate wafers which are parallel to each other. Each one has 340 nm Si layer, and a 2 μm SiO₂ layer on the Si substrate. The height of core is 5 μm. Fig 1.a) Shows HCGs with low index core of the air. The basic parameters that define design of grating have major impact on the grating reflectivity, its period Λ , the air gap a_g , and grating thickness t_g . Incident angle θ is between plane of gratings and incident light. Here θ is very small ($\theta \ll 1$) as wave is made parallel to gratings. High contrast gratings are at distance d apart (d is core height). At wavelength of 1.55 μm refractive index of silicon and core material air is obtained according to the At 1550 nm, they are 3.478 and 1, respectively.

Ray optic model can be implement to find the properties of propagation of HCGs based HW due to their ultra high reflectivity. The HW through which light travels has height d and incident at a angle θ travels the distance $d / \tan\theta$ per bounce of light in waveguide.

According to ray optics there is a loss of $\delta=1-R$ at each bounce, where R is the reflectivity of the HCGs . Assuming that there is no material loss in the HW's core, the optical propagation loss per unit length over distance L is

$$\alpha (dB/m) = \frac{10}{L} \log \left(\frac{P_t}{P_i} \right) = - \frac{10}{L} \log (R^N)$$

$$- \frac{10}{L} N \log (R) = - 10 \frac{\tan \theta}{d} \log(R)$$

where the number of bounces in distance L is represented by N and $N = L \tan \theta / d$.

Given that, $\delta \ll 1$, $\log (R) = \frac{\ln (1-d)}{\ln 10} = -4.3 \delta$

As $\theta \ll 1$, $\tan \theta$ becomes nearly equal to θ , therefore the waveguide loss can be estimated as

$$\alpha (dB/m) = 4.3 \alpha \frac{\theta}{d} \delta$$

HCG's various design parameters like reflectivity are calculated that is the result of calculations using rigorous coupled wave analysis (RCWA) , is used to calculate the gratings on the two wafers can provide light confinement in the z-direction. We choose grating parameter of 1170 nm, air gap is maintained 450nm. The grating thickness in all simulations is 340 nm.

4.4 VARIATION OF REFLECTIVITY WITH WAVELENGTH

At 1550 nm wavelength reflectivity (> 99.5 %) is maximum is shown in Fig. 4.2 therefore at this wavelength HCG-HW structure provide minimum loss. Here the property of HCGs based HW's property with the wavelength is represented through graph in which the unique

results at 1.55 μm wavelength have obtained and it is providing maximum reflectivity and minimum loss at this wavelength.

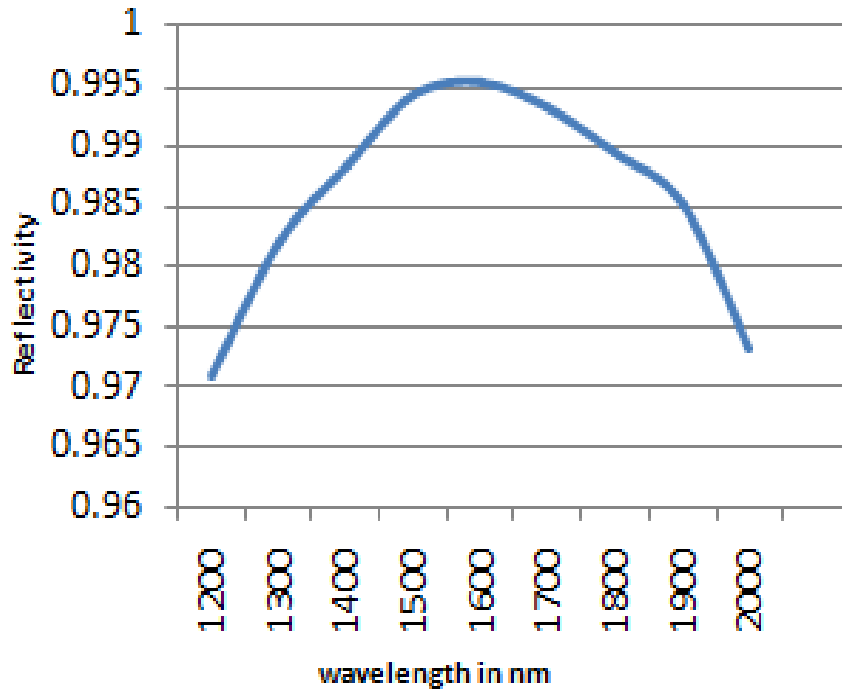


Fig 4.2 Simulated for HCGs based HW with grating period (Λ) = 1170 nm, thickness (t_g) = 340 nm, duty cycle (η) = 0.65. Incident angle $\theta \ll 1$

4.5 VARIATION OF REFLECTIVITY WITH INCIDENT ANGLE

The variation of reflectivity with incident angle is shown in Fig 4.3 which represents that incident angle has major impact on reflectivity of light in waveguide. From the RCWA calculations it is found that reflectivity of light in waveguide decreases with increase in incident angle. So with minimum angle of incidence maximum reflectivity can be obtained that is only when propagation of the light is parallel with grooves of HCGs gratings and maximum reflectivity is obtained at minimum incident angle .



Fig 4.3 Simulated for TE- HCG with grating period (Λ) = 1170 nm, thickness (t_g) = 340 nm, duty cycle (η) = 0.65. Wavelength = 1550 nm.

4.6 PROPAGATION LOSS

The grating parameters used to obtain low propagation loss are width: $\Lambda = 1170$ nm, $t_g = 0.340$ μm , $\eta = 65\%$, high index grating $n = 3.47$ and low index air $n = 1$. Low propagation loss with 10 μm core HCGs based HW can be achieved.

4.6.1 Variation Of Propagation Loss With Incident Angle

Dependence of propagation loss on wavelength is shown in Fig 4.4 RCWA results has shown that loss is minimum at 1550 nm wavelength and this has cleared from the results in fig 4.2 that at 1550nm the reflectivity is maximum and with maximum reflectivity the light has travelling in only zeroth mode and all other modes fade away which results in minimum loss (.031 dB/cm) that is shown in fig4.

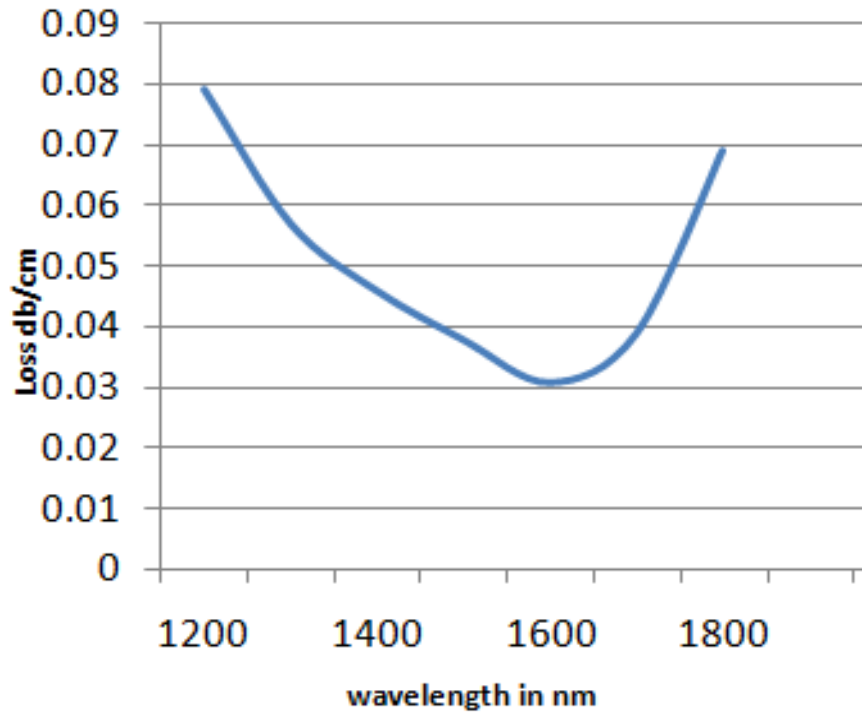


Fig . 4.4 Simulated for TE- HCG with grating period (Λ) = 1170 nm, thickness (t_g) = 340 nm, duty cycle (η) = 0.65. Incident angle $\theta \ll 1$

Loss in HCGs based HW is inversely proportional to the square of core height (d) therefore, large core size provides low loss in the waveguide. But, with large core height the number of modes increases that is not which desired. One of important advantage of HCGs based HW is that it provides single polarization. The reason behind this unique property is high HCG reflectivity and polarization dependence, The loss for the fundamental mode is very low that is 0.031dB/cm. The higher order mode loss increases significantly. Therefore design of waveguide in such a way that only lower order mode exists in waveguide to minimize the propagation loss. At the end of discussion it can be said that HCGs based HW able to obtain ultra low loss forthe zeroth mode and the other higher order modes fade away.

4.6.2 Variation of Propagation Loss With Incident Angle

The propagation loss varies with change in incident angle is shown in Fig 4.9. As mentioned before the reflectivity is maximum when propagation of light is parallel to HCG-HW structure. Loss in the waveguide is inversely proportional to reflectivity, so minimum loss (.031 dB/cm) is achieved when incident angle is $\ll 1$.



Fig.4.5 Simulated for TE- HCG with grating period (Λ) = 1170 nm, thickness (t_g) = 340 nm, duty cycle (η) = 0.65. Wavelength = 1550 nm

4.7 NONLINEARITY

In the communication system signal is transmitted through a channel. Due to nonlinearity of channel signal can badly degrade which affects the both analog communication system and digital communication system and applications related to these systems. HCGs based HW can reduce the nonlinear effects of waveguide used in data transmission, because the tight confinement of optical power. Second the core material is air due to this very less amount of the optical field interact with the material. From simulation results, it is found that the field intensity in high index region is very less only in the order of 10^{-7} . The net reduction in the nonlinear coefficient per unit length is of the order 10^{-5} which is less than that of silicon waveguides. The low non linearity make HCGs based HW a potential candidate for optical interconnects.

4.8 DISPERSION

The broadening of pulse is called dispersion. In waveguide there is chromatic dispersion which causes due to material dispersion and waveguide dispersion. Material dispersion is dominant in waveguide having solid material core. Material dispersion is of order of 1000 ps/nm/km in silicon waveguide which is very high []. In HCGs based HW the core material is air so material dispersion is negligible. Waveguide dispersion in designed high contrast gratings based hollow waveguide with defined parameters from the RCWA simulation results out 1.05 ps/nm/km at 1550 nm wavelength. The intensity of light in the high index silicon region is less as compare in the air core of the waveguide. This is major reason for low dispersion The waveguide dispersion for the zero mode is calculated for the HCGs based HW.

4.8.1 Dispersion Calculations

Phase Velocity

$$v = \frac{c}{n} \quad (4.4)$$

where c is the speed of light in a vacuum and n is the refractive index of the medium.

Group Velocity

$$v_g = c \left(n - \lambda \frac{dn}{d\lambda} \right)^{-1}. \quad (4.5)$$

Chromatic Dispersion

$$D = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2}. \quad (4.6)$$

Dispersion in waveguides

$$D = -\frac{2\pi c}{\lambda^2} \frac{d^2 \beta}{d\omega^2} = \frac{2\pi c}{v_g^2 \lambda^2} \frac{dv_g}{d\omega} \quad (4.7)$$

where $\lambda = 2\pi c / \omega$ is the vacuum wavelength and $v_g = d\omega / d\beta$ is the group velocity. The variation of dispersion with wavelength is represented in Fig 4.6. At 1550 nm where loss is minimum and due to air core material dispersion is negligible, low waveguide dispersion of 1.05 ps/(nm-km) is achieved which is very important for chip scale integrated platform.

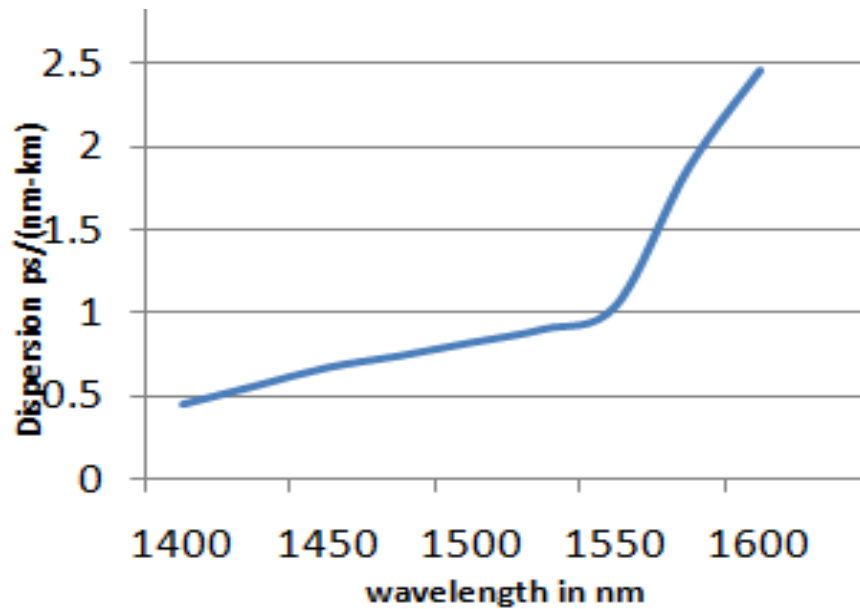


Fig 4.6 Simulated for TE- HCG with grating period (Λ) = 1170 nm, thickness (t_g) = 340 nm, duty cycle (η) = 0.65.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

The aim of dissertation is the designing of waveguide which is reliable for integrated chip scale platform of optical interconnects. For this purpose high contrast gratings shows ideal properties. In the design this has shown that by modifying the parameters of high contrast gratings like grating period, duty cycle of HCGs, thickness with the hollow waveguide parameters like core height, core width many desired properties can be obtained. In this work previous used photonic crystals, metals and distributed bragg reflectors (DBR) are discussed with their limitations in today's technology requirements of small size, high data speed, high bandwidth and high fabrication tolerance.

In this dissertation a 3 dimensional high contrast grating hollow waveguide structure is presented which possesses novel waveguide characteristics due to efficient confinement of light. For chip scale integrated platform low loss, low dispersion, low non linearity and easy fabrication are of prime importance and this proposed waveguide provide all such properties. HCGs based hollow waveguide ultra high reflectivity at 1550 nm wavelength and small incident angle which is greater than 99.5 %. This high reflective HCGs have replaced DBRs which were bulky, difficult to fabricate because of large number of layers and high dispersion. HCGs based hollow waveguide high bandwidth and high data rates which is need of today's communication systems.

Presented the all design parameters with experimental simulations results that represents HCGs based hollow waveguide is a potential candidate for integrated chip scale applications. It also used all applications where DBRs are used for example VCSELs (vertical cavity surface emitting lasers), high quality optical resonators. Proposed high contrast gratings based hollow waveguide have ultra low propagation loss that is 0.031 dB/cm which is obtained by rigorous coupled wave analysis. Loss can reduce further by using higher core width. Waveguide has low chromatic dispersion of 1.05 ps/(nm-km) at 1550 nm and ultra low non linearity (10^{-5} / W/m). With these properties HCGs based HW can used in chip scale integrated platform for optical interconnects.

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PUBLICATIONS

1. Sandeep and Anil Arora, "Three Dimensional High Contrast Grating Based Hollow Core Waveguide for Chip Scale Integrated Optical Interconnects," *International Journal of Advanced Research in Electronics and Communication Engineering (IJARECE)*, **Vol.5**, Issue 6, pp. 1834-1837, June 2016.

ORIGINALITY REPORT

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