Design And Analysis of On chip Optoelectronic Waveguides for Optical Communication and Sensing

A PROJECT REPORT

Submitted in partial fulfilment of the requirements for the award of the degrees

Of

BACHELOR OF TECHNOLOGY

In

ELECTRICAL ENGINEERING

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CANDIDATE’S DECLARATION

We hereby declare that the project entitled **“Design And Analysis of On chip Optoelectronic Waveguides for Optical Communication”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in Electrical Engineering completed under the supervision of **Dr. Mukesh Kumar (Assistant Professor)** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Prateek
07/12/17

Nitish Kumar **Prateek Dhanwadia** **Mukesh Poonia**

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Dr. Mukesh Kumar (Assistant Professor)

Preface

This project report on **“Design and Analysis of On chip Optoelectronic Waveguides for Optical Communication”** is prepared under the guidance of Dr. Mukesh Kumar.

In this report we have discussed about photonics and how can we use this branch of science for bio sensing and faster and better communication as well.

We have tried our best to explain this content to a reader in a lucid manner with comprehensive theory. We have added photographs and experimental results to make it more illustrative.

Nitish Kumar, Prateek Dhanwadia & Mukesh Poonia

B. Tech. 4th year,

Discipline of Electrical Engineering,

IIT Indore

Acknowledgements

We wish to thank **Dr. Mukesh Kumar** for his kind support and valuable guidance. This work has been done in framework of the IIT Indore project. We would like to acknowledge **Sulabh Srivastava**, **Lalit Jain, Sourabh Jain, Swati Rajput, Surbhi Tidke & Vishal Kaushik** for providing their sincere cooperation and guidance to carry out this research.

It is their help and support, due to which we were able to complete the design and the technical report. Without their support this would not have been possible.

Nitish Kumar, Prateek Dhanwadia & Mukesh Poonia

B.Tech. IV Year

Discipline of Electrical Engineering

IIT Indore

Abstract

In this article we discussed about photonics and how this branch of science can be used for bio sensing and faster and efficient optical communication. We basically divided our study into three parts-

Sensing with Slot waveguide: A theoretical investigation of Nano-photonic slot waveguide structure for optical sensing is proposed. Waveguide sensitivity has also been calculated in different ways like changing the refracting index medium alternatively, variation of Rib width, etc. We also design and demonstrate mode shaping of both TE and TM polarizations to achieve Modal Birefringence.

Sensing with Hybrid Plasmonic Waveguides: Our Hybrid Plasmonic Waveguide based Bio-Sensor Nano-device platform may serve as a fundamental building block for various functional photonic components can be used in applications such as sensing and biomolecular detection.

On chip reflector with low polarization dependency: Our proposed 2-D high contrast grating design provides high reflectivity (>99%) for both TE and TM modes of incidence.

List of Figures

CONTENTS

CHAPTER-1 INTRODUCTION TO ON CHIP DEVICES FOR MULTIDISCPLINARY APPLICATION

1.1 Introduction

On chip devices are developing as key components for high-performance bio sensing and advanced communication as well as other emerging technologies such as aerospace. These on chip devices can manipulate light for better bio sensing and optical communication.

Bio-sensing is the use of biomolecular probes to measure the presence or concentration of biological molecules, biological sensors, etc, by translating a biochemical interaction at the probe surface into a quantified physical signal. Optical Bio-sensing provides great advantages over conventional analytical techniques. The selectivity of the biological sensing element offers the opportunity for development of highly specific devices for real-time analysis in complex mixtures, without the need for extensive sample pre-treatment or large sample values. Optical biosensors are highly sensitive, rapid, reproducible and simple-to-operate analytical tools. The potential of optical bio-sensing is immense and research being done is mainly towards its application in health care, environmental and biotech industry.

Optical Communication- Optical communication is any type of communication in which light is used to carry the signal to the remote end. Optical communication relies on optical fibres to carry signals to their destinations. A modulator/demodulator, a transmitter/receiver, a light signal and a transparent channel are the building blocks of optical communication system. Because of its numerous advantages over other types of transmission, optical fibres have largely replaced other communication networks in the developed world.

1.2 Nano-photonic waveguides

Conventional Nano-photonic slot waveguides are commonly used in biochemical sensors based on integrated optics. In these waveguides, the guiding mechanism is based on total internal reflection (TIR) in a high-index material (core) surrounded by a low-index material (cladding); the TIR mechanism can strongly confine light in the high-index material.

On the other hand, there are also planar waveguides non-based on TIR, such as hollow-core waveguides, which are employed to guide light in low-index materials. This is especially interesting for biochemical sensing since the hollow-core can be filled with low-index fluids. However, in these guides, optical interference is involved and therefore they are highly wavelength dependent. Slot-waveguides allow light to be guided and strongly confined inside a nanometre-scale region of low refractive index. Thus, stronger light-analyte interaction can be obtained as compared to that achievable by a conventional waveguide, in which the light is confined to the high-refractive-index core of the waveguide. These advantages have made the use of slot-waveguides for highly sensitive biochemical optical integrated sensors an emerging field. Operating wavelength has been always fixed as 1550 nm.

Dielectric waveguides use total internal reflection to confine light in a high index region. They can guide light over a long distance with very low loss, but their light confinement ability is limited by diffraction. Plasmonic waveguides, on the other hand, use surface plasmon to confine light near a metal surface. The light confinement ability of plasmonic waveguides is not limited by diffraction, and, as a result, they can confine light to very small volumes. However, these guides suffer significant propagation loss because of the presence of metal as part of the guiding structure. The aim of designing the hybrid plasmonic waveguide was to combine these two-different waveguiding schemes and achieve high light confinement without suffering large loss. Many different variations of this structure have been proposed

1.3 On chip grating reflector

On chip grating reflectors have been used in communication for a long time. Distributed Brag Reflector is the common on chip reflector that has been used in lasers and in waveguides as well. It is a structure formed from multiple layers of alternating materials with varying refractive index or by periodic variation of some characteristic (such as height) of a dielectric waveguide, resulting in periodic variation in the effective refractive index in the guide. Each layer boundary causes a partial reflection of an optical wave. For waves whose vacuum wavelength is close to four times the optical thickness of the layers, the many reflections combine contractive interference and the layers act as a high-quality reflector. DBR is used in vertical cavity surface emitting lasers. Now days DBR are has been replaced by high contrast grating as it provides better reflectivity with single layer construction. HCG's has a wide range of application of optical communication. They can be used in waveguides, lasers, couplers and in many other devices.

1.4 Outline of project

In this report the study of on chip devices has been done in three different parts-

1. **Sensing with Slot waveguide-** Slot waveguide structure for sensing purpose is designed for the application of bio-sensing. We proposed a metal assisted slot waveguide for better sensitivity than that of conventional waveguide. This is further explained in chapter 2.
2. **Hybrid plasmonic wave based biosensor-** HPW silicon waveguide structure for large group delay difference for small change in refractive index. We proposed a model with grating introduced leading to increase in group delay difference which is discussed in detail in chapter 3.
3. **Design of on chip low polarization reflector-** HCG's has a wide range of application in optical communication. We will propose a 2-D HCG design that will provide low polarization high reflectivity. We will discuss about in more in chapter 4.

CHAPTER-2 NANO-PHOTONIC SLOT STRUCTURE FOR SENSING APPLICATION

2.1 Introduction

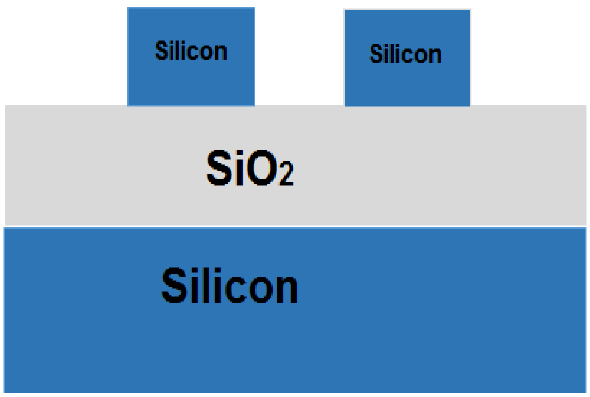
Optical technologies play a central role in chemical and biochemical analysis and their employment in lab-on-a-chip micro-systems has been demonstrated as very attractive. In these sensors the concentration change of a chemical analyte to be sensed affects the propagating mode effective index, which is measured in different ways, according with sensor architecture.

Among the existing waveguides, nanoscale optical waveguides based on the surface plasmon polariton (SPP) is generally taken in use because the SPP mode is strongly localized in the nanoscale region. To date, various types of SPP-based waveguides have been reported. For example, metal-insulator-metal (MIM) waveguides, dielectric-loaded SPP waveguides, and hybrid plasmonic waveguides (HPWs). It is well known that the TM mode has been widely used in SPP-based waveguides because the excitation of the SPP mode relies on the TM mode. And, also by inserting a metal layer in an under cladding, the radiation of light to the region under the cladding can be suppressed.

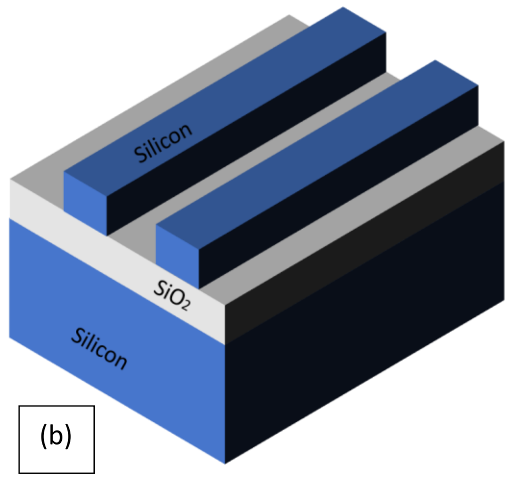
Additionally, the TE mode in the polymer-loaded SPP waveguide has been used for small bending with long propagation length. From the perspective of efficient bending, the use of the TE mode in the polymer-based SPP waveguides has an advantage compared with the use of the TM mode. This is because losses are given by the sum of the bending loss and the absorption loss due to the metal. Although the TE mode in SPP-based waveguides does not have a small field distribution compared with the TM mode, it has a longer propagation length. These studies suggest that the use of the TE mode in certain SPP-based waveguides would be useful for some applications. In this report we discuss on what is to the best of our knowledge the first demonstration of an integrated slot-waveguide device working as a biochemical sensor, operating at 1550nm wavelength.

2.2 Operation of 2-D and 3-D design

The performance of conventional slot waveguide based on 2D and 3D slot waveguide geometries are taken in account for better understanding of the optical mode confinement. Schematics of the 2D and 3D conventional slot waveguides are depicted in Figs. **2.1(a)** and **2.1(b)**. In both cases, dielectric part is air with a refractive index of 1, and Silicon ribs with a refractive index 3.434 at wavelength of optical light 1550nm.



(a)



(b)

Fig.2.1. Schematic view of conventional slot waveguides (a) 2-D slot waveguide and (b) 3-D slot waveguide

The optical mode propagation for the above designs are shown in the fig.2.2(c), 2.2(d)

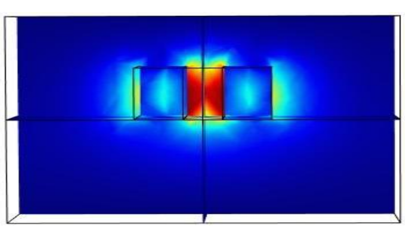


Fig.2.2. (c) 2-D Mode for Light Confinement in slot region having air

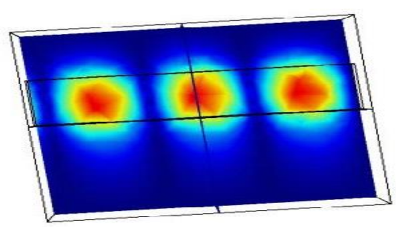


Fig.2.2. (d) 3-D Mode for Light confinement in the slot region having air

2.3 Conventional and metal-assisted slot waveguide

A slot-waveguide is an optical waveguide that guides strongly confined light in a subwavelength-scale low refractive index region by total internal reflection.

In the slot region, there is a discontinuity of the electric field at a normal boundary between two materials. For an Electro-Magnetic wave propagating in the z direction, the major electric field component undergoes a discontinuity at the perpendicular slot interfaces. Thus if n_H is much larger than n_S, this discontinuity is such that the E-field is much more intense in the low-index slot region than in the high-index slabs. Width of the slot is in nanometer scale and comparable to the decay length of field, so E-field remains high inside slot which further results in much higher power density in the slot than that in the high-index regions. The schematic view of a conventional slot waveguide and the propagation of light is shown below-

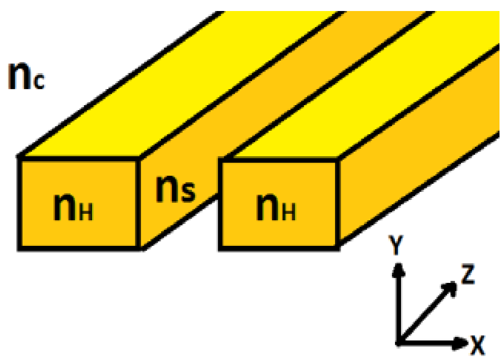


Fig.2.3 (a) Schematic view of a slot-waveguide

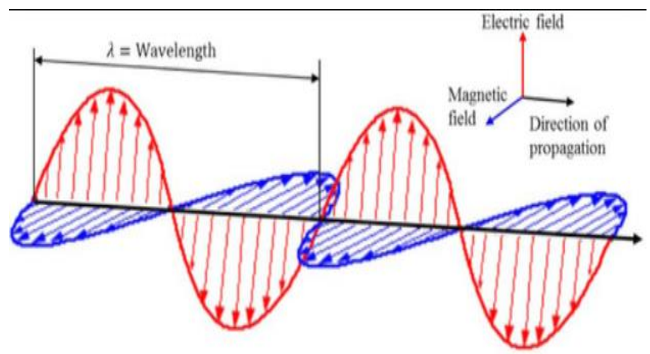


Fig.2.3 (b) Components of E-field and magnetic field and both of them are perpendicular to the direction of propagation.

Since, a slot-waveguide produces high E-field amplitude, optical power, and optical intensity in low-index materials at levels that cannot be achieved with conventional waveguides. Hence, the modified design from conventional slot waveguide is depicted below

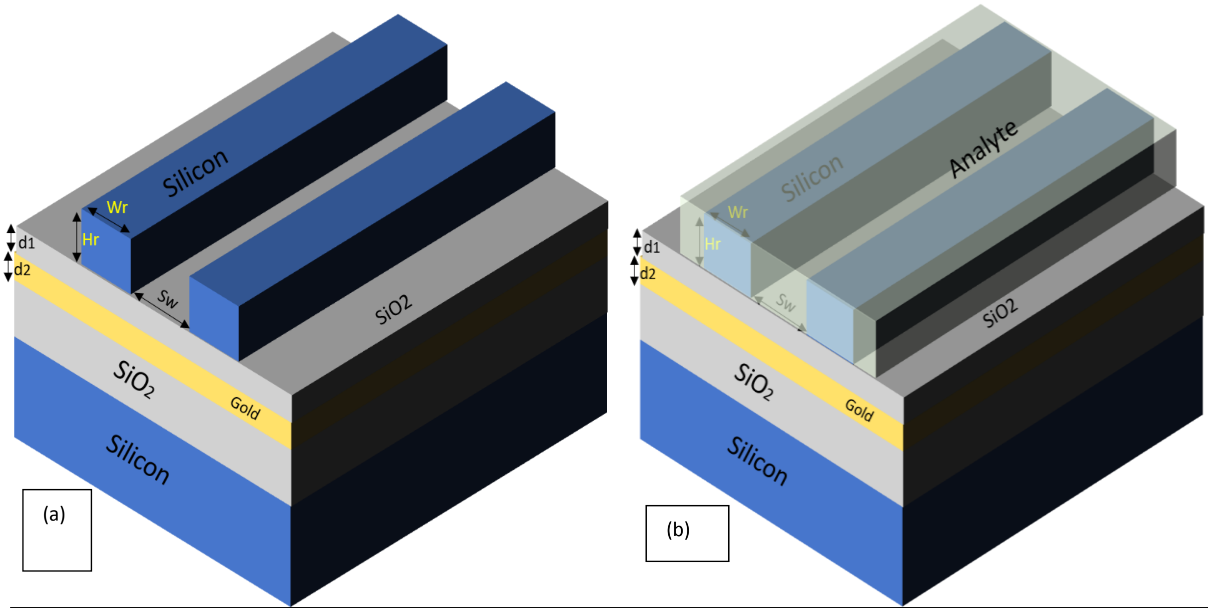


Fig.2.4. Schematic view of metal-assisted slot waveguide (a) without cladding (b) with analyte cladding

Dimensions for the above modified design are-

- Width of Si Ribs (Wr)=250nm
- Height of Si Ribs (Hr)=400nm
- Slot region width (Sw)=180nm
- Thickness of SiO2 (d1)=250nm
- Gold metal layer (d2)=300nm

Because the sensitivity of waveguide sensors is proportional to the optical confinement factor, a large light confinement in the top cladding leads to the improvement of the sensor sensitivity. When the optical confinement factor is large, the effective refractive index is strongly affected by the change of a cladding medium such as aqueous solution or plasma of blood. So, there is a need of Sensor to be more sensitive and stable for better application in Sensor industries.

In our proposed structure of metal-assisted slot waveguide, modification done for two things Ridge and Gold metal layer.

- A Si-Ridge of 20nm thickness is inserted between the High index Si ribs and with a common base with the bottom cladding. The confinement factor and Sensitivity of a Ridge slot waveguide is much higher than conventional waveguides.
- A gold metal layer is required to be inserted under the bottom clad of SiO2 because there is a radiation of light in under cladding. So, metal Suppresses that unnecessary radiation which further leads to a strong light confinement.

2.4 Cladding with different Analytes

Various analytes having different refractive index act as a cladding on the top of our waveguide. Below materials can be used for the measurement of sensitivity with variation in effective index-

- Air with refractive index 1.000 is generally used as a default cladding medium to check whether there is an optical mode confinement or not.
- Aqueous medium with refractive index 1.33
- Plasma of pure blood of refractive index 1.35
- Serum 1 of plasma of impure blood of refractive index with a change of 0.01 in pure blood plasma which is 1.36
- Serum 2 of plasma of virus infected blood of refractive index 1.37

2.5 Sensitivity and Effective mode index profile

It is clear that due to the variation of refractive index or one can say, the materials with different indices which are placed in the path of Electro-magnetic wave must have a variation in effective mode index. Homogeneous sensing or bulk sensitivity (effective index change of guiding structure due to cover medium refractive index change) enables to measure concentration of a wide spectrum of chemical species as water or plasma of pure and impure blood, usually present in a slot region. Cladding of slot waveguides are commonly adopted in optical sensing, in which the refractive index change of the cladding medium will cause a shift in effective index, and due to the change in effective index, homogeneous sensing also varies which is one of the important applications of slot waveguides. For example, when plasma concentration in an air solution changes, a shift of the solution refractive index is induced. In case of homogeneous sensing, waveguide sensitivity can be defined as-

$S = \partial neff / \partial nc$, where neff is the mode effective index, and nc is the cladding refractive index.

Fig.2.5. (a) describes the Effective index profile for the variation of ‘Si’ Rib width from 230 to 270 nm at a step of 10nm and slot material is air. Effective index is less obtained at 230nm rib width. So after increasing it is thickness and thus there is gradual increase in effective index also. Hence, there is a major difference in effective index at 250nm Si Rib width for different slots. Therefore, this dimension is used for the calculation of effective index by varying cladding indices.

In Fig.2.5. (b) We simulated the design for effective mode index by varying the refractive index inside the slot region by placing different cladding materials and plasma. As a result, we found that by increase in refractive index there is an increment in effective mode index also.

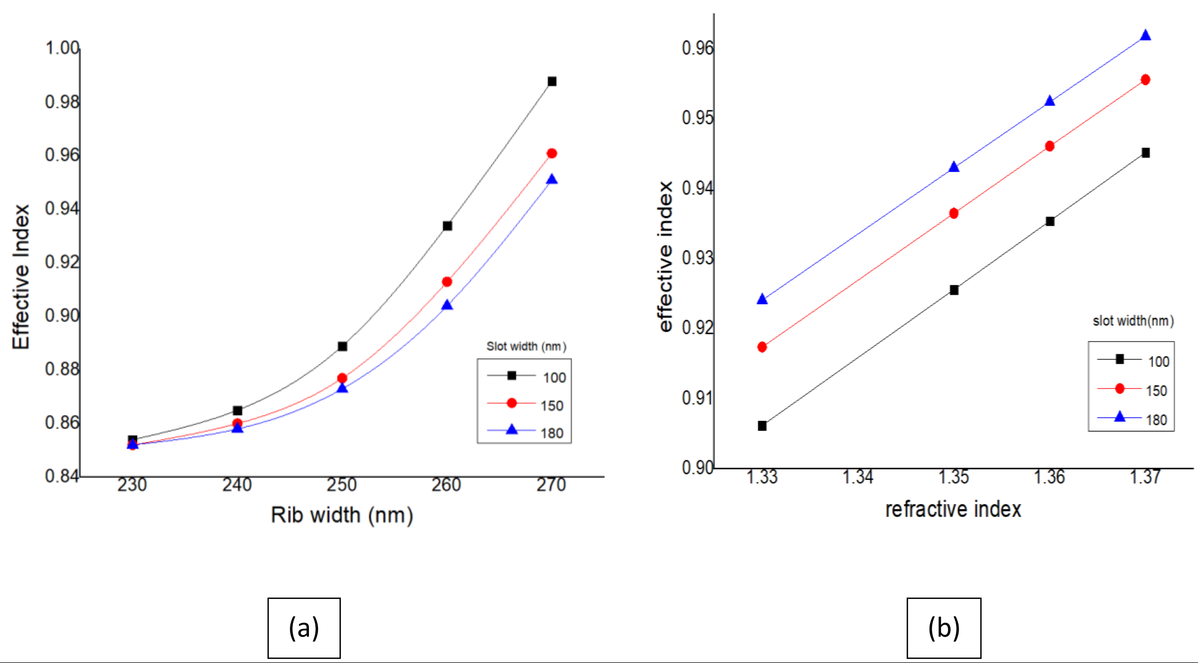


Fig.2.5. Effective index profile when (a) Rib width varies from 230nm to 270nm (b) refractive index varies from 1.33 to 1.37 at different slot widths 100nm, 150nm, 180nm.

In Fig.2.5. (c) Bulk sensitivity profile for different SiO2 dimensions 50nm, 100nm, 150nm, 200nm is shown. Firstly, variation of cladding index from 1.33 to 1.35 results in less sensitivity but we found our device to be sensitive when refractive index varies from plasma of pure blood (r.i =1.35) to plasma of virus infected blood (r.i=1.36) and by changing the dimension of SiO2 also.

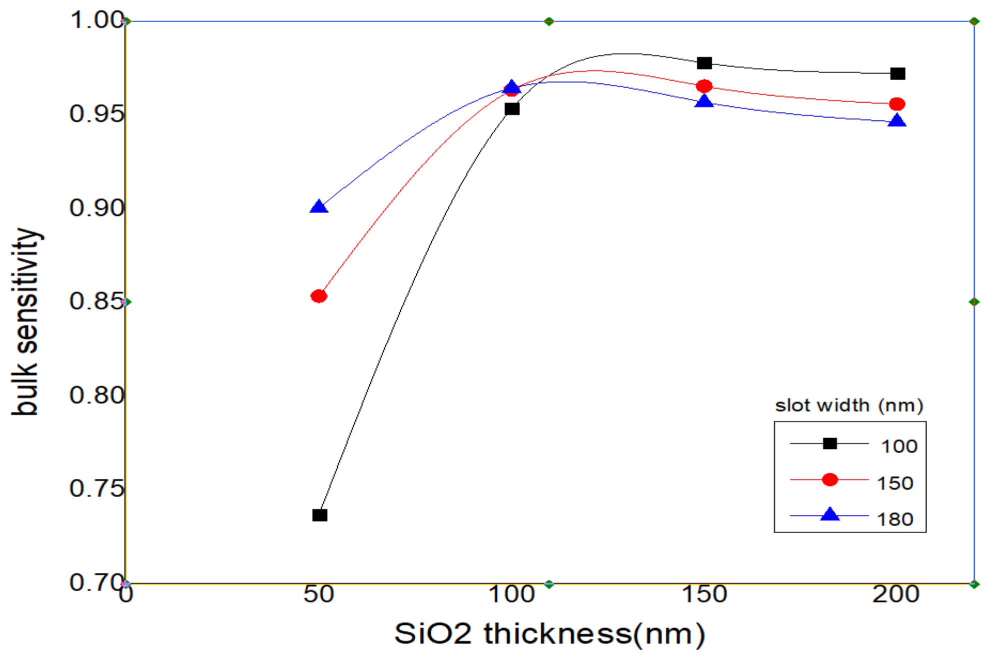


Fig.2.5. (c) Profile of Bulk sensitivity for variation of thickness of SiO2 from 50nm to 200nm for different slot widths 100nm, 150nm and 180nm.

2.6 Modal Birefringence

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. The birefringence is often quantified as the maximum difference between refractive indices exhibited by the material.

Modal birefringence (B) is the ratio of the maximum difference of effective mode index of TE and TM mode to the effective mode index of TE.

$B = \left|\frac{neff\,TE - neff\,TM}{neff\,TE}\right|$; where all the symbols have their usual meanings.

Optical birefringence has been demonstrated in polymeric region in a metal assisted silicon slot waveguide. Birefringent crystals are widely used in optics for the control of the polarization state of light. The reported slot-waveguide sensor exhibited refractive index sensitivity as high as several hundreds of nm/RIU (refractive index unit). Moreover, considering the contrast field distribution between orthogonal modes, slot waveguide can possess high birefringence.

Looking at waveguide theory it is possible that there are a number of formats in which an electromagnetic wave can propagate within the waveguide. Thus, there is a reflection inside those crystals and also the phenomena of refraction results in different waves. These different types of waves correspond to the different elements within an electromagnetic wave. These modes of propagation are described below-

- **TE mode:** This waveguide mode is dependent upon the transverse electric waves, also sometimes called H waves, characterized by the fact that the electric vector (E) being always perpendicular to the direction of propagation.

- **TM mode:** Transverse magnetic waves, also called E waves are characterized by the fact that the magnetic vector (H vector) is always perpendicular to the direction of propagation.

- **TEM mode:** The Transverse electromagnetic wave cannot be propagated within a waveguide, but is included for completeness. The TEM wave is characterized by the fact that both the electric vector (E vector) and the magnetic vector (H vector) are perpendicular to the direction of propagation.

The optical mode confinement in the Quasi TE and TM are shown below-

(a) (b

Fig.2.6 Electric field distributions of the metal-assisted silicon slot waveguide for (a) the TE mode and (b) the TM mode

2.7 Results

In Fig.2.7 (a) We simulated the design for Modal birefringence by varying the width of the slot for different SiO2 thicknesses 50nm, 100nm, 150nm and 200nm. As a result, we found that by increase in slot width, Modal birefringence will always be higher for 50nm SiO2 and least achieved by the 200nm.

Similarly In fig.2.7 (b) The results shows that due to the variation of SiO2 thickness there should be a decrement in modal birefringence and thus it is maximum for TM mode than TE mode. Individually, it is higher for 180nm slot width for TM mode and lesser for 100nm slot width and, same happens in the case of TE mode.

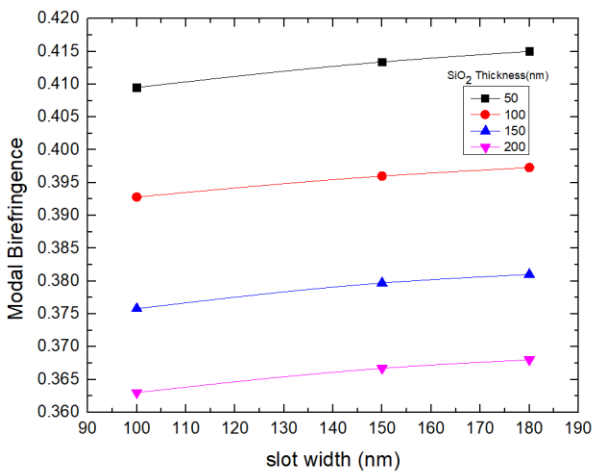


Fig.2.7. (a) Modal birefringence profile when there is a variation of slot width from 100 nm to 180nm.

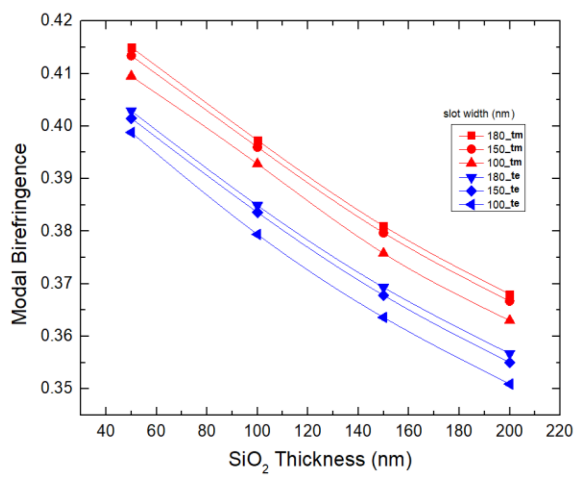


Fig.2.7. (b) Modal birefringence profile when there is a variation of SiO2 thickness from 50 nm to 200nm.

CHAPTER – 3 HYBRID PLASMONIC WAVEGUIDE (HPW) BASED BIOSENSOR

3.1 Introduction to hybrid plasmonic waveguides

Surface plasmon polariton (SPP) has been identified as a key enabling technology for highly integrated photonic components and circuits, due to its unique potential for manipulating the flow of light at scales much smaller than the diffraction limit. Among a variety of wave guiding configurations, plasmonic structures that incorporate metallic features are ideal for light transmission at the sub-wavelength scale. A number of SPP-based wave guiding schemes, such as metallic nanoparticles, nanowires, slots and dielectric-loaded structures have been proposed and demonstrated in recent years. In contrast to offering significantly better optical confinement than conventional all-dielectric wave guiding counterparts, the guiding performances of SPP configurations are still severely restricted by the fundamental tradeoff between confinement and loss, which greatly hinders their practical implementations.

Recently, a new class of hybridized plasmonic guiding structures combining dielectric wave guiding with surface plasmon polariton transport has been proposed, and it offers a promising solution to the limitations of traditional SPP waveguides. With the incorporation of additional low-index dielectric layers between metal structures and high-index dielectric configurations, these hybrid plasmonic waveguides (HPWs) allow both enhanced field localization and reduced transmission loss, as compared to most previously reported plasmonic structures. Their guiding performances render themselves as ideal candidates for realizing high-performance photonic components, and they also offer great potential for a number of intriguing applications. In addition to the conventional hybridized waveguide configurations, extensive efforts have also been devoted to the exploration of modified hybrid structures. Though some of these novel configurations exhibit improved optical performance as opposed to their conventional hybrid counterparts, most of them still suffer from the tradeoff between modal attenuation and field localization.

Moreover, due to additional fabrication complexities, many of these modified waveguides face great challenges when leveraged for practical applications. Therefore, there is a need for a simple but feasible way to reduce the propagation loss of traditional hybrid waveguide while maintaining its tight-field localization property.

Here in this article, we propose a new type of HPW based biosensor by combining dielectric-loaded wave guiding with a traditional hybrid structure, which we refer to as a Hybrid Plasmonic Waveguide based Bio-Sensor Nano-device which is beneficial for reducing the propagation loss and maintaining the tight field confinement. Based on systematic numerical simulations, we will show in detail the capability of the Our Hybrid Plasmonic Waveguide based Bio-Sensor Nano-device about its use in medical field and biomolecule detection and early disease detection by delay difference due to small change in refractive index, which will lay the foundation for future designs and investigations.

3.2 Proposed design of biosensor

This new waveguide geometry is composed of a rectangular waveguide of 300nm width and 200nm in height and a dielectric layer of 10nm high and 300nm wide. As shown in Fig. 1 Two square blocks of metal (Au) and one sample block placed between them. For transmission through the dielectric requires materials with properly matched dielectric constants, the wavelength of the incident light is chosen to be 1550nm and the materials for the metal, first, and second dielectrics are chosen to be gold, silicon dioxide (SiO_2), respectively.

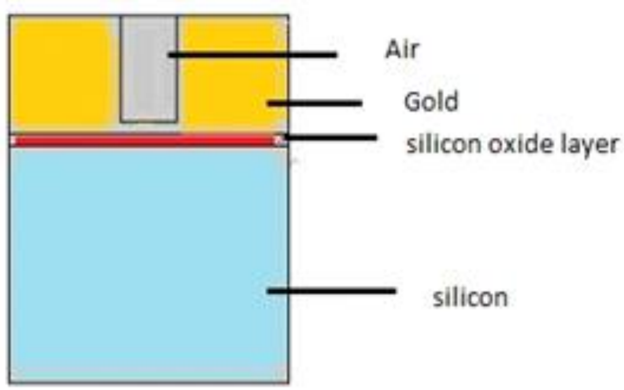
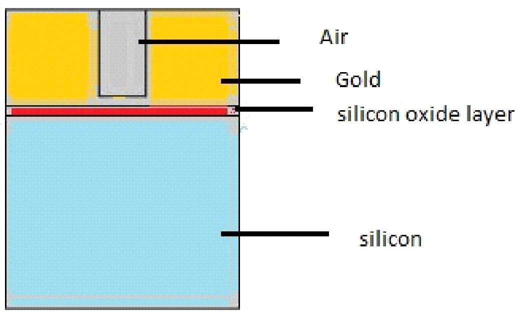


Figure 3.2 2-D Schematic for biosensor nano-device without grating.

3.3 HPW based biosensor without grating



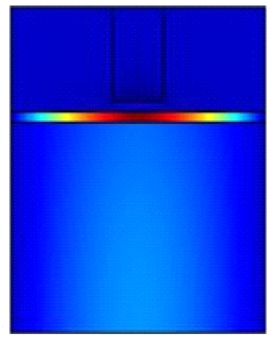


Figure 3.3(a) 2D Schematic for biosensor nano-device without grating.

Figure 3.3(b) Light confinement in desired region.

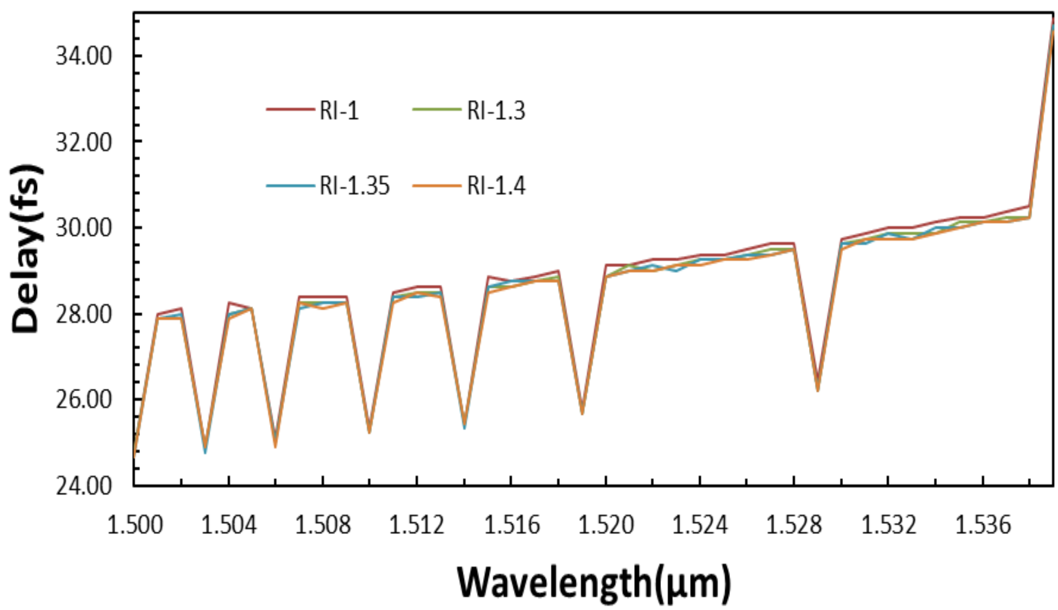
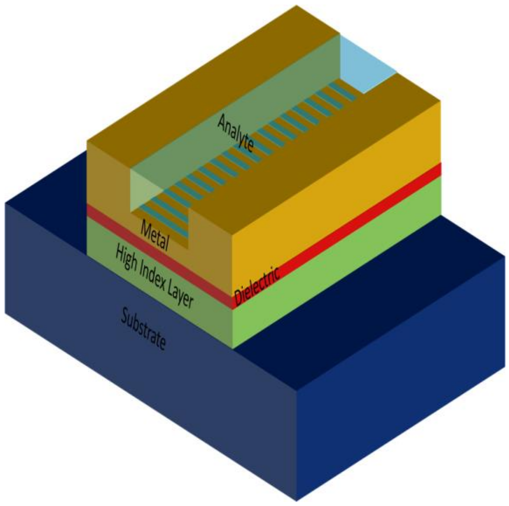


Figure 3.3(c) Delay graph of proposed design for different refractive index

3.4 HPW based biosensor with grating



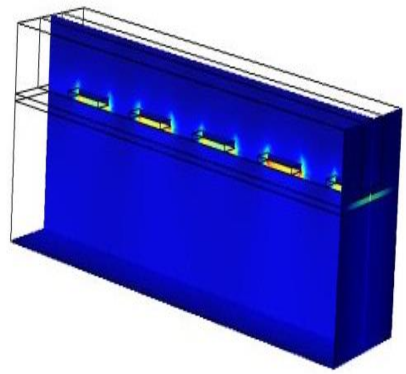


Figure 3.4(a) Schematic for biosensor with grating introduced in metal layer.

. Figure 3.4(b) Simulated results show light confined in desired region

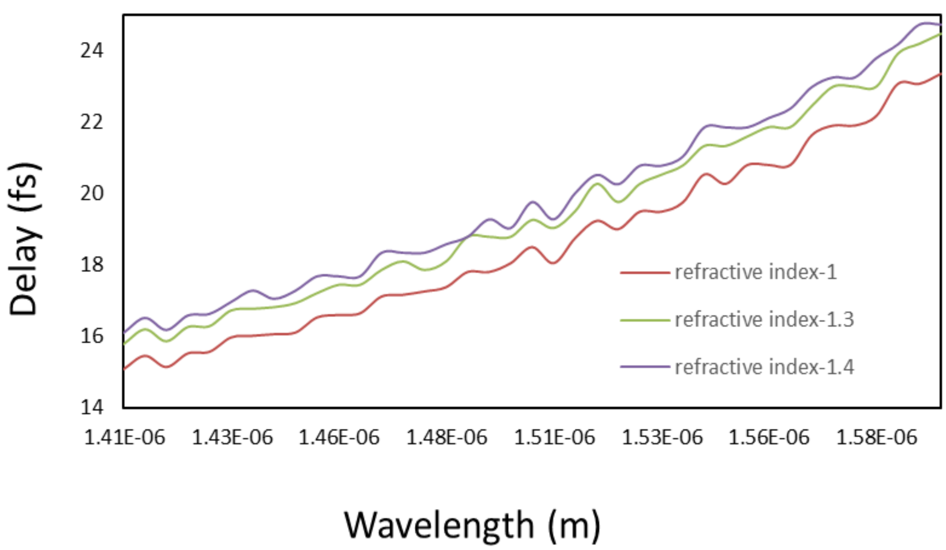


Figure 3.4(c) Graph (delay vs wavelength for different refractive index). Grating period 110-nm, device length 100-µm

A sensor device senses the analyte by measuring the delay difference of transmitted light into the device. The device works for near infra-red wavelength range. We monitored the interaction of light with different analytes assuming their refractive index. Most of the biological analytes has refractive indices from 1.3 to 1.4. Initial design shows a small delay difference by changing the analytes shown in fig. 4. For the improvement of delay difference, grating is introduced in metal layer (fig.5) and hence large delay difference is achieved (fig. 6). Refractive index of analytes is varied from 1.3 to 1.4. Figure 4 shows minimum group delay difference as R.I varies from wavelength 1500 nm to 1550 nm. Further we optimized our design considering a grating structure and observed a delay difference from wavelength 1400 nm to 1600 nm as shown in Fig. 6.

3.5 Relation between grating period and delay difference

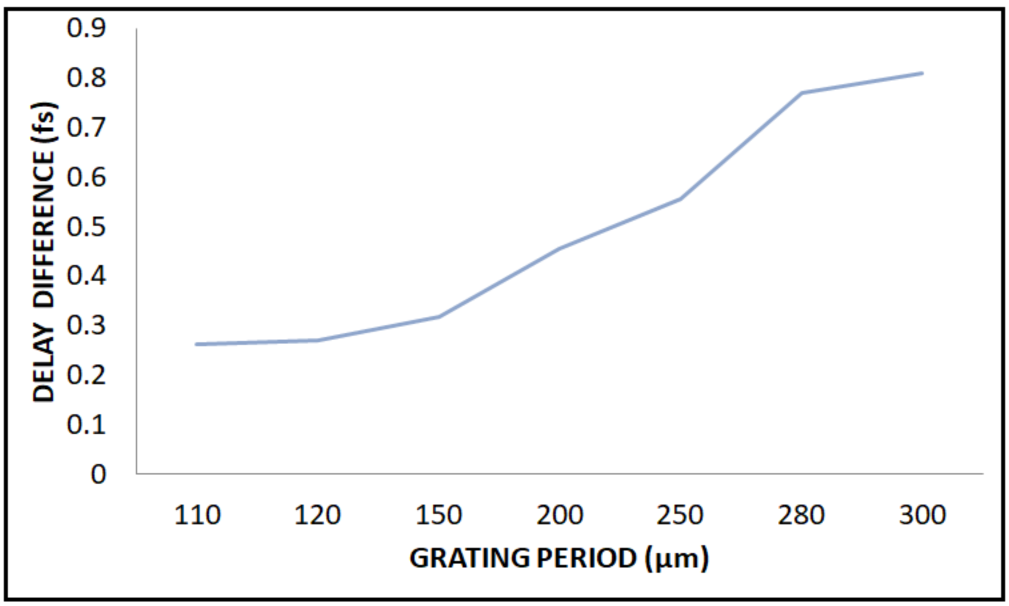


Figure 3.5 Graph (delay difference vs grating period for different refractive index 1.3 and 1.4) at λ= 1550nm.

From above graph we can see that grating period has a remarkable impact on the delay. Increase in Grating period results in increase in Delay difference.

Below 110nm grating period group delay difference is negligible while grating period more than 300nm mode confinement is not proper.

3.6 Conclusions & Future work

We have designed a hybrid plasmonic (HP) waveguide based device for optical sensing which show advantages with respect to small size, high performance and easy fabrication processes. However, further studies are still desirable for better performance and broader functionalities.

For optical sensing applications hybrid plasmonic waveguide show large interaction between tested liquids and optical mode, which results in large waveguide sensitivity, and so sensitive devices?

The fabrication of such a waveguide requires high precision of materials alignment as well as good quality of the plasmonic materials.

One of the benefits of the HP waveguide is the large optical confinement factor in the low-index layer, which leads not only to high sensitivity to the optical properties of the low-index materials, but also to its thickness.
From the simulation and experimental results of the HP waveguides and devices in this thesis, we propose future continuation of this work in the following areas:

1. Optimizations of the quality of plasmonic materials. Based on our experimental investigations, the quality of plasmonic material has a significant influence on the performances of the HP waveguides and devices. By using proper methods, like annealing of the metal film in high temperature and the flatness of sidewalls can be improved and the uniformity of the fabricated devices can be much improved.
2. Surface and gas sensing applications. In this thesis, our experimental investigations of HP sensors are based on liquid refractive index sensing. For the future continuation of this work, surface sensing with thin layer receptors can be developed. Moreover, an experimental setup of gas sensing can also be established, to broaden the application scope of HP sensors.

CHAPTER 4- ON CHIP GRATING REFLECTORS

4.1 Introduction to Optical Communication

Optical Communication is the transmission of optical beams carrying information either through free space in the atmosphere or by waveguides. This category of communication was discovered by Alexander Graham Bell in the late 19th century. Optical wireless communication is also known as Free Space Optical Communication.

A basic optical communication system consists of a transmitter using LEDs or LDs and the modulated light bearing information is collimated and transmitted through either free space or through waveguide. These beams of light, operating in the IR wavelengths, are focused on receiving lens connected to a high-sensitivity receiver.

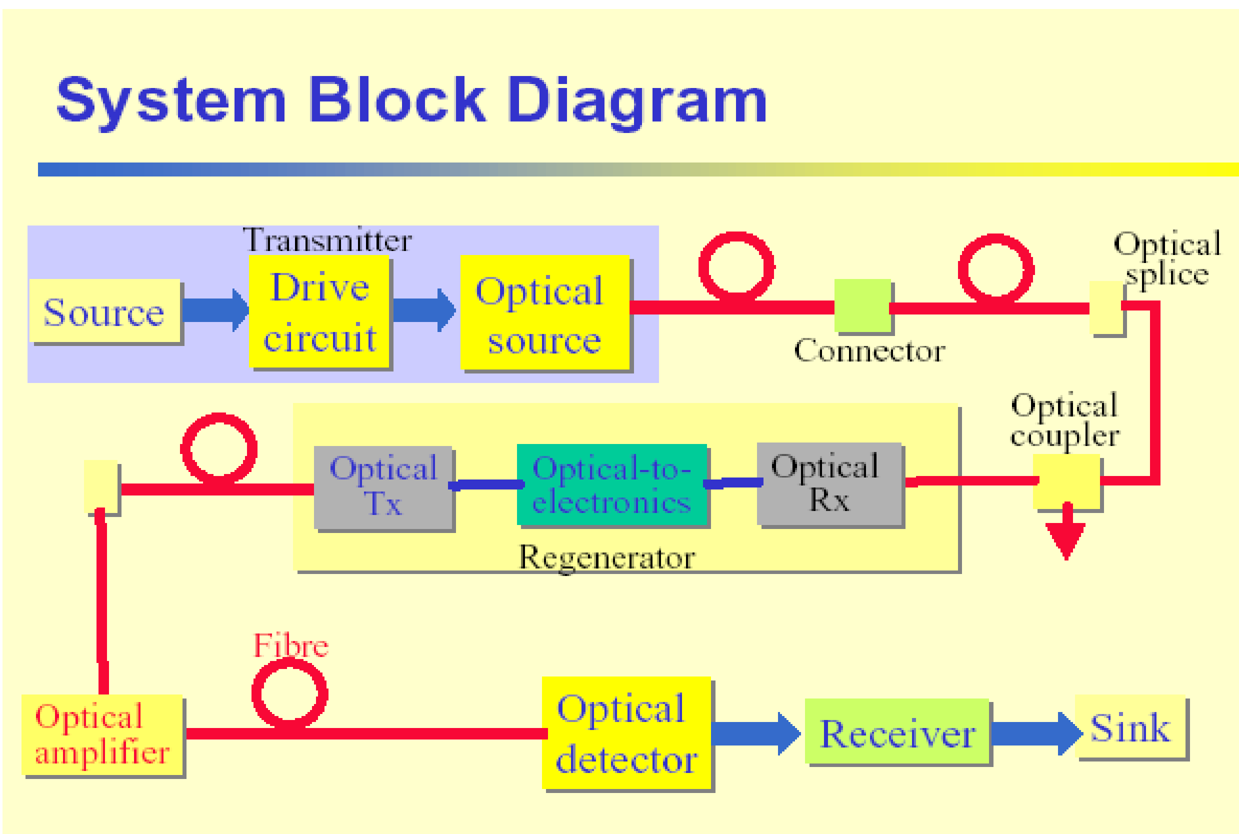


Fig4.1: A typical optical communication system block.

Optical communication has certain advantages over the conventional copper wire transmission and over Radio Frequency communication as well. The advantages are listed below-

Unlicensed spectrum: The freedom of the IR spectrum from licensing and regulation translates into ease, speed and low cost of deployment.

High speeds: Speeds up to orders of Gbps. Data rates comparable to optical fiber transmission can be carried by wireless optical systems with acceptable error rates.

Large bandwidth: Broader bandwidth as compared to Radio Frequency Communication is possible as in optical fiber because of the higher optical carrier.

Low power requirement: Much less consumption of power as compared to RF component counterparts.

No EMI: Unlike radio and microwave systems Free Space Optical Communication is an optical technology and hence no interference from or to other systems or equipment.

High security: More secure as any interception is detected immediately. Optical Wireless Communication laser beams cannot be detected with spectrum analyzers or RF meters. It requires a matching Optical Communication transceiver carefully aligned to complete the transmission. Interception is, therefore, very difficult and extremely unlikely. Light beam cannot penetrate walls hence prevents eavesdropping.

Low-cost deployment: Easier and cheaper installation as compared to deploying high-capacity fiber cables. Optical antennas and transceivers are much smaller in size, and hence, do not require much space to be installed as compared to RF antennas on the rooftops. In the last mile segment, it is also possible to mount these systems inside buildings as FSO transceivers can transmit and receive through the glass windows, reducing the need to compete for roof space, simplifying wiring and cabling and permitting FSO equipment to operate in a very favorable environment

4.2 Introduction to high contrast grating

Gratings and photonic crystals based on one-dimensional (1D) and two-dimensional (2D) structures, on Silicon-on-insulator (SOI), have recently made significant progress in realizing various optoelectronic devices for applications in high-end optical net-works, bio-chemical sensing and in optical interconnects. Due to the large refractive Index difference in vertical direction and resulting strong optical confinement, an SOI chip provides reduction in component size. Optical gratings exhibit interesting behavior when the period of grating becomes smaller than the wavelength; the grating in that case is called a sub-wavelength grating. A new concept of dielectric sub-wavelength grating with high-index contrast was proposed in which only the 0^{th} order diffraction exists as a propagation mode; all the higher diffraction orders become evanescent modes and the grating basically serves as a simple mirror with high and broadband reflectivity. High-index Contrast Grating (HCG) can control and manipulate the light to achieve various extraordinary properties. There are applications in optoelectronic devices using high index contrast gratings e.g. low-loss hollow-core waveguides (HWs), vertical-cavity surface-emitting lasers (VCSELs), tunable VCSELs and high- Q optical resonators. HCGs can serve as high-reflectivity mirrors for surface-normal incident light which is useful to replace conventional distributed Bragg reflectors in optical devices. Also, high reflection with glancing angle incidence is desirable for many applications e.g. hollow waveguides, high focusing power reflectors and lenses.

High contrast grating is a physical structure where a low refractive index material is surrounded by a high refractive index material. In HCG, the grating period will lie between the optical wavelength in grating material and optical wavelength in surrounding material. HCG's show high reflectivity (<99%) and high-quality resonance factor. These qualities can cause some drastic change in optical communication.

History of High Contrast Grating

The concept of high contrast grating took off with a report on a broadband high reflectivity reflector for surface-normal incident light (the ratio between the wavelength bandwidth with a reflectivity larger than 0.99 and the central wavelength is greater than 30%) in 2004 by Constance J. Chang-Hainan which was demonstrated experimentally in the same year. The key idea is to have the high-refractive-index material all surrounded by low-refractive-index material. They are subsequently applied as a highly reflective mirror in VCSEL's as well as monolithic, continuously wavelength tunable vertical-cavity surface-emitting lasers. The properties of high contrast grating are rapidly explored since then.

In 2008, a single layer of high contrast grating was demonstrated as a high-quality factor cavity. In 2009, hollow-core waveguides using high contrast grating were proposed, followed by experimentally demonstration in 2012.This experiment is the first demonstration to show a high contrast grating reflecting optical beam propagating in the direction parallel to the gratings, which is a major distinction from photonic crystal or distributed Bragg reflector.

In 2010, planar, single-layer lenses and focusing reflectors with high focusing power using a high contrast grating with spatially varying grating dimensions were proposed and demonstrated. Some literatures quote the high contrast gratings as photonic crystal slabs or photonic crystal membranes.

HCG’s can of many types based on their grating period periodicity in different dimensions. Two basic type of HCG’s are shown below-

1. Periodic in one dimension

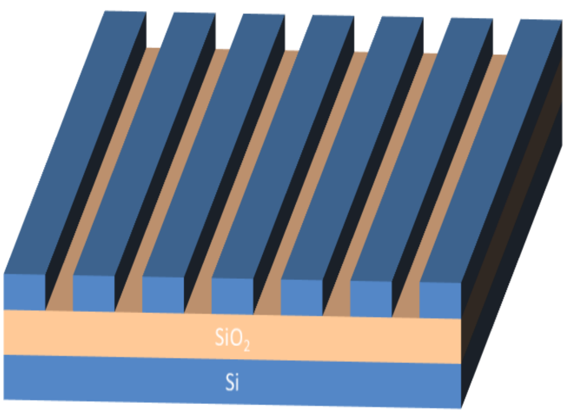


Fig4.2: A typical 1-Dientional periodic high contrast grating

2. Periodic in two dimensions

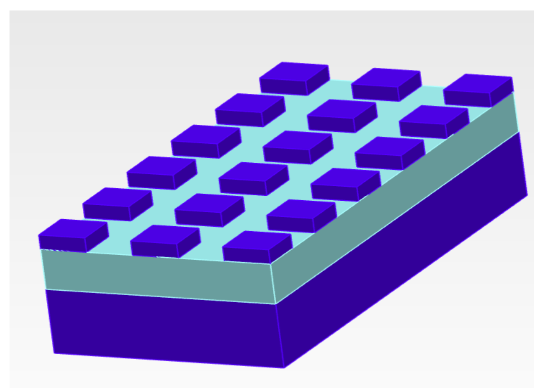


Fig4.3:A typical 2-Dientional periodic high contrast grating

4.3 1-D high contrast grating

HCG CHARASTERISTICS

To obtain a polarization free high reflectivity grating we first keep the thickness (T_g) constant at 0.983µm and Duty Cycle (DC) at 0.5 than we incident a wave of wavelength 1.55µm at an angle of 8° on the grating and then observe the reflectivity of the grating for different periods of grating for both TM mode and TE mode. Fig4.4 clearly shows that this design offers good reflectivity for grating periods Λ (in µm) = 0.63,0.67,0,68,0.71,0.73 on TM mode incidence but Fig4.5 suggests any of these grating periods does not show good reflectivity on TE mode incidence. So clearly, we cannot obtain a polarization free grating which has good reflectivity on offer.

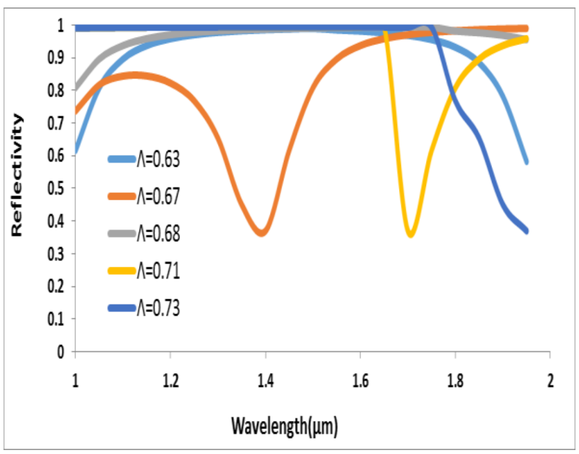


Fig4.4: This graph shows the reflectivity of grating for different grating periods for TM mode of incidence at different

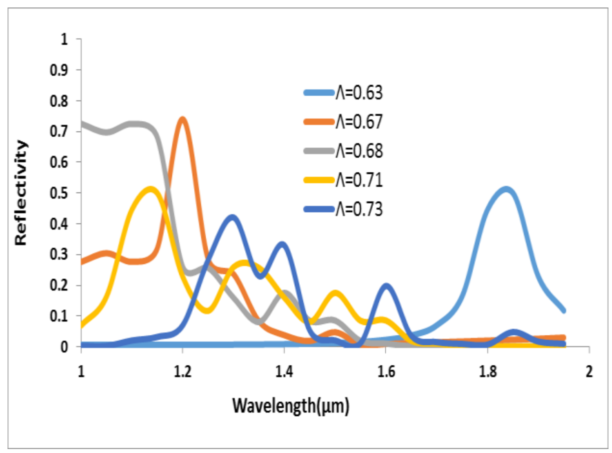
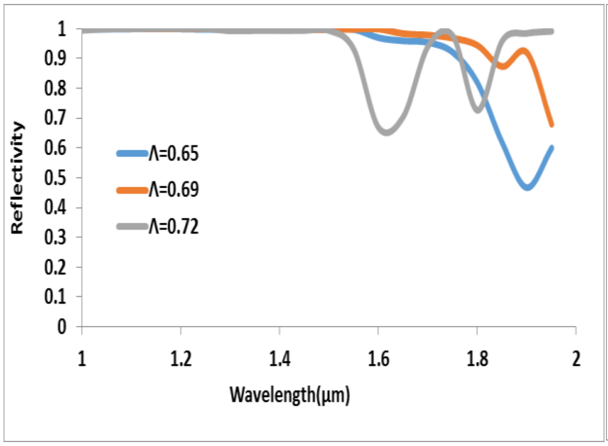


Fig4.5: This graph shows the reflectivity of grating for different grating periods for TE mode of incidence at different wavelength**.**

Now we incident a TE polarized wave of wavelength 1.55µm on the grating at an incidence angle of 8° and then we observe the reflectivity of the grating.



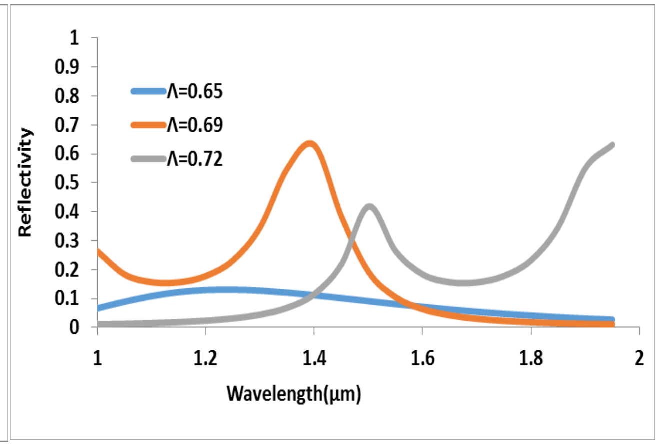
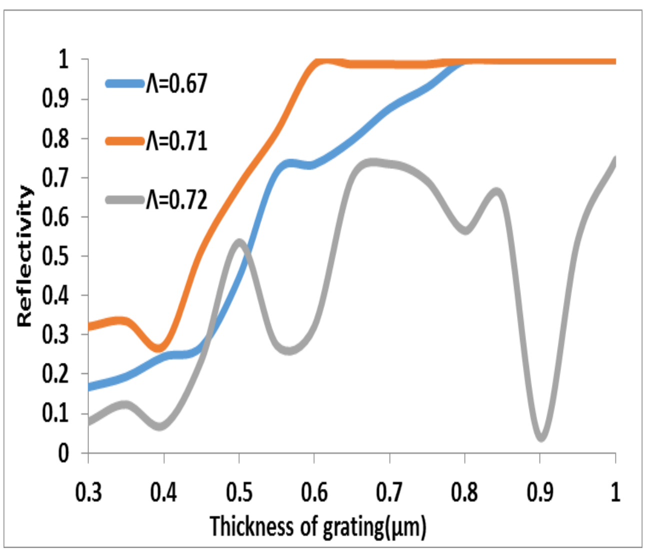


Fig4.6: This figure shows reflectivity for different grating periods for TE mode of incidence.

Fig4.7: This figure shows reflectivity for different grating periods for TM mode of incidence.

Fig4.6 suggests that this grating has good reflectivity on offer for incident wavelength 1.55µm at an incidence angle of 8° for the grating period Λ (in µm) =0.65,0.69,0.72 but in Fig4 we can see that these same grating periods does not offer good reflectivity on TM mode of incidence. So clearly, we cannot design a polarization free grating which has good reflectivity to offer.

Now we will vary the grating thickness and duty cycle keeping the wavelength of incident wave constant at 1.55µm and check the reflectivity of grating for different grating periods.



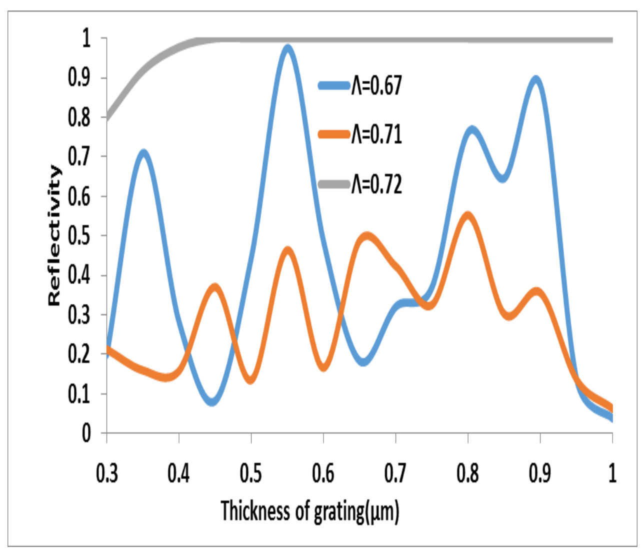


Fig4.8: This graph depicts the reflectivity change in the grating with thickness of grating at 1.55µm at different grating periods for TM mode of incidence.

Fig4.9: This graph depicts the reflectivity change in the grating with thickness of grating at 1.55µm at different grating periods for TM mode of incidence.

Fig4.8 clearly shows that this grating will have good reflectivity for grating period 0.67µm and 0.71µm at a thickness of 0.983µm but for these two grating periods the same thickness will not offer good reflectivity as we can see in Fig4.9. For TE mode of incidence we have good reflectivity

for grating period 0.67µm at a thickness of 0.983µm but as we can see in Fig5 that the same grating period will not provide good reflectivity for TM mode of incidence.

So, the variance of grating thickness also could not provide a polarization free high reflectivity design. Now we will see the effect of duty cycle variance of this design.

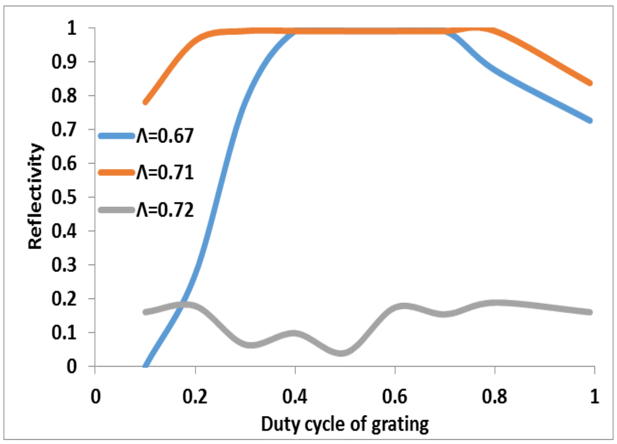


Fig4.10: This graph depicts the duty cycle dependence of reflectivity of the design at an incidence angle of 8° for TM mode of incidence.

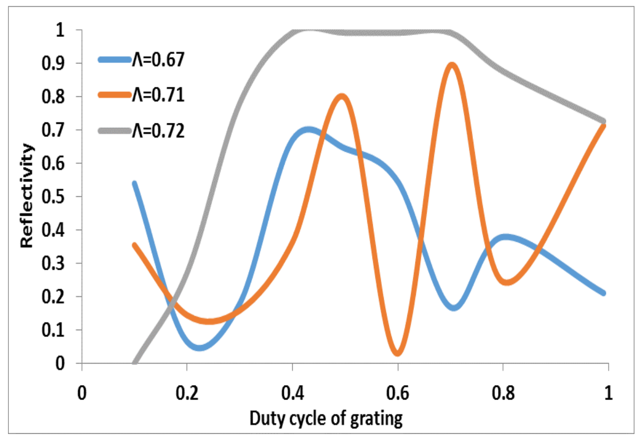


Fig4.11: This graph depicts the duty cycle dependence of reflectivity of the design at an incidence angle of 8° for TE mode of incidence.

Fig4.10 shows that for grating period 0.67µm and 0.71µm this design will have good reflectivity for duty cycle of 0.4 to 0.6 at TM mode of incidence but Fig4.11 shows that for the same duty cycle and grating period design will not exhibit good reflectivity for TE mode of incidence.

From above observations we can say that we cannot design a 1-D grating that will have a polarization free good reflectivity for 1.55µm optical wavelength and shallow angle incidence.

4.4 2-D high contrast grating

A 2-D grating is defined as a grating which is periodic in 2 dimensions. In the previous chapter we saw that it is not possible to design a 1-D design which will have a polarization free high reflectivity on offer for shallow angle incidence of optical wavelength 1. 55µm.But in this chapter, we propose a2-D High Contrast Grating which exhibits polarization free high reflectivity on offer for shallow angle incidence of optical wavelength 1.55µm.

2-D Design-

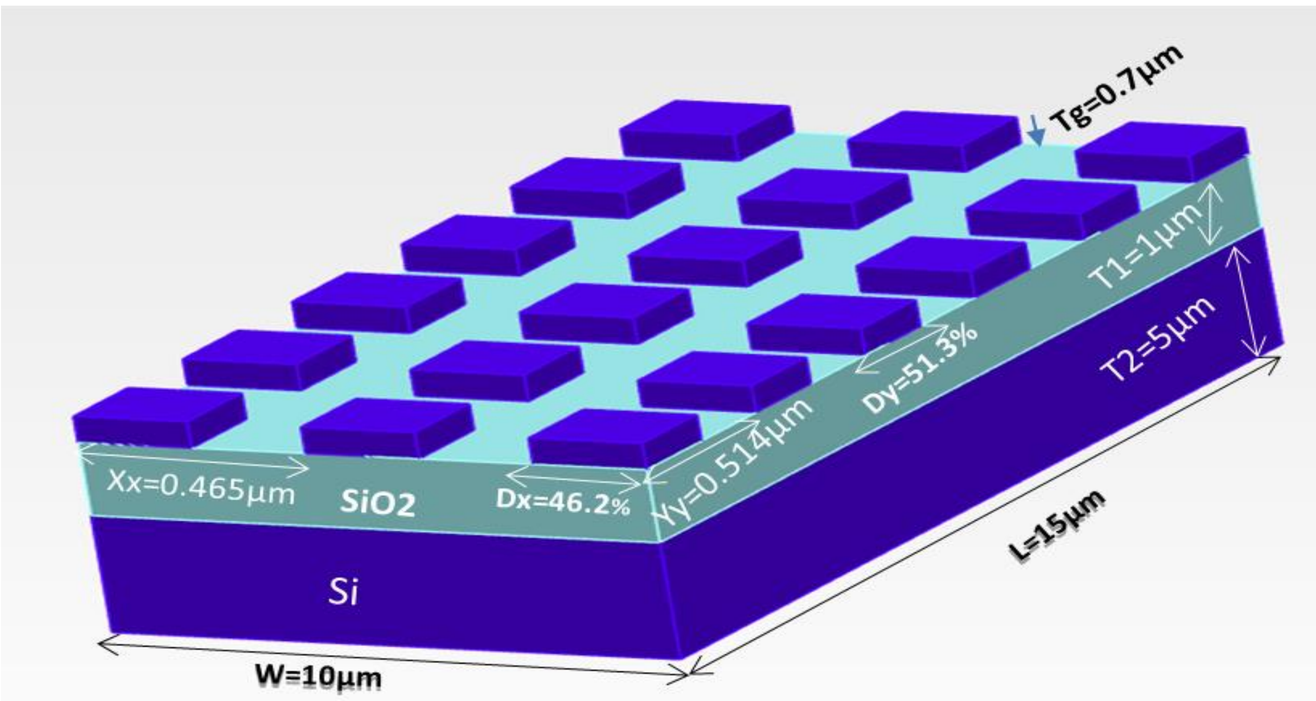


Fig4.12: 2-D high contrast grating

2-D HCG DESIGN CHARACTERISTICS

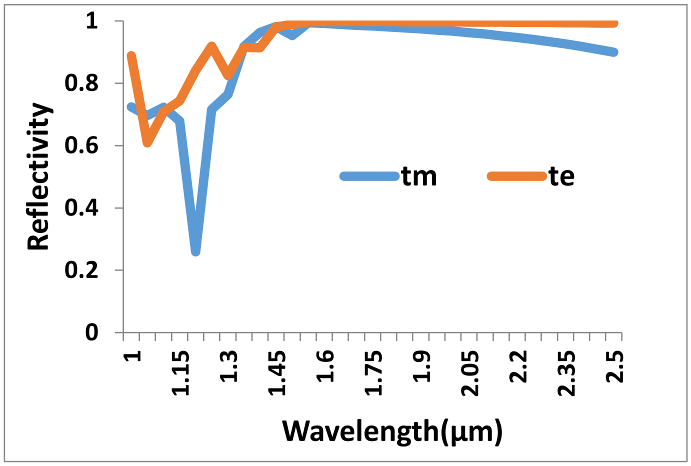


Fig4.13: This graph depicts the change in reflectivity of the 2-D design with the variance of incident optical wavelength with incidence angle of 8°.

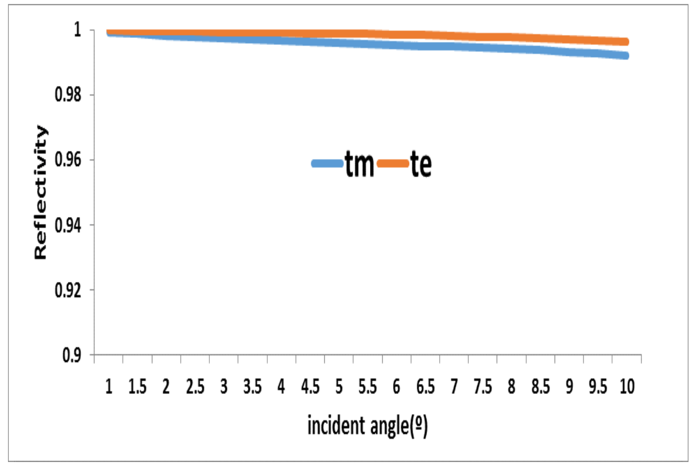


Fig4.14: This graph depicts the change in reflectivity design with change in incidence angle with optical wavelength 1.55µm.

We can clearly see that this design will have very good reflectivity for an incident optical wavelength of 1. 55µm.Exact reflectivity of this design for TM mode of incidence is 99.58% and for TE mode of incidence is 99.76%. So clearly this design offers good reflectivity for both modes of incidence at an angle of incidence 8°.

Fig4.14 shows the change in reflectivity with change in angle of incidence of incident optical wavelength 1.55µm. In Fig3 we can clearly see that this design will just not offer good reflectivity for an incidence angle of 8° but it will exhibit for all shallow angle incidence.

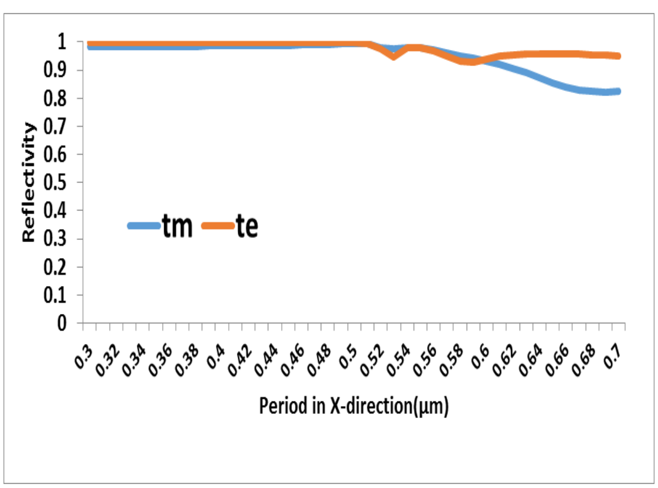


Fig4.15: This graph depicts the change in reflectance of design with change in grating period of X-direction.

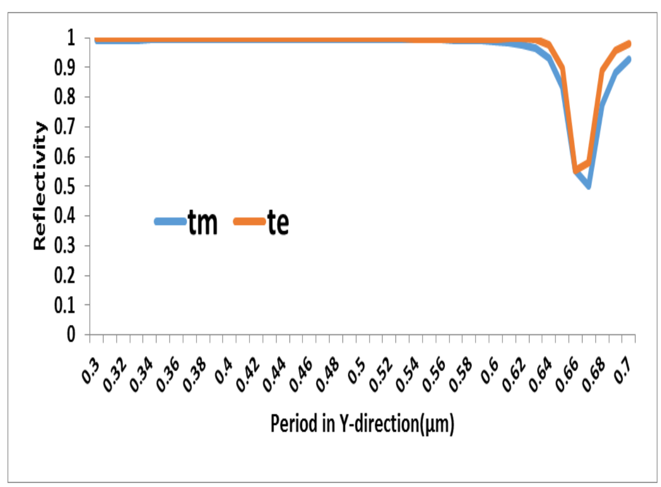


Fig4.16: This graph depicts the change in reflectance of design with change in grating period of Y-direction.

Fig4.15 shows the variance of reflectivity with change in X-direction grating period. From Fig4.15 we can see that this design has an acceptable tolerance for the X-direction period fabrication error which is around 0.4µm.

Fig4.16 shows the variance of reflectivity with change in Y-direction grating period. From Fig5 we can clearly tell that this design has good tolerance for Y-direction period fabrication error which is around 0.5µm.

Fig4.15 and Fig4.16 clearly suggest that this design has very good fabrication error tolerance for both X-direction and Y-direction grating period error.

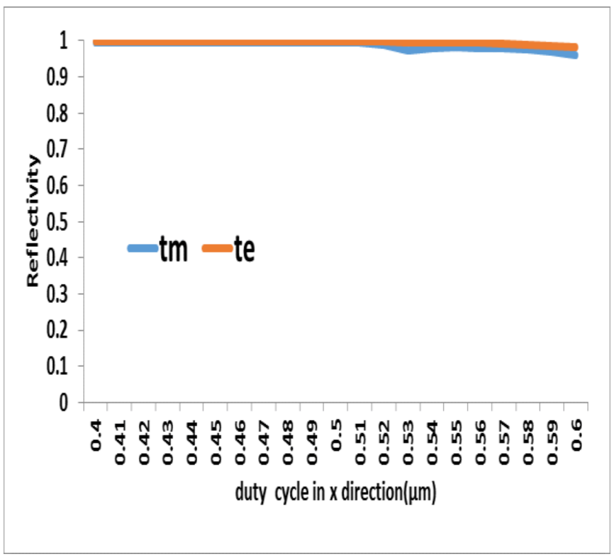


Fig4.17: This graph depicts the change in reflectance of design with change in grating duty cycle of X-direction.

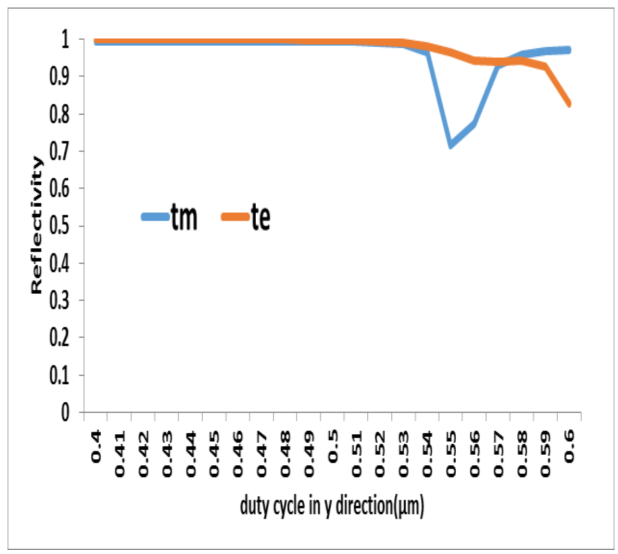


Fig4.18: This graph depicts the change in reflectance of design with change in grating duty cycle of Y-direction.

Fig4.17 we can see that this design has an acceptable tolerance for the X-direction duty cycle fabrication error which is around 2%.

Fig4.18 shows the variance of reflectivity with change in Y-direction grating duty cycle. From Fig4.18 we can see that this design has an acceptable tolerance for the Y-direction duty cycle fabrication error which is around 4%.

Fig4.17 and Fig4.18 clearly suggest that this design has very good fabrication error tolerance for both X-direction and Y-direction grating duty cycle error.

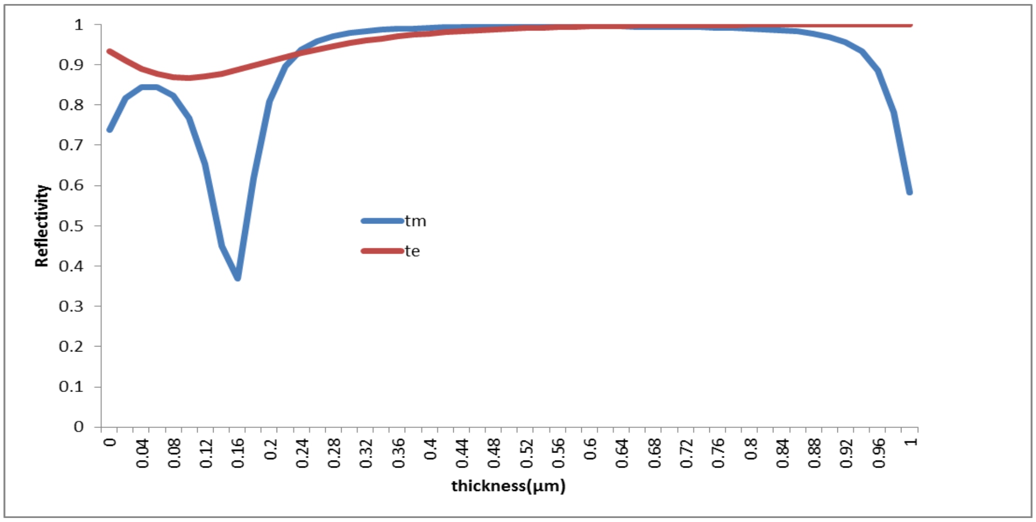


Fig4.19: This graph depicts the change in reflectance of design with change in grating thickness.

Fig4.19 shows the variance of reflectivity with change in X grating thickness. From Fig4.19 we can see that this design has an acceptable tolerance for the X-direction duty cycle fabrication error which is around 0.5µm.

4.5 Conclusion

As we have observed the characteristics of 1-D and 2-D high contrast grating we can say that it is very difficult to find polarization independent high reflectivity in 1-D high contrast designs but it provides very good polarization dependent reflectivity. our proposed 2-D high contrast design offers very good low polarization dependent reflectivity for incident optical wavelength 1.55µm at all shallow angles with large fabrication error.

CHAPTER- 5 CONCLUSION

- Homogeneous sensitivity of metal assisted slot waveguide is higher than conventional slot waveguide and reduction in effective index is observed when wavelength is increased from 1500nm to 1600nm for refractive index change of 1.33, 1.35 and 1.37. After introduction of proposed structure, we concluded that Quasi TM mode has higher effective index than TE mode when SiO_2 dimension is varied. Therefore, Modal birefringence is maximum when SiO_2 thickness is 50nm and minimum when 200nm with variation in slot width.

- It was desired to have large group delay difference for small changes in refractive index. In the first model of HPW without grating the group delay difference was small for change in refractive index. After introduction of grating, larger group delay difference was observed for change in refractive index. The final result obtained was 1FS group delay difference for a change of 0.1 refractive index.

- It is really difficult to find polarization independent high reflectivity in 1-D high contrast grating as this grating transverse in one direction only.1-D design can provide good polarization dependent reflectivity. Our proposed 2-D high contrast design offers very high reflectivity for both TE (99.76%) and TM (99.52%) mode of incidence optical wavelength 1.55µm at incidence angle 8°.This design provides good reflectivity (>99%) for both TE and TM mode of incidence of optical wavelength 1.55µm at all shallow angle incidences.

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