

Design and Simulation of a High Index Contrast Grating Based Hollow Optical Waveguide

A Thesis

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By

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28th December, 2020

Certificate

I, Harpinder Kaur hereby declare that the work which is being presented in the thesis entitled "**Design and Simulation of a High Index Contrast Grating Based Hollow Optical Waveguide**" is an authentic record of my own work carried out toward the partial fulfillment for the award of degree of Doctoral of Philosophy in Electronics and Communication Engineering Department, Thapar university, Patiala, under the guidance of Dr. Mukesh Kumar.

The matter presented in this thesis is not submitted in any other university or institute for the award of any degree.

Dated

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Signature of student

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

Dated 16/11/2017

Mukesh
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Abstract

A new era in sub-wavelength grating study was opened after the first High index Contrast Grating broadband mirror was designed. The extraordinarily broad band and the high reflectivity from the High index Contrast Gratings was achieved by the arrangement of gratings which is unique as the low-index medium surrounds entirely the high-index region. The distributed Bragg reflectors (thick and multilayer) can be replaced by HCGs. There are many uses of high index contrast gratings in the fields of optoelectronic devices such as hollow-core waveguides with low loss, vertical-cavity surface-emitting lasers, tunable devices etc. Hollow Waveguides remain an attractive choice in photonic technology because even in very low refractive index materials and many such other applications, they enable light guiding capabilities.

In this work, we have studied and optimized High index contrast gratings and thus achieving maximum reflectivity. Some important HCG design parameters include grating duty cycle and grating period along with thickness of grating and that of our underlying low index layer which are deeply studied and optimized to achieve the desired results. One dimensional high index contrast grating has been optimized so that it can be used in the design of grating based hollow optical waveguide.

In the area of integrated photonics, due to design flexibility and low cost fabrication of hollow optical waveguides, they are finding applications in the numerous tunable optical functions. The Broadband high reflectivity of HCG is taken as a base to propose an on chip hollow optical waveguide. A low loss providing HCG based hollow optical waveguide is thus designed and proposed. In parallel, low loss is further attained by optimizing the grating period at an air core thickness which is narrow. We have studied the wavelength spectrum with the optimized grating period to get broadband narrow core low loss hollow optical waveguide. Recently, slow light has come up as a new research area in field of photonic crystal waveguides. There is a compromise with the slow light benefits because of the propagation loss and dispersion. We have studied the slow light characteristics of proposed design of grating based hollow optical waveguide with narrow core and low loss.

Bragg reflectors are used in broad range of applications in optical fiber communications including lasers and sensing. To achieve high reflectivity, a two-dimensional HCG is further optimized for both TE and TM mode. Also a design of an on chip two-dimensional HCG reflector at Bragg incidence with low polarization dependence been proposed. The proposed reflector provides high reflectivity more than 99.99% with polarization independence at $1.55\mu\text{m}$. The polarization insensitivity of the proposed reflector has the potential to innovate optoelectronic devices for various applications in high end optical network.

Next proposition was of a two-dimensional HCG based two-way on chip reflector. The design, which is a two-way reflector, reflects efficiently at Bragg incidence and also at vertical incidence. The results of the proposed design are simulated using improved Fourier modal method. The dependence of grating period, grating thickness on reflectivity at Bragg and vertical incidence is obtained for the proposed structure for TE mode. The results are also obtained for angular dependence of proposed reflector with optimized design parameters using FMM. It is also validated using FDTD. The wavelength spectrum of proposed Reflector has been obtained at Bragg and vertical incidence.

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List of symbols	
dB	Decibels
λ	Wavelength
Ag	Silver
Au	Gold
Si	Silicon
SiO ₂	Silica
E	Electric field
n	Refractive Index
n_L	Refractive Index of low index material
n_h	Refractive Index of high index material
Θ	Incident angle
ϵ	Permittivity
ϵ_{si}	Permittivity of Silicon
ϵ_{SiO_2}	Permittivity of Silica
n_{eff}	Effective refractive index
L	Length
W	Width
t_g	Grating Thickness
Λ	Grating Period
Λ_x	Grating Period in x direction
Λ_y	Grating period in y direction
C	Duty Cycle
Γ	nonlinear coefficient
β	Propagation constant
Ψ	wave function
k	wave vector

List of Acronyms and Abbreviations	
EM	Electromagnetic
UV	Ultraviolet
Nm	Nanometer
Mm	Millimeter
μm	Micrometer
THz	Terahertz
PC	Photonics Crystals
IR	Infrared
TE	Transverse Electric
TM	Transverse Magnetic
TEM	Transverse Electromagnetic
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
1DPCs	One Dimensional Photonics Crystals
2 DPCs	Two Dimensional Photonics Crystals
3 DPCs	Three Dimensional Photonics Crystals
TIR	Total Internal Reflection
IO	Integrated Optics
RCWA	Rigorous Coupled Wave Analysis
FDTD	Finite Difference Time-Domain
HCG	High Index Contrast Grating
VCSEL	Vertical Cavity Surface Emitting Laser
DBR	Distributed Bragg Reflector
SOI	Silicon on Insulator
CMOS	Complementary Metal Oxide Semiconductor
WG	Waveguide
HCW	Hollow core Waveguide

CR	Contrast ratio
MMI	Multi-Mode Interference
TFTs	Thin-Film Transistors
NBIS	Negative Bias Illumination Stress
IGZO	Indium-Gallium-Zinc Oxide
FBG	Fiber Bragg Grating
FRM	Faraday Rotator Mirror
MMFE	Modal Method by Fourier Expansion
FMM	Fourier Modal Method
FEM	Finite Element Method
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
PM-PCF	Polarization-Maintaining Photonic Crystal Fiber

Chapter 1

Introduction to Integrated Photonics

1.1 Introduction

The understanding of materials in terms of their properties and characteristics has resulted in much advancement in our technology. Nanotechnology is emerging trend of the present day. It takes into account miniaturization of structures of the size of up to several 100 nanometers. The size of the structures is generally smaller than the wavelength of light. Over time, engineers have learned to garnish the electrical properties of the materials. Due to the advancements in semiconductor physics we are able to change the conducting properties of some materials [1]. All these technological advancements have an impact on our society, and we are striving towards the betterment. The research and investigation have been done on superconductors with high-temperature and other interesting materials that could be the base of upcoming technologies [2]. In the recent years, a new era has come up which aims on the control the optical properties of materials. A number of advancements in technology are possible by tailoring the properties of materials and allow us to manipulate them according to our desire.

1.2 Integrated Photonics

Miller in 1969 [3], introduced the term Integrated optics (IO). Thin films and technology of micro fabrication can be used for generation, switching, modulation multiplexing, de-multiplexing and many other optical functions in IO forms of optical counterparts of integrated electronics. Integrated optics is a technology which aims at constructing photonic integrated circuits which contains several or many optical components which are combined to fulfill some more or less complex functions. The main aim of integrated optics is the miniaturization of optical circuits same as the silicon chips that have made a revolution in the electronics industry. Due to the advancements of integrated optics it is recommended to make all the functional elements small in size and also realize on chip integration. The benefit of optical approach is that the processing of data can be at much higher speed. As Photonics is the new emerging field in the optics, so the integration of photonic devices on a chip is called

Integrated Photonics.

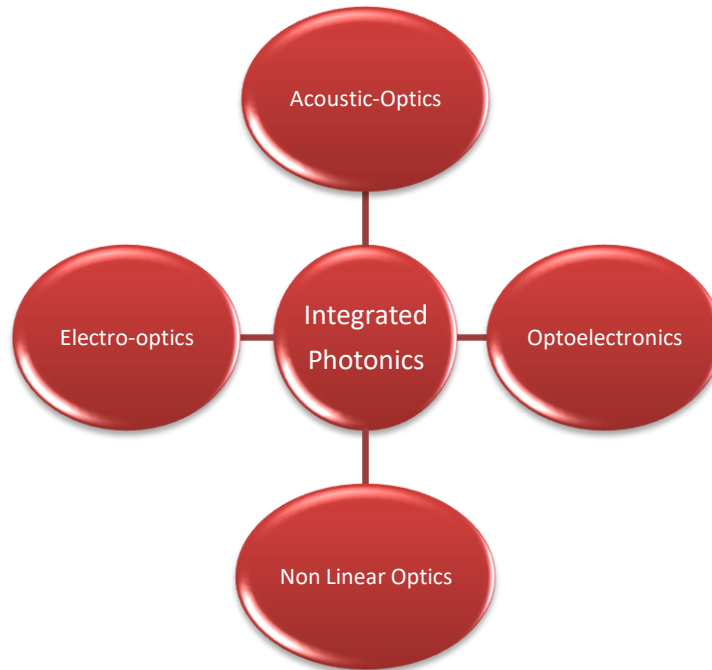


Figure 1.1: Convergence of many different fields into integrated photonics

To achieve economical and better optical systems, the methods of integrated circuitry have been used. Integrated optics is a method to apply thin-film technology to optical circuits and devices. Integrated photonics are the integrated optical circuits which include flow of photons. Figure 1.1 is showing the various fields where integrated optics is used. If we talk about various areas of optics like acoustic-optics, nonlinear optics [4], opto-electronics and electro-optics, they are different fields of optics using different media. Electro-optics deals with the behavior of electric fields on light and on optical properties of substances. Acoustic optics is the branch of physics involves the interaction between sound waves and light waves. If we talk about the behavior of light in nonlinear media, it is called non-linear optics. Optoelectronics deals with source, detection and control of light. All these areas of optics are using integrated photonics for the betterment. Application potential of photonics has been enhanced due to integration.

One of the amazing class of physical structures investigated in nanotechnology are photonic crystals. Due to the eye-catching benefits of fiber optic wires, the need for photonic crystals is often ignored by public. But there are some issues related to fiber optic wires and also with plastic wires that they are can only bend to a little resulting in cable fracture or

signal loss.

Another problem with cables based on fiber optics is that they have notable signal loss for long distances, and transmitter is required to strengthen the signal in order to be observable by the receiver. These problems are reduced, or we can say eliminated with Photonic crystals, having very signal loss up to a small extent as compared to the conventional fiber optic wires. [2]

Photonic crystals are classified into three different kinds of categories: one-dimensional Photonic Crystals (1DPCs), two-dimensional Photonic Crystals (2DPCs), and three-dimensional Photonic Crystals (3DPCs) photonic crystals. Figure 1.2 shows examples of 1DPCs, 2DPCs and 3DPCs. One-dimensional photonic crystals are periodic in one direction only.

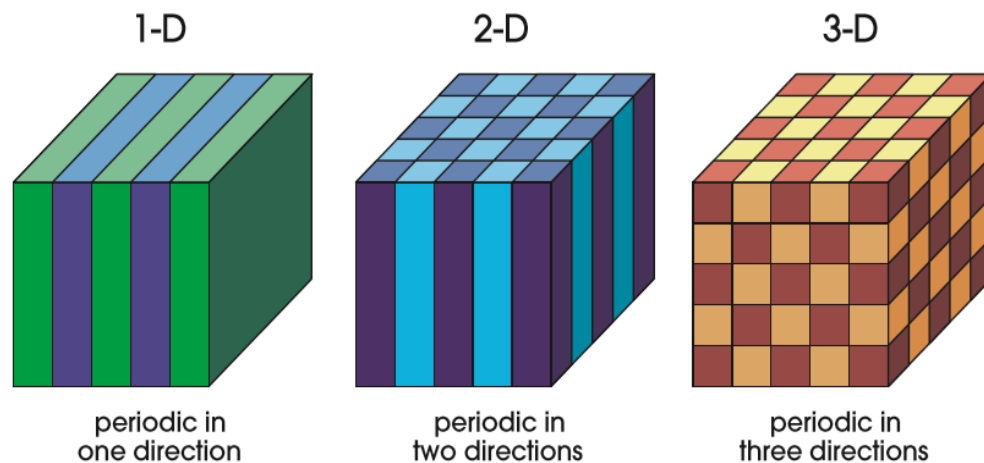


Figure 1.2: (a) 1 -Dimensional Photonic crystal (b) 2-Dimensional Photonic crystal (c) 3-Dimensional Photonic crystal [2]

Bragg grating is a perfect model of 1D Photonic crystal. Its major applications are in VCSELs as a distributed reflector. The light travels in straight line in case of one-dimensional crystals which limits their applications. But, two and three-dimensional photonic crystals can be useful in applications where periodicity in two or three directions is required. Two dimensional Photonic crystals can be configured in large varieties, as they have periodicity of light along two directions, whereas the medium is uniform in the third direction. 2D and 3D Photonic crystals enable control over the light flow at any incidence angle. The best way to understand

the photonic crystals is the understanding of dependency of interaction between light waves and period of the structure. The medium's refractive index will determine the photonic crystals optical properties. Range of wavelength over which light transmission occurs inside the crystal is called photonic band and the wavelength range over which light is not transmitted is called photonic band gap. Photonic crystals have capability to function on nanometer scale because of the nature of bend light even in a tight space. 2D and 3D Photonic crystals have not been commercialized because they require extreme intensive processing technology for fabrication.

Photonic crystals are promising for optical devices like micro waveguides, micro cavities, Bragg mirrors etc. because of the capability of modeling and localizing the flow of light.

1.3 Grating based Reflector

Optical gratings are one of the main and important building blocks in optics. Due to its variety of applications in various fields like holography, lasers, spectroscopy a, nonlinear optics and many other optoelectronic devices, an extensive research has been done on optical gratings. Diffraction grating was first discovered by James Gregory (1638-1675). A diffraction grating defined as a periodic structure consisting of dielectric materials having different refractive indices. David Rittenhouse made the first man-made diffraction grating in 178. He constructed a half-inch wide grating by wrapping fine wire around the threads of a pair of fine-pitch screws, which has an spacing of about 100 lines per inch approximately [5]. But credit goes to the German physicist Joseph von Fraunhofer for invention of diffraction grating. Fraunhofer used a kind of similar method used by Rittenhouse to develop a wire diffraction grating [6] in 1821. His research came out in gratings of sufficient quality and he was also successful in measuring the solar spectrum's absorption lines which are also aliased as The Fraunhofer lines. Further, Fraunhofer went on to explain the phenomenon of diffracted orders, and also to derive and verify the grating equation so he is credited with laying the foundation for the modern optical grating theory [7]. Grating structures can be one-dimensional (1D), two-dimensional (2D) or even three-dimensional (3D) guided by spatial direction of periodicity. Due to the advancement in manufacturing technologies, the cost was gratings were high and they were having less precision. In 1882, at Johns Hopkins University, U.S. physicist Henry Augustus Rowland constructed sophisticated ruling engines, for fabricating gratings with

much higher precision than anything available before. Rowland recognized grating as the prime optical element in a paper [8] which he very famously published in 1882 on spectroscopic technology, which opened up a new era of spectral analysis.

If talking about the theoretical analysis, first developed the grating theory almost 180 years ago [9]. Now a days, gratings and many other periodic structures have been used widely in a variety of areas of science and engineering which includes Solid state physics, optoelectronics, acoustics, nonlinear optics, holography, and x-ray instrumentation [10]. Optical wavelength is usually always less than the grating period of the grating. But this changes drastically and grating exhibits unusual characteristics as and when the wavelength becomes greater than grating period. As a result, a lot of grating characteristics require revision. A sub-wavelength grating has wavelength larger than grating period. 0^{th} order diffraction in sub wavelength gratings is only a propagation mode. Higher diffraction orders are evanescent modes. A mirror like behavior will be emulated by the grating.

1.4 High-Contrast Grating (HCG)

In the recent past [11-13], the studies on Sub-wavelength grating reports that sub-wavelength gratings can have major implementations in VCSELs to achieve polarization selectivity. HCG acts as a high refractive index single layer grating which exhibits a high difference of contrast between high and low index regions. Here, refractive index contrast refers to the delta of refractive indices. Mode mixing and coupling are results obtained from the high reflective index which leads to high reflectivity and broad band. The main difference of HCG from the previous research is that it is entirely enclosed by a low-index media that also includes bottom and top interfaces. HCGs play a very important role in integrated optics. A lot of extraordinary and unexpected properties are due to the complex index contrast. Various devices can be proposed and simulated using HCG considering various factors like loss, dispersion, bandwidth etc. The characteristics of the HCG can further change by the materials used and design parameters chosen. HCG has design flexibility and rich properties. These extraordinary properties can be turned into novel devices. HCG is a promising and new base for integrated photonics with various applications for waveguides, detectors, filters and lasers. The first proposal of a sub-wavelength high-contrast grating applicable as a surface normal highly reflective broadband mirror was reported in 2004 [14].

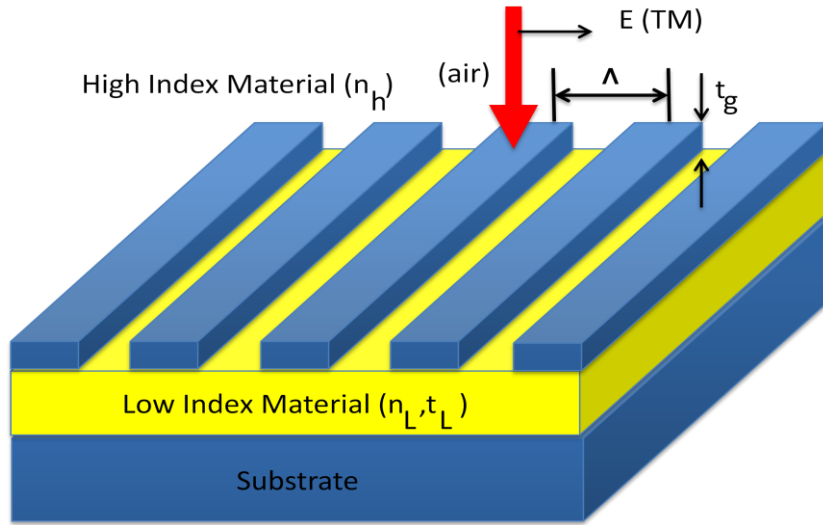
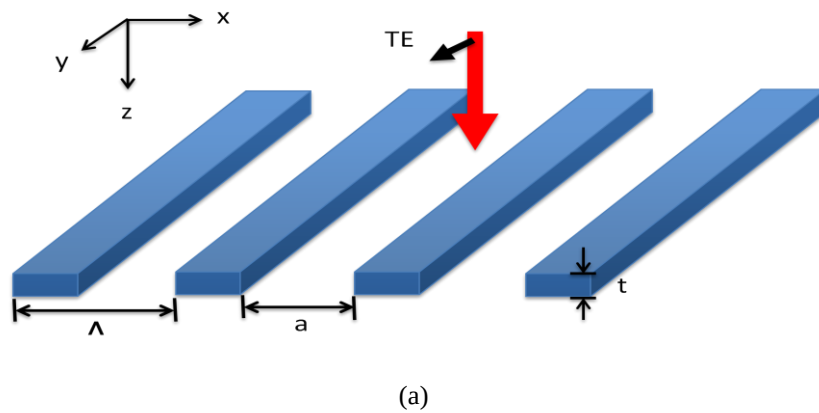


Figure 1.3: SOI based on Sub-wavelength high-contrast grating reflector [14]

Fig.1.3 shows a schematic of a SOI based sub-wavelength HCG mirror. The HCG shows a periodic grating single layer structure with a highly refractive index material like Si or it may even be AlGaAs and a material having a low-index like oxide or air surrounds the high index material. Extraordinarily high reflectivity over a wide bandwidth for transverse-magnetic (TM) polarized light is provided by the HCG design, where the electric field is 90° to the grating incident when directed from surface-normal. In Figure1.3, Si stripes constitute HCG, having low-index medium air in the stripes with air also on the top. For ease of production of the structure on Silicon-on-insulator (SOI) substrates, low index material, SiO_2 is used below the gratings.

Incident Wave



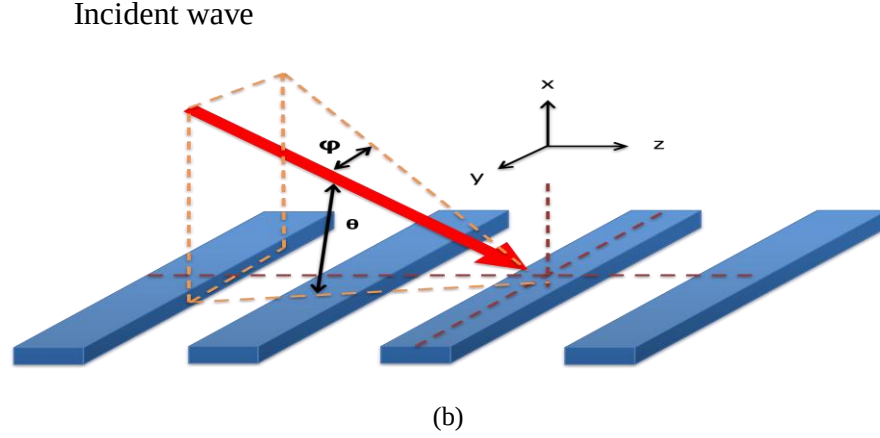


Figure 1.4: (a) HCG for surface-normal TE mode, (b) oblique-incidence light for 1.55μm center wavelength for surface-normal TE mode [19]

Fig. 1.4(a) has a 2nd low-index material underneath the stripe for TE mode. 1.4(b) shows incident beam at oblique incidence angle. For the identification of incident angle, we use 2 incident angles Θ and ϕ . The angle between the y-z plane and the beam which is incident is Θ whereas ϕ is the angle between the x-z plane and the incident beam. The parameters of design of the structure are the grating period (Λ), grating thickness (t_g), grating duty cycle (C), and the thickness of the low index layer under the grating (t_L). The design parameters embodies to be an integral part in terms of reflectivity of the grating. Duty cycle (C) is defined as the ratio of the width of the high index material with respect to the period. Mentioned SOI HCG is designed for 1.55μm wavelength, whose design parameters are: $n_{\text{substrate}} = 3.48$ (Si), $n_{\text{superstate}} = 1$ (air), $n_h = 3.48$ (Si.), $n_L = 1$ (air), $\Lambda = 0.7\mu\text{m}$, $t_g = 0.46\mu\text{m}$ and $C = 0.75$. Two methods Rigorous Coupled Wave Analysis (RCWA) [9] and Finite Difference Time-Domain (FDTD) methods [15, 16] are used to carry out the theoretical calculations HCG structure. An extraordinarily broad ($\Delta\lambda/\lambda \sim 35\%$) and high-reflectivity (greater than 99%), having a range of 1.33μm to 1.80μm, is obtained using both FDTD and RCWA methods. Analysis from both calculation methods agree very well with each other. The HCG mirror can still provide a very broad reflection bandwidth from 1.40μm to 1.67μm for a higher reflectivity requirement ($R > 99.9\%$). For a clear comparison, the wavelengths of both reflectivity spectra are normalized to 1.

HCGs are far better candidate as compared to conventional DBRs. HCG has reflectivity almost equal to forty pairs of distributed Bragg reflector (DBR). Another advantage is a wider

bandwidth and thickness reduction of nearly 10 times. Apart from replacing DBRs, there are many other applications of HCGs. The high reflectivity in one polarization is another advantage of HCG, which is very much required for many applications like Vertical Cavity Surface Emitting Laser (VCSEL) mirrors. Prof. Yuri Suzuki and his team has fabricated a silicon/silicon dioxide based HCG structure which was a broadband ($1.12\mu\text{m}$ to $1.62\mu\text{m}$), has high reflectivity ($R > 98.5\%$) HCG mirror for TM polarized light and was experimentally demonstrated [17]. A 2D HCG has a square periodic lattice is used in the making of Surface emitting lasers. So, a drop of the reflectivity is obtained which has supported by exciting the resonant cavity-mode inside the proposed HCG. The optimization of various design parameters can lead to achievement of high Q factor [18]

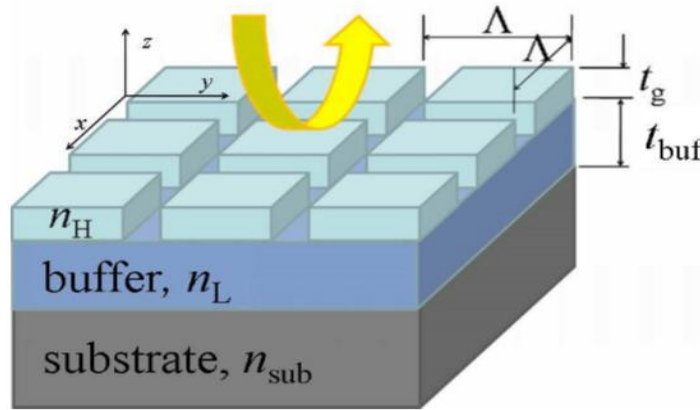


Figure 1.5: Schematic of a 2D HCG in which t_g is 460 nm, n_H is 3.48, n_L is 1.45 and n_{sub} is 3.48 [18]

A new era in sub-wavelength grating study was opened after the proposal of the first HCG broadband mirror. The extraordinarily broad band and the highly reflective HCG are attained by exceptional placement of high-index gratings which are encroached by low-index material. HCG structure is far more than just a surface normal TM polarized broadband mirror. HCG can have very unique and exceptional functionalities and can be used in a number of applications if the dimensions of the grating structure are carefully designed and optimized. A different approach of sub-wavelength grating has arisen. It was examined that HCG controls light flow resulting in various exquisite and extraordinary qualities. A number of designs were derived by using broadband high reflectivity mirrors for incident light in surface normal direction and a grazing angle like high Q resonators with surface normal output, planar high

focusing power reflectors and lenses and ultra-low loss hollow core waveguides has been discussed [19]. This is clearly understandable that simple structure of HCG has resulted in advancement of new era in the field of optics. Large scales of improvement in opto-electronic devices have been noticed using HCG.

Sub wavelength gratings not only address the challenges of the silicon-on-insulator material platform, but they also open up new opportunities for innovation. By changing their geometry, sub wavelength gratings can also be used as anti-reflection or high-reflection structures.

1.5 Hollow Core Waveguide

Hollow Waveguides is an attractive choice in photonic technology because they have a tendency to propagate light in very low refractive-index materials. Conventional solid waveguides face difficulties like undesirable non-linear effect and optical absorption. These problems have been reduced using hollow-core waveguides (HCWs). Hollow waveguides can be used as a replacement to solid core fibers. Because of the presence of air- core, hollow waveguides are used for applications where broad spectrum, high power transmission is required. As there is no core material, Hollow-core waveguides (HCW) are bright and favorable candidate for attaining ultra-low loss, nonlinearity and dispersion. In a liquid core-based arch-shaped waveguide, optical mode guiding has been demonstrated. Optical confinement is based on anti-resonant reflecting optical waveguide principal for this device [20].

The active and increasing expansion in the one of the popular internet medium which is broadband, needs large capacity networks with high speed. Nowadays we are finding numerous applications where waveguides with hollow core can be implemented. A field where this concept can be applied is optical switch with a tunable air core which consists of a coupler having multi-mode interference has been demonstrated. A compressed sized waveguide having a switching length of 1.1 mm is shown in the results. The size can be reduced further by decreasing the air core gap [21].

To keep the level of loss low while propagating and less polarization dependence, a 3D Hollow Waveguide is designed for wide tunability and temperature insensitivity in photonic devices and the results are shown for the same. It can be used in future DWDM networks. By

further altering the shape of the 3D waveguide structure, less dependence on polarization and low loss while propagating has been achieved. 3D HWG based devices having low loss, temperature insensitivity, polarization insensitivity and wide tunability for future flexible DWDM networks can be realized from the results [22].

1.5.1 Hollow core optical fiber

Hollow core optical fibers guide light within the hollow region. Main attributes of hollow core fibers are that the nonlinear effects are minimized. High optical intensity can be achieved in air or gas filled in the fiber for the realization of high harmonic generation [23] and Raman lasers [24]. A poly methyl methacrylate hollow core fiber is proposed and a very strong anti-resonant reflecting optical waveguiding has been demonstrated. The proposed fiber design can be used for future investigations like optofluidics applications, nonlinear effects based on gas. Fig 1.6(a) shows the initial Optical fiber image and 1.6 (b) Scanning electron microscopy (SEM) image of the proposed fabricated hollow-core fiber [25].

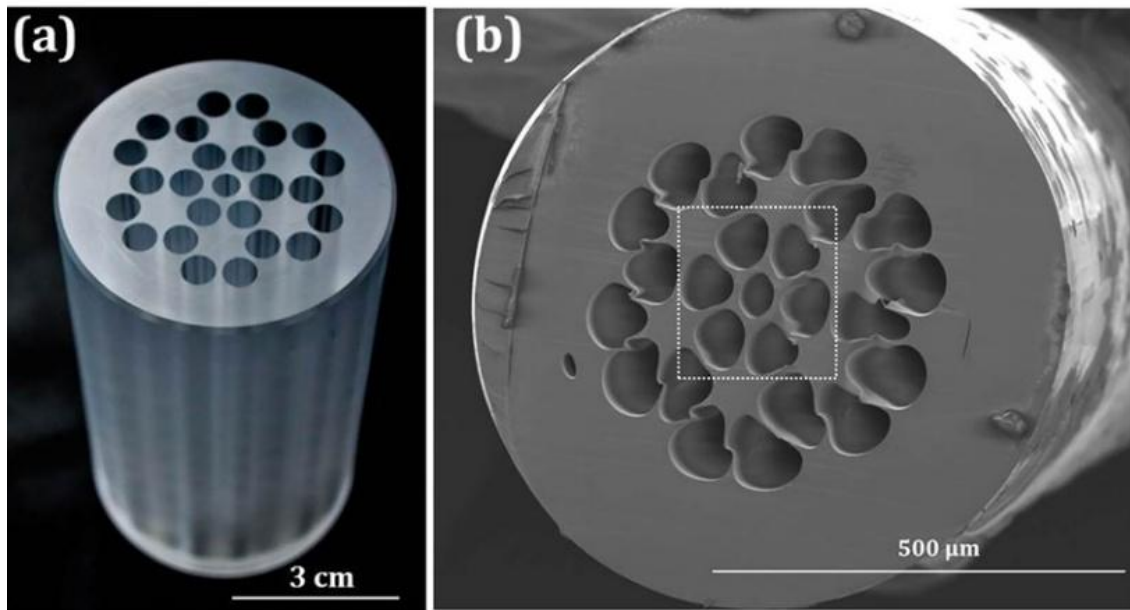


Figure 1.6: (a) Optical fiber. (b) Scanning electron microscopy (SEM) of the fabricated hollow-core fiber[25]

There are number of applications in which Optical fibers are used due to their capability to produce long optical delays with small loss. Some of such applications are signal processors, RF filters, optical buffers, optical switches, and optical sensing. Optical fibers are used

because of the benefits like very minimal loss, less dispersive nature and non-linearity, and a wide bandwidth. But the disadvantage with optical fibers is that their large size and also compromise with scalability during manufacturing. To solve this problem lithographically defined, chip-scale waveguides are recommended because of the compact size, less weight and they can collaborate with ease with other electro optic devices.

1.5.2 Hollow core planar waveguide

Hollow waveguides have many attractive attributes that includes low temperature dependence, power transmission at a high rate, low nonlinearity and good optical confinement which make them better candidate as compared to conventional waveguides. Also, waveguides can be used for various devices which are better with respect to decrease in size and collaboration of various optical components. Such properties are useful for applications in a number of optoelectronic devices. Hollow core waveguides based on optical fibers have opened up a number of new applications which includes gas sensing [26, 27], nonlinear optics and laser surgery. Hollow Waveguides are active candidate for achieving very low loss, and dispersion due to the hollow core.

1.5.3 High confinement Optical Waveguide

There have been certain different moves to HWs, categorizing from waveguides having a metallic shell, to waveguides using a DBR, to waveguides photonic crystals etc. The high optical confinement is the main key for the waveguides required in the present day. The essential base is to direct the light which propagates through a medium, in this case air with many reflections at the cladding. The DBR has been used in a waveguide [28]. It has DBRs as a mirror above and below. Adjustability and alterations in the design of waveguides is the key to build various photonic devices with different functionalities and applications. In chip-based waveguides the lowest reported loss is 1dB/m [29]. The major reasoning for the more losses are absorption due to direct band-edge, free carrier and optical phonons interaction [30] which results in high non-linearity and dispersion. Hollow waveguides are very much useful in attaining low loss like optical fibers, non-linearity and low dispersion due to the absence of solid core. There are many advancements in hollow-core waveguides and also further many

devices can be made from these hollow core waveguides like Bragg reflectors, dispersion compensators etc. [31-34]. The main base of hollow waveguides is to direct the light so that it can propagate in the air inside core by many reflections at the cladding. A photonic crystal optical fiber having a hollow core shows minute loss of approximately 0.001 dB/m [34] whereas the minimum loss attained from a chip based hollow waveguide using DBR is comparably more, is approximately 10 dB/m [32]. The reflectivity of the DBR mirrors in DBR base hollow waveguides not being high enough causes the major loss of the waveguides. To attain very low loss, hollow waveguides with high reflectivity is essential.

A design has been demonstrated for a 3D hollow waveguide which are periodic in lateral and vertical direction. Vertical and lateral-optical confinements have been provided by a HCG. Low polarization dependence is achieved by the combined effect of lateral and vertical periodicity [33].

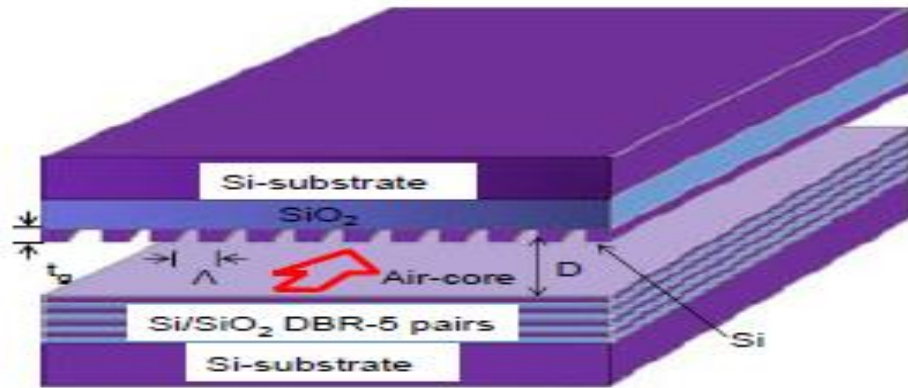


Figure 1.7: Hollow waveguide with a DBR and an HCG as bottom and top mirror respectively [35]

Hollow core waveguides based on HCG are quite popular these days. Chip-scale low loss and long optical delay is essential in applications like signal processing, RF filters, optical buffers, and optical sensors. Huge losses due to material absorption and scattering are minimized in HCG HWs by eliminating the core material. Field intensity inside the HCG being small as compared with to traditional distributed Bragg reflector (DBR) further decreases the loss. The diagram of a hollow waveguide with HCG and DBR mirrors on bottom and top respectively is shown below in figure 1.7 [35].

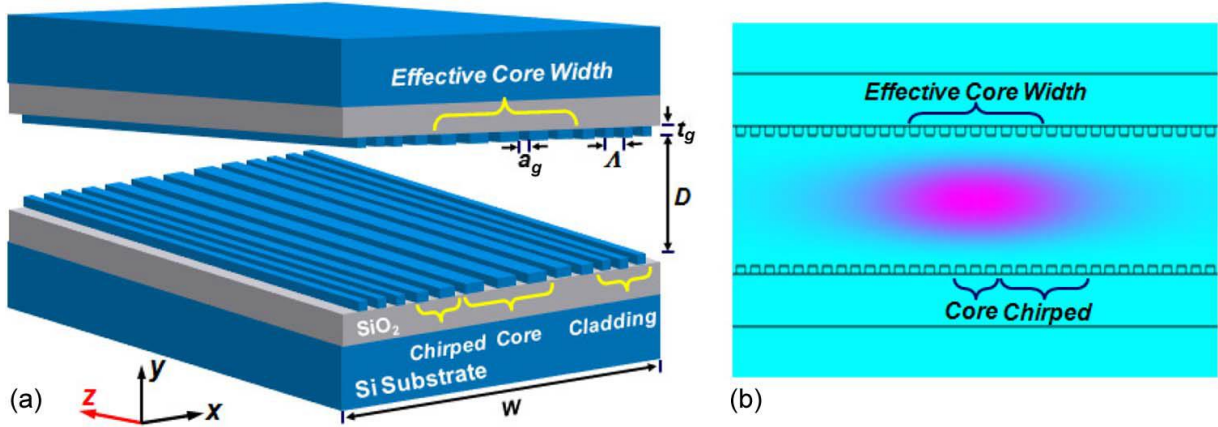


Figure 1.8: (a) 3-D HCG-HW with two HCG mirrors in the y-direction. Two designs of grating are used as core and cladding (b) Transverse Electric field in the chirped HCG-HW [65].

Figure 1.8 shows a 3-D chirped HCG based hollow-core waveguide that has high optical confinement in transverse and lateral direction. The proposed chirped HCG based hollow waveguides can easily reduce the propagation loss more than ten times without making a compromise with the lateral index contrast as compared to step-index HW [65].

There are many upcoming terms which are very much useful in chip scale integration and devices. Slow light is one of the emerging terms which is used. Slow light can be useful for on-chip scale applications to realize compact optical delay lines and also another advantage of slow light is miniaturization of various optical devices [36-38]. The major areas where slow light can advantageous are optical delay scanning and optical signal processing. The most important and amazing feature of slow light is the delay which can be tuned. PhC waveguides on SOI having the feature of slow light can be beneficial for multiple applications, such as buffers or optical switches, biosensors and data processing devices [36] and better interaction of light and matter in the both linear and nonlinear regimes [39-43]. PhC waveguides on SOI are suitable for applications as at room temperature they generate on chip slow light which is wide-band and tunable [40]. The change in the group velocity occurs when the imaginary and real parts of refractive index change with the frequency, so the time delays vary resulting in tunable delays [44]. The two major concerns arising from slow light are propagation loss and dispersion.

The fundamental element of optical signal for processing, storing and buffering straightway in optical format which are required in future information processing systems and all-optical communications is the time delay for optical signal which can be achieved by slow light. The functions like frequency conversion and complete stopping of light [45] can be provided by the dynamic turning of slow light.

There are many devices in which we can use the high optical confinement waveguides like dispersion compensators, Bragg reflectors etc. Many devices have been realized and proposed using high confinement hollow waveguides. A Bragg mirror is a mirror comprised of two alternating layers of optical materials. Fiber Bragg gratings (FBG's) are finding applications in the areas of optical fiber communications [46], lasers [47] and sensing [48]. Various kinds of waveguide-type Bragg reflectors have been reported like on polymer or dielectric waveguide based Bragg reflectors. Bragg gratings are also proposed for devices like tunable dispersion compensators. For tuning operations, the method used is thermo-optic effect which depends on environment temperature. The only solution to it is precise temperature controllers which raises the cost or feedback control systems [49] excluding the ones which are controlled by loaded heaters [50].

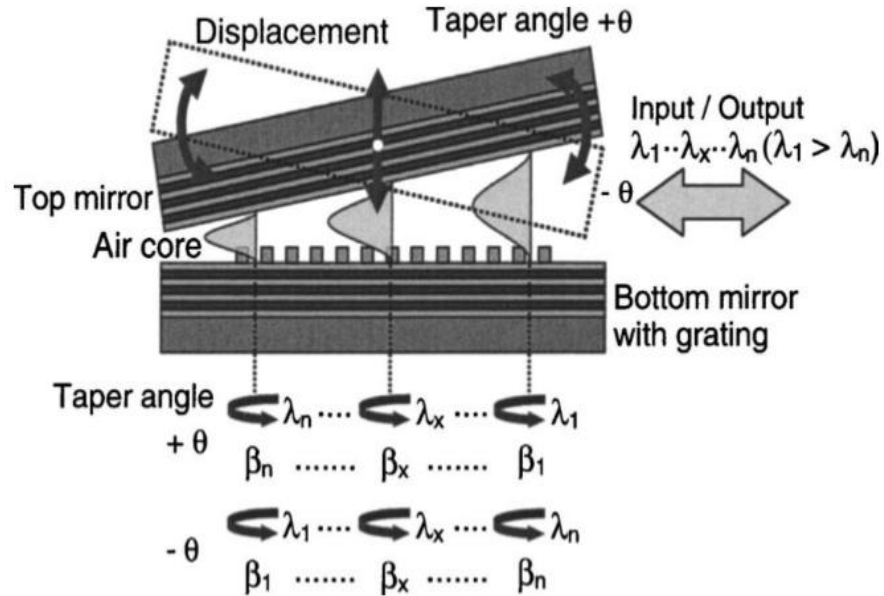


Figure 1.9: Tunable stop-band hollow waveguide Bragg reflector [51]

A fluctuating air core hollow optical waveguide is proposed and demonstrated for widely tunable waveguide devices [51]. Figure 1.9 is the design of proposed tunable stop-band hollow waveguide Bragg reflector. The confinement of light inside the air core is because of the two highly reflective mirrors having many layers.

Due to the vast application range of photonic crystals in optoelectronics, there is a need of investigating photonic crystals analytical as well as simulation method is required. HCG is a grating is widely used in a number of applications including lasers, waveguides, and reflectors etc. The development and advancements in these devices have a great impact on industrial and academic front. We can propose, derive and simulate various integrated devices to attain betterment in the technology.

1.5.4 Fabrication of Hollow Core waveguides

The introduction of HCG into hollow waveguides can extend the fabrication tolerance of the structure because of the large fabrication tolerance of HCG and it can provide the lateral optical confinement as well [35]. Also, because of the ease of fabrication of HCG, it is possible to design it for one particular polarization, making polarization control very flexible. With the flexibility of HCG-design, it is possible to build hollow waveguides with widely tunable polarization nature for variety of applications. With the collaboration of HCG and the inherent properties of hollow waveguides such as temperature insensitivity and wide tuning, it will be possible to design novel tunable optical functions with large design tolerances. Monolithic integration of HCG hollow-core waveguides can be made possible through various bonding schemes or by using sophisticated multi-layer SOI wafer topologies.

Chapter 2

Literature Review

2.1 Introduction

There has been great deal of extensive research in the field of integrated photonics in recent years. The photonic circuits are advantageous as compared to conventional electronic circuits in a vast range of applications. Therefore, so much research has been done on photonic devices, such as HCGs and photonic crystal based hollow waveguides, Bragg reflectors and their integrations with electronic devices.

2.2 Literature Review

High index contrast gratings have been a very appealing choice over conventional DBRs in terms of high reflection, size etc, also unlike DBRs, they provide phase and polarization control of light. The large incompatibility between the two different kinds of devices that is electronic devices and photonic devices makes the high level of implementation of both technologies difficult. The presence of low index material around the high index material in HCGs results in high reflection. Because of all these extraordinary properties, HCGs is now part of many optoelectronic devices. Hollow optical waveguides have come up with a numerous application like gas sensors, laser surgery and nonlinear optics. In order to integrate these waveguides with other devices into system on a chip, it is required that these waveguides are compact and light weight. Other issue which has to be taken care of is low loss waveguide design. HCG based hollow optical waveguide is an answer to these issues. Slow light is another new term which enhances the applications of HCG based hollow optical waveguides. Not only in hollow waveguides, HCGs have shown extensive developments but also in other optical devices like Bragg reflectors. HCG based Bragg reflectors are also very useful.

Enaulhaq Shaik et al. – 2017 [52] proposed a clocked D-flip flop based on photonic crystal. Multi-mode interference (MMI) is used. A central MMI waveguide is developed. They have placed ports at input and output ends. The design used has resulted with a contrast ratio (CR) of 9.63dB and 5.84 dB at the outputs Q and $Q\bar{Q}$ with a delay/response time <0.29

ps. The delay in output is one of the fundamental features of D-flip flop. So, to increase the delay of the structure, the input waveguide is extended with sharp bend waveguide and the output waveguide with a smooth bend waveguide. The altered design of D-flip flop has been resulted with a delay of more than twofold of the normal design by having almost the same CR at the output. The simulation results as well as compact design of the proposed structure make it appropriate for photonic integrated circuit.

Takeo Katayama et al. – 2016 [53] investigated on the optical coupling between a polarization-insensitive HCG and couple of orthogonal in-plane waveguides. They fabrication of HCG with waveguides is done on a SOI. The proposed waveguide-coupled HCG can be used in a polarization bi-stable VCSEL, which would switch the waveguide at output. It has been demonstrated that we can switch a waveguide having a strong output by making a change in the polarization of signal into the HCG. The light perpendicular to the polarization of the incident signal is more efficiently coupled to the waveguide than to the one in the parallel direction.

Eungtaek Kim et al. – 2016 [54] suggested functional passivation layers as a ZnS and LiF distributed Bragg reflector (DBR) for transparent thin-film transistors (TFTs) in order to increase the stabilization for negative bias illumination stress (NBIS). When the thicknesses of ZnS were 42 nm and LiF was 85 nm, the luminous transmittance of the DBR was 82% and the number of dyads was 3.5. They have applied the DBR to TFTs based on amorphous indium-gallium-zinc oxide (IGZO) without affecting the electrical properties, such as the mobility, sub threshold swing, ON-OFF ratio and V_{ON} . The suggested functional passivation layers have provided a solution to suppress the instability of TFTs in the NBIS which will enhance the optical transmittance of transparent displays.

Bala Pesala et al. – 2016 [55] proposed a low-loss HCG HW. Self-imaging property is used which is important for the design of MMI components. The compact size of optical components is because of the strong optical confinement of light in the waveguide core and low-index guiding. The Simulation results have shown very compact 2 by 2 coupler which has a length of $26\mu\text{m}$ (16λ), footprint (length into width) of $85\mu\text{m}^2$ ($35\lambda^2$) and a 3-dB splitter which has a length of $3.6\mu\text{m}$ (2.4λ), and a footprint of $12\mu\text{m}^2$ ($5\lambda^2$). The two have been separated with the help of single layer HCG. The light is switched between the channels, with a minor alteration in the refractive index of the HCG. By the proper optimization of HCG

parameters, an optical switch which is ultra-compact having a switching length of $60\mu\text{m}$ can be made because only MMI region excites higher order modes.

Yung-Jr Hung et al. – 2015 [56] implemented a HCG reflector in standard bulk CMOS by making polysilicon gate as HCG layer. A TE preferred CMOS HCG reflector experience high reflectivity of greater than 90%, reflection bandwidth of 100-nm, and TE/TM polarization ratio of a 1.64:1, which is reduced by the thin field oxide layer between the HCG and the silicon substrate. It is resulted in optical leakage of the substrate. With the elimination of the substrate of HCG, amazing betterments in maximum reflectivity (almost to 100%) and polarization ratio (10:1) has been attained. The proposed structure and its fabrication used the foundry regulations without any requirement of modification in frontend process. The HCG reflectors with high reflection bands have resulted from the guided-mode resonances. These guided mode resonances are supported by the leaky modes which are validated by the measured transmission dips. RCWA simulations have been used. HCG implementations in bulk CMOS can be helpful in the improvement of on-chip VCSELs and the optoelectronic devices.

Koji Nagai et al. – 2015 [57] proposed a plastic laser with tunable wavelength. Asymmetric DBRs are used. The proposed design comprises of a couple of waveguide gratings having long grating periods and organic dye is used to dope a polymeric active waveguide. The lasing wavelength can be tuned according to the Vernier effect of the resonance because of the delta between periods of grating of the two DBRs. The plastic laser design is operated with Vernier effect. A minute deviation of the effective index can make a big shift in wavelength in a broad emission band of a luminescent material which can lead efficiently packed and highly configurable light source.

Marcin Gębski et al. – 2015 [58] proposed and investigated a VCSEL design which consists of a thickness of λ active optical cavity placed in the middle of two planar monolithic HCGs. The etching of MHCGs is done straightway into the semiconductor layers which surround the cavity. The design has allowed the shrinkage of the thickness in the vertical direction of the proposed MHCG VCSEL to nearly $0.6\mu\text{m}$ for the emission at 980 nm. In comparison to the conventional DBR VCSEL, the effective cavity length of MHCG VCSEL is a smaller and therefore roundtrip cavity time will be short.

James Ferrara et al. – 2015 [59] reported a hybrid cavity AlGaInAs-silicon VCSEL having a long wavelength and is pumped electrically. It is comprised of a HCG mirror on a SOI substrate. The proposed HCG-VCSEL design enables reduction in cost of light sources for optoelectronic links. The proposed design works at silicon transparent wavelengths of approximately $1.57\mu\text{m}$ having greater than 1mW CW power. The power is coupling out of the DBR and operates at single mode up to 65°C . The 1.46 K/mw thermal resistance is measured in the proposed device. Also, a design of SOI-HCG is proposed theoretically which can be used as VCSEL reflector as well as waveguide coupler. It makes it possible to integrate a VCSEL and silicon photonic circuits together. The proposed design is resulted not only a lower cost and scalable solution but also makes its energy efficient for integrated laser sources. It is shown in the paper that high reflection of greater than 99.4% is attained with Si-HCG and it can be used as waveguide coupler.

Kensuke Nakamura et al. – 2014 [60] proposed a slow light Bragg reflector waveguide array. It is useful for beam steering in two-dimensions (2D). The proposed design is made up of a Bragg reflector waveguide array. It is dispersive in nature. The proposed design has quarter-wavelength stack semiconductor mirrors and a Y-branch 1 into 4 splitter which is branched at a 30° angle. By proper tuning the input wavelength of the proposed device, the clarification of characteristics of beam steering in the two orthogonal directions has been achieved. Beam steering has been achieved by tuning the wavelength and also by delay sections. The two-dimensional beam steering is achieved using proposed design with the combination of thermo-optic phase tuning and wavelength tuning.

H Ahmad et al. – 2014 [61] proposed and generated a single longitudinal mode operation which relies on the configuration of DBR cavity. The erbium-doped fiber having depressed-cladding has been used as the gain medium along with the end mirrors which are comprised of FBG and Faraday rotator mirror (FRM), for operation in the S-band region. To restrict the lasing frequency, the FBG has a central wavelength of 1506 nm. A lower value of line-width which is measured at 20 KHz. A slope between average pump powers versus output power has established efficiency at almost 0.01%.

J. Tang et al. – 2014 [62] demonstrated a technique for the optimization of the slow light in an ellipse hole PhC waveguide. The method used for simulation results is Finite Difference Time Domain (FDTD) method. There is need of high group index and lower rate of dispersion

for slowing of light at a broad bandwidth. A numerous alteration can be made to the design to optimize these parameters to achieve desired results.

Weijian Yang et al. – 2012 [63] demonstrated a new concept of wave guiding using a planar, SOI wafers with HCG parallel to each other. A loss of 0.37dB/cm for a length of 9 μm waveguide has been reported which is quite a low value. For fast flow of gases and liquids to achieve fast sensing response, a 2D light confinement has been experimentally realized in hollow waveguide with no side walls. This new technique is useful in terms of low cost and in lab applications.

C. Chevallier et al. – 2012 [64] proposed a Si/SiO_2 HCG for use in VCSEL at a wavelength of 2.65 μm . This HCG has shown a 250 nm large band- width for R_{TM} greater than 99.9 % as well as good polarization sensitivity by making R_{TE} less than 90%. There is an improvement in the quality of the VCSEL emitted beam with a less than 2 μm thick reflector.

Yang Yue et al. – 2012 [65] proposed a 3-D chirped HCG hollow-core waveguide (HCG-HW) that has shown 2-D light confinement efficiently. The proposed design has can easily lower the propagation loss more than ten times without making a compromise with the lateral index contrast as compared to step-index HW. Results have shown that 0.04 dB/cm loss has been achieved. Chirped HCG-HW having 6 μm core height displayed 30nm and 141nm spectral widths for 0.1 dB/cm and 1dB/cm loss. The proposed design has also show nonlinear coefficient, of the order of $10^{-5}/\text{W}/\text{m}$ which is very low in value.

Mukesh Kumar et al. - 2012 [66] proposed a high-contrast-grating (HCG) based hollow-waveguide. The HCG is used instead of one of the DBRs in hollow waveguides. This design helps to reduce the sensitivity in terms of temperature and polarization. A theoretical demonstration of strong optical confinement and a low propagation loss for millimeter long devices have been shown [67].

In the proposed design the light is confined in an air core between a DBR mirror and a HCG mirror. It has shown a very small modal birefringence of the order of 10^{-4} [35]. They have demonstrated experimental fabrication of a hollow waveguide with very low birefringence. Hence, they ended up with a conclusion that with future design optimizations their proposed design with narrow air core which can lead to broadly tunable photonic devices having low dependence on polarization and temperature. Complete polarization insensitivity can be

realized by further optimization of hollow waveguide structure. A small polarization loss of 1.36dB/cm and also a low modal birefringence of 1.01×10^{-4} has been recently reported with such an optimized waveguide [66].

Hongjun Yang et al. - 2012 [68] reported a broadband membrane reflector which is based on crystalline silicon nano membrane photonic crystal. The proposed design has shown a very high performance. For transfer of large area silicon membrane to glass substrate, a modified polydimethylsiloxane stamp technique was introduced. From silicon membrane reflectors on substrate, a polarization insensitive broad reflectivity at wavelength of 1550 nm was obtained.

M. Shinkawa et al. - 2012 [69] reported the fabrication of PhC waveguides having the feature of slow light. The integration of the proposed waveguide is done with multi-heaters. With the optimization of heating powers and adjustment of the index distribution, a delay in peak was seen clearly. By the proper adjustment of the heating pattern, the compensation of fabrication errors is possible and also a clear delay peak was reported.

Xing Sheng et al. – 2011 [70] integrated a light extraction HCG structure with self-assembly. It is used for Light Emitting Diode efficiency enhancement. By the use of numerical simulations, they have investigated that the design parameters and materials used HCG plays a very important role in the light extraction. It has been shown that high-index contrast gratings are very useful and efficient choice for the improvement of light extraction. The integration is done on GaAs based LEDs with the use of self-assembled AAO membranes which is used as a template. It is a better choice than lithographic fabrications because of the cost issue. A good improvement of 27% in emission intensity has been shown by the proposed LED device with the optimized HCG. The results were validated by comparison of the performance evaluation of gratings made from a-Si and SiO₂. Because of the non-ideal periodicity, the device which is fabricated with a-Si grating has a Lambertian emission pattern that is not noticeable in simulation studies.

Luca Carletti et al. – 2011 [71] suggested and investigated HCG mirrors which provides wave front control of the transmitted light. A numerical and experimental results show that it provides high reflection for a wide range of bandwidth. Generalization of design rules to make different designs using HCGs for various applications has also been derived. It is shown that

HCG reflectors can be used for the manipulation of the transmitted beam, also at the same time high reflectivity can be maintained for the incident light. The structure having HCG region, which is not periodic in nature, depicted a deflection of beam of approximately 6° , with very good validation with numerical simulations. The proposed HCGs has feature of high reflectivity and wave front control which can be useful in various applications, like laser fabrication at lower cost. Also, this strategy can be used to have various phase profiles from the grating, opening up new fields and also the improvement in integration of other functions in compact and low-price devices.

Akihiro Imamura - 2011 [72] presented a new functionality of HCG HW with a variation on HCG parameters. A spatial mode de-multiplexer based on HCG hollow waveguides has been proposed. This can be useful in high-capacity interconnects with spatial-mode de multiplexing. Spatial mode de-multiplexing in a HCG hollow waveguide having variable design parameters of grating has also been proposed. The proposed scheme can help in design of compact multiplexing- de-multiplexing for optical interconnects.

Toshihiko Baba - 2011 [73] presented two affairs related to PhCs which are slow light waveguides and nano-lasers bio sensors. Both these topics are very unique by means of performance and functions. PC waveguides devices having slow light are capable of wide band dispersion compensation with a larger buffering capacity and wider tuning capability.

Ju-Hyung Kang et al. – 2011 [74] reported the distinct description of lasing modes observed in a cavity based on single cell PhC. It has used a solid angle scanning system. These measurements have resulted in unambiguous characteristics of every mode and also differentiate it from the other modes. This feature is not there in other optical characterization methods. The observation and identification of features which distinguish between Monopole, Quadrupole, and Hexapole lasing modes have been done. It has showed a good validation with simulation created numerically. The knowledge of the lasing modes from this research will be beneficial in the determination of amazing advantages in ultra-compact integrated photonic circuits.

Werner Hofmann et al. -2010 [75] proposed a VCSEL structure having a long wavelength based on a sub-wavelength HCG which act as the mirror at output [8]. The proposed design, has been highly polarization stable and is a good solution for VCSEL-mirror long wavelengths

problems. The InP substrate is used to grow the device, including a BTJ is used for a design with minute losses both electrical and optical and avoiding p- type material. For the bottom mirror, they have used a hybrid reflector and the coupling of light is done with a HCG reflector. Mass fabrication is done which will provide low cost. The manufacturing of grating was done from a silicon layer on a silica isolator. The device has been made with a low-parasitic, design with a higher speed. The bandwidths more than 10GHz is used to work well. The pulsed operation for the first time with peak powers in excess of 4mW and cooled CW operation with single-mode emission in excess of 0.4mW has been demonstrated.

Aftab Ahmed et al. – 2010 [76] analyzed structure of HCGs using Truncated coupled mode theory (CMT). CMT has an advantage that it provides deep study of the behavior of every mode in the total response and it also provides a better design. An expression has been derived analytically for the broadband reflectors which provides within 0.08% of the highest calculated reflectivity. The method used is the FDTD method. They have shown that CMT is a good option for the design of a narrow-band reflector having superior quality with an improvement of Q factor by 28% in comparison to the results which have been reported previously as quantified by RCWA. A CMT method was also used to enhance the characteristics and properties of HCGs for all the important parameters of design of grating such as grating period, duty cycle, thickness and wavelength. A structure is explained stepwise for applications requiring wideband high reflectivity which has a very good performance with a minimal ripple broadband reflection. Such broadband reflectors are promising candidate for number of applications, which includes VCSELs with tunability, high Q resonators. These high-Q resonators can be useful for sensor applications

Vadim Karagodsky et al. – 2010 [77] developed a easy analysis of the very promising application of sub wavelength gratings which is ultra-high reflectivity. The phenomenon of ultra HCG has been explained, categorizing it as a destructive interference having dual mode. A formula for converging matrix transmission line to calculate the reflectivity of HCG has been presented and also an algorithm for designing a wideband HCG mirrors has also been discussed graphically. This broadband is very useful for bandwidth as well as fabrication tolerance.

Ayumi Fuchida et al. – 2010 [78] proposed slow light with zero dispersion in HCG-HW having an optical bandwidth of 15nm. The loss while propagating was observed less than

1dB/mm and group index was raised to 8. The design of waveguide finds its benefits for the realization of on-chip photonic circuits.

Amin Khorshidahmad et al. – 2010 [79] numerically demonstrated and proposed a nested photonic crystal (PhC) cavity which is configured and beneficial for applications associated with conversion of wavelength. Adiabatic tuning of a resonator is used for it. The proposed device is useful in improving the wavelength conversion range. The structure is comprised of a statically formed hetro-structure PhC cavity which is implanted on a second outer hetro-structure cavity. In the proposed design two distinct cavities are switched by the combination of change in structure with index change has enhanced the frequency conversion range.

Jessie Rosenberg et al. – 2010 [80] designed a polarization-sensitive resonator so that it can be used for mid infrared photo detectors, with the utilization of a PhC cavity and a single metal plasmonic waveguide or dual metal plasmonic waveguide. The enhancement in the efficiency of detector have been achieved because of the better confinement of light inside the active region. The proposed structure can be beneficial in chip-based spectrometers and cameras in which high degree of precision is required that can differentiate between various materials and different temperatures as the cavity is very much sensitive in terms of frequency and polarization. The proposed resonator design has shown good frequency and polarization selectivity which can be used in hyper spectral and hyper polarization detectors. The conditions that enhances optimal detector absorption has been analyzed and the PhC hole size and thickness of metal on top has been varied in order to adjust the vertical coupling efficiency so that it can compensate the resonator loss to achieve critical coupling. Almost 100 percent absorption in the detector can be attained by additional increase in coupling efficiency or reductions in loss.

Ye Zhou et al. – 2009 [81] presented a detailed review on recent advancements in sub-wavelength HCGs and their applications. They have shown that HCGs can be used as broadband, high-reflectivity greater than 99 percent mirrors for incident light normal to the surface to be a replacement to conventional DBRs in optical devices. They have also demonstrated that HCGs can serve in different devices with different functionalities such as shallow angle reflectors or surface emitting high-Q optical resonators. By integration of a HCG having single layer in a VCSEL, a number of beneficial and also previously unachieved properties were achieved. An example of which is polarization control using lithography and

single transverse mode devices with larger aperture. They have also experimented on the previous work which leads to a large tolerance in fabrication in HCG VCSELs i.e. variation in critical dimension of the uniform HCG and critical variation of 30% of dimension in a HCG with random size. A tunable VCSEL based on HCG which has a very fast adjusting speed has also been analyzed. By the integration of a mechanically movable actuator along with a HCG as the VCSEL top mirror an accurate, broad and ongoing wavelength adjustment of 18 nm at room temperature was attained. They have also simulated and experimentally measured a surface normal high-Q resonator based on HCG with a large Quality factor.

They have also proposed a single-mode hollow-core waveguide with an ultra-low loss using sub-wavelength high-contrast grating (HCG). Analytical simulation result for the propagation loss has been shown. The proposed waveguide can achieve a low loss of 0.006dB/m. They have demonstrated the design of HCG based HW which has an extremely wide bandwidth of approximately 100nm and also a large fabrication tolerance. Because of the unique dependence on polarization and angle of incidence of the HCG reflection spectrum, HCG-HW can perform single mode operation having a larger core than conventional waveguides. It has been shown that HCG-HW can minimize non-linear effects and dispersion during transmission of data and also it does not depend on temperature variation. With all these promising features, their proposed HCG-HW can be a promising design for applications like on chip optical communication, optical delay lines with low loss etc. [75].

Rakesh G. Mote et al. – 2009 [18] proposed a 2D HCG with square periodic lattice for the realization of surface-emitting lasers. The excitement of number of resonant leaky modes takes pace with the use of 2D HCG by the two orthogonal directions of the grating has been shown. The reflection properties of 2D HCGs were also analyzed. With suitably choosing of grating period and thickness of the 2D HCGs, a rise in the reflectivity has been observed. Due to the excitation of additional resonant leaky mode, the excitation of cavity mode in 2D HCGs is caused because two zones with high reflectivity are formed in the reflection spectrum. It has been observed that there is a very small spectrum of wavelength, grating period Λ , and thickness t_g for the generation of the cavity mode. By the insertion of a thin active layer between the grating and buffer layers, a 2D HCG surface-emitting laser with a high Quality factor of 1032 can be created. The Q factor depends on thickness of the buffer layer. 2D HCG having a symmetrical tendency makes it independent to the incident polarization unlike one

dimensional HCG. The applications like amplifiers and optical filters can be implemented because of this property.

Juraj Topolancik et al. – [83] characterized propagation of optical wave towards the line defects in 2D arrays of air holes in silicon slabs. The band-edge and disorder enhanced polarization conversion PhC-based slab waveguides which are vertically asymmetric have been characterized. The in-plane translational symmetry has perturbed due to the alterations in direction of the photonic lattice elements in the proposed fabricated waveguides. By tilting of the etched sidewalls, the vertical slab symmetry has been broken. Also, a discussion on the effect of lattice imperfections on out of plane scattering losses has been done. The phenomena on excitement of high Q cavity in relation to polarization merging has been introduced. It is indicated that longitudinal disorder efficiently explains the intermittent nature of the mode-edge, the transverse and vertical asymmetries that are required for converting the polarization in the device. It has been validated that the polarization conversion has increased due to the narrow spectral nature at the band edge. The mechanism for PhC nano cavity excitation which is depends on TM-TE polarization merging in vertical slabs which are asymmetrical in nature also has been introduced. The results seem to be useful for applications of PhC cavities and waveguides in the areas of optical signal processing and refractometric sensing.

H. Y. Fu et al. – 2009 [84] proposed and demonstrated a novel design of intrinsic fiber optic pressure sensor that is formed with a polarization maintaining photonic crystal fiber (PM-PCF). It is based on Sagnac interferometer. The observations have been obtained on the basis of experimental and theoretical explanation of the pressure sensor. A large wavelength–pressure coefficient of 3:42 nm/MPa has been calculated using a 58:4 cm long PM-PCF which act as sensing element. The proposed design of sensor is an efficient design and it shows low temperature dependence because of the thermal dependence and loss is also low while bending of the PM-PCF.

Juntao Li et al. – 2008 [85] presented a systematic approach for design of flat bands of PhC waveguides for the application where slow light is used. The numerical calculation of characteristics of slow light in flat band of PhC waveguides has been carried. The aim is to increase the group index bandwidth product to a high value. It is done by making change in the position of the first two rows of holes of W1 line defect PhC waveguides. Almost constant product of group index and bandwidth has been observed for group indices n_g of 30-90. This

method has the benefit of keeping a constant hole size over the device. The proposed method has been used as a demonstration by three flat band slow light structures experimentally. The proposed design approach have shown the good chance of utilizing PhC waveguides travelling in slow light region that results in the use of applications like in enrichment of linear and nonlinear effects.

Federica Poli et al. – 2006 [86] investigated large-mode-area, double-cladding, rare-earth-doped photonic crystal fibers for a better understanding of distribution of refractive index and the competition of mode is given by the amplification which ensure single mode propagation. Fibers having various core diameters, i.e., 35 μm , 60 μm , and 100 μm are considered. The mode effective index, gain, effective area, overlap, and power evolution along the doped fiber are analyzed providing a clear explanation on the physical properties of fiber, to be synchronized in the process of fabrication to achieve an efficient single-mode output beam. Also, numerical demonstration is presented of effect of little core down-doping which can insist the high order modes below the SFM effective index curve.

Young-Geun Han et al. – 2006 [87] proposed and experimentally demonstrated a new technique, which depends on the symmetric bending for the adjustable pulse repetition rate multiplication, to keep a control on the chromatic dispersion of a Bragg grating which is uniform in nature.

Yasuki Sakurai et al. – 2006 [88] presented an adjustable stop band HW Bragg reflector for a tunable dispersion compensation device with a variable tapered air core. Chirped Bragg reflection is provided by tapered air core structure. The dynamic adjustment of stop bandwidth and center wavelength of Bragg reflection is enabled by the exact management of thickness of tapered air core and angle. With time difference in delay of about 10ps, center wavelength tuning of 20.1nm with respect to 1.3% of change in propagation constant is demonstrated along with stop band extension up to 5nm and dispersion adjusting operation is possible in dispersion range which can be negative or positive.

Andreas Hakansson et al. – 2005 [89] proposed the integration of 2D photonic crystal diplexer with a waveguide coupler. The proposed structure is created by computer with an inverse design process, but it is restricted within an area measuring 5 $\mu\text{m} \times 5 \mu\text{m}$. The device

has exhibited cross talks suppressed less than 40dB and also has coupling efficiency near to 80%.

Tsuyoshi Yamashita et al. – 2005 [90] evaluated Self-collimated beams and photonic band gap mirrors in photonic crystals. It is useful in the application of an on-chip interconnect system. The results are carried out using the Plane Wave Expansion method (PWE) and Finite Difference Time-Domain (FDTD) method have been used for designing and performance evaluation. Because of the borderless confinement of signal, it is called a virtual waveguide. These waveguides using 2-dimentional and 3-dimentional photonic crystals have a possibility for the revolution in integrated optical interconnects. It also has additional benefits in the area of free-space optics and guided wave optics which will lead to a full management of the signal. The fabrication error tolerance on the performance has been carried out in a very systemic manner. The Coupling efficiency is found to be an interesting parameter which is a dependent on waveguide length and also on the frequency of light. Demonstration of 90° bending capabilities of turns and also no crosstalk signal crossings has been done. PhC virtual waveguides are appropriate candidates for on-chip optical signal routing. The self-collimation process has a less effect on fabrication imperfections in comparison with the other resonant sub wavelength optical devices. The capability to perform 90° bends and also to cross signals without coupling makes flexible routing circuit which is better than electrical interconnects. With the advent of the resonator-like transmission properties, improvement beyond the limits of Fresnel reflection is possible.

S. Ramachandran et al. – 2003 [91] demonstrated an adjustable dispersion compensator in which higher order mode fibers and switchable fiber gratings are used. The proposed design is broadband and wavelength continuous, yielding a bit rate dispersion compensator for adjusting bit format, single bandwidth and channel spacing. Compromise between tuning range and bandwidth is not required in this device. The adjusting range is 435ps/nm with a bandwidth of 30 nm. The lowest loss tunable dispersion compensator has been achieved due to its all fiber configuration. The device was the first tunable compensator that is bit-rate, bit-format wavelengths as well as channel spacing transparent.

Ding- Wei Huang et al. – 2000 [92] designed and proposed a device with which the Bragg reflectivity of a fiber grating can be modulated with the excitement of the transverse vibration of the fiber through an acoustic wave. There is a merging of the fiber core mode into the

cladding modes due to the excitation of the transverse vibration. This results in the decrease of core mode power that will in turn reduce the Bragg reflection. This mechanism controls the reflectivity after the fabrication of fiber Bragg grating.

2.3 Relative Issues

Performance evaluation of HCG: - High index contrast gratings are one of the latest trends in the field of integrated photonics due to the extra ordinary properties. The performance of the HCG can be evaluated as well enhanced by optimizing the design parameters of the HCG. A number of HCG based devices are reported in literature like HCG based hollow waveguides, VCSELs, Bragg reflectors .HCGs have replaced DBRs in many devices .By carefully selecting the design parameters like grating period, grating thickness, duty cycle etc we can make the HCG grating suitable for a particular optical device. The deep study of the properties of HCG with respect to incidence angles, various wavelengths is required to design a particular optical device. Also effect of the polarization on the HCG properties also needs to be explored.

Polarization sensitivity of HCG:- As polarization selectivity is important in many applications like VCSELs. It has been shown through the literature that most of the research is done on the 1 dimensional HCGs. Because of the asymmetrical grating profile for TE and TM polarizations, 1-D HCGs are polarization sensitive. So they can provide high reflectivity in one polarization at a particular wavelength. But there is a need of Polarization insensitive HCGs. Polarization independent HCGs needs two dimensional HCG. So, there is a need to study the properties of 2-D HCGs for polarization insensitivity.

Analysis of propagation characteristic of HCG based hollow optical waveguide: - Optical waveguide is the basic element for photonic Integrated circuit. Hollow optical waveguides have been reported in the literature for various applications which includes sensing, optical communication and spectroscopy. Hollow waveguides is the main element to build photonic devices with various functionalities because of the design flexibility and low cost. Low propagation loss and broad wavelength range is required with increase in the performance demand. It is shown in the literature that there has been much advancement in the structures of

the hollow core waveguide. The HCG based hollow core waveguides are finding applications in number of optoelectronic devices. There is a need to analyze the propagation properties of HCG based waveguide.

Concept of slow light:- Reduction in the group velocity of light is referred to as slow light. Slow light is one of the latest research areas in photonic crystal waveguides. Slow light has offered very efficient control over interaction between light and matter. The recent literature shows that the unique and attractive application of slow light is tunable delay. Slow light is useful in optical delay lines and optical buffers which are compact in size. Two main concerns are propagation loss and dispersion that can be compromised by the slow light. The high dispersion caused by slow light in photonic crystals trades with most of the benefits of slowing down the light. So slow light characteristics of photonic crystal waveguides are needed to be studied and analyzed.

2.4 Research Gaps

1. Not much work has been published on performance evaluation of HCG for different values of angle of incidence and with different wavelengths. Also, the effect of polarization on the grating properties has not been explored yet [19].
2. Less work has been done on tight optical confinement hollow waveguide with low temperature dependence [63].
3. Older high index contrast grating based ultra-low loss hollow core waveguides are not cost effective because of the requirement of long gratings necessary for wave guiding [64].
4. No report on hollow core waveguide with high index contrast grating as top and bottom mirror inserted as lateral periodicity [66]

2.5 Research Objectives

From the literature review and the understanding of the topic, the proposed objectives are as following:

1. Design and simulation of a novel broad band and high reflective single-layer high index contrast grating for larger bandwidth at grazing optical incidence.

2. Design and simulation of a Hollow Waveguide (with improved propagation characteristics- loss, dispersion, bandwidth, spot size, optical confinement etc.) where proposed High Index Contrast Grating will be used as top and bottom mirror.
3. Simulation of dispersion characteristics of proposed hollow core waveguide
4. Design and simulation of a Bragg Reflector based on to-be-proposed hollow core waveguide

2.6 Thesis Organization

The thesis has been divided into six chapters. The brief description of the content of each chapter is given below:

Chapter 1: This chapter gives a description about introduction of photonic crystals and their role in integrated photonics. This chapter will also give an overview of gratings then an introduction to High index Contrast Grating, Hollow waveguides and Bragg reflectors. Then a conclusion on the importance of photonic crystal-based devices is made.

Chapter 2: After the introduction of the integrated photonics and its role in previous chapter, chapter 2 will cover the literature review related to research area, relative issues and research gaps and objectives of the research.

Chapter 3: This chapter is comprised of detailed analysis and optimization of high index contrast grating design parameters like grating period Λ , grating thickness t_g , duty cycle C etcto achieve high reflectivity of one-dimensional HCG.

Chapter 4: This chapter describes an efficient design and simulation of HCG based hollow optical waveguide with betterment in propagation characteristics. In this chapter, narrow air core hollow waveguide is designed with a low loss. This chapter also comprises of study of slow light properties of proposed hollow optical waveguide.

Chapter 5: In this chapter, 2-dimensional HCG has been discussed. The design parameters are optimized to attain maximum reflectivity. A polarization insensitive design of 2 D HCG on SOI is proposed. This chapter is also confined to design and study of proposed two-way HCG based reflector. This chapter will cover the reflection properties and incidence angle dependence of the two-dimensional HCG based reflector.

Chapter6: This chapter comprises of the conclusion, and also scope of the present work for the future.

Chapter 3

On chip Reflector based on High-index Contrast Grating

3.1 Introduction to sub-wavelength gratings

The optical gratings have been an important research topic from past for many functional applications like spectroscopy, lasers, holography etc. Optical gratings are used as an integral part in the field of engineering and science. Figure 3.1 mentions some of the areas where gratings are used. The grating period of most of the diffraction gratings is larger than the wavelength. The grating will experience many unique features where grating period of the grating will be smaller as compared to the wavelength. If the grating period is lesser than the incident optical wavelength, the grating is called sub wavelength grating.

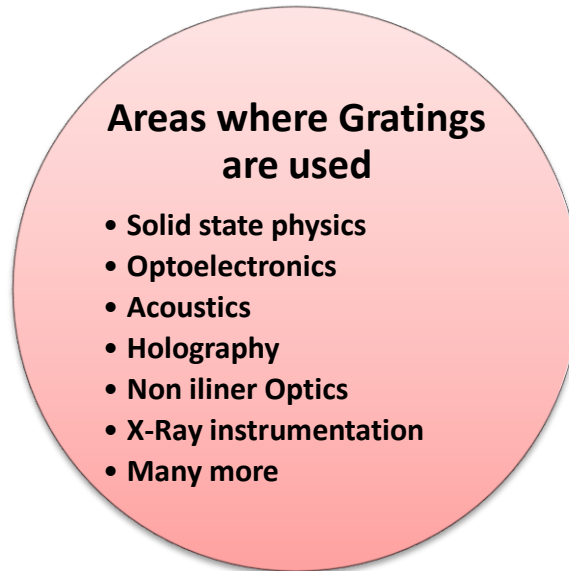


Figure 3.1 Applications of gratings.

High-index contrast grating (HCG) is defined as a grating with a single layer of sub wavelength grating (grating period smaller than the wavelength) with high refractive index difference as compared to the materials that surrounds it. HCGs can manipulate and control the flow of light which can make it a promising candidate in various on chip integrated devices exhibiting extraordinary properties. HCGs possess broadband high reflectivity and compact size which makes it a better replacement to conventional distributed Bragg reflectors

(DBRs) in various applications such as VCSEL. With the replacement DBRs with HCG in a VCSEL, a number of attractive VCSEL designs having extraordinary properties have come up. They have been demonstrated [19,35]. The design parameters of HCG which includes grating period Λ , width of the grating w , thickness of the grating d , and spacing S and electric field which is parallel to the grating (TE) is Self-explaining in figure 3.2.

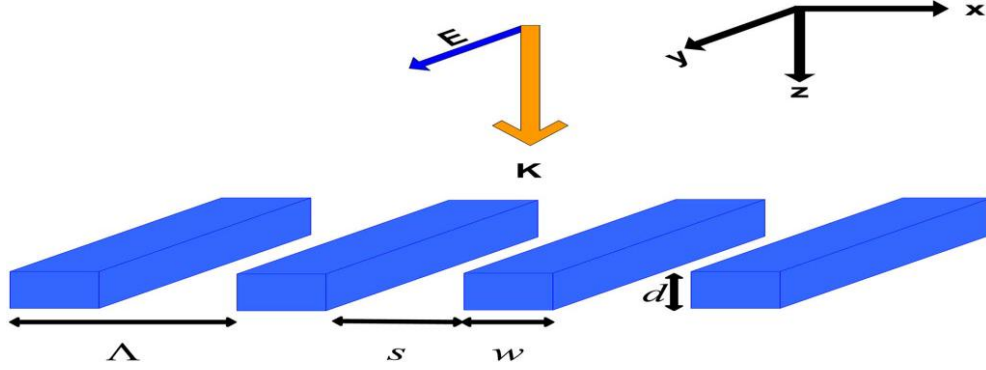


Figure 3.2: High index contrast grating [65]

HCGs have a unique and extra ordinary quality that they can be used in very different functions according to the incident light and such as surface normal broadband mirrors, shallow angle reflectors etc. HCGs with different functionalities are shown in Figure 3.3 [81]. Also, by optimizing the design parameters accordingly; we can make HCG as a particular optical component.

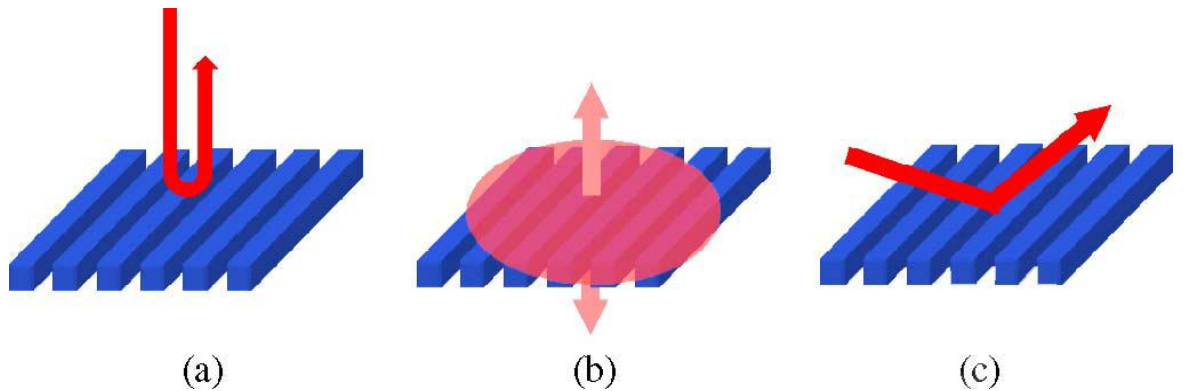


Figure 3.3: HCG as (a)Surface-normal broadband mirror (b) Surface-normal high-Q resonator (c) Shallow angle reflector [81]

Normally HCGs can be designed to show high reflectivity either modes i.e. TM mode or TE mode. Figure 3.4 shows the TM polarized HCG and TE polarized HCG. In TM mode, electric field is perpendicular to the direction of grating stripes and in TE mode; electric field is parallel to the direction of grating stripes.

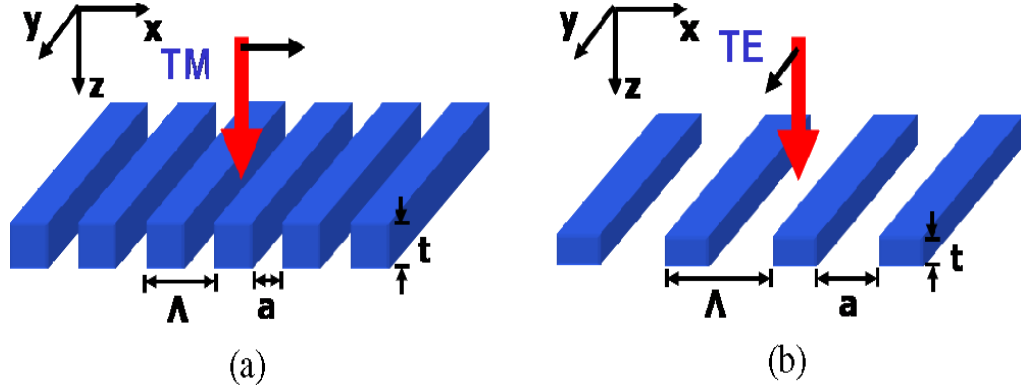


Figure 3.4: (a) TM polarized HCG (b) TE polarized HCG [81]

Silicon-on-insulator (SOI) based optoelectronic devices have been an interesting and significant topic of research. The component size is reduced with SOI because of the high refractive index difference and good optical confinement. HCG can function in very differently and can be utilized in a number of applications if the dimensions of the grating structure are carefully designed and optimized.

3.1.1 Design Parameters of High Index contrast grating

The design parameters of HCGs play an important role on its reflectivity. There are four main design parameters that can control the reflectivity of HCG. These parameters for the HCG which include the period of the grating (Λ), thickness of the grating (t_g), duty cycle (C), and the thickness of the low index layer under the grating (t_L). Duty cycle is the ratio of the width of the high index material to the grating period.

Figure 3.6 shows the front view of High index contrast grating on SOI, silicon stripes surrounded by air constitutes to HCG. Low index material SiO_2 is used below the gratings and then Si substrate.

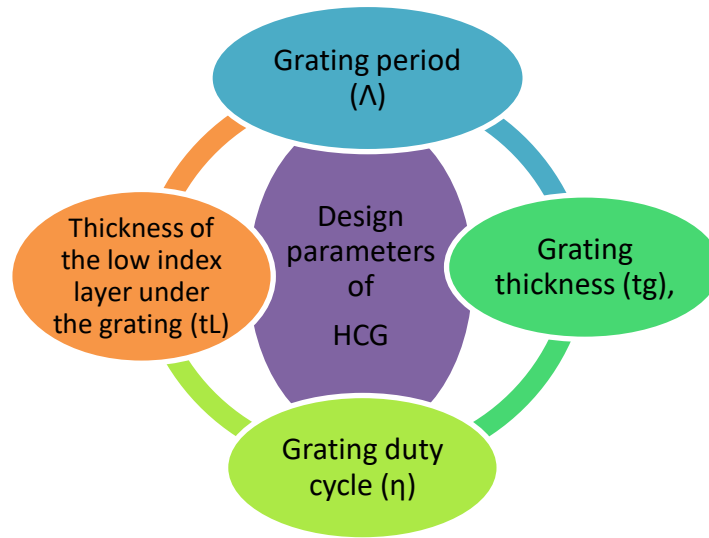


Figure 3.5: Design parameters of HCG

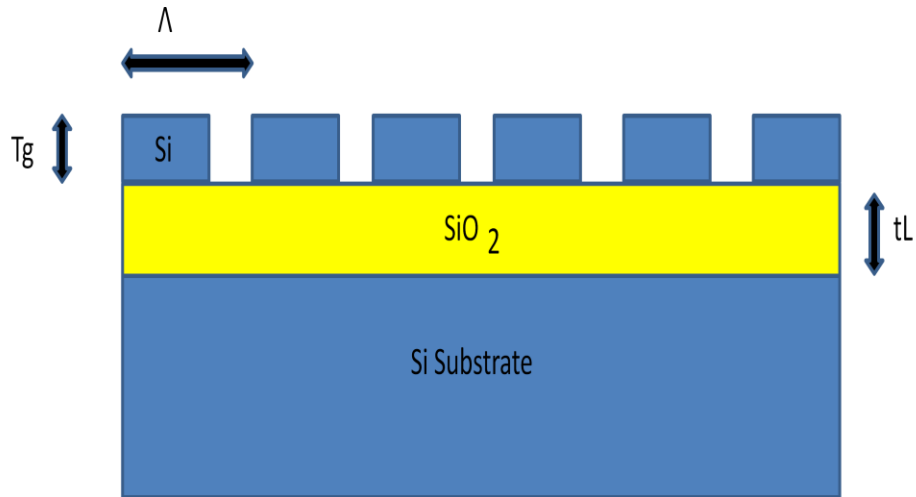


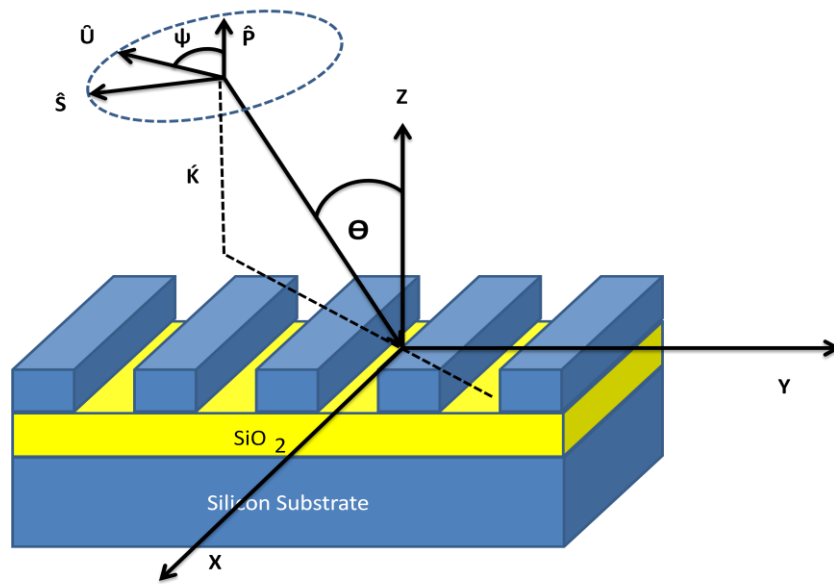
Figure 3.6: Front view of HCG on SOI

Figure 3.6 shows the front view of HCG on SOI describing the design parameters. In this chapter we will analytically study the one-dimensional model of HCG and then we will simulate the results of one-dimensional and two-dimensional HCG to get high reflectivity.

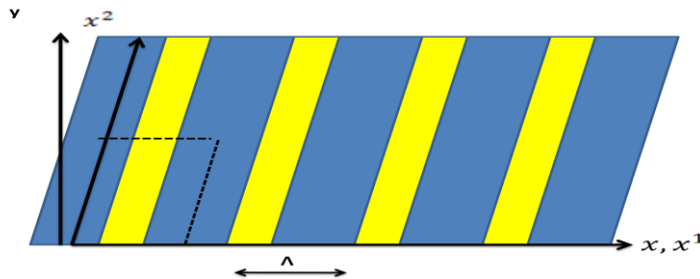
3.2 Analytical model of HCG

A model of HCG is described analytically in this section. Many numerical methods are there to model the gratings. To name some of them are the differential method, the coordinate transformation method, the integral method, the Fourier modal method, the Rayleigh method and the Boundary variation method. But mentioned techniques use a lot of memory and are time consuming [75, 93]. An improved Fourier modal method (FMM) is used for analysis. It tends to improve the speed of the Fourier modal method (FMM). It is also called the Modal method by Fourier expansion (MMFE). There are various advantages that make this method better than prior FMM [94, 95]. The basic FMM used a rectangular Cartesian coordinate system in the plane of the grating. A Cartesian coordinate system is used in improved FMM where two axes in the grating plane have two periodic directions of the grating. The Cartesian coordinate system generalizes the theory and makes the presentation easy. Another advantage is that it reduces computation time and lesser memory is used [96].

(a)



(b)



(c)

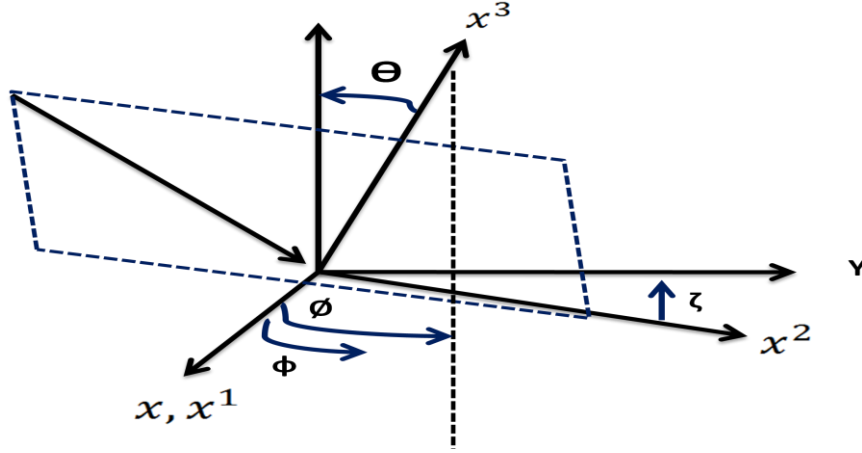


Figure 3.7 : (a) 2DHCG reflector based on Silicon-on-insulator (SOI). (b) Top view of HCG and Cartesian coordinate system in the grating plane. (c) The rectangular Cartesian coordinate system used for the incident angles.

The diagram of a grating where a rectangular Cartesian coordinate system is used is shown in Fig.3.7.(a).one periodic directions of the grating is parallel in x direction whereas grating plane is perpendicular in the z direction.. The propagation direction of the incident plane wave is given by polar angle Θ and azimuthal angle ψ . the polarization is considered linear, is given by angle c with respect to the p - s coordinate system. The unit vector $\hat{p}$ is in the plane of incidence and $\hat{s}$ is perpendicular to it; both are orthogonal to the incident k vector. Figure 3.7 (b) shows the HCG from top. Figure 3.7(c) shows the top view of HCG. A nonrectangular coordinate system $Ox^1x^2x^3$ is introduced such that x^1 axis is parallel to x axis and x^3 axis is parallel to z axes but the x^2 axis is parallel to another periodic direction of the grating. In all, x^1 and x^2 axes, are the two directions with shortest periods i.e. d^1 and d^2 , respectively. The origin of the z axis is considered to be at the lower boundary of the grating layer. The angle formed between x^2 and y axes is $\zeta, |\zeta| < \pi/2$ The two unit cells of periodic pattern which are possible are parallelogram and the rectangle and they are shown by the dashed and solid lines [97]. The rectangular Cartesian coordinate system and a skew Cartesian coordinate system are used for the incident angles, and periodic variation of the permittivity tensor in the grating region respectively.

The two coordinate systems are transformed by

$$x^1 = x - y \tan \zeta$$

$$\begin{aligned}x^2 &= x - y \sec \zeta \\x^3 &= z\end{aligned}$$

The covariant and basis vectors for the nonrectangular coordinate system is given by

$$\begin{aligned}b_1 &= \hat{x} \\b_2 &= \hat{x} \sin \zeta + \hat{y} \cos \zeta \\b_3 &= \hat{z}\end{aligned}$$

The contra-variant, basis vectors are

$$\begin{aligned}b^1 &= \hat{x} - \hat{y} \tan \zeta \\b^2 &= \hat{y} \sec \zeta \\b^3 &= \hat{z}\end{aligned}$$

The two sets of basis vectors

$$b_\rho b^\sigma = \delta_\rho^\sigma$$

Where δ_ρ^σ is the Kronecker delta symbol

By using contra-variant basis vectors the wave vector of the incident plane wave is given by

$$k = k_\sigma b^\sigma = \alpha_0 b^1 + \beta_0 b^2 - \gamma_{00}^{+1} b^3$$

$$\alpha_0 = k^{+1} \sin \theta \cos \varphi$$

$$\beta_0 = k^{+1} \sin \theta \sin(\varphi + \zeta)$$

$$\gamma_{00}^{(+1)} = k^{+1} \cos \theta$$

Where $k^{(+1)} = 2\pi\sqrt{[\epsilon^{(+1)} \mu]}/\lambda$

λ is the vacuum wavelength. k^{-1} is defined in the same manner.

The covariant components of the electric field vectors in regions ± 1 are given by Rayleigh expansions:

$$E_\sigma = I_\sigma \exp[i(\alpha_0 x^1 + \beta_0 x^2 + \gamma_{00}^{(+1)-} x^3)] + \sum_{m,n} R_{\sigma mn} \exp(i\alpha_m x^1 + \beta_n x^2 + \gamma_{mn}^{(+1)+} x^3) \quad (3.1)$$

$$E_\sigma = \sum_{m,n} T_{\sigma mn} \exp(i\alpha_m x^1 + \beta_n x^2 + \gamma_{mn}^{(-1)-} x^3) \quad (3.2)$$

Where I_{σ} , $T_{\sigma mn}$ and $R_{\sigma mn}$ is the incident and diffracted (transmitted and reflected) field amplitude

$$\alpha_m = \alpha_0 + mK_1, \beta_n = \beta_0 + nK_2$$

And γ_{mn}^a can be solved from:

$$\sec^2 \zeta (\alpha_m^2 + \beta_n^2 - 2\alpha_m \beta_n \sin \zeta) + \gamma_{mn}^{(a)2} = k^{(a)2}$$

The sign of γ_{mn}^a is chosen such that $\text{Re} [\gamma_{mn}^{(a)}] + \text{Im} [\gamma_{mn}^{(a)}] > 0$

The $(m, n)^{th}$ -order diffraction efficiency in medium a is

$$\eta_{mn}^{(a)} = \frac{1}{\gamma_{mn}^{(a)}} [(k^{(a)2} - \beta_n^2) |E_{1mn}^{(a)}|^2 + (k^{(a)2} - \alpha_m^2) |E_{2mn}^{(a)}|^2 + (\alpha_m \beta_n - k^{(a)2} \sin \zeta) \times (E_{1mn}^{(a)} \overline{E_{2mn}^{(a)}} + E_{2mn}^{(a)} \overline{E_{1mn}^{(a)}})] \quad (3.3)$$

Where $E_{\sigma mn}^{(+1)} = R_{\sigma mn}$ and $E_{\sigma mn}^{(-1)} = T_{\sigma mn}$.

The correct Fourier factorization of Maxwell's equations and a non rectangular Cartesian coordinate system is used. So by solving the equation mentioned above, the reflectivity a transmittivity can be obtained by calculating the diffraction efficiency.

3.3 Simulation of One-Dimensional HCG

Simulations have been carried out for one dimensional HCG on SOI and also for two dimensional SOI. To achieve this objective, the analysis and optimization of the design parameters of HCG is done. Figure 3.8 shows the schematic High-Contrast Grating.

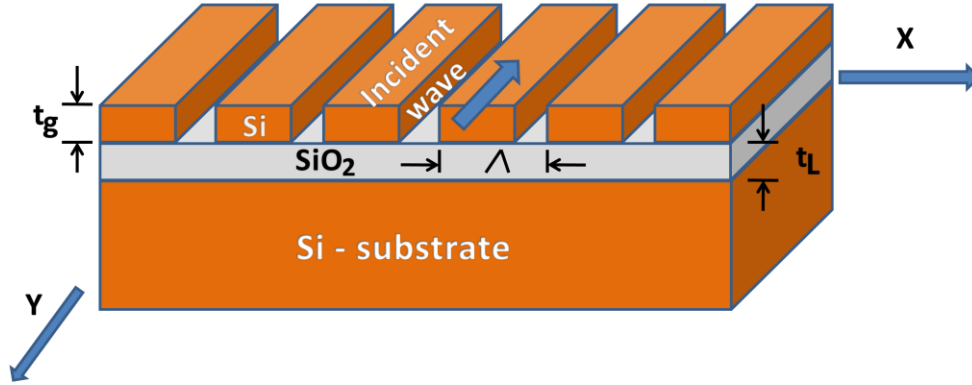


Figure 3.8: High index contrast grating on SOI

It is a single-layer grating in which the difference of refractive index between the high index region and low index region of the grating is very high. In the Figure 3.8, Si stripes constitute HCG, using air that surrounds the stripes. SiO₂ is used below the gratings. The design parameters are shown in the Figure which are the grating period (Λ), grating thickness (t_g), grating duty cycle (C), and the thickness of the low index layer under the grating (t_L). The reflectivity of the HCG is dependent on all these design parameters.

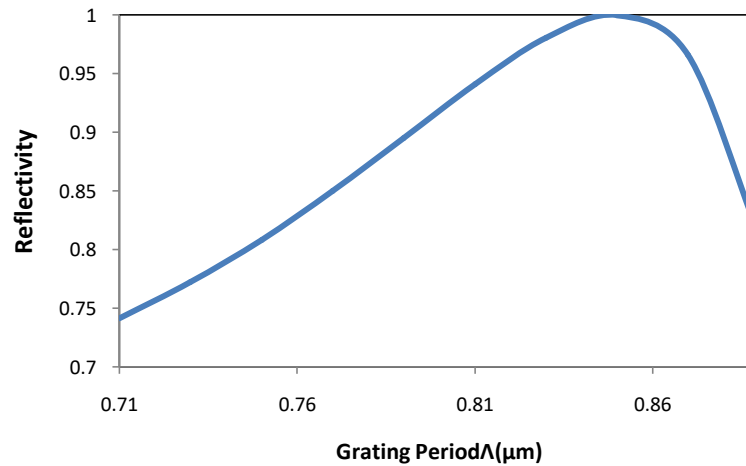


Figure 3.9 : Reflectivity of one dimensional HCG at different grating periods for TE mode at 1550 nm.

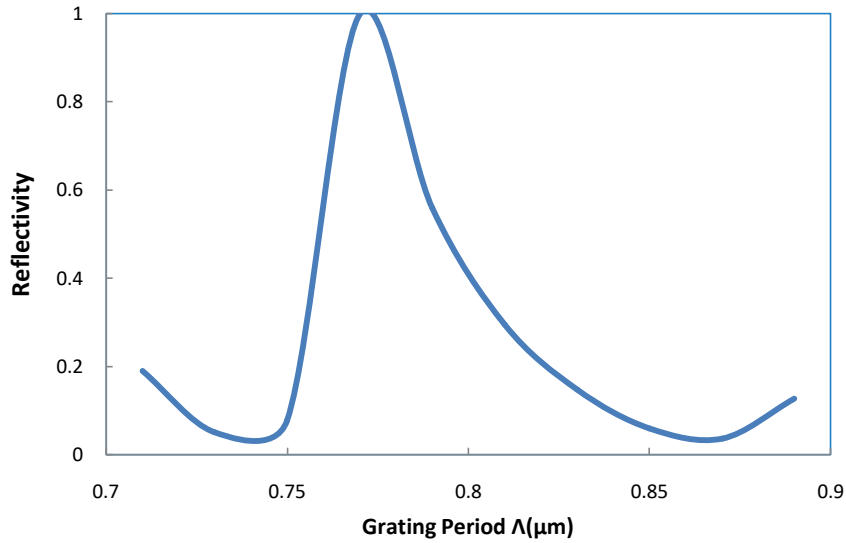


Figure 3.10 : Reflectivity at different grating periods of one dimensional HCG for TM mode at 1550 nm

Mentioned SOI HCG is designed for 1.55 μm center wavelength, whose design parameters are: refractive index of substrate is 3.48 (Si), refractive indices of air and low index material (SiO_2) are 1 and 1.47 respectively, grating period Λ is varied from 0.71 to 0.89 μm , grating thickness t_g is varied to 0.6 to 1.5 μm and duty cycle C is varied from 0.1 to 0.5. The design parameters are optimized to achieve maximum reflectivity for TM and TE polarization. In figure 3.9, reflectivity is maximized to 99.99 % with optimum value of t_g of 0.7 μm , Λ is 0.85 μm , C is 0.2 for TE mode and Figure 3.10 shows the reflectivity spectra for TM mode with maximum reflective of 99.84 % with optimum value of t_g of 0.6 μm , Λ is 0.77 μm , C is 0.6. Table 3.1 shows the set of optimized value of design parameters of 1D HCG for TE and TM mode.

1D HCG	TE	TM
Grating Period (Λ)	0.85 μm	0.77 μm
Duty Cycle (C)	0.2	0.6
Grating thickness (t_g)	0.7 μm	0.6 μm

Table 3.1 optimized values of 1-dimensional HCG of TE and TM mode at 1550nm.

3.5 Summary

The design parameters of one-dimensional and two-dimensional HCG have been discussed. The design parameters of the HCG play an important role on reflectivity. All the design parameters have a great impact on the reflectivity of HCG. Analytical model of HCG have been discussed. Simulations of one-dimensional HCG and two-dimensional HCG have been carried to achieve maximum reflectivity for TE and TM mode. For one-dimensional HCG, the design parameters are $n_{substrate}$ (refractive index of substrate) = 3.48 (Si), $n_{superstrate}$ (refractive index of air) = 1, n_H (Refractive index of high index material) = 3.48 (Si.), n_L (refractive index of low index material = 1.47 (SiO₂), grating period Λ is varied from 0.71 to 0.89 μm , grating thickness t_g is varied to 0.6 to 1.5 μm and duty cycle c is varied from 0.1 to 0.5. the design parameters are optimized to achieve maximum reflectivity for TE and TM mode. The maximum reflectivity of 99.99 % is achieved with optimum value of t_g of 0.7 μm , Λ is 0.85 μm , C is 0.2 for TE mode and the reflectivity spectrum for TM mode with maximum reflective of 99.84 % with optimum value of t_g of 0.6 μm , Λ is 0.77 μm , and c is 0.6. These optimum values of design parameters can be useful for the various devices like hollow optical waveguides based on HCG.

Chapter 4

Grating based Hollow optical Waveguide

In this chapter, Hollow waveguides are discussed, and a high index contrast based hollow optical waveguide design is proposed. The properties in terms of propagation of the proposed waveguide have been studied. Also, the concept of slow light is discussed.

4.1 Introduction to hollow optical waveguides

There are various applications where Optical fibers have been used which includes optical signal processors, optical buffers, RF filtering and optical sensing. The use of optical Fibers in all these applications is due to benefits such as low dispersion, a wide bandwidth, ultra low loss and nonlinearity. But they have some disadvantages too, they are bulky, heavy and difficult to manufacture. In the today's scenario of science and technology the miniaturization is one of the main criteria. Hollow waveguides without having core material are deserving candidates for achieving fiber like nonlinearity and dispersion and low loss. Hollow core waveguides (HCWs) consists of a hole covered by a highly reflective wall/cladding. The core can have air, inert gas, and vacuum or liquid (water, methanol, ethanol, etc.) which makes these waveguides to transmit a large range of wavelengths with low loss.

The flexible design and cost-effective fabrication are two main advantages of hollow core waveguides. These two advantages are the reason that they are beneficial in numerous applications based on optoelectronic devices. Hollow waveguides have the additional advantages like no end reflection, high laser power thresholds, small insertion loss, low beam divergence and ruggedness. Sensing and high transmission is the area where Hollow core waveguides are used because they are having characteristics like low nonlinearity, low loss and high thermal stability [34, 82, 97-103]. As we know that waveguide structures are advantageous by means of reducing the size of integrated optical components [104-105]. As the need for better performance has increased, low propagation loss and wide wavelength spectrum is required. There are numerous advancements in the waveguides. In the past few years, there have been improvements in the hollow core waveguides, and the latest trend in hollow waveguides is the ones with photonic crystals (PhCs), etc. [106-108].

A new tool for applications has been emerged by directing light in a low index media that

is covered by a high index media. Chip scale hollow optical waveguides are required due to the low cost of manufacturing of on chip devices which has a capability to monolithically integrate the detectors, light sources etc. .

Because of the high reflectivity of HCG it finds a use in one of the fields that interests this study which is reflector in Hollow optical waveguides. Hollow core waveguides with top and bottom mirror as high index contrast grating are able to confine light without the sidewalls. It is useful for gases or fluids which have are not easy to flow into a device with narrow cores. A high index contrast grating (HCGs) offers a high reflection for surface-normal incident light [105, 107-108]. An extremely low loss has been achieved by hollow waveguide having HCGs on top and bottom surrounded by air. It has a capability to reflect light at shallow angles. HCG HW can be utilized as a fundamental element in a number of on chip integrated photonic devices which can be used in various optoelectronic devices like optical delay lines, optical interconnects etc. [109].

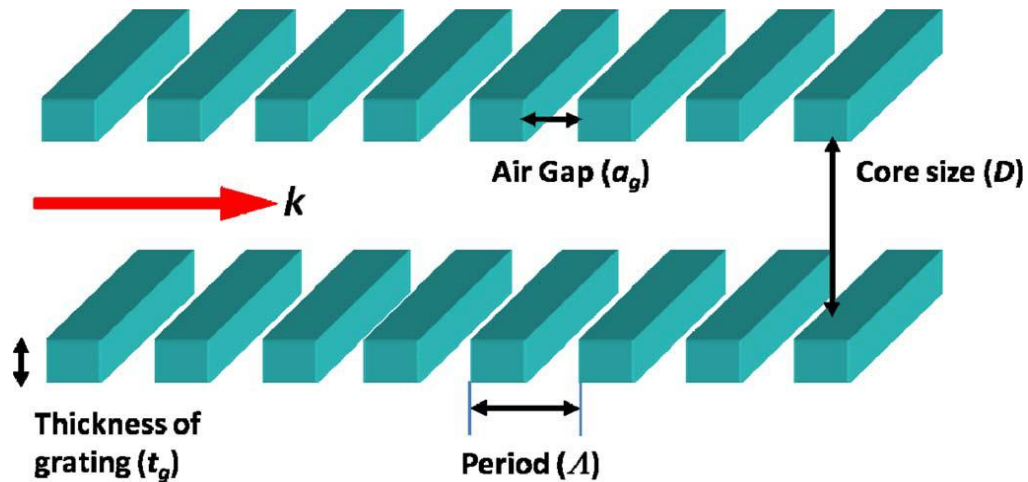


Figure.4.1: High index Contrast Grating –Hollow optical Waveguide [97]

The light can propagate in parallel or perpendicular direction of the grating strips. Figure 4.1 shows the diagram of HCG hollow waveguide indicating the light propagating in the perpendicular direction to the grating bars [97]. Figure 4.2 is the HCG based hollow optical

waveguide which has light propagation in parallel direction to the grating bars. According to ray optics, the incident optical light is directed inside the waveguide by zigzag reflections from the walls. The design parameters grating thickness t_g , gating thickness of low index material t_L , air core gap D and the incident light is given by the red arrow.

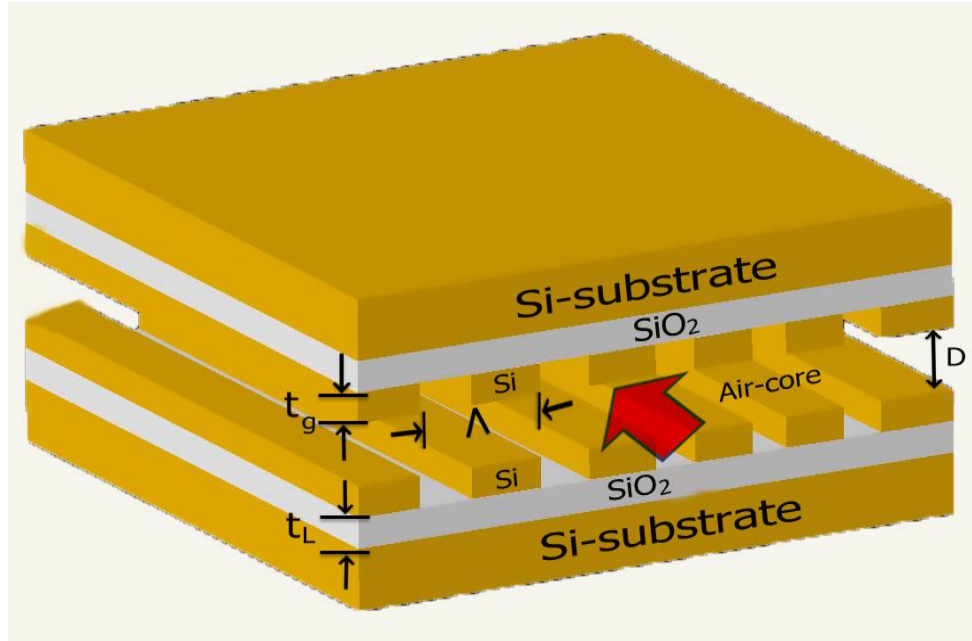


Figure4.2: Hollow optical waveguide with HCG at the top and bottom on a Silicon-on-insulator (SOI) wafer.

HCG based hollow optical waveguides have very useful applications in the field of integrated optoelectronics and have come up with various new on chip applications such as slow light, gas sensing, optical switch, coupler etc.

In the recent years, slow light is the new research term in the area of photonic crystal (PC) waveguides (PCWs). There is a broad range of applications where slow light is used in waveguides, a few to name are optical delay lines or buffers and enhancement in interaction of light and matter, in the linear and nonlinear regime. The reason behind it is that the effect of slow light is well conditioned at room temperature and fabrication of various application based devices is done standard planar semiconductor technologies [109-110]. The two main reasons /terms which are propagation loss and dispersion which may overshadow the benefits from slow light because of excessive loss or pulse broadening [111-114].

In this chapter, a HCG based hollow optical waveguide is proposed and analyzed and also

slow light characteristics are studied. An air-core which is narrow can be useful to slow the light in hollow core optical waveguide. But the loss while propagating through the hollow core waveguides at narrow air core is a main concern. By using the excellent features of sub-wavelength HCG, we can overcome this problem. The propagation loss of hollow waveguides at narrow cores can be reduced with the help of HCGs. In the proposed structure of waveguide, light travels in air with HCG on top and bottom of waveguide. The method used for the results in the proposed design is FDTD method. By the optimization of design parameters of the proposed waveguide, a low propagation loss of 1.8dB/cm is achieved along with large bandwidth with a low loss. Also, the flat band slow light is carried out at a grating period of 0.8 μm with a thickness of core of 1- μm . Also, slow light characteristics are analyzed in which there is a reasonable tolerance in the variations of group index with the grating period (Λ) is attained to compensate error tolerance during fabrication.

4.2 Design of proposed HCG based hollow optical waveguide

The design of the proposed hollow waveguide structure is shown in Figure 4.3. The hollow waveguide consists of a HCG as mirror on top and bottom. HCG's high reflectivity confines the light in narrow core. The HCG mirror consists of a high index contrast between the high index material silicon and low index material air grating. Many in-plane reflections come up and results in the high reflection of a HCG mirror [30]. It is comprised of a Si-substrate which is 5 μm thick topped with a SiO_2 layer which is 1 μm thick, these are the values used commercially, then we have a HCG mirror which makes HCG on SOI. This same structure is employed on top and bottom between is the air gap D. The length L and width W of the grating region of the structure is taken 6.5 μm and 3.5 μm respectively. The refractive index of SiO_2 is 1.47 and Si is 3.48. The proposed structure is designed at 10° incident angles. The main parameters for the design of the hollow waveguide are thickness of air core D, grating thickness t_g , period of grating Λ , width of grating W and grating duty cycle C. Grating period (Λ) is grating width of high index material and low index material [31,63]. The two mirrors are separated by air gap, called air core thickness D. When the incident light falls on a grating, it simultaneously excites many diffraction orders. So, the representation of solution is given by [82].

$$(E_y)_{core} = \sum_m \rho_m \cos(k_{xm} x) e^{i(k_z + mk_g)z} \quad (4.1)$$

The Bragg wave number $k_g = 2\pi/\Lambda$, k_{xm} is the lateral wave numbers and k_z is the axial wave number, which is expressed as in below :

$$k_{xm}^2 + (k_z + mk_g)^2 = k_0^2 \quad (4.2)$$

Here k_0 is the free space wave number.

Inside the grating region, the field is given by addition of the infinite number of harmonics in high index and low index regions. The solutions are given by:

$$(E_y)_{grating} = \sum_n A_n \cos(\beta_n x + \phi_n) e^{i\Gamma_n z} + B_n \cos(\beta_n x + \psi_n) e^{-i\Gamma_n z} \quad (4.3)$$

The yellow arrow in the Fig. 4.3 depicts the incident light. The optimizations of the structure to attain low loss and broad range is done on the basis of two main design parameters, period of grating Λ and thickness of air core D . The Optimization of these two important parameters is the main concern. The values of parameters used for the design of the both HCG mirror is taken same. The simulations are carried for TE mode at 1550 nm.

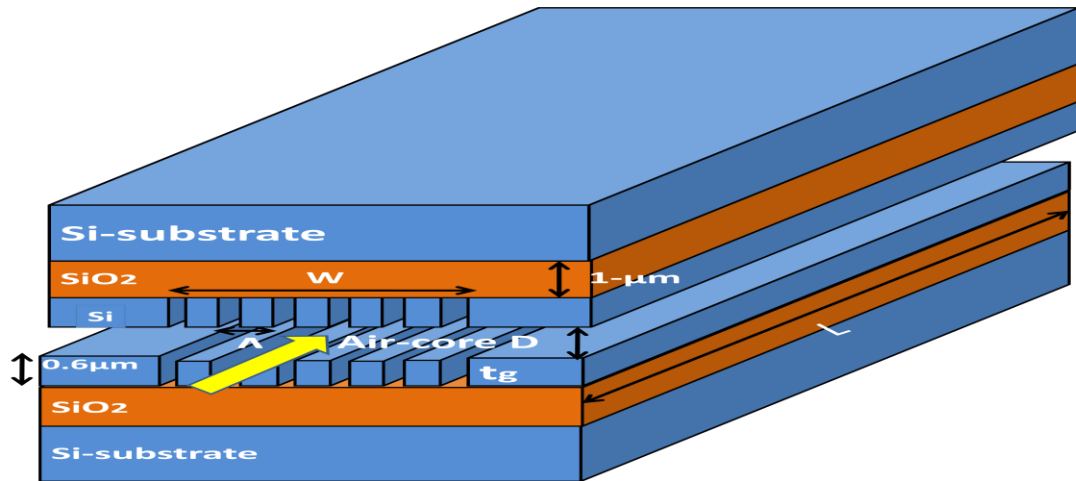


Figure4.3: Design of proposed hollow optical waveguide with HCG mirror on top and bottom on a SOI designed for 1.55 μm.

The arrangement of the proposed design gives a very clear understanding of the HCG wave-guiding concept. The optimization of both the design parameters air core thickness as

well as grating period is to attain low loss. On chip implementation of HCG based HCWs is possible by a number of bonding techniques or with the use of SOI wafer topologies having multiple layers.

A hollow-core waveguide is best understood by the ray optics model, with an optical beam guided by zigzag reflections from the guiding walls [63]. Due to large number of reflections, the propagation loss is strongly dependent on the reflectivity of walls. In the HCG based hollow waveguide, where the optical beam is guided by zigzag reflections from the HCG. High-contrast sub wavelength gratings (HCGs) provide very high reflection for surface-normal incident light and can be designed to provide high reflectivity at other angles too.

The field distribution of the wave inside the hollow air core waveguide for the optimized parameters is shown in the Fig.4.4 Shows the propagation of light wave through the waveguide without any sidewalls with a low loss. The incident light is in the Y direction at 10° incidence and the waveguide is in x-z direction.

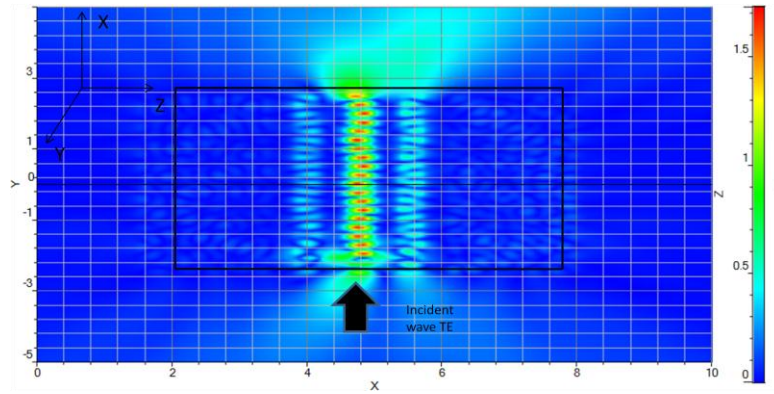


Figure 4.4: Field propagation in the HW at 1550 nm wavelength for TE mode. The air core 1 μm thick, grating period is 0.8 μm , grating thickness is 0.6 μm for both HCG mirrors

The optimization of one of the important design parameter i.e. grating period is done in a way that the light is propagating in the air core which is having a narrow thickness ,it possess a low loss and low dispersion with no side walls for TE mode at 1550 μm .This makes it implementable for gases and liquids as well. Propagation loss of 1.8 dB/cm is achieved at Λ is 0.8 μm , C is 0.5 and grating thickness t_g is 0.6 μm for TE mode and at an air core D 1- μm thick.

The characteristics of slow light are studied at an air core thickness of 1 μm . There is a noticeable effect on the data signal in terms of delay with a change in group index n_g . The group velocity of light is the inverse of first order dispersion, i.e. $\left(\frac{dk}{d\omega}\right)^{-1}$ [45]. The group velocity V_g of light is defined as: $V_g = \frac{d\omega}{dk}$, where k is the wave number and ω is angular frequency.

The group index is defined as [38]

$$n_g = \frac{c}{V_g} = c \left(\frac{dk}{d\omega} \right) \quad (4.4)$$

To raise the group delay in the device, we need to minimize the value of group velocity; therefore, we need a maximum value of group index. A high group index is required to decrease the propagation speed of light.

4.2.1 Propagation Characteristics of proposed waveguide

FDTD method is used for the calculation of propagation loss of the HCG based HW. Two high index contrast gratings on SOI are separated with an air core D . Low loss and large bandwidth is achieved by optimizing the grating period Λ and D . Also, characteristics of slow light are studied for the proposed structure. In conventional hollow waveguides, loss is inversely proportional to D^2 . So for loss to be minimum, air core thickness needs to be more. For the realization of wide tuning in hollow optical waveguides, narrow core and low loss is required.

Fig. 4.5 is the graph of loss at different grating period's Λ (0.2 μm to 1 μm) at various air core thicknesses D (1 to 5 μm). The air core thickness has a strong impact on hollow waveguide in terms of propagation. Hence wide tuning can be achieved by carefully choosing the value of air core thickness. we can see, for all values of D , at grating period 0.2 μm which is a small value, the loss is high which has a value above 6.8 dB/cm for all the air core thickness D . Then value of loss drops to 2.5 dB/cm after that it begins to increase at value of grating period Λ of 0.6 μm , then again its starts to drop at Λ of 0.8 μm

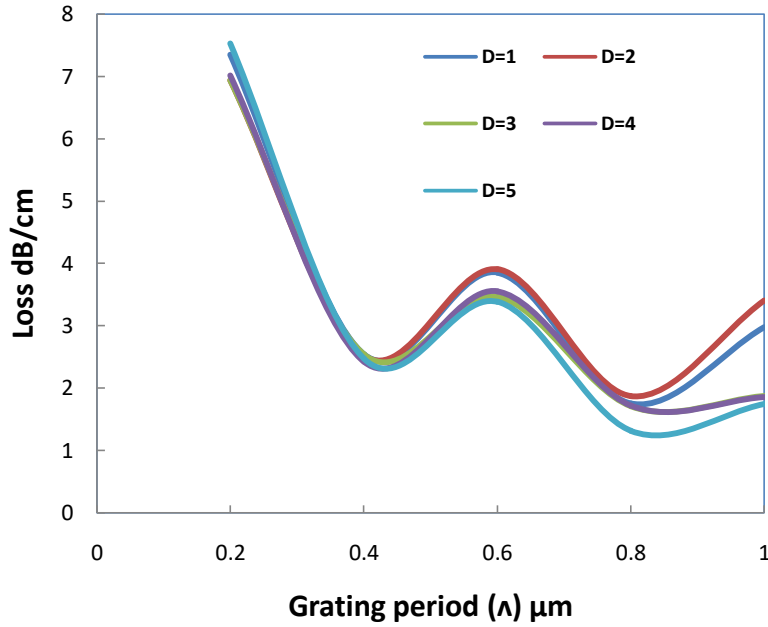


Figure4.5: Loss at various grating periods (Λ) from 0.2 μm to 1 μm for different air core thickness (D) (1-5 μm) with a grating thickness t_g 0.6 μm and duty cycle C 0.5 for TE mode.

So, grating with a grating period smaller than the wavelength has more loss in the case of proposed design hence is not suitable in order to achieve low loss in waveguide. With the amazing characteristics of HCGs mirrors, we can lower the loss of the proposed waveguide at a narrow air core. The optimized grating period is 0.8 μm at the narrower air D of 1 μm , the loss achieved is 1.8 dB/cm which is considerably a low value with the air core thickness chosen. Narrow air core waveguides are useful in many low temperature dependent optical devices with control on tunability. A waveguide with a small value of air core thickness having a low loss with wider bandwidth is important which will be beneficial in achieving broadband low loss for numerous integrated photonic devices.

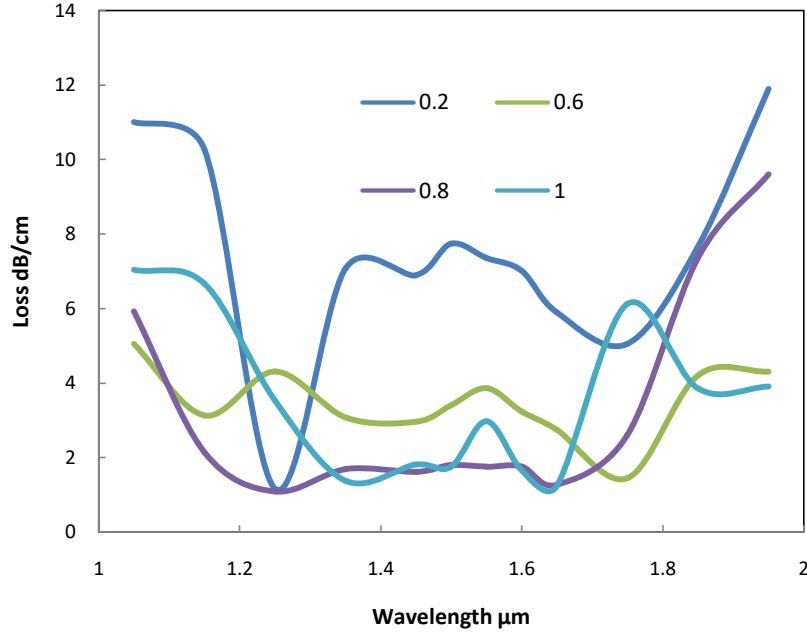


Figure.4.6: wavelength spectrum at various grating periods (0.2 μm , 0.6 μm , 0.8 μm and 1 μm).The air core is 1 μm thick, grating has thickness t_g of 0.6 μm and duty cycle c is 0.5.

In Fig. 4.6, the loss is calculated from 1150 nm to 1950 nm wavelength range at different values of grating periods Λ which are 0.2 μm , 0.6 μm , 0.8 μm , and 1 μm at an air core which 1 μm thick and it is narrow. If we analyze the wavelength spectrums for all the grating periods, the grating period 0.8 μm is having the best results out of all. At grating period Λ 0.8 μm , loss has a higher value at wavelength of 1150 nm, after that it starts to take a dip and the value remain slow for 1200 nm to 1650 nm wavelength range and then further it begins to increase. The loss below 2 dB/cm at grating period Λ of 0.8 μm is achieved for a wide wavelength from 1200 to 1650 nm. The optimum grating period is 0.8 μm with a narrow air core thickness D of 1 μm .

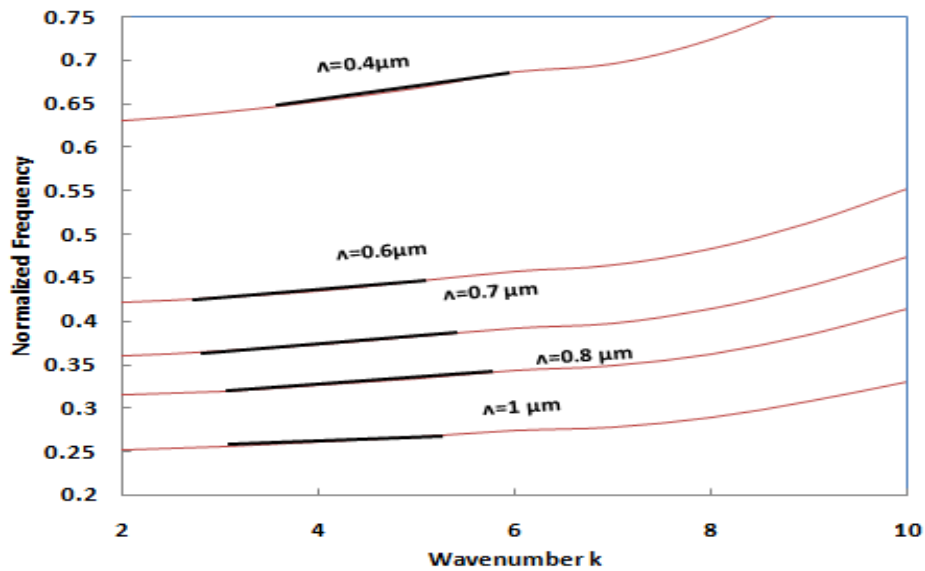
4.3 Slow Light Characteristics

The characteristics of slow light are studied for the proposed on chip HCG HW to reduce the speed of light while propagating, which should have a constant value of frequencies over a large range.

The photonic band is shown in Figure 4.7(a) of proposed HCG HW for the main mode of propagation for TE mode at different grating period λ . As the value of grating period goes high it, the band shifts to lower frequencies. Each curve in Figure 4.7(a) has a curve which goes from upwards, linear then again up facing. The highlighted black region shows the linear region i.e. flat band region. The group indices at various values of air core thickness D taken which are $1\mu\text{m}$, $2\mu\text{m}$, $3\mu\text{m}$, $4\mu\text{m}$ and $5\mu\text{m}$ is shown in Figure 4.7(b) at a value of grating period that is already optimized as $0.8\mu\text{m}$. At lower values of air core thicknesses the value of group index is high, when there is a increase of air core thickness D , the group index starts to decrease with respect to wave number. It is self-explained in Fig. 4.7(b) that propagating speed of light is slow at small thicknesses of air core of the proposed design. At the larger value of D which is $5\mu\text{m}$, the group index n_g has lesser value. The group index n_g is increasing as there is a decrease in the value of air core thickness D . Therefore, there is a slow propagation of light propagation at $1\mu\text{m}$ thick air core.

Figure 4.7(b) is the characteristics of group index for the photonic bands (Figure 4.7(a)). We can clearly see in the graph that a slow wave is observed at lower wavenumbers as group index is high at lower wavenumbers. The values of group indices are carried out for the various values of grating periods which are taken as $0.4\mu\text{m}$, $0.6\mu\text{m}$, $0.7\mu\text{m}$, $0.8\mu\text{m}$ and $1\mu\text{m}$.

(a)



(b)

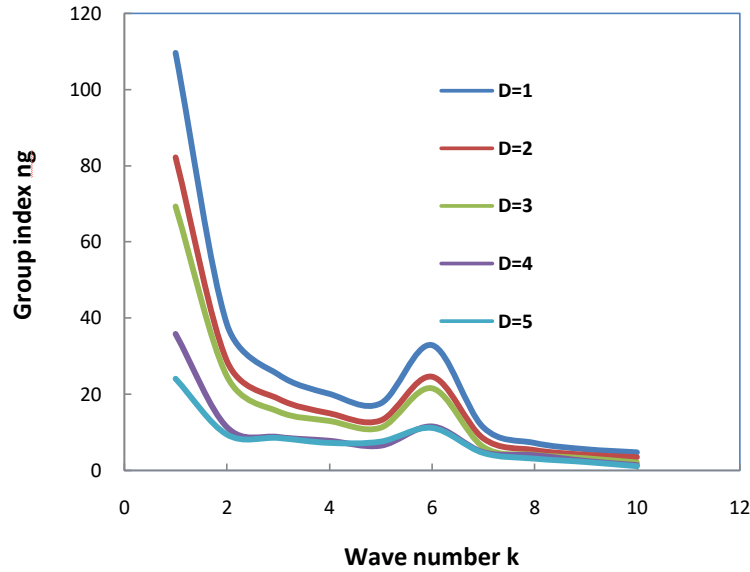


Figure 4.7: (a) photonic band (b) Group indices at different air core thickness D

The D is 1 μm . We can see in the graph, a step like behavior. Generally, the group index n_g is considered as constant within a range of $\pm 10\%$ [115-116]. It can be clearly seen in the graph that the bandwidth of flat band is more, and value of group index is less when grating period is low. On the other hand, at larger grating periods, the value of group index is more and flat band region is reducing. We can say that, there is a compromise between large flat band region and high group index in the proposed structure.

To slow down the speed of light value of grating period is be varied. The value of grating period can be chosen in accordance with the application whether they require high n_g , with low bandwidth or vice versa. Taking into consideration of all these conditions, the optimum value of grating period Λ is 0.8 μm and air core thickness D is 1- μm . In the inset graph, a smaller range of grating period is studied; the range of grating period is taken from 0.79 to 0.84 μm . A similar kind of behavior of slow light can be observed for these given set of grating periods. The value of group index remains almost same with similar flat band region which makes the proposed design more practical as it is able to tolerate the errors caused during fabrication.

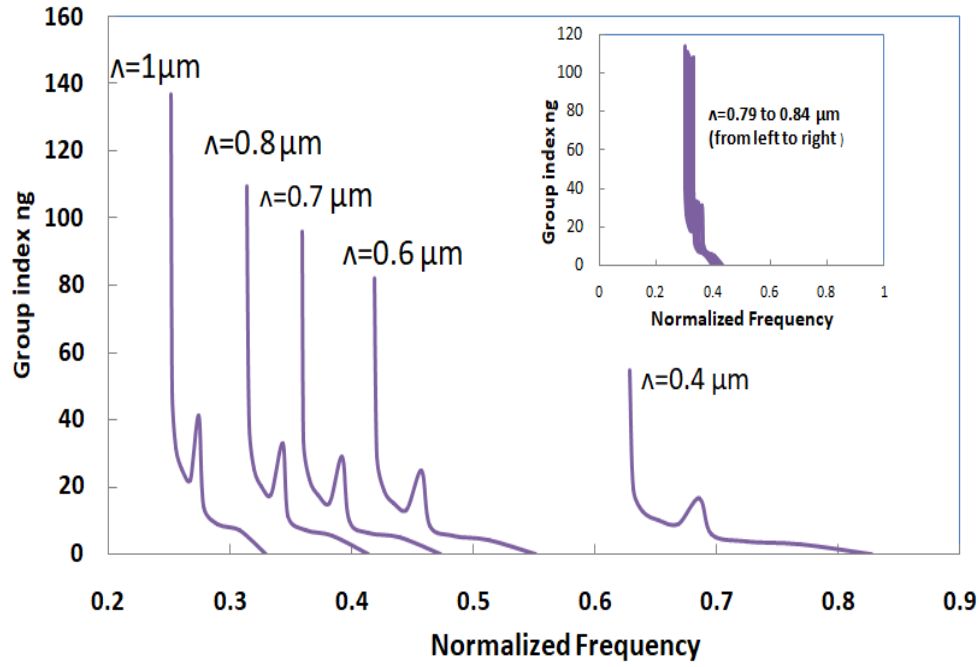


Figure4.8: Group indices at various grating periods proposed HCG based hollow waveguide design at an air core thickness D of 1- μm . Inset graph show the slow light characteristics for a grating period λ range of 0.79 μm to 0.84 μm .

The group index calculated for the proposed HCG HW is not high in comparison with the photonic crystal waveguides but taking into account the other design parameters like narrow core, low loss and SOI wafer used in the proposed design of hollow optical waveguide, it can be a good candidate to be used in a number of on chip integrated photonic devices. The analysis of the work is done in two steps: first we have tried to reduce the loss of the proposed HCG based hollow optical waveguide at a narrow core for a wide wavelength range. After that with the same set of design parameters which have been optimized for the proposed waveguide design, we have studied the behavior of slow light. There is a compromise between high group index and large flat band region. The set of optimized design parameters are air core thickness D of 1 μm grating period λ is 0.8 μm , a similar kind of behavior can be observed for grating period range of 0.79 to 0.84 μm that increases the fabrication error tolerance.

4.5 Summary

A hollow waveguide using HCGs is proposed and designed. Low loss with a narrow air core is achieved. The behavior of slow light is also studied for the proposed on chip waveguide design. The slowing of light occurs in air core between the HCG mirrors without any sidewalls. The propagation characteristics of slow light of a proposed narrow core HCG HW at 1550 nm at 10° incidence for TE mode are studied. The proposed waveguide design has a low propagation loss of 1.8dB/cm at a narrow air core of $1\mu\text{m}$. The loss is low for a broad wavelength range which is from 1200 to 1600 nm. Also, the flat band slow light is realized at the optimized grating period and air core thickness. Slow light properties are studied in which reasonable tolerance of variations in group index with respect to grating period (Λ) is obtained to accommodate fabrication errors, making it useful for many practical applications such as optical buffers and delay. The properties of slow light remain unaltered for the grating period Λ range 0.79 to $0.84\mu\text{m}$. The proposed design can find applications in various on chip integrated devices.

Chapter 5

Two-dimensional HCG based on chip optical Reflectors

5.1 Introduction

Fiber Bragg gratings (FBG) play an important role in applications used in optical fiber communication including lasers and sensing. Various tunable optical devices like filters, tunable lasers, and tunable dispersion compensators are finding importance in many future high-speed (WDM). All the characteristics possessed by FBG, the reflectivity is fixed after fabrication [92]. The most promising quality of an FBG is the slim bandwidth reflection spectrum. There has been a lot of research done on dielectric or polymer waveguides-based Bragg reflectors.

Surface normal broadband reflectors (BBRs) which are ultra-compact are fundamental components for a variety of applications in optoelectronic devices, like micro cavities, photo detectors, lasers, sensors, silicon photonics etc. [117-119]. The multi-layer distributed Bragg reflectors (DBR) can be changed by a high index contrast sub-wavelength grating (HCG). It can be utilized broadband reflectors which are highly compact; it can be advantageous for a large variety of on chip device applications. Few applications in electro-optic devices where HCGs are used including hollow-core waveguides (HWs), vertical-cavity surface-emitting lasers (VCSELs), high-Q optical resonators etc.. HCGs can be used as broadband high-reflectivity mirrors for surface-normal incident light which can be used as a in place of DBR in various optical devices [19,120--124] making the device compact in size. However, one-dimensional HCG structures are polarization-dependent due to periodicity in one direction. Recently, a number of polarization independent reflectors have been proposed and reported which consists of complicated grating structures [125, 126]. Whereas two-dimensional HCGs can be used for the realization of both polarization independent and dependent operation [67]

The broad band and the high reflectivity of the sub-wavelength grating are the results of the large Refractive Index difference. Distributed Bragg reflectors (DBRs) (thick and multilayer) can be replaced by HCGs most importantly for VCSEL applications. The implementation of HCGs is done by materials having high refractive index such as silicon, silicon nitride etc. for visible and near-infrared applications.

Most of research on HCGs has been focused on one-dimensional (1D) HCGs. The

HCGs periodic in one-dimension have a high reflectivity only in one polarization either for TE and TM mode [127]. One-dimensional HCG reflectors are polarization sensitive. So, they can have high reflectivity at a particular polarization i.e. TE or TM. The low polarization dependence is very much useful for VCSELs in communication applications. Recently so many applications have come up where polarization insensitive HCGs are required, which are two-dimensional (2D) HCG. VCSEL using a polarization insensitive HCG mirror on SOI for a polarization bi-stable device that is it can be used for both polarizations; have been designed [128].

In addition, high reflectivity with oblique incidence is also required for a number of applications like hollow waveguides, planar power reflectors and lenses. It is possible to further enhance the functionality of an HCG by providing periodicity in one more direction thereby making it 2D HCG which exhibit low polarization dependence between two orthogonal linear polarization modes, the reflectivity has to be high for these cases.

In this chapter, we have studied the reflection characteristics of a two dimensional HCG with respect to various important design parameters. Also we have proposed and designed a on chip reflector with low polarization dependence at Bragg. The design parameters of the proposed two dimensional HCG are optimized to get a high reflectivity at both polarization making it a polarization insensitive design.

Also, another design we have proposed is of a two-way reflector which shows high reflectivity at vertical as well as Bragg incidence. The proposed reflector behaves like a Bragg mirror at Bragg incidence ($\theta = 90^\circ$), it can be used in hollow optical waveguides at oblique incidence ($\theta = 80^\circ, 85^\circ$), and at normal incidence ($\theta = 0^\circ$), it can be beneficial in VCSELs. Depending on the angle of incidence the proposed design will behave accordingly. Analysis of the proposed design is done using FMM. The high reflectivity is attained for the proposed design by optimizing the design parameters which includes grating thickness and grating period for normal, oblique and Bragg incidence. Also, the angular dependence is obtained and the validation of results is done using FDTD method. The wavelength spectrum of the proposed two-way reflector is also analyzed, making an efficient design of the 2D HCG.

5.2 Simulation of Two-Dimensional Reflector

Figure 5.1 shows the schematic of a two-dimensional HCG. Mentioned SOI HCG is designed for $1.55\mu\text{m}$ wavelength, whose design parameters are: refractive index of substrate is 3.48 (Si), refractive indices of air and low index material (SiO_2) are 1 and 1.47 respectively, grating period is taken same in both x and y directions and varied from 0.71 to $0.89\mu\text{m}$, grating thickness t_g is varied to 0.6 to $1.5\mu\text{m}$ and duty cycle C is varied from 0.1 to 0.5.

The design parameters are optimized to achieve maximum reflectivity for both TE and TM mode. All the design parameters are same as discussed in chapter 3 for 1D HCG; the only difference is that the grating period is having periodicity in both directions. So, the grating period in x and y direction has the same values.

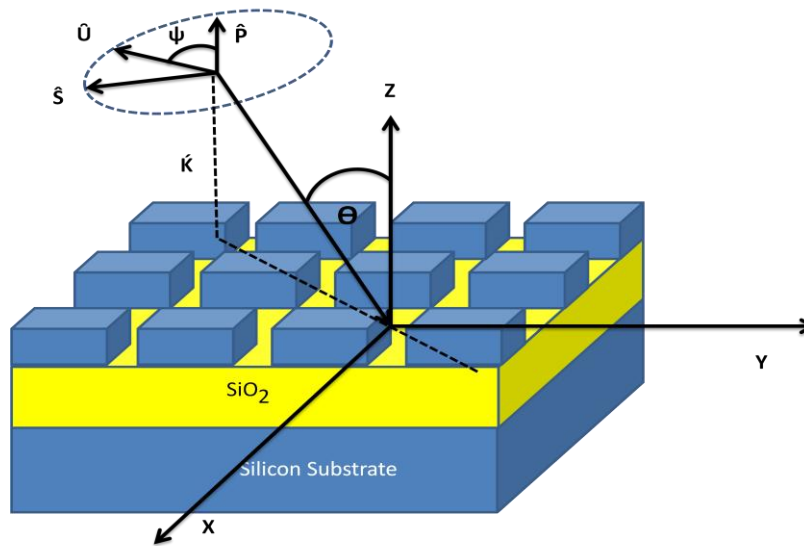


Figure 5.1: 2-Dimensional High index contrast grating on SOI

Figure 5.2 and 5.3 shows the reflectivity of the two-dimensional HCG on SOI for TM and TE mode respectively at various grating periods. Fig. 5.2 shows the values of reflectivity of two-dimensional HCG for various values of grating period 0.71 to $0.89\mu\text{m}$ for TM mode. The nature of the plot shows the reflectivity is above 96 % for the range of grating period taken. It is evident from the results that a small change in the grating period can change the reflectivity. As the grating period increases from 0.71 to $0.73\mu\text{m}$, the reflectivity increases, then takes a dip at $0.76\mu\text{m}$ then reaches to its maximum value of 99.99% at $0.77\mu\text{m}$, then its again the value of reflectivity drops at $0.82\mu\text{m}$ then begins to rise at $0.86\mu\text{m}$. So to conclude, the maximum reflectivity of 99.99% for TM mode with optimum value of grating period Λ in both

directions as $0.77\mu\text{m}$, duty cycle C 0.6 and grating thickness t_g of $1.1\mu\text{m}$.

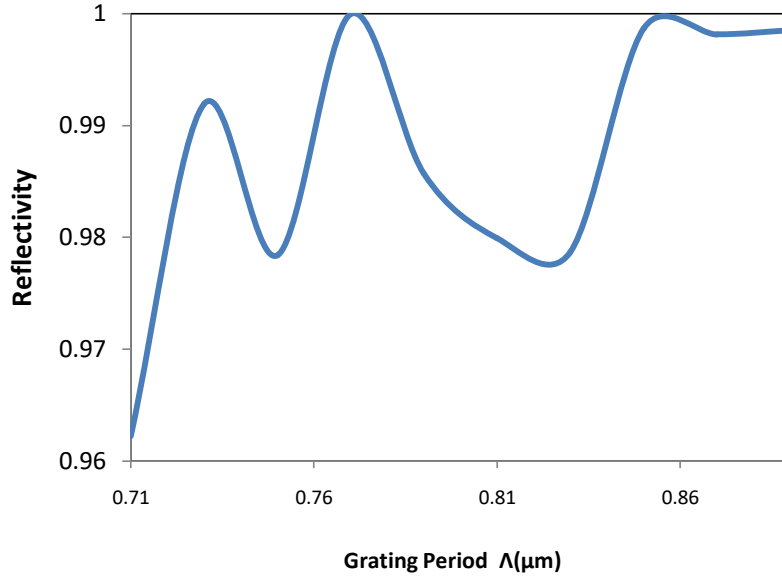


Figure 5.2: Reflectivity at different grating periods of two-dimensional HCG for TM mode at $1550\mu\text{m}$.

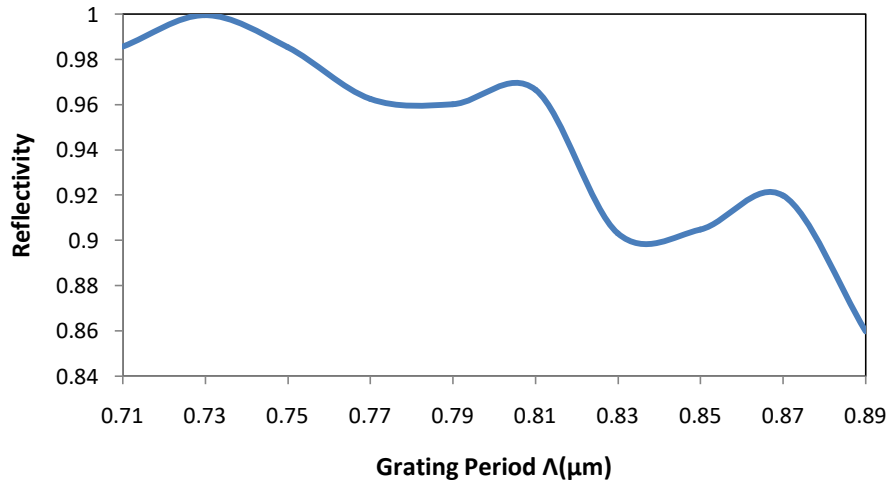


Figure 5.3: Reflectivity at different grating periods of two-dimensional HCG for TE mode at $1550\mu\text{m}$.

Figure 5.3 is the graph for reflectivity with various values of grating period for TE mode. As clear from the graph the reflectivity at different values from 0.71 to $0.79\mu\text{m}$. The maximum

reflectivity is achieved is 99.99 % for TE mode at grating period of $0.73\mu\text{m}$. The optimized values of design parameters can be useful for the base for different devices which can be made using HCG having periodicity in two directions.

5.3 On chip Bragg Reflector with low polarization dependence

Two-Dimensional photonic crystals can be useful in obtaining polarization insensitivity. We are proposing a two-dimensional HCG on SOI as a Bragg reflector, a polarization insensitive design. Figure 5.4 shows a schematic diagram of a 2D HCG on SOI. It is comprised of a Si-substrate $5\mu\text{m}$ thick, then we have SiO_2 layer with thickness $1\mu\text{m}$ over which there is 2-D HCG. The length L of the proposed design is taken as $7\mu\text{m}$ and the width W is $10\mu\text{m}$. The proposed reflector is for grazing/Bragg incidence. The other design parameters are optimized to get the desired results, so the grating thickness of the grating t_g is varied from $0.4\mu\text{m}$ to $1.5\mu\text{m}$, C (Duty Cycle) is varied from 0.2 to 0.7, Grating Period in y direction is Λ_y is $1.2\mu\text{m}$, and it is taken constant.

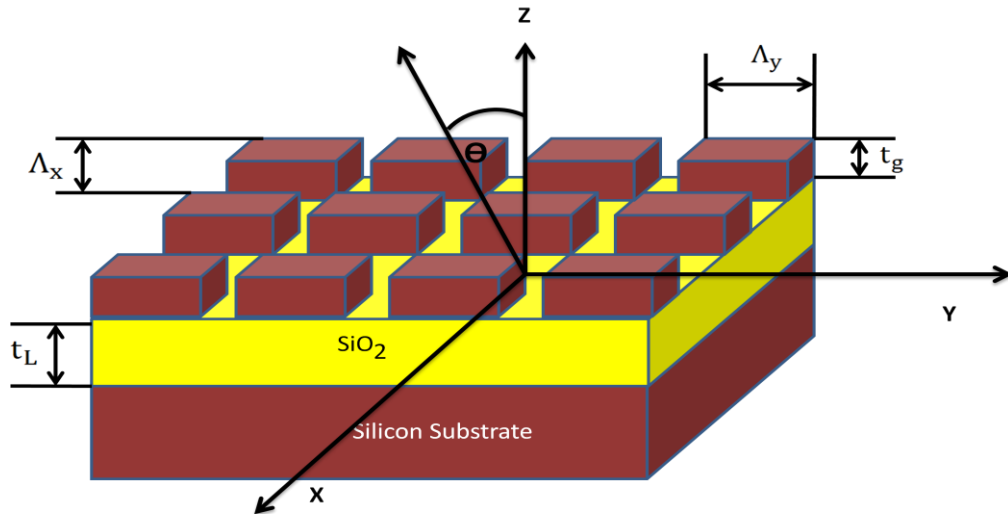


Figure 5.4: 2D HCG Reflector on a SOI wafer designed at $1.55\mu\text{m}$

Grating Period in the x direction Λ_x is varied from $0.7\mu\text{m}$ to $0.85\mu\text{m}$. All the design

parameters have been optimized to obtain maximum reflectivity at both TE as well TM mode.

Fig.5.5 shows the calculated reflectivity spectra for TE and TM mode at various Grating Period in the x direction Λ_x which is varied from $0.7\mu\text{m}$ to $0.85\mu\text{m}$ whereas Grating Period in y direction is Λ_y is $1.2\mu\text{m}$ which is constant, all other parameters of the design are taken as the grating thickness of the grating t_g is taken as $1.3\mu\text{m}$, C (Duty Cycle) is 0.6. These values are taken from the simulation results from 5.2, the optimized parameters for maximum reflectivity for TE mode. It can be observed in the figure the maximum value of reflectivity of 99.95 % is achieved for both polarizations are at the optimum value of Λ_x of $0.85\mu\text{m}$.

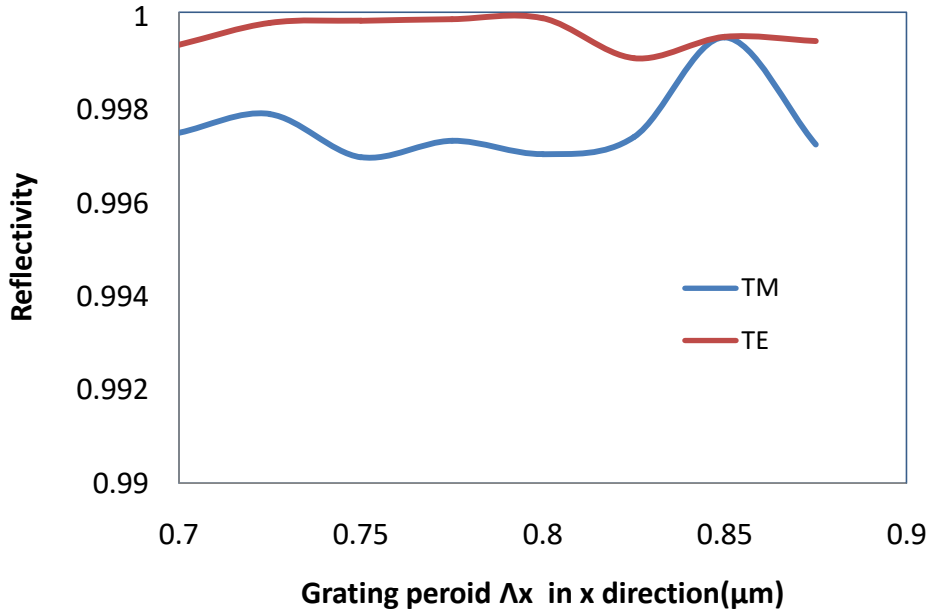


Figure 5.5: Reflectivity of 2D HCG on a SOI wafer at various values of grating period in x-direction Λ_x , designed for $1.55\mu\text{m}$ wavelength for TE and TM mode.

After getting the optimum value Λ_x of $0.85\mu\text{m}$, grating thickness t_g will be another parameter. we need to optimize the value of t_g . We have varied from t_g $0.4\mu\text{m}$ to $1.5\mu\text{m}$, Figure 5.6 shows the reflectivity versus grating thickness for TE and TM mode, the optimized value of t_g is coming out to be $0.5\mu\text{m}$ which has reflectivity of 99.73% for TM mode and 99.99% for TE mode.

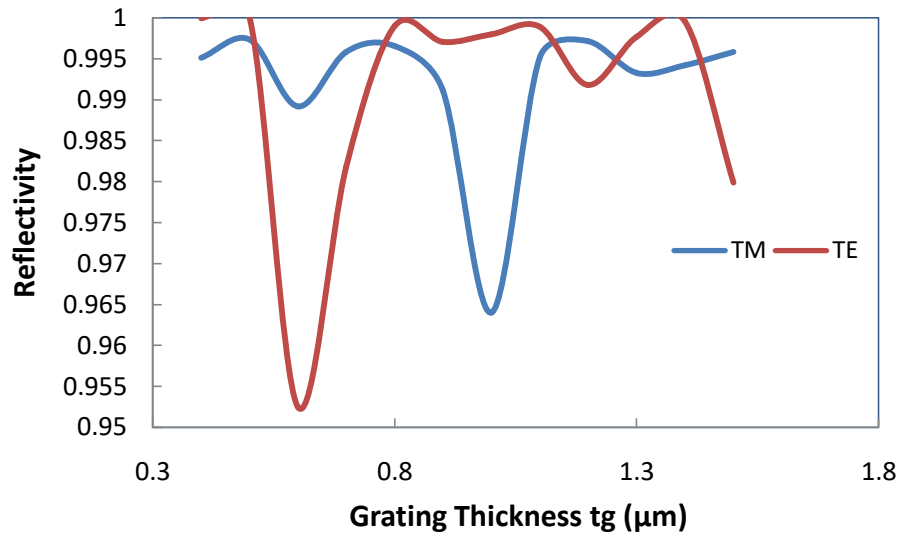


Figure 5.6: Reflectivity of 2D HCG on a Silicon-on-insulator (SOI) wafer at various grating thickness t_g .designed for $1.55\mu\text{m}$ center wavelength for TE and TM mode.

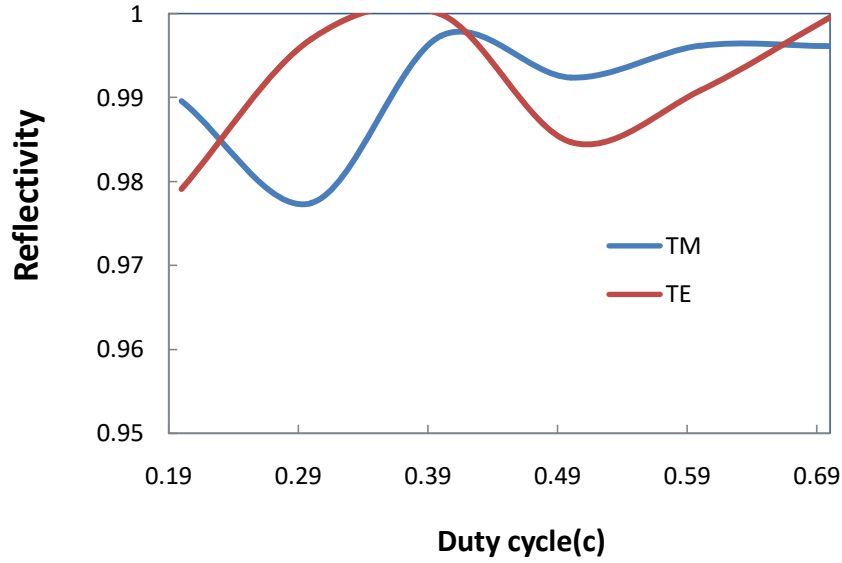


Figure.5. 7: Reflectivity of 2 D HCG on a Silicon-on-insulator (SOI) wafer at various duty cycles for 1.55 μm center wavelength for TE and TM mode.

To further increase the reflectivity to make a polarization independent design, we will optimize the another important design parameter is duty cycle c , We have varied duty cycle from 0.2 to 0.7. Figure 5.7 is the calculated reflectivity at various duty cycles for TE and TM mode. The optimum value of duty cycle is 0.4, where the reflectivity for TM mode is 99.73% and 99.99 % for TE mode.

Angular dependence with the optimized parameters is shown in Figure 5.8 for TE and TM mode. The angles are varied from 80° to 90° . The graph shows that the reflectivity is highest at Bragg incidence at $\Theta = 90^\circ$. Also the wavelength spectrum is shown in Figure 5.9. The wavelength is used from 1250 nm to 1750 nm. At 1550 nm we have maximum reflectivity for both polarizations TE and TM.

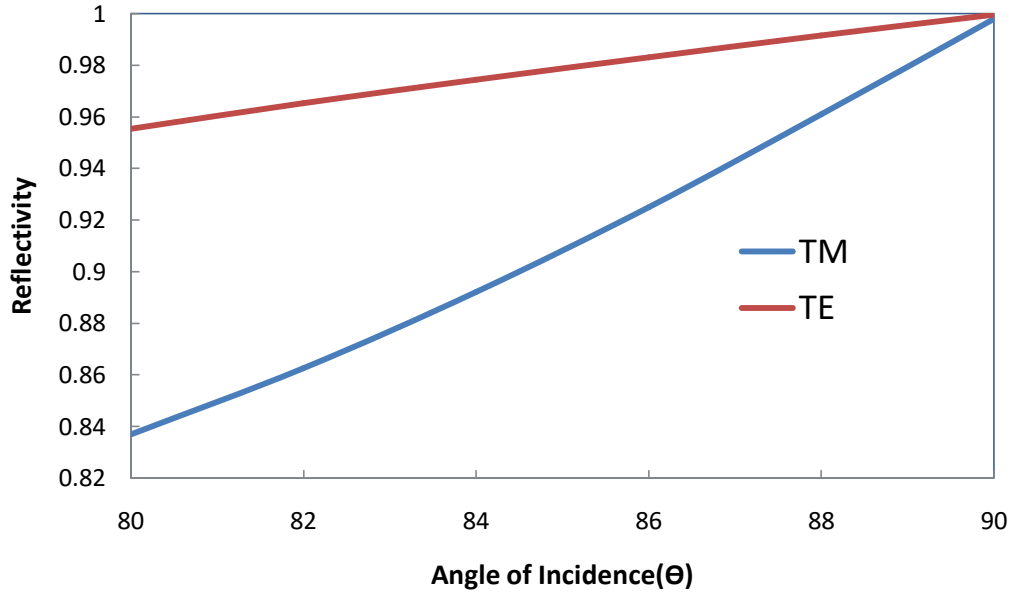


Figure 5.8: Angular dependence for both TE and TM mode at 1550 nm.

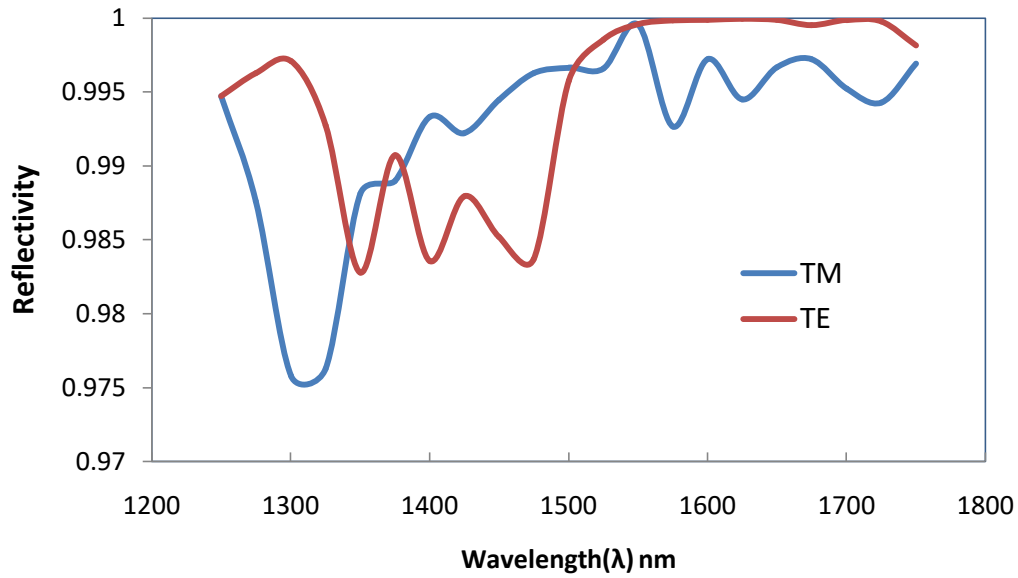


Figure 5.9: Wavelength spectrum of 2 D HCG based SOI for TE and TM mode at 1550 nm

A 2-D HCG on SOI is proposed as Bragg reflector which has a reflectivity of 99.97% for TM mode and a reflectivity of 99.99% for TE mode with optimized parameters as design so the grating thickness of the grating t_g is $0.5\mu\text{m}$, C (Duty Cycle) is 0.4, and Grating Period in y direction is Λ_y is $1.2\mu\text{m}$, Grating Period in the x direction Λ_x is $0.85\mu\text{m}$.

5.4 Two-dimensional HCG based two-way Reflector on SOI

:

A 2D HCG is proposed as a on chip two-way reflector. The proposed reflector provides high reflectivity at vertical and Bragg incidence, therefore it can act as a vertical mirror as well as a Bragg mirror depending on the angle of incidence. Two important of value of angles of incidence - normal ($\theta = 0^\circ$) and oblique/grazing ($\theta = 80^\circ - 85^\circ/90^\circ$) are deeply studied. The results are carried out using improved Fourier modal method. The vertical mirror is beneficial in VCSEL while grazing/oblique incidence can be useful in HCG hollow waveguides and Bragg reflectors. The proposed design can be useful in broadband photonic devices as it has large reflection bandwidth.

The important parameters for the design of the two way reflector are grating period in x direction as well as in y direction (Λ_x, Λ_y), grating thickness (t_g), grating duty cycle (C) and the thickness of the low index layer under the grating (t_L). All these design parameters are optimized. 2D PhC structures are used for the implementation of polarization sensitive and insensitive designs. The high reflectivity is shown by the study of angular dependence of photonic crystal mirror. The proposed two way reflector has a large reflection bandwidth which can be beneficial for a number of broadband photonic based devices. The proposed device can be useful in a number of on chip photonic crystal based devices like VSCELs, hollow optical waveguides and Bragg reflectors based on the incidence angle.

The proposed 2D reflector is shown in Figure 5.10. It comprised of a Si-substrate which is $5\ \mu\text{m}$ thick, SiO_2 layer having thickness of $1\ \mu\text{m}$ then over it there is 2-D HCG. The length L of the proposed reflector is taken as $6\ \mu\text{m}$ and the grating region width W is $10\ \mu\text{m}$. The proposed reflector is designed for vertical and oblique incidence. One of the main design parameters of the proposed structure is C (Duty Cycle); its value is taken as 0.4. The other design parameters are grating thickness, t_g which is varied from 0.3 to $0.8\ \mu\text{m}$, the value of grating period in the y direction Λ_y is $0.775\ \mu\text{m}$ which is kept constant, Grating Period in the x direction Λ_x is varied from $1\ \mu\text{m}$ to $1.35\ \mu\text{m}$, air Gap in the y direction a_y is $0.46\ \mu\text{m}$ and in the x direction a_x , its value depends on the value of grating period in x direction.

5.4.1 Reflection characteristics of the proposed reflector Design

Mentioned SOI two way reflector has different periodicities in x & y direction, whose design parameters are: Refractive index of SiO_2 is 1.54, Refractive index of Si is 3.48, θ (incident angle) is taken as $0^\circ, 80^\circ, 85^\circ$ and 90° , C (Duty Cycle) is 0.4, Thickness of Silicon Substrate is $5\ \mu\text{m}$, Thickness of SiO_2 is $1\ \mu\text{m}$. Grating thickness is an important design parameter. Grating thickness of the two-dimensional photonic crystal reflector is varied to attain high reflectivity for the set of incident angles mentioned. The thickness of the grating t_g is varied from $0.3\ \mu\text{m}$ to $0.8\ \mu\text{m}$. The value of grating period in x direction Λ_x is $1.2\ \mu\text{m}$ and grating period in y direction Λ_y is $0.775\ \mu\text{m}$. The value of air gap (a_x) in the x direction is $0.72\ \mu\text{m}$ and in the y direction (a_y) is $0.46\ \mu\text{m}$.

The simulation results are carried out for the proposed two way reflector using the modal method by Fourier expansion (MMF) in figure 5.11, reflectivity characteristics with respect to the grating thickness ranging from $0.3\ \mu\text{m}$ to $0.8\ \mu\text{m}$ at all the four incident angles is analyzed. Grating period plays an important role on the reflectivity. As shown in the figure 2, when the grating thickness is around $0.35\ \mu\text{m}$ the reflectivity is very high for oblique/grazing incidence ($\theta = 80^\circ - 85^\circ/90^\circ$), its below 70% for normal incidence ($\theta = 0^\circ$). The reflectivity starts to drop in the range from $3.5\ \mu\text{m}$ to $4.5\ \mu\text{m}$ then it suddenly increase to a high value and remains at the same value between the range $4.5\ \mu\text{m}$ to $6.5\ \mu\text{m}$ then afterwards it begins to drop for normal and oblique /grazing incidence. The highest value of reflectivity is observed in the range of grating thickness between $0.5\ \mu\text{m}$ to $0.6\ \mu\text{m}$. The highest reflectivity greater than 99.3% is obtained at $0.6\ \mu\text{m}$ grating thickness for all the incident angles with the grating period in the x direction of $1.2\ \mu\text{m}$ for TE mode. To improve the reflectivity further we will optimization of grating period in the x direction is done. The grating period in the y direction is kept constant as $0.775\ \mu\text{m}$ which is requirement for the Bragg reflection.

Λ (Grating Period) is an important design parameter of the proposed structure. It is taken different in two periodicities i.e. x and y direction. The grating period in the y direction is constant which Λ_y is $0.775\ \mu\text{m}$ and we are varying the Grating Period in the x direction Λ_x is $1\ \mu\text{m}$ to $1.35\ \mu\text{m}$ keeping the optimized grating thickness $0.6\ \mu\text{m}$. The reflectivity characteristics are observed for different values of grating periods in the x direction and keeping the grating period constant in the y direction. Other design parameters are same as mentioned in the previous discussion.

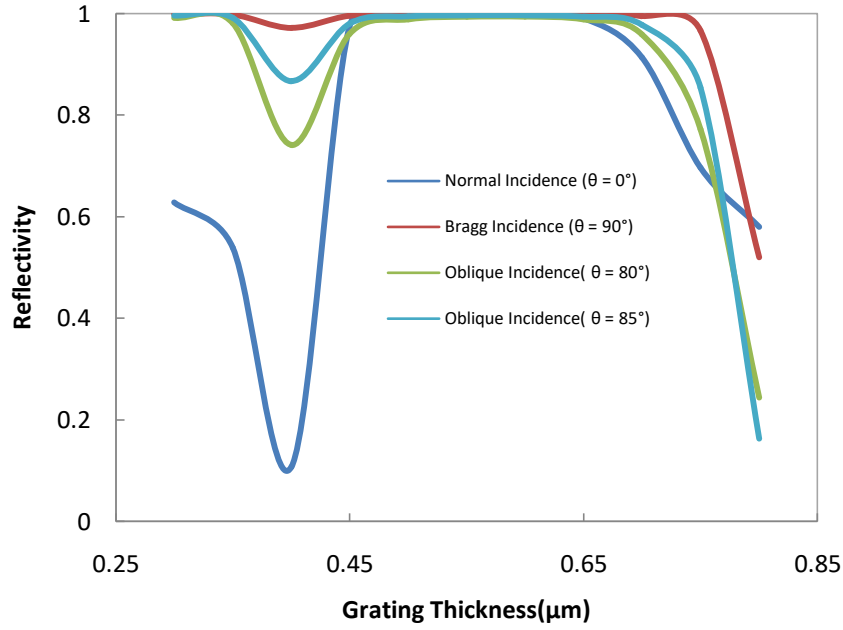


Figure 5.11: Calculated reflectivity at different grating thicknesses at of at normal incidence ($\theta = 0^\circ$), oblique incidence ($\theta = 80^\circ$ and 85°) and at Bragg incidence($\theta = 90^\circ$) for TE mode. Grating Period in the x direction Λ_x is $1.2\mu\text{m}$ and grating period in the y direction is Λ_y is $0.775\mu\text{m}$.

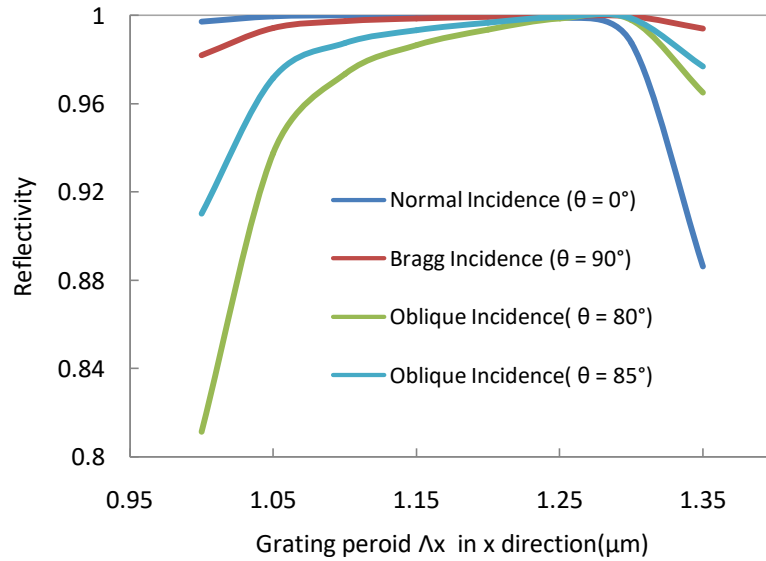


Figure 5.12: Calculated reflectivity for various grating periods in the x direction keeping the grating period in the y direction constant at incidence angles of 0° , 80° , 85° and 90° with Duty Cycle, c of 0.4, Grating Thickness t_g is $0.6\mu\text{m}$ For TE Mode.

In Figure 5.12, the reflectivity analysis with respect to the grating period in x direction Λ_x of the proposed reflector design for TE mode for all the four angles of incidence which are of 0° , 80° , 85° and 90° is carried out. As it is clear from the figure, for $\theta = 0^\circ$, the reflectivity is more than 99% for all grating periods in x direction taken. For $\theta = 90^\circ$, the reflectivity is approximately 98% at a grating period in the x direction of $1\mu\text{m}$.

With the increase of the grating period, the reflectivity begins to increase, it comes to maximum value which is 99.9% at $1.25\mu\text{m}$ grating thickness in x direction then again it starts to fall to 98% at grating period in x direction of $1.35\mu\text{m}$. For $\theta = 80^\circ$, the reflectivity at $1\mu\text{m}$ grating period in the x direction is approximately 81%, it starts to increase with increase in the grating period, it reaches to the maximum value at Λ_x of $1.3\mu\text{m}$ then again it starts to fall to a value of 98.5% at Λ_x of $1.35\mu\text{m}$. For the oblique incidence $\theta=85^\circ$, the reflectivity is 91% at $1\mu\text{m}$. As we increase the value of Λ_x , the reflectivity begins to rise and reaches to its highest value at Λ_x of $1.3\mu\text{m}$ then it starts to fall and attains the reflectivity of 96% at $1.35\mu\text{m}$. The highest value of reflectivity which is more than 99.8% has been attained for the four angles of incidence chosen at grating period of $1.25\mu\text{m}$ in x direction. At $\theta = 0^\circ$, the reflectivity is 0.999398224, at oblique incidence ($\theta = 80^\circ$) and ($\theta = 85^\circ$) the reflectivity is 0.9986576136 and 0.9993344761 respectively and at grazing incidence ($\theta = 90^\circ$) the reflectivity is 0.9998617856. The optimum value of grating period in x direction Λ_x keeping the grating period constant in the y direction Λ_y ($0.775\mu\text{m}$) is $1.25\mu\text{m}$.

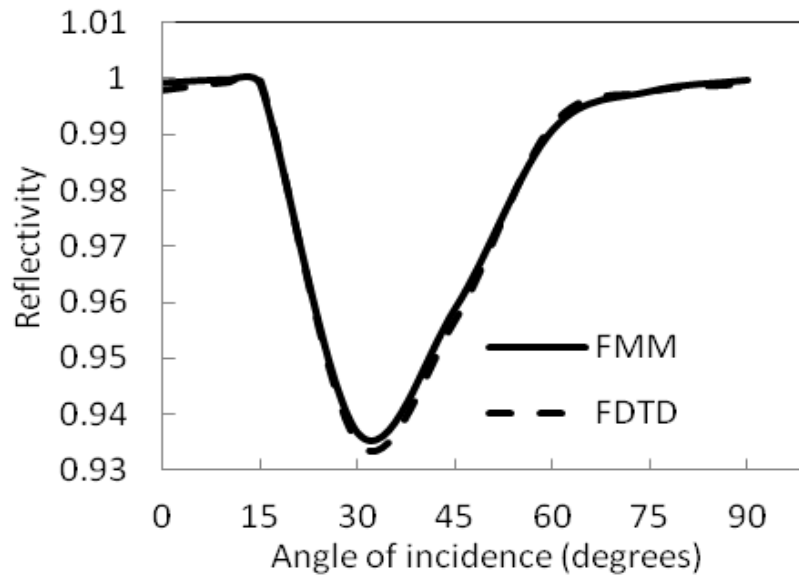


Figure 5.13: The angular dependence on Reflectivity of proposed reflector on SOI is shown for TE mode at 1550 nm using FMM and FDTD method.

The angular dependence of proposed 2d HCG reflector has its importance to find optimized grating parameters to attain high reflectivity. As shown in Fig 5.13, the reflectivity has a high value in the range 0° to 15° and then it decreases down to a lower value from the range 20° - 30° , after which it starts to rise again and achieve maximum value at 90° . The results are validated using FDTD method .

The reflectivity spectrum of the proposed designed is shown in Figure 5.14 at normal incidence ($\theta = 0^\circ$), at oblique incidence ($\theta = 80^\circ, 85^\circ$) and at grazing incidence ($\theta = 90^\circ$) is shown for TE mode. As it is clear from the graph for the wavelength range between 1300 nm to 1700 nm the reflectivity is highest for the four angles of incidence which are $0^\circ, 80^\circ, 85^\circ$ and 90° . The reflectivity is higher than 99.99% at 1550 nm. So, it can be used as a Bragg reflector and a vertical mirror at the same value of wavelength. At Bragg incidence, it can be used as Bragg reflector, at oblique incidence it can be of great use in grating based hollow optical waveguides and at normal incidence it can be beneficial in VCSELs.

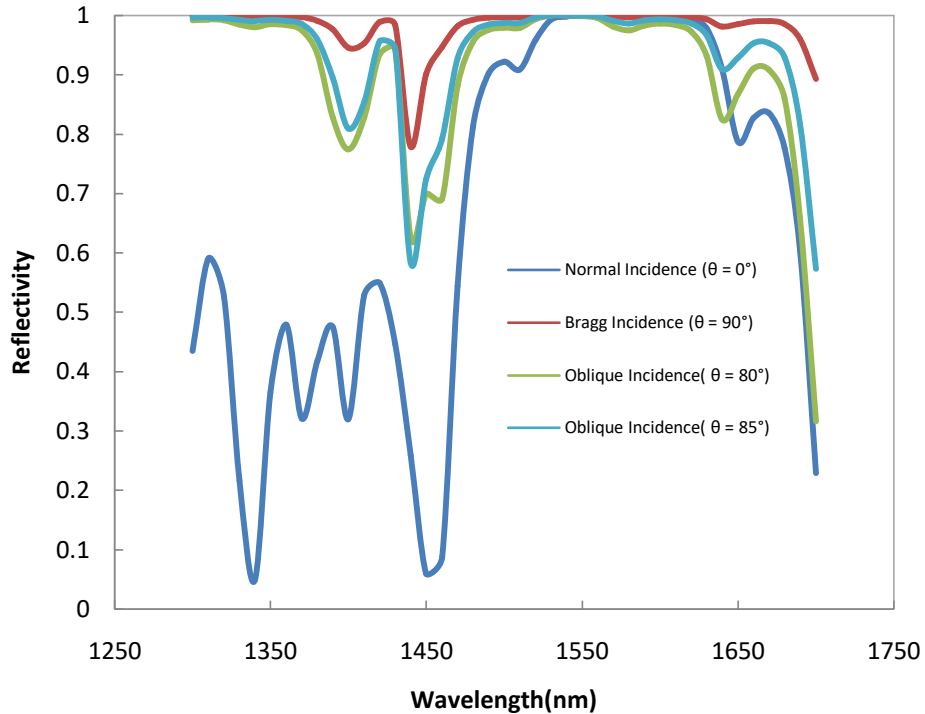


Figure 5.14: Reflectivity spectrum of a two-dimensional HCG reflector on a SOI is shown at $0^\circ, 80^\circ, 85^\circ$ and 90° incidence for TE mode. Grating Period in the x direction Λ_x is $1.25 \mu\text{m}$ and grating period in the y direction is Λ_y is $0.775 \mu\text{m}$, grating thickness is $0.6 \mu\text{m}$, duty cycle is 0.4.

5.4 Summary

The optimum values of design parameters are achieved to get maximum reflectivity for two-dimensional HCG. The maximized value of reflectivity for TM mode is 99.99% with optimized design parameters as grating period Λ in both directions as $0.77\mu\text{m}$, duty cycle c 0.6 and grating thickness t_g of $1.1\mu\text{m}$ and for TE mode the maximum reflectivity is 99.96% with optimized parameters as grating period Λ in both directions as $0.73\mu\text{m}$, duty cycle C 0.6 and grating thickness t_g of $1.3\mu\text{m}$. We can use these optimal design parameters to propose and design various devices.

A 2-D HCG on SOI is proposed as Bragg reflector which has a reflectivity of 99.97% for TM mode and a reflectivity of 99.99% for TE mode with optimized parameters as design so the grating thickness of the grating t_g is $0.5\mu\text{m}$, C (Duty Cycle) is 0.4, Grating Period in y direction is Λ_y is $1.2\mu\text{m}$, it is chosen constant, grating Period in the x direction Λ_x is $0.85\mu\text{m}$.

In this chapter a deep study of all important grating parameters on the different designs of the HCGs are analyzed. In section 5.3.1, a two-dimensional HCG SOI structure is proposed called two-way reflector which will behave as a Bragg reflector and a vertical mirror depending on the incidence angle. The dependence of grating period and grating thickness on reflectivity at normal incidence ($\theta = 0^\circ$), oblique incidence ($\theta = 80^\circ, 85^\circ$) and at grazing incidence ($\theta = 90^\circ$) for TE mode is obtained in the proposed design. The optimum value of Grating Period in the x direction Λ_x is $1.25\mu\text{m}$ and grating period in the y direction is Λ_y is $0.775\mu\text{m}$, grating thickness is $0.6\mu\text{m}$, and duty cycle is 0.4. Angular dependence of the same has also been obtained with optimized parameters. The results of angular dependence are validated using FDTD method. Also, wavelength spectrum of the proposed reflector has been analyzed at normal and oblique/ grazing incidence.

Chapter 6

Conclusion and Future scope

6.1 Conclusion

HCGs (High index Contrast Grating) have come up as a new area in sub-wavelength grating. The extraordinarily high reflectivity from the HCG is the results of the extraordinary feature of high-index gratings in which high index media is surrounded by a media. The performance evaluation of HCG for different values of angle of incidence and with different wavelengths taking into consideration the various parameters makes it easy for us to guide light inside it, according to our requirement. The Design parameters of the HCG are optimized for both one dimensional as well as two dimensional HCGs to attain maximum reflectivity. The base and motivation of this thesis is the study and optimization of HCG structures with various functionalities. Also, the polarization dependence of HCG is another important topic which has been covered in this thesis. Various types of HCGs based on chip integrated devices have been proposed in this work.

The one of the main aim of this research work is to design and analyze a grating based hollow core waveguide. A narrow air-core can be a promising choice to slow down the light guided inside hollow optical waveguide. But the main concern is the large loss while propagating is observed in hollow waveguides with narrow air cores. By using the extraordinary properties of sub-wavelength HCG, it can overshadow the lossy nature of hollow waveguides. Light can be directed in air with the help of HCG mirror based waveguide design. Further the concept of Slow light characteristics are studied of the proposed hollow waveguide

Also, 2D HCG based Bragg reflector with low polarization dependence has been designed and proposed. A polarization insensitive design of 2D HCG Bragg reflector has been proposed in this thesis. A 2D HCG is also proposed as a two-way reflector on SOI. The proposed device is resulted in high reflectivity over vertical as well as Bragg incidence.

The major findings obtained are summarized as follows:

1. The one-dimensional HCG on SOI designed for $1.55\ \mu\text{m}$ possess high reflectivity with

optimized design parameters. The reflectivity is 99.84 % with optimum value of grating thickness t_g of $0.6\mu\text{m}$, grating period Λ is $0.77\mu\text{m}$, duty cycle c is 0.6 for TM mode and for TE mode reflectivity is 99.84 % with optimum value of grating thickness t_g of $0.7\mu\text{m}$, grating period Λ is $0.85\mu\text{m}$, duty cycle C is 0.2.

2. A HCG HW design with a low loss for a broad wavelength range is proposed. The light is guided inside the air with the help of HCG as a top mirror and bottom mirror of a hollow waveguide. The structure is made up of a Si-substrate which is $5\mu\text{m}$ thick over which we have SiO_2 layer with thickness $1\mu\text{m}$ which is taken from standards of commercially available SOI wafers, and then there is a HCG on both top and bottom. The length L of the structure is taken $6.5\mu\text{m}$ and the width W of the grating region is $3.5\mu\text{m}$. Oblique incidence can be beneficial in the high confinement HCG hollow optical waveguides. The optimized value of grating period is $0.8\mu\text{m}$ at the narrow air core D of $1\mu\text{m}$, the loss is 1.8 dB/cm which is a low value taking into consideration the narrow air core gap.
3. Further Slow light characteristics of proposed low loss hollow optical having narrow core have been studied. It is shown by the results that, at narrow cores, the group index are high, as the air core thickness D is increasing; there is a decrease in the group index at different wave numbers, so the light is propagating at a slow speed at narrow air-cores. At the air- core thickness D of $5\mu\text{m}$, the values of group index n_g are low the values of group index n_g is increasing as we lower the value of air core thickness D . So, the propagation speed of light is reduced at a narrow air core thickness D of $1\mu\text{m}$.
4. 2D HCG has reflectivity of 99.99% for TM mode with optimum value of grating period Λ in both directions as $0.77\mu\text{m}$, duty cycle C is 0.6 and grating thickness t_g of $1.1\mu\text{m}$. For TE mode the reflectivity of 99.96% with optimum value of grating period Λ in both directions as $0.73\mu\text{m}$, duty cycle C is 0.6 and grating thickness t_g of $1.3\mu\text{m}$. These optimized design parameters have been used as base for another devices proposed in this thesis.
5. A 2D HCG on SOI is proposed as Bragg reflector which has a reflectivity of 99.97% for TM mode and a reflectivity of 99.99% for TE mode with optimized parameters as design so the grating thickness of the grating t_g is $0.5\mu\text{m}$, C (Duty Cycle) is 0.4, Grating Period in y direction is Λ_y is $1.2\mu\text{m}$, it is taken constant, Grating Period in the x direction Λ_x is $0.85\mu\text{m}$.
6. Also, we have proposed a 2D HCG based two-way reflector on Silicon-on-insulator

(SOI). It will behave as a Bragg mirror as well as a vertical mirror depending on the angle of incidence. The grating period dependence and grating thickness dependence on reflectivity at normal incident ($\theta = 0^\circ$), at oblique incidence ($\theta = 80^\circ, 85^\circ$) and at grazing incidence ($\theta = 90^\circ$) have been studied for TE mode. The optimum value of grating period in the x direction Λ_x is $1.25 \mu\text{m}$ and grating period in the y direction, Λ_y is $0.775 \mu\text{m}$, grating thickness is $0.6 \mu\text{m}$, and duty cycle is 0.4. Angular dependence of the same has also been obtained with optimized parameters and it is validated using FDTD method. Also, reflectivity spectrum of the proposed design has been analyzed at normal and oblique/ grazing incidence.

The proposed work is based on the design; analysis and simulation of the HCG based hollow optical waveguide as well as proposed two-way reflector which can be used to realize a nano photonic platform with acceptable low-loss and high reflectivity.

6.2 Future Scope

The future scope of the HCG based Hollow Waveguide and two-way reflector from this thesis is drawn as

The proposed HCG based hollow waveguide with a narrow core and having low loss have capability of slowing down the light, can be useful in optical delay lines or buffers and enhancement in interactions between light and matter, both in the linear and nonlinear regimes. There is need of improvement in the propagation loss and dispersion caused by slow light. Our proposed waveguide design can be useful to enable an integrated platform to make devices which need slow light.

The grating based two-way reflector can be utilized in integrated photonic circuits by varying the angle of incidence of the input light. It can be useful in a number of optoelectronic applications like Bragg reflector, Hollow core waveguides, VCSELS. So, for the further application in the field of the optoelectronics, the proposed reflector design should be checked for fabrication errors.

References

- [1] S. John, "Strong Localization of Photons in Certain Disordered Dielectric Super lattices," *Physical Review letters*, vol. 58, no. 20, 1987.
- [2] J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R.D. Meade, "Photonic Crystal Molding the Flow of Light," *Princeton University Press*, 2008.
- [3] S.E. Miller, "Integrated Optics: An Introduction," *The Bell System Technical Journal*, vol. 48, no. 7, pp. 2059–2068, 1969.
- [4] B. Jalali, "Nonlinear optics in the mid-infrared," *Nature Photonics*, 2010.
- [5] D. Rittenhouse, "Explanation of an optical deception," *Transactions of the American Philosophical Society*, vol. 2, pp.37-42, 1786.
- [6] J. V.Fruanhofer, "Report on the results of recent experiments on the laws and theory of light," *Annalen der Physik*, vol. 74, pp. 337- 378, 1823.
- [7] M. C. Hutley, "Diffraction gratings", *Academic Press*, 1982.
- [8] H. Rowland, "Preliminary notice of results accomplished on the manufacture and theory of gratings for optical purposes," *Philosophical Magazine Supplement*, vol.13, pp. 469-474, 1882.
- [9] Z.Wang, J.R. Heflin, R.H.Stolen and S. Ramachandran, "Analysis of optical response of long period fiber gratings to nm-thick thin-film coatings, " *Optics Express* ,vol.13, issue 8 , pp. 2808-2813,2005.
- [10] M. G. Moharam and T. K. Gaylord, "Rigorous coupled-wave analysis of planar grating diffraction," *Journal of Optical Society of America*, vol. 71, pp. 811-818, 1981.
- [11] L. Zhuang, S. Schablitsky, R. C. Shi, and S. Y. Chou, "Fabrication and performance of thin amorphous Si sub wavelength transmission grating for controlling vertical cavity surface emitting laser polarization," *Journal of Vacuum Science and Technology*, vol. 14, pp. 4055-4057, 1996.
- [12] S. Goeman, S. Boons, B. Dhoedt, K. Vandeputte, K. Caekebeke, P. V. Daele, and R. Baets, "First demonstration of highly reflective and highly polarization selective diffraction gratings (GIRO-gratings) for long-wavelength VCSELs," *IEEE Photonics Technology Letters*, vol. 10, pp. 1205-1207, 1998.

- [13] A. Haglund, S. J. Gustavsson, J. Vukusic, P. Jedrasik, A. Larsson, "High-power fundamental-mode and polarization stabilized VCSELs using sub-wavelength surface grating," *Electronics Letters*, vol. 41, pp. 805- 807, 2005.
- [14] C. F. R. Mateus, M. C. Y. Huang, D. Yunfei, A. R. Neureuther, and C. J. Chang-Hasnain, "Ultra broadband mirror using low-index cladded sub wavelength grating," *IEEE Photonics Technology Letters*, vol.16, pp. 518-520, 2004.
- [15] K. Yee, "Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media," *IEEE Transactions on Antennas and Propagation*, vol. 14, pp. 302-307, 1988.
- [16] K. S. Kunz and R. J. Luebbers, "The Finite Difference Time Domain Method for Electromagnetics," *Boca Raton: CRC Press*, 1993.
- [17] C. F. R. Mateus, M. C. Y. Huang, C. Lu, C. J. Chang-Hasnain, and Y. Suzuki, "Broad-band mirror (1.12-1.62 μm) using a sub wavelength grating," *IEEE Photonics Technology Letters*, vol. 16, pp. 1676-1678, 2004.
- [18] R. G. Mote, S.F. Yu, , W. Zhou, and X.F. Li, "Design and analysis of two-dimensional high index-contrast grating surface-emitting lasers", *Optics Express*, issue 1, pp. 260-265, 2009.
- [19] C. J. Chang-Hasnain, "High-Contrast gratings as a new platform for integrated optoelectronics," *Semiconductor Science and Technology*, 2011.
- [20] J. T Barber, E. J. Lunt, Z. A. George, D. Yin, H. Schmidt and A. R. Hawkins, "Integrated Hollow waveguides with Arch-shaped Cores," *IEEE Photonics Technology Letters*, vol. 18, no..1, 2006.
- [21] C. Bae and F. Koyama, "Fabrication and characterization of hollow waveguide optical switch with variable air core," *Optics Express*, vol. 13, no. 9, 2005.
- [22] M. Kumar, T. Sakaguchi and F. Koyama, "Polarization-Insensitive and Low-Loss 3D Nano-step Hollow Waveguide for Widely Tunable Photonic Devices," *Journal of Light wave Technology*, vol. 26, no. 11, 2008.
- [23] O. H. Heckl, C. R. E. Baer, C. Kränkel, S. V. Marchese, F. Schapper, M. Holler, T. Südmeyer, J. S. Robinson, J. W. G. Tisch, F. Couny, P. Light, F. Benabid and U. Keller, "High harmonic generation in a gas-filled hollow-core photonic crystal fiber," *Applied Physics B*, pp. 369-373, 2009.

- [24] F. Couny, F. Benabid, P. S. Light, "Sub watt threshold cw Raman fiber-gas laser based on H₂-filled hollow-core photonic crystal fiber," *Physical Review Letter*, 2007.
- [25] C. Markos, K. Nielsen and O. Bang, "Antiresonant guiding in a poly(methylmethacrylate) hollow-core optical fiber," *Journal of Optics*, 2015.
- [26] B. Kumari, A. Barh, R. K. Varshney and B. P. Pal, "Silicon-on-nitride slot waveguide: A promising platform as mid-IR trace gas sensor," *Sensors and Actuators B-Chemical*, vol. 236, pp. 759-764, 2016.
- [27] A. Dhawan and J. F. Muth, "In-line fiber optic structures for environmental sensing applications," *Optics Letters*, vol. 31, issue 10, pp. 1391-1393, 2016.
- [28] S. Harish, D. Venkitesh and B. K. Das, "Highly Efficient DBR in silicon waveguides with eleventh order diffraction," *Proceedings of SPIE*, vol. 8629, pp. 86290H1-86290H7, 2013.
- [29] H. Ou, "Different index contrast silica-on-silicon waveguides by PECVD," *Electronics Letters*, vol. 2, pp. 212-213, 2003.
- [30] P. Y. Yu and M. Cardona, "Fundamentals of Semiconductors: Physics and Material Properties," *Springer*, 2001.
- [31] J. N. McMullin, R. Narendra and C. R. James, "Hollow metallic waveguides in silicon V-grooves," *IEEE Photonics Technology Letters*, vol. 5, pp. 1080-1082, 1993.
- [32] Y. Sakurai and F. Koyama, "Control of group delay and chromatic dispersion in tunable hollow waveguide with highly reflective mirrors," *Japanese Journal of Applied Physics*, vol. 43, pp. 1091-1093, 2004.
- [33] M. Kumar, C. Chase, V. Karagodsky, T. Sakaguchi, F. Koyama and C. J. Chang-Hasnain, "Novel 3D Hollow Optical Waveguide with Lateral and Vertical Periodicity for Tunable Photonic Integrated Circuits," *European Conference on Optical Communication*, 20-24 September, Vienna, Austria, 2009.
- [34] P. Roberts, F. Couny, H. Sabert, B. Mangan, D. Williams, L. Farr, M. Mason, A. Tomlinson, T. Birks, J. Knight, and P. St. J. Russell, "Ultimate low loss of hollow-core photonic crystal fibers," *Optics Express*, vol. 13, pp. 236-244, 2005.
- [35] M. Kumar, C. Chase, V. Karagodsky, T. Sakaguchi, F. Koyama and C. J. Chang-Hasnain, "Low Birefringence and 2-D Optical Confinement of Hollow Waveguide With Distributed Bragg Reflector and High-Index-Contrast Grating," *IEEE Photonics Journal*, vol. 1, no. 2, 2009.

- [36] R. W. Boyd, D. J. Gauthier, and A. L. Gaeta, "Applications of slow light in telecommunications," *Optics Photonics News*, vol.17, pp. 19-23, 2006.
- [37] L. Wang, Y. Chen, H.K. Tsang and C. Shu, "Generation of Multichannel Delayed Pulses by Four-wave-Mixing-Assisted Simulated Brillouin Scattering Slow-Light system," *IEEE Photonics Journal*, vol. 4, issue 4, 2012.
- [38] L. Wang, B. Zhou, C. Shu and S. He, "Stimulated Brillouin scattering slow-light based fiber-optic temperature sensor," *Optics Letters*, vol. 36, no. 3, pp. 427-429, 2011.
- [39] T. F. Krauss, "Slow light in photonic crystal waveguides," *Journal of Physics D.*, vol. 40, pp. 2666-2670, 2007.
- [40] Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, "Active control of slow light on a chip with photonic crystal waveguides," *Nature*, vol. 438, pp. 65-69, 2005.
- [41] M. Soljacic and J. D. Joannopoulos, "Enhancement of nonlinear effects using photonic crystals," *Nature Materials*, vol. 3, pp. 211-219, 2004.
- [42] J. T. Li and J. Y. Zhou, "Nonlinear optical frequency conversion with stopped short light pulses," *Optics Express*, vol. 14, pp. 2811-2816, 2006.
- [43] J. B. Khurgin, "Optical buffers based on Slow light in electromagnetically induced transparent media and coupled resonator structures: comparative analysis," *Journal of the Optical Society of America B*, vol. 22, issue 5, pp. 1062-1074, 2005.
- [44] J. E. Sharping, Y. Okawachi, and L. Gaeta, "Wide bandwidth slow light using a Raman fiber amplifier," *Optics Express*, vol. 13, pp. 6092, 2005.
- [45] T. Baba, "Slow light in photonic crystals," *Nature*, vol. 2, pp. 465-473, 2008.
- [46] K. N. Park, Y. T. Lee, M. H. Kim, K. S. Lee, and Y. H. Won, "All-fiber drop-pass filters with fiber Bragg gratings," *IEEE Photonics Technology Letters*, vol. 10, pp. 555-557, 1998.
- [47] S. Yamashita and K. Hsu, "Single-frequency, single-polarization operation of tunable miniature erbium:ytterbium fiber Fabry-Perot lasers by use of self-injection locking," *Optics Letters*, vol. 23, pp. 1200-1202, 1998.
- [48] G. C. Lin, L. Wang, C. C. Yang, M. C. Shih, and T. J. Chuang, "Thermal performance of metal-clad fiber Bragg grating sensors," *IEEE Photonics Technology Letters*, vol. 10, pp. 406-408, 1998.

- [49] H. Zou, K. W. Beeson, and L. W. Shacklette, "Tunable planar polymer Bragg gratings having exceptionally low polarization sensitivity," *Journal of Lightwave Technology*, vol. 21, issue 4, 2003.
- [50] J. A. Rogers, B. J. Eggleton, and P. Kuo, "Temperature Stabilized Operation of Tunable Fiber Grating Devices That Use Distributed On-Fiber Thin Film Heaters," *Electronic Letters*, vol. 35, pp. 2052-2053, 1999.
- [51] Y. Sakurai, A. Matsutani and F. Koyama, "Tunable stop-band hollow waveguide Bragg reflectors with tapered air core for adaptive dispersion compensation," *Applied physics letters*, vol. 88, no. 12, pp. 121103, 2006.
- [52] E. Shaik and N. Rangaswamy, "Investigation on photonic crystal based all-optical clocked D-flip flop," *IET Optoelectronics*, vol. 11, issue 4, pp. 148-133, 2017.
- [53] T. Katayama, J. Ito and H. Kawaguchi, "Polarization-dependent coupling between a polarization-independent high-index-contrast subwavelength grating and waveguides," *Applied Physics Express*, vol. 9, issue 7, pp. 072703, 2016.
- [54] E. Kim, W. J. Jang, W. Kim, J. Park, M. K. Lee, S. K. Park and K. C. Choi, "Suppressed Instability of a-IGZO Thin-Film Transistors Under Negative Bias Illumination Stress Using the Distributed Bragg Reflectors," *IEEE Transactions on Electron Devices*, vol. 63, issue 3, pp. 1066-1071, 2016.
- [55] B. Pesala, W. Yang, C. J. Hasnain, "Compact On-Chip Optical Components Based on Multimode Interference Design Using High-Contrast Grating Hollow-Core Waveguides," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 22, issue 6, 2016.
- [56] Y. Hung, M. Hsieh, and J. Shih, "High-Contrast Polysilicon Grating Reflectors Implemented in a Standard Bulk CMOS Line," *IEEE Photonics Technology Letters*, vol. 27, no. 20, pp. 2170-2173, 2015.
- [57] K. Nagai and K. Yamashita, "Wavelength Tunability of Plastic Waveguide Laser with Asymmetric Distributed Bragg Reflectors," *Journal of Lightwave Technology*, vol. 33, issue 22, 2015.
- [58] M. Gębski, M. Dems, M. Wasiak, J. A. Lott and T. Czyszanowski, "Monolithic high-index contrast grating: A material independent high-reflectance VCSEL mirror," *Optics Express*, vol. 23, no. 9, pp. 11674-11686, 2015.

- [59] J. Ferrara, W. Yang, L. Zhu, P. Qiao and C. J. Chang-Hasnain, "Heterogeneously integrated long-wavelength VCSEL using silicon high contrast grating on an SOI substrate," *Optics Express*, vol. 23, no. 3, pp. 2512-2523, 2015.
- [60] K. Nakamura, A. Matsutani, M. Ahmed, A. Bakry and F. Koyama," Slow-light Bragg reflector waveguide array for two-dimensional beam steering,"*Japanese Journal of Applied Physics*, vol. 53, no. 3,2014.
- [61] H. Ahmad, N. S. Azhari, M. Z.Zulkifli, F. D. Muhammad and S. W. Harun, "S-band SLM distributed Bragg reflector fiber laser,"*Laser Physics*, vol. 24, no. 6, 2014.
- [62] J. Tang, T. Wang, B. Liu, B. Wang and Y. He, "Systematic design of wideband slow light in ellipse-hole photonic crystal waveguides," *Journal of the optical society of AmericaB*, vol. 31, pp. 1011-1017, 2014.
- [63] W. Yang, J. Ferrara, K.Grutter, A. Yeh, C. Chase,Yang , Yue, A. E.Willner,Ming C. Wu and C. J. Chang-Hasnain, "Low Loss Hollow – Core waveguide on a silicon substrate,"*Nanophotonics*, vol. 1, pp. 23-29, 2012.
- [64] C. Chevallier, F. Genty, J. Jacquet, "Optimized Si/SiO₂ high contrast grating mirror design for mid-infrared wavelength range: robustness enhancement," *Optics and Laser Technology*,vol. 44, pp. 626-630,2012.
- [65] Y. Yue, Y. Yue, L. Zhang, X. Wang, H. Huang, W. Yang, J. Ferrara, V.Karagodsky, C. Chase, M. Tur, C. J. Chang-Hasnain, A. E. Willner,"Three-Dimensional Chirped High-Contrast Grating Hollow-Core Waveguide," *IEEE Photonics Journal*,vol. 4, no. 5, 2012.
- [66] M. Kumar, "Polarization Insensitive Hollow Optical Waveguide,"*Optics Communication*, vol. 285, pp. 2360-2362, 2012.
- [67] M. Kumar, F. Koyama and C.J. Chang-Hasnain, "Tunable Hollow Optical Waveguide with High-Contrast Grating," *IEEE lasers and electro-optics society*, pp. 523-524,2008.
- [68] H. Yang, D. Zhao, Jung-Hun Seo, S.Chuwongin, S. Kim, J. A.Rogers, Z. Ma and W. Zhou, "Broadband Membrane Reflectors On Glass," *IEEE Photonics Technology Letters* ,vol. 24, no. 6, 2012.
- [69] M. Shinkawa, N. Ishikura, Y. Hama, K. Suzuki, and T. Baba, "Nonlinear enhancement in photonic crystal slow light waveguides fabricated using CMOS-compatible process", *Optics Express*, vol. 19, pp. 22208, 2012.
- [70] X. Sheng, L. Z. Broderick, J. Hu, L. Yang, A.Eshed, E. A. Fitzgerald, J. Michel and L. C. Kimerling, "Design and fabrication of high-index-contrast self-assembled texture for

light extraction enhancement in LEDs,” *Optics Express*, vol. 19, issue S4, pp. A701-A709, 2011.

- [71] L.Carletti, R.Malureanu, J.Mørk, and Il-Sug Chung, “High-index-contrast grating reflector with beam steering ability for the transmitted beam,”*Optics Express*, vol. 19,issue 23,pp. 23567-23572,2011.
- [72] A.Imamura, W. Yang, J. Ferrara, Y.Hasidume, X.Gu, F. Koyama and C. J. Chang-Hasnain, “Spatial Mode Demultiplexer Based on High-Contrast Sub-Wavelength Grating Hollow Waveguide,”*The 16th Optoelectronics And Communications Conference, Kaohsiung, Taiwan*, July 4-8,2011.
- [73] T. Baba, “Slow Light and Bio-Sensing With Photonic Crystals,” pp. 811-812, 2011.
- [74] J. Kang,S. Kim, K.Jeong, Y. Lee, M. Seo, and H. Park, “ Polarization-resolved far-field measurement of single-cell photonic crystal lasing modes,”*Applied Physics Letters*, vol. 98, pp. 211116,2011.
- [75] W. Hofmann, C. Chase, M. Müller, Y. Rao, C. Grasse, G.Böhm, M.Amann and C. J. Chang-Hasnain, “Long-Wavelength High-Contrast Grating Vertical-Cavity Surface-Emitting Laser,”*IEEE Photonics Journal*,vol. 2, no. 3, 2010.
- [76] A. Ahmed, M.Liscidini and R. Gordon, “Design and Analysis of High-Index-Contrast Gratings Using Coupled Mode Theory,”*IEEE Photonics Journal*, vol. 2, no. 6, 2010.
- [77] V.Karagodsky, F. G. Sedgwick, and C. J. Chang-Hasnain, “Theoretical analysis of sub wavelength high-contrast grating reflectors,” *Optics Express*, vol. 18, no. 16, pp. 16973–16988,2010.
- [78] A. Fuchida, B. Pesala, V.Karagodsky, F. G. Sedgwick,F. Koyama and C. J. Chang-Hasnain,“Zero-dispersion Slow Light in Hollow Waveguide with High-contrast Grating,” *Lasers and electro-optics (LEO) and quantum electronics and laser science conference(QELS)*,2010.
- [79] A.Khorshidahmad,and A. G. Kirk, “Nested Photonic Crystal Cavity for On-Chip Wavelength Conversion,”*IEEE Photonics Technology Letters*, vol. 22, no. 10, 2010.
- [80] J. Rosenberg, R. V. Shenoi, S. Krishna, and O. Painter, “Design of plasmonic photonic crystal resonant cavities for polarization sensitive infrared photodetectors,”*Optics Express*, vol. 18, no. 4,pp. 3672-3686, 2010.
- [81] Y. Zhou, M. C. Y. Huang, C. Chase, V.Karagodsky, M.Moewe, B.Pesala,F. G. Sedgwick and C. J. Chang-Hasnain, “High-Index-Contrast Grating (HCG) and Its

- Applications in Optoelectronic Devices,” *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 15, issue 5, pp. 1485-1499, 2009.
- [82] Y. Zhou, V.Karagodsky, B.Pesala, F. G. Sedgwick and C. J. Chang-Hasnain, “A novel ultra-low loss hollow-core waveguide using sub wavelength high-contrast gratings”, *Optics Express*, vol. 17, issue 3, pp 1508-1517, 2009.
- [83] J. Topolancik, F. Vollmer, R. Ilic, and M. Crescimanno, “Out-of-plane scattering from vertically asymmetric photonic crystal slab waveguides with in-plane disorder,” *Optics Express*, vol. 17, no. 15, pp. 12470-12480, 2009.
- [84] H. Y. Fu, H. Y. Tam, Li-Yang Shao, X. Dong, P. K. A. Wai, C. Lu, and S. K. Khijwania, “Pressure sensor realized with polarization-maintaining photonic crystal fiber-based Sagnac interferometer,” *Applied Optics*, vol. 47, no. 15, pp. 2835-2839, 2008.
- [85] J. Li1, T. P. White, L. O’Faolain, A. Gomez-Iglesias and T. F. Krauss, “Systematic design of flat band slow light in photonic crystal waveguides,” *Optics Express*, vol. 16, no. 9, pp. 6227-6232, 2008.
- [86] F.Poli, A.Cucinotta, D.Passaro, S.Selleri, J.Laegsgaard, and J.Broeng, “Single-Mode Regime in Large-Mode-Area Rare-Earth-Doped Rod-Type PCFs,” *IEEE Journal Of Selected Topics In Quantum Electronics*, vol. 15, no. 1, pp. 54-60, 2009.
- [87] Y. G. Han, J. H. Lee and S. B. Lee, “Uniform Fiber Bragg Grating Based Tunable Dispersion Compensator & Its Application To Tunable Pulse Repetition – Rate Multiplication,” *Conference On Laser And Electro Optics (CLEO)*, 2006.
- [88] Y. Sakurai, A.Matsutani and F. Koyama, “Tunable stop-band hollow waveguide Bragg reflectors with tapered air core for adaptive dispersion compensation,” *Applied physics letters*, vol. 88, issue 12, pp. 121103, 2006.
- [89] A. Hakansson and J. Sanchez-Dehesa, “Inverse designed photonic crystal de-multiplex waveguide coupler,” *Optics Express*, vol. 13, no. 14, pp. 5440-5449, 2005.
- [90] T. Yamashita, and C. J. Summers, “Evaluation of Self-Collimated Beams in Photonic Crystals for Optical Interconnect,” *IEEE Journal On Selected Areas In Communications*, vol. 23, no. 7, pp. 1341-1347, 2005.
- [91] S.Ramachandran, S.Ghalmi, S.Chandrashekhar, I. Ryazansky, M.F.Yan, F.V.Dimarcello, W.A.Reed and P.Wisk, “Tunable dispersion compensators utilizing higher order mode fibers,” *IEEE Photonics Technology Letters*, vol. 15, no. 5, 2003.

- [92] D. Huang, W. Liu, C. Wu and C.C.Yang, "Reflectivity- Tunable Fiber Bragg Grating Reflectors," *IEEE Photonics Technology Letters*, vol. 12, no. 2, 2000.
- [93] H. Peng and G. M. Morris, "Efficient implementation of rigorous coupled-wave analysis for surface-relief gratings," *Journal of the Optical Society of America A*, vol. 12, no. 5, pp. 1087-1096, 1995.
- [94] R. Bräuer and O. Bryngdahl, "Electromagnetic diffraction analysis of two-dimensional gratings," *Optics Communications*, vol. 100, issues 1–4, pp. 1-5, 1993.
- [95] E. Noponen and J. Turunen, "Eigenmode method for electromagnetic synthesis of diffractive elements with three dimensional profiles," *Journal of the Optical Society of America A*, vol. 11, issue 9, pp. 2494-2502, 1994.
- [96] L. Li, "New formulation of the Fourier modal method for crossed surface-relief gratings," *Journal of the Optical Society of America A*, vol. 14, no. 10, 1997.
- [97] L. Li, "Fourier modal method for crossed anisotropic gratings with arbitrary permittivity and permeability tensors," *Journal of Optics a: Pure and Applied Optics*, vol.5, no. 4, pp. 345–355, 2003.
- [98] H. Huang, Y. Yue, L. Zhang, C. Chase, D. Parekh, F. Sedgwick, M. C. Wu, C.J. Chang-Hasnain, M. Tur, and A. E. Willner, "Analog Signal Transmission in a High-Contrast Gratings-Based Hollow-Core-Waveguide ," *Journal of Lightwave technology*, vol. 30, no. 23, 2012.
- [99] M. Kumar, "A hollow waveguide Bragg reflector: A tunable platform for integrated photonics" *Optics & Laser Technology*, vol. 65, pp. 5-13, 2015.
- [100] C. H. Cox, III, *Analog Optical Links: Theory and Practice*. : Cambridge University Press, pp. 201–205, 2004.
- [101] W. S. C. Chang, *RF Photonic Technology in Optical Fiber Links*. Cambridge University Press, pp. 25–32, 2002.
- [102] A. Barh, S. Ghosh, R. K. Varshney, and B. P. Pal, "An efficient broad-band mid-wave IR fiber optic light source: design and performance simulation, " *Optics Express*, vol. 21, issue 8, pp. 9547-9555, 2013.
- [103] Y. Zhang, A. Dhawan and T. Vo-Dinh, "Design and Fabrication of Fiber-Optic Nanoprobes for Optical Sensing," *Nanoscale Research Letters*, vol.6, no. 1, 2010.
- [104] B. Painam, R.S. Kaler, M. Kumar, "Photonic Crystal Waveguide Biochemical Sensor for the Approximation of Chemical Components Concentrations," *Plasmonics*, 2016.

- [105] J. K. Thind, M. Kumar and B.K. Kaushik, "Electrical Tuning of Optical Delay in Graphene based Photonic Crystal Waveguide", *IEEE Journal of Quantum Electronics* , no. 10, 2015.
- [106] H.Dalir and F.Koyama, "Highly Efficient out-of-plane optical coupler based on tapered hollow waveguide," *Japanese Journal of Applied Physics*, vol. 53, no. 4,2014.
- [107] J. N. McMullin, R. Narendra, and C. R. James, "Hollow metallic waveguides in silicon V-grooves," *IEEE Photon. Technology Letters*, vol. 5, pp. 1080-1082,1993.
- [108] Y. Sakurai and F. Koyama, "Control of group delay and chromatic dispersion in tunable hollow waveguide with highly reflective mirrors,"*Japanese Journal of Applied Physics*, vol. 43, pp. 1091-1093,2004.
- [109] C. Koos, P. Vorreau, T. Vallaitis, P. Dumon, W. Bogaerts, R. Baets, B. Esembeson, I. Biaggio, T. Michinobu, F. Diederich, W. Freude, and J. Leuthold, "All-optical high-speed signal processing with silicon-organic hybrid slot waveguides," *Nature Photon.* vol. 3, issue 4, pp. 216-219, 2009.
- [110] B. Corcoran, C. Monat, C. Grillet, D. J. Moss, B. J. Eggleton, T. P. White, L. O'Faolain, and T. F. Krauss, "Green light emission in silicon through slow-light enhanced third-harmonic generation in photonic-crystal waveguides," *Nature Photon*,vol. 3, pp. 206-210, 2009.
- [111] T. F. Krauss, "Slow light in photonic crystal waveguides," *Journal of Physics D*, vol. 40, pp. 2666-2670, 2007.
- [112] Y. A. Vlasov, M. O'Boyle, H. F. Hamann, and S. J. McNab, "Active control of slow light on a chip with photonic crystal waveguides," *Nature*,vol. 438, pp. 65-69, 2005.
- [113] S. Hughes, L. Ramunno, J. F. Young, and J. E. Sipe, "Extrinsic optical scattering loss in photonic crystal waveguides: role of fabrication disorder and photon group velocity," *Physical Review Letters*, vol. 94, pp. 033903,2005.
- [114] R. J. P. Engelen, Y. Sugimoto, Y. Watanabe, J. P. Korterik, N. Ikeda, V. Hulst, K. Asakawa, and L. Kuipers, "The effect of higher-order dispersion on slow light propagation in photonic crystal waveguides," *Optics Express*,vol. 14, pp. 1658-1672, 2006.

- [115] M. D. Settle, R. J. P. Engelen, M. Salib, A. Michaeli, L. Kuipers, and T. F. Krauss, "Flatband slow light in photonic crystals featuring spatial pulse compression and terahertz bandwidth," *Optics Express*, vol. 15, pp. 219–226, 2007.
- [116] L. H. Frandsen, A. V. Lavrinenko, J. Fage-Pedersen, and P. I. Borel, "Photonic crystal waveguides with semislow light and tailored dispersion properties," *Optics Express*, vol. 14, pp. 9444–9450, 2006.
- [117] A. E. Willner, "Lasers: All mirrors are not created equal," *Nature Photon*, vol. 1, no. 2, pp. 87–88, 2007.
- [118] R.K.Gupta and B. K. Das, "Multi-input and multi-output SOI (MIMO-SOI) platform for silicon photonics," *CSI Transactions on ICT*, vol. 5, no. 2, pp. 189-193, 2017.
- [119] Z.Tan, C.Wang, E.D. Diebold, N.K.Hon and B.Jalali, "Real-time wavelength and bandwidth-independent Optical integrator based on modal dispersion, *Optics Express*, vol. 20, issue 13, pp. 14109-14116,2012.
- [120] M. C. Y. Huang, Y. Zhou, and C. J. Chang-Hasnain, "A surface-emitting laser incorporating a high-index-contrast subwavelength grating," *Nature Photon.*, vol. 1, pp. 119–122, 2007.
- [121] R. Magnusson and M. Shokooh-Saremi, "Physical basis for wideband resonant reflectors," *Optics Express*, vol. 16, no. 5, pp. 3456–3462, 2008.
- [122] S.Ghosh, R. K. Varshney, and B. P. Pal, "Generation of a low divergent supercontinuum for mid-IR high power delivery through a large mode area photonic bandgap fiber," *Laser Physics*, vol. 23, no. 9, 2013.
- [123] S.Dahiya, S. Kumar and B.K. Kaushik, " Modeling and optimization of single-mode vertical cavity surface emitting lasers," *Journal of Nanophotonics, International Society for Optics and Photonics (SPIE)*, vol. 10, no. 4, pp. 046008-046008, 2016.
- [124] H.Dalir and F.Koyama , "29 GHz directly modulated 980 nm vertical- cavity surface emitting lasers with bow-tie shape transverse coupled cavity," *Applied Physics Letters*, vol. 103, issue 9, 2013
- [125] H. Wu, "A high performance polarization independent reflector based on a multilayered configuration grating structure," *Journal of Optics*, vol. 12, no. 4, pp. 045703-1–045703-6, 2010.
- [126] D. Peters, "Demonstration of polarization-independent resonant subwavelength grating filter arrays," *Optics Letters*, vol. 35, no. 19, pp. 3201– 3203, 2010.

- [127] Y. Zhou, M. C. Y. Huang, and C. J. Chang-Hasnain, “Tunable VCSEL with ultra-thin high contrast grating for high-speed tuning,” *Optics Express*, vol.16, pp. 14221–14226, 2008.
- [128] Y. Tsunemi, N. Yokota, S. Majima, K. Ikeda, T. Katayama, and H. Kawaguchi, “1.55 μm VCSEL with polarization-independent HCG mirror on SOI,” *Optics Express*, vol. 21, no. 23, pp. 28685–28692, 2013.

List of Publications:

- [1] Harpinder Kaur, Mukesh Kumar, “Two-way Reflector Based on Two-dimensional Sub-wavelength High-index Contrast Grating on SOI,” *Elsevier, Optics Communication*, volume 366, pp. 266-270, 2016, **(IF: 1.542)**.

- [2] Harpinder Kaur, Varun Kumar, Mukesh Kumar, “Slow Light in Narrow Core Hollow Optical Waveguide with Low loss and Large Bandwidth”, *OSA: Applied Optics*, volume. 55, number.35, pp. 1011-10123, 2016, **(IF: 1.649)**.

- [3] Varun Kumar, Harpinder Kaur, Mukesh Kumar, “Narrow Core Hollow Optical Waveguide with Nanostructured SOI as Ultra-low Loss Platform for Efficient Photodetection”, *Springer: Photonic Network Communication* , volume 34, number 2, pp.241-247, 2017, **(IF: 0.55)**.