DESIGN AND FABRICATION

OF A

RECYCLED CARRIER MODULATOR

by

Ugochukwu J. Nsofor

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering

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ABSTRACT

In this thesis, I outline several design and fabrication approaches that can be used to achieve a Distributed Bragg Gratings on a Lithium Niobate (LiNbO₃) based substrate. These gratings function as wavelength selective mirrors and help create a Fabry-Perot resonator topology for recycling an optical carrier wave.

First and foremost, the choice of material was made bearing in mind the implication it would have on the fabrication and operation of the device. Lithium Niobate was chosen given the fact that over the years it has been proven to be a more matured and well understood wave guiding technology with excellent mechanical and chemical stability. Grating materials were chosen bearing in mind the substrate material that was selected for the modulator. Factors such as material compatibility (adhesion), and ease of processing were carefully considered.

Numerical simulations were conducted to determine the effects that the different grating materials have on the reflection and transmission of the optical signal. Factors such as refractive index, material thickness, loss, duty cycle and the quality of the grown material were shown to have effects on the reflection and transmission.

Actual devices were then fabricated and tested. Due to the size of the grating (with a pitch of about 360 nm and smallest feature size of ~180 nm), electron beam lithography was clearly the most viable option for a high precision and repeatable process. Material growth was done using plasma enhance chemical vapor deposition (PECVD), and thermal (resistive and electron beam) evaporation. Pattern transfer was carried out with an inductively coupled plasma (ICP) etch. Every step of the

fabrication was carried out in the nanofabrication facility here at the University of Delaware.

In this thesis, I present the different results that were achieved with the different material systems used. Furthermore, I discuss possible future endeavors towards achieving a higher index contrast and incorporating electrode structures.

Chapter 1

INTRODUCTION

1.1 Background

In his work published in 1900, Max Planck put forward for the first time the relationship between the energy and frequency of radiation of an electromagnetic wave [1]. He ascertained that energy can be absorbed or emitted in discrete particles called quanta. This was further investigated by Albert Einstein a few years later in 1905. Einstein's studies led to the discovery of the photoelectric effect – which describes the emission or ejection of electrons from the surface of a metal in response to an incident light [1]. The relationship between photon energy and frequency (wavelength) of radiation can be expressed as:

$$E(eV) = \frac{1.24}{\lambda(\mu m)} \tag{1.1}$$

where *E* represents the energy expressed in electron volts and λ represents the wavelength in micrometers. Einstein also went forward to propose the possibility of going beyond emission and absorption of light spontaneously to stimulated emission of light at specific wavelengths with the aid of electrons [1]. This led to the creation of the MASER (Microwave Amplification by Stimulated Emission of Radiation) by Charles H. Townes, Herbert J. Zeiger and James P. Gordon at Columbia University [1] following Einstein's prediction. It was not until 1960 that Theodore H. Maiman, a physicist at Hughes Research Laboratory in Malibu, California developed the first LASER (Light Amplification by Stimulated Emission of Radiation) using photographic flash lamps as the source of the laser pump.

The invention of the laser in the early '60s was followed by the invention of the laser diode, low-loss optical fibers (both in 1970) and erbium-doped fiber amplifiers in the '80s [2]. The synergy of these technologies led to the massive deployment of fiber optic networks in the '90s. They formed a basis for the 20th century telecommunication revolution and setting up the platform for the Internet. Since then, the telecommunication industry has seen exponential growth and with this comes the need to improve the performance of key components to match this growth.

As engineers and innovators, we are constantly looking for opportunities to improve existing technologies and in some cases develop new ones. Our drive for innovation has continually made us question the status quo. From eliminating the cathode ray tube (CRT) technology used in manufacturing the vacuum tube display to fabricating smart phones that are many times faster, smaller and cheaper than the first computer at MIT. The same enthusiasm has led to the idea of replacing electronics with photonics – the science of generating, manipulating and detecting radiant energy (such as light) [3].

Photons have a unique set of properties. They travel with the speed of light in free space; many of them can be in the same place at the same time and they rarely interact with each other. These properties are useful because transmitting terabits of data per second using photons is made possible without the existence of cross talks and interference. Electrons on the other hand are great for computation because two of them cannot be in the same place at the same time as they would interact with each other. As such, they can be used in building non-linear switching devices like transistors but suffer from interference when used in transmission [4]. Thus, the shift from electronics in communication is largely due to this and similar limitations that

include narrow bandwidth, high power consumption, high heat dissipation, high weight of metallic conductors, and high cost.

The need for ultra-broadband, high frequency transmission of information has continually steered advancement in the study of the behavior and properties of light (optics). To match current demands and to comply with next generation applications, electrical and optical devices will have to operate at a much higher speed, manage increased capacity, consume less power, minimize their footprint, reduce loss and be easily integrated with other components. A key component of optical integrated circuit (OIC) is the modulator which functions to translate an electrical signal to an optical signal.

This research is geared towards the realization of a new class of high efficiency broadband electro-optic modulators – a promising new development in the field of RF photonics, with an important application in a recently developed millimeter wave imaging system. A Recycled Carrier Modulator (RCM) as it is called improves an existing device, a modulator, used for manipulating an optical beam with an electrical signal. By recycling the optical carrier in a Fabry Perot resonant cavity, the efficiency of the modulator is increased.

1.2 Operating Principles of a Modulator

Certain materials have the ability to change their optical properties like refractive index when an electrical field is applied across them. This special characteristic has led to the creation of a very fundamental component of most telecommunication device – Modulators. A Modulator is an electrical device that is used to impress an electrical (radio-frequency, RF) signal onto an optical beam (light wave) by varying one or more properties of the beam. This change in property can result in a change in amplitude (amplitude modulation), or a change in phase (phase modulation) or a change in polarization (polarization modulation) of the light wave. In some cases, a modulator can also be made to function as a switch depending on the interaction of the optical wave and the electrical signal, as well as the design of the input and output ports.



Figure 1.1: A conventional modulator

Often times when modulators are discussed, one may be inclined to think of it in one instance as only the interaction between an electrical signal (modulating signal) and an optical (carrier) wave utilizing electro-optical effect. In essence, modulation can be achieved by a number of different techniques. By introducing some form of mechanical strain on certain material, their refractive index can experience a change (acousto-optic effect). An applied field can also shift the absorption edge of a semiconductor material to a longer wavelength (Franz - Keldysh effect) which can be exploited to achieve modulation.

1.3 Types of Modulation

1.3.1 Phase Modulation

Phase modulation is achieved when a beam of light is made to pass through a Pockels cell of length, L to which an electric field is applied. The change in phase experienced by the beam is represented as:

$$\Delta \phi = \beta l = n(E)k_o L = \frac{2\pi n(E)L}{\lambda_o}$$
(1.2)

$$\Delta \phi = \frac{\pi r n^3 E L}{\lambda_o} = \frac{\pi r n^3 V L}{d\lambda_o} , \qquad (1.3)$$

which implies that the voltage V, connected across the terminals of a Pockels cell separated by a distance d, will bring about a $\Delta \phi$ change in phase on an optical beam that traverses the length L, of the Pockels cell. This expression can be modified to derive a key phase modulator figure of merit – the half wave voltage V_π, which is the voltage that is required to cause a π -phase shift.

$$V_{\pi} = \frac{d\lambda_o}{L\Gamma n^3} \quad (\text{for } \Delta \phi = \pi) \tag{1.4}$$

1.3.2 Amplitude Modulation

An Amplitude (Intensity) modulation can be achieved by making use of phase modulation in an interferometer. A beam of light is first made to pass through a beam splitter that splits the beam equally into the two arms of a Mach-Zehnder interferometer. By placing a phase modulator on one arm of the interferometer, as illustrated in Fig 1.2, the intensity of the output signal can be modulated by varying the voltage applied across the phase modulator.



Figure 1.2: An Intensity modulation using Mach-Zehnder Interferometer

The intensity through each arm of the beam splitter is given as:

$$I_o = \frac{1}{2}I_i + \frac{1}{2}I_i \cos\phi = I_i \cos^2\left(\frac{\phi}{2}\right)$$
(1.5)

where $\phi = \phi_1 - \phi_2$ is the phase difference of the light travelling across the two arms of the interferometer. Since this is a Y splitter, it makes sense that for a zero phase shift ($\phi = 0$, no phase modulation), the output from each port of the interferometer will add up to I_i .

The transmittance on the other hand is represented as the ratio of the output signal to the input signal:

$$\tau = \frac{I_o}{I_i} = \frac{I_i Cos^2\left(\frac{\phi}{2}\right)}{I_i} = Cos^2\left(\frac{\phi}{2}\right)$$
(1.6)

We see then that the transmission is a function of the phase difference ϕ , which is a function of the voltage that brings about the phase modulation. Therefore, the transmittance can be said to be dependent on the applied voltage.

1.3.3 Polarization Modulation

To effectively use a phase modulator, a phase-coherent detection system is needed. In phase modulation, the phase change is usually in one direction (y-polarized

waves TM, or x-polarized waves TE). The modulated light (which is now circularly polarized) is converted back to linearly polarized light using a cross analyzer and detected by a photocell. The field component perpendicular to the analyzer is not captured during this conversion, resulting in a 50% loss of optical power [10]. Polarization modulation provides an option to get around this limitation and achieve two times the modulation efficiency of an intensity modulator. By introducing a linearly polarized optical wave 45° between the x and y axes, there will be a rotation of the polarization vector in the z-direction which can be detected by a polarization-sensitive filter (also called an analyzer). Fabricating this filter is however difficult and has limited the use of polarization modulation in comparison to intensity modulation.

1.4 Types of Modulators

1.4.1 Electro-Optic (EO) Modulator

Electro-optic modulators utilize the first order Pockels effect (linear EO effect) and the Kerr effect (quadratic EO effect) to bring about a change in an optical beam. The Pockels effect denotes a linear relationship between the change in the refractive index and the magnitude of the applied electric field.

$$n(E) = n - \frac{1}{2} \Gamma n^3 E , \qquad (1.7)$$

where n = refractive index, r = Pockels coefficient (linear EO coefficient) and E = the electric field.

This change in the refractive index is quite small, usually about 10^{-6} to 10^{-4} [5] but sufficient to create a substantial change in the property of the travelling optical wave. Pockels effect is mostly common in certain crystals that are anisotropic in nature. Examples include LiNbO₃, LiTaO₃, CdTe, NH₄H₂PO₄ (ADP), and KH₂PO₄ (KDP). On the other hand, the Kerr effect is expressed as a quadratic relation. The change in refractive index being proportional to the square of the electric field

$$n(E) = n - \frac{1}{2} \Gamma n^3 E - \frac{1}{2} \mathfrak{s} n^3 E^2 , \qquad (1.8)$$

where s is the Kerr coefficient (quadratic EO coefficient).



Figure 1.3: Dependence of the refractive index on the electric field.

All materials exhibit some form of the Kerr effect, but the effect is stronger with materials that are centro-symmetric given the symmetric nature of the quadratic equation that describes it [6]. Examples include DAST (4-N,N-dimethylamino-4'-N'methystibazolium tosylate), IKD-1-50, and a broad range of polymers that have given rise to a fast-growing field known as organic electro-optic modulators (OEOMs). Many OEOMs are known to exhibit the Pockels effect when poled (applying electric field to cause the alignment of chromophores). Electro-optic polymers have also shown the possibility of reaching a low $V_{\pi}L$ (figure of merit) of about 3.3 Vcm [7] due to their high EO coefficient, which can exceed 300 pm/V [8], and in some cases are characterized by fast EO response time (less than 10 femtoseconds). In addition, their RF and optical refractive indices are closely matched [9]; they show little dispersion up to 200GHz and some are relatively cheap. On the down side they lack the mechanical strength and chemical stability of inorganic crystals like LiNbO₃. Table 1.1 summarizes the properties of polymers in comparison to LiNbO₃.

Property	LiNbO ₃	Polymers
EO coefficient (pm/V)	30.8	~300
V_{π} (V) in device	5	<1
Mechanical Strength	Very good	poor
Chemical Stability	Very good	Fair
Manufacturability	Fair	Fair
Cost	Relatively high	Fair

Table 1.1: Comparing Material and EO Properties of Inorganic Crystal and Polymers

1.4.2 Electro-Absorption Modulator

Electro-absorption is a phenomenon that describes the change in the absorption characteristics of a semiconductor (SC) material due to an applied electric field (Franz-Keldysh effect). Prior to the application of the electric field, an optical beam at the operating wavelength is passed without being absorbed. On applying an electric field, the absorption edge is shifted to longer wavelengths (lower energies) and thus the optical beam is absorbed.

Figure 1.4: Schematic representation of the Franz-Keldysh shift of the absorption edge of a semiconductor [25].

The continuous curve is the zero-field absorption curve for the semiconductor while the dotted curve shows the shifted absorption edge for a field of about 1.3×10^5 V/cm [25]. The large change in the value of α at the marked photon energy indicates a large change in absorption due to the applied field.

The mechanism responsible for this shift is mostly due to band bending resulting from the applied electric field. By connecting one surface of a semiconductor to a metal, a Schottky barrier contact (shallow p-n junction) is formed. Applying a reverse-bias voltage at this junction results in charge depletion at the surface extending into the semiconductor. This depletion region results in band bending close to the semiconductor surface while other regions where the field is maintained still has flat band. This provides allowable electron states within the bandgap so that a transition could occur with less amount of photon energy (longer wavelength). Figure 1.5 is an illustration of this phenomenon.

Figure 1.5: Energy band diagram showing band bending on an n-type and p-type semiconductor in the presence of a strong E field [26].

where Φ_M represents the metal work function, Φ_S the semiconductor work function, Φ_B the energy barrier, χ the electron affinity, V_{BI} the built in voltage, E_c the conduction band energy, E_V the valence band energy, E_F the Fermi-level energy and E_i Intrinsic Fermi-level energy.

The effective change in band gap energy, ΔE , can be represented as:

$$\Delta E = \frac{3}{2} (m *)^{-1/3} (q\hbar E)^{2/3}$$
(1.9)

with
$$\hbar = h/2\pi$$
 (1.10)

where m* is the effective mass of the carrier, q is the magnitude of the electric charge, h is the Planck's constant and E is the electric field.

Quantum Confined Stark Effect (QCSE) is another phenomenon that is used to create an electro-absorption modulator using a quantum well structure. A quantum well consists of very thin layers of low band gap semiconductors sandwiched between layers of high band gap semiconductors. The thickness of these layers is usually around 100 Å which approaches the same order of magnitude as the electron wavelength thereby giving rise to certain unique properties.

Figure 1.6: A schematic diagram of a GaAs/AlGaAs Multiple Quantum Well (MQW) structure with a pair of identical photons with wave vector k_0 produced by a two-photon down-conversion crystal [24].

Figure 1.7: Band Energy of a MQW Structure [23].

Among these unique properties is the ability to confine the electrons and holes of the exciton pair when an electric field is applied in a direction normal to the wells. Thus, field ionization of the exciton is disallowed, thereby preserving the sharp excition absorption peak. Electro-absorption is estimated to be about 50 times stronger in multiple quantum well structures as compared with bulk semiconductors because the QCSE is capable of creating a much significant change in absorption with moderate electric field than it is with the Franz Keldysh effect.

1.4.3 Acousto-Optic Modulator

By applying some form of mechanical strains on a solid, its refractive index can be altered so that the properties of an optical beam passing through the solid are modulated. This effect is known as photo-elastic effect, denoted by a photo-elastic tensor, ρ . In an acousto-optic modulator, the strain is produced by the passage of an acoustic wave. This results in a periodic index change in the material with a pitch corresponding to the wavelength of the acoustic wave. The Photo-elastic effect is mostly applied in optical integrated circuit involving modulators and beam deflectors but can also be used for designing frequency shifters. The acoustic wave used in this case is generally a travelling wave. This results in a dynamic periodic structure. Thus, there is a relative motion between the mobile periodic regions (created by the travelling acoustic wave) and the propagating optical beam. The result is a shift in the frequency of the mth order diffracted light. This shift is quite negligible given that the frequency of the optical beam is much higher than that of the periodic structure. However, this slight shift can be harnessed to achieve frequency division multiplexing of optical waves.

1.5 Distributed Bragg Reflection

This phenomenon was first discovered by William Lawrence Bragg, an Australian-born English Physicist, while conducting his famous experiment on "Diffraction of X-ray by Crystals". In that experiment he found out that it was possible to determine the position of the atoms in a crystal by analyzing the x-ray beam diffracted by the crystal – an important step in x-ray crystallography. Many other applications of this observation have been discovered over the years. The recycling of the optical carrier in this research is expected to be achieved using this principle.

Figure 1.8: Illustration of Bragg Reflection [20]

For the two waves to be in phase, their path length must equal a multiple of their wavelength, λ

$$l = dsin\theta \tag{1.14}$$

$$Path \, length, 2l = 2dsin\theta \tag{1.15}$$

$$m\lambda = 2dsin\theta \tag{1.16}$$

where d is the period of the grating and m = 1, 2, 3...

Bragg grating is thus a set of uniformly spaced parallel layers of alternating materials that act as partially reflecting planar mirrors. Depending on the pitch of the grating, the effective index and angle of the incident beam, this structure can be made reflective at a set of specific frequency intervals. As discussed earlier, the acousto-optic effect can be used to produce this periodic structure. However, this structure can also be achieved by fabricating a device with alternating material.

1.6 Thesis Overview

The subsequent chapters in this thesis present the design and fabrication steps that were utilized followed by a careful analysis of the test results. In chapter two, I present the fundamental theory of a guided wave modulation using Ti-diffused LiNbO₃ modulator. I then proceed to outline the process for fabricating a Ti-diffused LiNbO₃ modulator. In chapter three, I introduce the concept of a recycled carrier modulator by explaining the fabrication procedure and the rationale for using the different materials for achieving index contrast. In chapter four, I present the results from the three different grating materials that were used. Each result was analyzed differently stating their fabrication process, possible merit or demerit and how they informed the next approach. Chapter five covers the optical simulations that were carried out to examine the optical characteristic of each material used in the grating structure. The thickness, material quality, duty cycle and refractive index were shown to affect the index contrast of the grating. In chapter six, I present a summary of the results and how they stack with the required result. The thesis concludes with my recommendation as regards future work and areas of possible improvement.

Chapter 2

Ti-DIFFUSED LiNbO3 MODULATOR

This chapter begins with an introduction to Ti-diffused LiNbO₃ waveguides, which are used in this research. The different constituent crystal orientations and properties of LiNbO₃ are highlighted. This is followed by an analysis of the diffusion profile of titanium on a LiNbO₃-based substrate and the corresponding mathematical equations that are used to characterize it. This chapter ends in a detailed narrative of the laboratory procedure to fabricate a Ti-diffused LiNbO₃ waveguide.

2.1 Channel Waveguide Fabrication

Lithium Niobate (LiNbO₃) is a compound composed of lithium, niobium and oxygen that exists in crystalline form with very unique properties useful in many optical integrated circuits. It has excellent ferroelectric, electro-optic, photo-elastic and piezoelectric properties with broad applications in optical modulators and Qswitching, second harmonic generation, phase matching, difference frequency mixing etc. It is arguably one of the most thoroughly characterized optical materials and has a low propagation loss (~0.1 dB/cm) [22]. Single crystals of LiNbO₃ are grown using Czochralski process [8] after which it is cut into wafers with different crystal orientations (x-cut, y-cut or z-cut). Quasi-TM optical mode propagation on a z-cut, xpropagated LiNbO₃ substrate utilizes the dominant electro-optic coefficient r_{33} of about 30.8 pm/V [15]. LiNbO₃ is often used to fabricate channel waveguides by allowing the in-diffusion of titanium to form a graded index region. Titanium is in-diffused to increase the effective index of a particular region within the LiNbO₃ substrate to produce a waveguide. This is the first step in fabricating the modulator. A stripe of titanium is patterned on the LiNbO₃ substrate, Fig 2.1(a), and then slowly heated in a diffusion furnace at temperatures between 900° C - 1050° C for about 10 - 12 hrs with sufficient flow of oxygen and nitrogen (about 500 sccm). These conditions are maintained to prevent the out-diffusion of lithium ions, which often accompanies the in-diffusion process [14] and results in the formation of surface waveguide. The titanium ions penetrate the host substrate to form a graded index region having the shape of a Gaussian distribution as shown in Fig 2.1(b).

The in-diffusion of the titanium is the prevalent method of creating a channel waveguide in LiNbO₃. In a z-cut LiNbO₃ substrate, the presence of the titanium ions causes a change in both the ordinary (axis parallel to the substrate surface) and extraordinary (axis perpendicular to the substrate surface) refractive index in the optical wavelength range according to [15] [17] [18]. This change can be expressed as:

$$n_o = n_{os} + \Delta n_o [f(x)g(y)]^{0.55}$$
(2.1)

$$n_e = n_{es} + \Delta n_e f(x) g(y) \tag{2.2}$$

Where
$$f(x) = \frac{\operatorname{erf}\left(\frac{2x+W}{2d_x}\right) - \operatorname{erf}\left(\frac{2x-W}{2d_x}\right)}{2\operatorname{erf}\left(\frac{W}{2d_x}\right)}$$
 (2.3)

And
$$g(y) = \exp\left[-\left(\frac{y}{dy}\right)^2\right]$$
 (2.4)

where n_{os} = ordinary refractive index of LiNbO₃, n_{es} = extraordinary refractive index of LiNbO₃, Δn_o = max ordinary refractive index change, Δn_e = max extraordinary refractive index change, W = Width of the Ti stripe before in-diffusion, d_x = Diffusion length in the x-direction and d_y = Diffusion length in the y-direction.

By substituting the estimated values for these parameters (n_{os} =2.214, n_{es} =2.138, Δ_{no} =0.0062, Δ_{ne} =0.0146, W=6 µm, dx=4.850 µm, dy=4.105 µm) according to [11] [13] [15] and taking a point at the center of the diffused region (where x=0, y=2.052 µm), the ordinary and extraordinary refractive index can be found to be 2.2194 and 2.149 respectively. For a TM- (TE-) polarized light guided in a Z-cut LiNbO₃ waveguide, the electric field is seen to be perpendicular (parallel) to the substrate surface so that the refractive index that is used is $n_e(n_o)$. Using the Lumerical optical simulation tool and accounting for the presence of air, I found the optical effective index (n_{eff}) of the fundamental quasi-TM mode, propagating in the electro-optically unmodulated Ti:LiNbO₃ waveguide, to be 2.1423. This matches closely with 2.142 as stated in [15].

Figure 2.1: (a) Ti stripe on $LiNbO_3$ (b) A

(b) After Ti in-diffusion

2.2 Device Structure and Fabrication

The first step in the fabrication of the modulator is the creation of the optical waveguide. The optical waveguide consists of a titanium strip diffused at very high

temperature into the LiNbO₃ substrate. In this section, I will go about explaining the step by step approach on how a Ti-diffused LiNbO₃ waveguide is fabricated.

The fabrication process consists of three main aspects:

- i. Lithography and patterning of the waveguide
- ii. Titanium deposition and lift off
- iii. Diffusion

2.2.1 Waveguide Lithography

The first step in the fabrication of the modulator is the creation of the optical waveguide. The optical waveguide consists of a titanium strip diffused at a very high temperature into the LiNbO₃ substrate.

A bare 500 μ m-thick LiNbO₃ wafer is first cleaned in acetone, methanol and isopropanol (AMI) for about 2 minutes. This can also be achieved using piranha solution (a mixture of sulphuric acid and hydrogen peroxide, H₂SO₄: H₂O₂; 3:1) to remove any organic compound before the lithography. However, extreme caution must be observed when using piranha solution with LiNbO₃ material. LiNbO₃ is a piezoelectric material; it undergoes mechanical stress when it experiences a sharp change in temperature from being suddenly dipped into the hot reacting piranha solution. This causes a quick accumulation of electric charges in the LiNbO₃ substrate. Depending on the thickness of the LiNbO₃ wafer being processed, the electrical charging of the wafer can ultimately lead to the shattering of the wafer. To prevent the destruction of the wafer or just limit stress in the LiNbO₃ crystalline structure, it is necessary to gradually heat or cool it each time the process temperature variation is beyond 50°C. This gradual temperature ramp is extremely critical at every stage where the sample experiences a temperatures gradient. When employing a piranha solution whose temperature can go up to about 120° C, the LiNbO₃ wafer is first ramped up to about 80° C using a small hotplate initially set at room temperature. Once the hotplate has reached the set temperature of 80° C, the LiNbO₃ wafer is quickly transferred into the piranha solution for a cleaning of approximately 20 minutes, enough time for the reaction between H₂SO₄ and H₂O₂ to be mostly consumed and therefore for the solution to have cooled down. The wafer can then be safely removed from the solution. Before rinsing the wafer in deionized (DI) water, the wafer needs to be held in the air at room temperature to allow it to cool down. During that process, the wafer should be held in the air above the piranha solution at a reasonable height to avoid spilling for about 1 minute. Finally, the wafer can be rinsed in DI water under a continuous steady flow.

Subsequently, an ultraviolent (UV) optical lithography is performed on the LiNbO₃ wafer to pattern the optical waveguide. First, a 1µm thick layer of NR7-1500-PY negative photoresist from Futurrex Inc. is spun onto the wafer. The sample is made to spin at 3000rpm, 1000rev/s for 60secs. After the spinning, the photoresist needs to be soft baked to evaporate the solvent in the photoresist and harden it. This is a three-step process that takes place on two different hotplates. The first step consists of heating up gradually the LiNbO₃ substrate with the purpose of alleviating the mechanical stress exercised on the LiNbO₃ wafer by temperature change. It is accomplished by placing the LiNbO₃ wafer on a small hotplate at room temperature that has the capability of quickly heating up to the soft-bake temperature, the wafer is transferred to a bigger and more accurate hotplate previously set at 135°C for the second step of the process. The wafer is soft baked on that hotplate for 1minute before

being removed for the final step, the cool down to room temperature. Next, the photoresist is exposed under UV light at 365 nm with a 135 mJ/cm² exposure dose. After the exposure, a post exposure bake similar to the soft bake is performed. Finally, to complete the lithography process, the photoresist is developed in the RD-6 Developer solution for 12 seconds and rinsed under DI water

A breakdown of the lithography process is therefore given as:

- i. Wafer cleaning: Using piranha solution (or acetone, methanol and isopropanol, AMI in that order for about 2 minutes).
- Photoresist coating: Spin deposit NR71-1500PY, at 3000 rpm, 1000 rev/s for 60 seconds.
- iii. Photoresist soft-bake: Ramp up the temperature from 25°C to 135°C by setting the hotplate to 175°C, and then bake for 1 minute at 135°C.
- Rinse the wafer under DI water for few seconds and dry it using the nitrogen, N₂ blower.
- Exposure: Measure the current optical power of the mask aligner in mW/cm² and find the equivalent time to achieve a 135 mJ/cm² exposure.
- vi. Post-exposure bake: Ramp up the temperature from 25°C to 135°C by setting the hotplate to 175°C, and then bake for 1 minute at 135°C.
- vii. Development: RD6-Developer, 12 seconds with a little agitation.
- viii. Oxygen plasma: Place the sample in oxygen plasma for about 3 minutes to eliminate any photoresist that is left.


Figure 2.2: Photoresist stripe on a LiNbO3 substrate after development

2.2.2 Titanium Deposition and Lift-off

Next, a 100 nm titanium layer that will later be diffused in the LiNbO₃ substrate is evaporated on top of the LiNbO₃ wafer with the photoresist pattern. The titanium is thermally evaporated onto the substrate at the locations where the photoresist has been washed away during the previous photoresist development, but it's prevented from depositing on the rest of the wafer by the 1µm thick layer of photoresist. Afterwards, a photoresist lift off is performed using acetone, methanol and isopropanol (AMI) to remove the photoresist from the wafer. The sample is first placed on the spinner while a sufficient amount of acetone is dropped on it. The sample at this point is left to sit for about 2 minutes on the spinner to allow the acetone to penetrate and dissolve the underlying resist before the spinner is allowed to spin. As the sample spins, more acetone is sprayed for about a minute before methanol and isopropanol are sprayed to complete the process. During the lift off, the layer of titanium on top of the photoresist is also removed from the wafer. Thermal evaporation was preferred for this deposition because it creates a step coverage [12] that makes the lift-off process possible. Ideally, the only material that should remain

on the wafer after this process is the 100nm-thick titanium strip that was directly evaporated on the LiNbO₃ substrate, but this is not usually the case. Some resist is left behind as well, so oxygen DE-scum is done on the sample to remove all organic material (e.g. photoresist) completely prior to diffusion. The presence of resist material during the diffusion process produces bubbles in the diffused region which increase the loss in the waveguide. Recipe 7 is executed on the Oxygen De-scum for 3 minutes, at 3 Pa, 12 sccm of O_2 , RF Forward Bias Power of 150 W and Reflected Power of 0 W.



Figure 2.3: Steps for patterning titanium stripe

2.2.3 Titanium Diffusion

The diffusion of the titanium strip in the LiNbO₃ substrate is the final step in the fabrication of the optical waveguide. The titanium diffusion takes place in a dry oxygen-filled environment at 1050°C for 10 hours. A typical profile of the diffusion process is presented in Fig 2.4. The LiNbO₃ wafer is loaded into the furnace in the quartz diffusion tube at room temperature. Nitrogen gas continuously flows in the furnace to dry up the environment until the temperature reaches 200°C. Afterward, the nitrogen line is closed and oxygen is introduced into the tube to create an oxygen filled atmosphere. Then, the temperature in the furnace is ramped up to 1050°C at a constant rate over a 3-hour time period. The temperature is maintained at 1050°C for 10 hours for the titanium to completely diffuse in the LiNbO₃ substrate and produce the waveguide cross-section profile desired. Oxygen gas flows continuously in the furnace tube until the temperature drops to 200°C at the end of the diffusion process. Finally, the oxygen flow is stopped and the nitrogen gas starts flowing until the furnace reaches room temperature again.

A breakdown of the titanium deposition and lift-off process is as follows;

- i. 100nm-thick titanium is deposited on the LiNbO₃ substrate (already patterned with resist) using thermal evaporation.
- ii. Lift-off: Load wafer on the spinner, spray a thick layer of acetone on the wafer and allow it to sit for about 2 minutes until the resist is clearly dissolving (i.e. Ti layer should be peeling off). Start spinning the wafer at 1500 rpm for 90 seconds while continuously spraying acetone on the wafer for the first 60 seconds, methanol for the next 10 seconds and then isopropanol for another 10 seconds. Allow the wafer to dry for the last 10 seconds.
- iii. Make sure there is sufficient Oxygen at least 500 Psi for a 10-hour process
- iv. The LiNbO₃ wafer is sandwiched by several 3-inch silicon wafers. To avoid a sharp contact between the LiNbO₃ wafer and the quartz loading boat, introduce a very small amount of wool between the LiNbO₃ wafer and the loading boat.



Figure 2.4: A typical diffusion profile

2.3 Modulation in LiNbO₃

In the RF wavelength range, the ordinary and extraordinary refractive index is somewhat high, given the high relative permittivity of 28 and 43 [16] perpendicular and parallel to the LiNbO₃ surface. This results in index (or velocity) mismatch between the optical and RF signal at high frequencies, thus limiting the usage of LiNbO₃ modulators to low frequency systems operating below 40 GHz [19] until recently. The 3 dB modulation bandwidth is known to be inversely proportional to the index mismatch [20]. Therefore to achieve broadband width for high frequency operation, minimizing the index mismatch becomes necessary. Modulation in LiNbO₃ is improved by optimizing the interaction between the optical wave and RF signal. To maximize this interaction, researchers have come up with several techniques, which include fabricating a ridge coplanar waveguide (CPW) structure, thickening the electrode and incorporating a silicon dioxide (SiO₂) buffer layer [13] [16]. The high dielectric LiNbO₃ substrate ($n_{os} = 5.29$, $n_{es} = 6.56$) is etched away and replaced with lower dielectrics like air (1.0) and SiO₂ (1.46) while a thick electrode structure

pulls the electric field out into the air. This has been shown to improve the index matching between the optical and RF signal [17].

2.4 Conclusion

In this chapter I have described the theory surrounding the use of Ti indiffusion to bring about a change in index in LiNbO₃. I have also outlined a step-bystep approach on how a waveguide is fabricated in LiNbO₃-based substrate. I have stressed the need for careful handling of the LiNbO₃ wafer and details of the process in the diffusion chamber. So far I have introduced the concept of modulation, fabricating a waveguide in an electro-optic material (LiNbO₃) and improving modulation in LiNbO₃.

In the next chapter I will go about introducing the concept of Recycled Carrier Modulation (RCM). This will be followed by some of the initial works I carried out at the earlier stage of this research.

Chapter 3

RECYCLED CARRIER MODULATOR

In this chapter, I introduce the concept of a Recycled Carried Modulator (RCM) and describe how it relates to a conventional modulator. Then I explain the technique that is used to achieve the recycling of the optical carrier. Next I discuss the theory of operation of this modulator as it pertains to the reflection and transmission of electromagnetic waves at a planar dielectric boundary. The three material systems that were considered for this experiment are analyzed. This chapter ends in a detailed description of the procedures to fabricate this modulator using any of the three material systems.

3.1 Introduction

A Recycled Carrier Modulator is a modification to a modulator. It enhances the efficiency of a conventional modulator by recycling an optical carrier in a Fabry Perot resonant cavity. An RCM functions by splitting a modulated signal into optical carrier and sideband signals, allowing the sideband to pass through while recycling the optical carrier. In the frequency domain, modulation is evident by the appearance of sidebands on either side of the carrier frequency in the modulated signal. These sidebands are separated from the optical carrier by some kind of wavelength selective filters and fed back to the input as shown in figure 3.1



Figure 3.1: Recycled Carrier Modulator

This research was centered on the idea of creating a Fabry Perot resonance cavity with distributed feedback mirrors. These mirrors reflect only the carrier frequency while allowing the sideband to pass through. The reflected carrier frequency is combined with the input, thereby increasing the overall optical power entering the modulator. This will invariably lead to increased power in the sideband of the modulated signal (i.e. better modulation efficiency). The frequency (or wavelength) selectivity in this research is achieved using a set of Bragg grating. The distributed Bragg reflectors shown in figure 3.2, function as the Demultiplexers (Demux).



Figure 3.2: Implementing RCM with a Fabry Perot Topology

3.2 Theory of Operation

Bandwidth, speed of operation, drive voltage, extinction ratio and modulation efficiency amongst others, are the chief figures of merit that are desired in a modulator [18]. In electro-optic modulators, V_{π} , which is the voltage required to cause a π phase shift in the propagating light wave, is often used to express the efficiency of the modulator. In this scenario, a lower value for V_{π} is desirable because it would mean that the modulator requires a low drive voltage to operate. Alternatively, the modulation efficiency can be represented as an expression of the ratio of the amount of power in the sidebands of the modulated output to the amount of power at the input (a product of the optical power and the RF power entering the modulator).

$$Modulation Eff, M_{eff}(W^{-1}) = \frac{P_{sb}}{P_{opt}*P_{rf}}$$
(3.1)

where P_{sb} is the power in the sideband of the modulated output (*W*). P_{opt} is the input optical power and P_{rf} is input RF power.

The idea behind recycling the optical carrier is to improve the amount of power entering the modulator without having to increase the power of the optical source. Thus, the power in the sideband of the modulated output is substantially increased while maintaining the original amount of optical power at the input. Take for example a modulator with an efficiency of 1 W^{1} . If the input optical power and the RF power entering the modulator are both 1 W, then the power in the sideband of the modulated output would be 1 W. From equation 1.3,

$$P_{sb} = M_{eff} * P_{opt} * P_{rf} = 1 * 1 * 1 = 1W$$
(3.2)

By incorporating a grating structure that would create an optical power 10 times the initial amount of optical power circulating in the loop, the power in the sideband of the modulated output can be improved by a factor of 10. Again, from equation 1.3,

$$P_{sb} = M_{eff} * P_{opt} * P_{rf} = 1 * 10 * 1 = 10 W$$
(3.3)

with 10 W as the amount of power in the sideband of the modulated output, the efficiency would have been increased by a factor of 10 as well.

$$M_{eff} = \frac{P_{sb}}{P_{opt}*P_{rf}} = \frac{10}{1*1} = 10 \ W^{-1}$$
(3.4)

The efficiency in eqn3.4 was calculated using P_{opt} as 1 *W* because that is still the amount of power from the optical source. The 10 *W* used in eqn3.3 was only achieved by recycling the optical carrier. Thus we can see that by recycling the optical carrier, the modulator efficiency can be improved substantially.

An important point to stress here is that this concept improves modulation efficiency without sacrificing the bandwidth, as is seen in other approaches that utilize resonant phenomena. Here, the modulated signal is only made to pass through the modulation region once, after which the sideband is separated from the optical carrier. This is unlike the other approaches, where both the optical carrier and sidebands are recycled, thereby limiting the bandwidth to the quality factor Q of the resonator. For example, imagine a modulator operating at a wavelength of 1.5 μ m, which translates to an optical frequency of 200 THz. If the quality factor Q, of the resonator is 10^3 , then the bandwidth is limited to 200 GHz.

3.3 Reflections and Transmission of Electromagnetic Waves

Dielectric materials have been used in diverse applications where their insulating properties were utilized to form insulating layers between metallic contacts. They also exhibit reflection and transmission characteristics that are dependent on frequency as used in the dielectric resonator antennae (DRA). In these antennas, radio waves introduced into a resonator material from a transmitter circuit bounces back and forth between the resonator walls, forming a standing wave. However, the walls of the resonator are partially transparent to radio waves, allowing the radio power to radiate into space at specific frequencies. Similar idea is utilized here using dielectric materials (e.g. Silicon dioxide grating) to reflect the optical carrier while allowing the sideband frequencies to pass through. From figure 3.1, if we wish to increase the amount of optical power circulating in the loop to 10 times the amount of optical power entering the device from the laser on the left, then we would need mirrors having a combined reflectivity of 90% at the carrier wavelength to achieve this. This is accomplished using a grating pattern in which every layer reflects a portion of the incident beam ($\sqrt{0.9} = 0.95$ for each of the mirrors). In this section I would introduce the concept of reflection from a planar dielectric slab and the effect when this is cascaded to multiple dielectric interfaces.

3.3.1 Reflection and Transmission of a Single Slab Layer

When a wave is normally incident on a planar interface between two materials, it experiences some form of reflection and transmission due to discontinuities across the boundary between the two media. The fraction of the reflected and transmitted wave is dependent on their constitutive parameters (i.e. permittivity and permeability).



Figure 3.3: Reflection and Transmission of a normally incident wave on a planar interface

If an x-polarized electric field of magnitude E_o is incident on the interface, the incident, reflected and transmitted electric field can be expressed as:

$$E^i = \hat{a}_x E_o e^{-j\beta 1z} \tag{3.5}$$

$$E^r = \hat{a}_x \Gamma E_o e^{j\beta_{1Z}} \tag{3.6}$$

$$E^t = \hat{a}_x T E_o e^{-j\beta 2z} \tag{3.7}$$

where Γ represents the reflection coefficient and T represents the transmission coefficient. Using the right hand rule, the equivalent magnetic field can be written as:

$$H^{i} = \frac{\hat{a}_{y} E_{o}}{\eta_{1}} e^{-j\beta_{1}z}$$
(3.5)

$$H^r = -\frac{\hat{a}_y \Gamma E_o}{\eta_1} e^{j\beta_1 z} \tag{3.6}$$

$$H^t = \frac{\hat{a}_y T E_o}{\eta_2} e^{-j\beta_{1Z}}$$
(3.7)

where η (the wave impedance) is given as the ratio of the permittivity to the permeability of the material and β is the wave number. Both are expressed as:

$$\eta = \sqrt{\frac{\varepsilon}{\mu}} \tag{3.8}$$

$$\beta = \omega \sqrt{\mu \varepsilon} \tag{3.9}$$

The value of the reflection and transmission coefficient can be derived by applying boundary conditions at the interface. For example, since the electric and magnetic fields are both tangential to the interface, we would expect them to be continuous at the interface. This leads to the expressions:

$$E^i + E^r = E^t \tag{3.10}$$

$$H^i + H^r = H^t \tag{3.11}$$

which translates to:

$$1 + \Gamma = T \tag{3.12}$$

$$1 - \Gamma = \frac{\eta_1}{\eta_2} T \tag{3.13}$$

By dividing 3.12 with 3.13, we get:

$$\frac{\eta_2}{\eta_1} = \frac{1+\Gamma}{1-\Gamma} \tag{3.14}$$

By solving equation 13.12 and 13.13 simultaneously, the reflection and transmission coefficients are derived as:

$$\Gamma = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1} \tag{3.15}$$

$$T = \frac{2\eta_2}{\eta_2 + \eta_1}$$
(3.16)

The reflection at an interface z = -d distance away can be related to the reflection at the boundary by:

$$\Gamma_{in(z=-d)} = \frac{E^{r}(z)}{E^{i}(z)} = \frac{\Gamma E_{0} e^{j\beta_{1}z}}{E_{0} e^{-j\beta_{1}z}} = \Gamma e^{-j2\beta d}$$
(3.17)

Similarly the transmission at a distance $z = d_2$ away from the boundary can be related to the transmission at the boundary by:

$$T_{(z1=-d1, z2=d2)} = \frac{E^{t}(z2)}{E^{i}(z1)} = \frac{TE_{o}e^{-j\beta^{2}d2}}{E_{o}e^{j\beta^{1}d1}} = Te^{-j(\beta^{2}d2+\beta^{1}d1)}$$
(3.18)

where d1 and d2 would represents distances measured from the interface to media 1 and 2 respectively.

This confirms that the reflection and transmission of a normally incident wave at a planar interface is dependent on the constitutive parameters of the materials at the interface. Equation 3.13 is also known as Fresnel equation. The goal in this study is to make use of materials which when graded onto the Ti:LiNbO₃ substrate would produce a change in effective index that is enough to cause reflection at the carrier wavelength. This same material as mention earlier should also be compatible with LiNbO₃.

3.3.2 Reflection and transmission at Multiple Interface

If instead of a single layer we now have multiple interfaces, the cavity that is created is able to confine the incident light at a resonant frequency that corresponds to the pitch of the cavity. This is synonymous to an electronic resonant circuit. An optical resonator can take the forms like planar or spherical mirrors, micropillars, microtoroids, photonic crystals etc. Here we are considering a Fabry Perot resonator topology where light is reflected multiple times between two planar mirrors. The planar mirrors in this case are replaced with periodic dielectric structures (Distributed Bragg Reflectors) that are partly transmissive.



Figure 3.4: Multiple reflections and transmission from planar mirrors forming a resonant cavity

Figure 3.4 gives an illustration of the multiple reflections and transmission that occurs within a cavity. For this reflections and transmissions to add constructively, the round trip distance between the interfaces is expected to equal an integer multiple of the wavelength:

$$2d = m\lambda = \frac{m\lambda_o}{n_{eff}}$$
 $m = 1,2,3,...$ (3.19)

Different models could be used to analyze this multiple reflection in order to determine the input reflection coefficient Γ_{in} at z = 0. By using the ray tracing model, the input reflection coefficient can be derived as follows:

$$\Gamma_{in}(z=0) = \Gamma_{12} + \Gamma_{23}T_{12}T_{21}e^{-j2\theta} + \Gamma_{21}\Gamma_{23}^2T_{12}T_{21}e^{-j4\theta} + \cdots$$
(3.20)

Where Γ_{in} represents the intrinsic reflection coefficient of the first reflection while the other terms represent contributions to the input reflection arising from multiple bounces between the interfaces as shown in figure 3.4.

If we proceed to reduce equation 3.20, Γ_{in} becomes:

$$\Gamma_{in}(z=0) = \Gamma_{12} + \Gamma_{23}T_{12}T_{21}e^{-j2\theta}[1 + \Gamma_{21}\Gamma_{23}e^{-j2\theta} + (\Gamma_{21}\Gamma_{23}e^{-j2\theta})^2 + \cdots]$$
(3.21)

$$\Gamma_{in}(z=0) = \Gamma_{12} + \frac{\Gamma_{23}T_{12}T_{21}e^{-j2\theta}}{1 - \Gamma_{21}\Gamma_{23}e^{-j2\theta}}$$
(3.22)

$$\Gamma_{in}(z=0) = \frac{\Gamma_{12} - \Gamma_{12}\Gamma_{21}\Gamma_{23}e^{-j2\theta} + \Gamma_{23}T_{12}T_{21}e^{-j2\theta}}{1 - \Gamma_{21}\Gamma_{23}e^{-j2\theta}}$$
(3.23)

$$\Gamma_{in}(z=0) = \frac{\Gamma_{12} - \Gamma_{23}e^{-j2\theta}(\Gamma_{12}\Gamma_{21} - T_{12}T_{21})}{1 - \Gamma_{21}\Gamma_{23}e^{-j2\theta}}$$
(3.24)

By substituting $\Gamma_{12} = -\Gamma_{21}$ (3.25)

$$T_{12} = 1 + \Gamma_{21} = 1 - \Gamma_{12} \tag{3.26}$$

$$T_{21} = 1 + \Gamma_{12} \tag{3.27}$$

$$\theta = \beta_2 d \tag{3.28}$$

We can derive the equation for the input reflection coefficient as:

$$\Gamma_{in}(z=0) = \frac{\Gamma_{12} + \Gamma_{23}e^{-j2\beta_2 d}}{1 + \Gamma_{12}\Gamma_{23}e^{-j2\beta_2 d}}$$
(3.29)

In the same way we can derive the overall transmission coefficient as:

$$T(z=d) = T_{32}T_{21}e^{-j\theta} + \Gamma_{21}\Gamma_{23}T_{32}T_{21}e^{-j3\theta} + \Gamma_{21}^2\Gamma_{23}^2T_{32}T_{21}e^{-j5\theta} + \cdots]$$
(3.30)

$$T(z=d) = T_{32}T_{21}e^{-j\theta}[1 + \Gamma_{21}\Gamma_{23}e^{-j2\theta} + (\Gamma_{21}\Gamma_{23}e^{-j2\theta})^2 + \cdots]$$
(3.31)

$$T(z=d) = \frac{T_{32}T_{21}e^{-j\theta}}{1 - \Gamma_{21}\Gamma_{23}e^{-j2\theta}}$$
(3.32)

By substituting eqn. 3.25 and eqn. 3.28,

$$T(z = d) = \frac{T_{32}T_{21}e^{-j\beta_2 d}}{1 + \Gamma_{12}\Gamma_{23}e^{-j2\beta_2 d}}$$
(3.33)

3.4 RCM Fabrication

As stated in chapter 2, the very first step in RCM fabrication is the formation of optical waveguide in the LiNbO₃ substrate. The waveguide was first fabricated using the steps outlined in chapter 2 and later tested by coupling a beam of light from a laser source and observing how well it guides light by the help of an infra-red (IR) camera. The experimental setup is shown in Fig 3.5:



Figure 3.5: Experimental setup for observing guided light through a LiNbO₃ waveguide

3.4.1 Silica Grating

The very first device that was fabricated used silicon dioxide as the grating material. 800 nm of silicon dioxide was deposited using the Samco[®] PD-220N PECVD unit. This thickness was chosen bearing in mind the fact that silicon dioxide has a low refractive index (1.46) Thus to achieve the index contrast required to simulate graded index layers, we need a layer this thick. Also the choice of using the plasma-enhance chemical vapor deposition (PECVD) for growing the oxide was because of the low temperature at which this process is carried out as shown in Table

3.1. A high temperature process will lead to possible cracking of the $LiNbO_3$ and could alter the diffusion profile of the Titanium ions.

Product	Reactants	Deposition temperature, ºC
Silicon dioxide	SiH_4 +CO ₂ + H ₂	850 - 950
	$SiCl_2H_2 + N_2O$	850 - 900
	$SiH_4 + N_2O$	750 - 850
	$SiH_4 + NO$	650 - 750
	Si(OC ₂ H ₅) ₄	650 - 750
	$\mathrm{SiH}_4 + \mathrm{O}_2$	400 - 450
Polysilicon	SiH ₄	575 - 650
Plasma silicon dioxide	$SiH_4 + N_2O$	200 - 350

Table 3.1: Temperature range for different methods of growing oxides and nitrides

Oxygen clean is first run in the PECVD chamber before the actual oxide growth. The parameters for the oxide growth are 6 sccm SiH₄, 120 sccm N₂O, 300°C, 67 Pa, 50 W RF for 10 minutes and 6 seconds. This will deposit 800 nm of SiO₂ on the LiNbO₃ wafer. After this the wafer is diced into 15 mm x 15 mm samples tilted at 6° to the right. To protect the surface of the wafer, a photoresist is spun on the wafer before dicing. The wafer is then diced using a Disco Automatic Dicing Saw 3220. From this point, each of the samples is processed separately. Taking one of the diced samples, the resist is removed using piranha or AMI. After which a new layer of resist (Polymethyl methacrylate – PMMA A4) is spun using the following spin recipe – 3000 rpm, 1000 rev/s, 45 seconds, soft baked at 180°C for 10 minutes. A 10 nm layer of gold (Au) is then evaporated on this resist layer using the resistive boat in the Armstrong Evaporator System. This is done to prevent drifting effect during electron beam (e_beam) writing resulting from charge accumulation on the resist and silica layers. The gold layer should be deposited using the resistive boat as against e_beam crucible as the later will lead to the exposure of the resist.



Figure 3.6: Sample ready for e_beam exposure

The sample at this point is then loaded into the Raith e_LiNE (electron beam writing) lithography system.



Figure 3.7: Sample holder: Top side

The sample at this point is then loaded into the Raith e_LiNE (electron beam writing) lithography system. The writing process using the e_LiNE appears to be the most sensitive and complex aspect of the device fabrication and should be done with utmost diligence. The proper sequence for loading and unloading the chamber, sample alignment and setting up exposure parameter must be consistent in order to establish a repeatable process.

After the e_beam exposure, the chamber is pumped down and the sample unloaded for further processing. The gold conducting layer is first removed by dipping the sample in an iodine solution (Au etch), after which it is rinsed in DI water and dried gently in N_2 . Three different solutions of MIBK+IPA (1:3), IPA and Ethanol are then prepared for the actual development. The steps for the gold etch and actual development cab be summarized as follows:

- Dip in iodine solution for 15 seconds, DI water rinse and dry gently with N₂
- Dip in MIBK+IPA solution for 30 seconds
- Dip in IPA for 15seconds
- Dip in MIBK+IPA solution for 15 seconds
- Dip in IPA for 15 seconds
- Dip in ethanol for 10 seconds and dry gently with N₂

The final step involving ethanol was included to prevent the grating from collapsing due to surface tension. It was noticed that while drying with the N_2 , the IPA dries up very fast and this could make the grating (couple of nanometers thick) to collapse. By dipping the sample in ethanol, we allowed for a longer and steadier

drying. In addition the N_2 must be applied gently and held at a distance from the sample. This breaking off of the grating structure is better shown in Fig 3.8:



Figure 3.8: Grating structure breaking off during processing

The development process will dissolve and wash away the exposed areas leaving behind a grating pattern in the resist. When viewed from the dark field of an optical microscope, the existence of a grating pattern is observed by the appearance of a distinct coloration corresponding to the pitch of the grating.



Figure 3.9: Dark field image showing grating areas of fixed periodicity (purple lines) and areas with irregular period (white line).

Next this pattern is transferred to the SiO₂ layer underneath by an Inductively Coupled Plasma (ICP) etch. Prior to the ICP etch, a hard etch mask is introduced. The etch mask functions to limit the etch to certain areas of the substrate so that the pattern is transferred completely. In this case, Nickel was chosen as the hard mask because it can withstand fluorine (the ICP etchant) better than the resist (PMMA). After a number of test etch, it was clear that a layer of 50 nm Ni would be sufficient for the entire duration of the etch. So a layer of 50 nm Ni was deposited using the e_beam evaporator and then by applying lift-off technique the Ni layer was made to replace the resist pattern.



Figure 3.10: Lift-off process to replace PMMA with Nickel

The sample with the PMMA grating coated with Ti hard mask is then loaded into the Samco[®] RIE-200IP Fluorine ICP and etched. The initial etch recipe for this process was a 5 loop counts of 10 sccm C_4F_8 , 100W Bias, 500W ICP, 1 Pa for 30 seconds with a 50 sccm flow of Helium after each loop. The reaction chamber is first pumped down to vacuum, and then 10 sccm C_4F_8 is fed into the chamber. The C_4F_8 dissociates into fluorine ion (F⁻) and other fluorocarbon ions when the ICP power is applied. The bias accelerates the F⁻ so that they are directed towards the sample to create an anisotropic etch. The SEM image of the initial etch results is shown below:



Figure 3.11: SEM images of SiO₂ grating with tilted sidewalls



Figure 3.12: SEM images of SiO₂ grating with fluorocarbon deposit

The above SEM images show the formation of scum-like deposits and coating on the grating. This was later determined to have emanated from the formation of nonvolatile fluorocarbon deposit which inhibits the etch process. Further studies on this subject matter revealed that by adding small concentration of oxygen to the C_4F_8 feed gas, the etch rate can be improved substantially [12]. The oxygen is believed to react with the carbon atoms to produce CO_2 and CO which are volatile. Thus by removing some of the carbon atoms from the plasma, the plasma becomes fluorine rich and the etch rate is increased. Other adjustments in Bias power, loop counts and C_4F_8 feed gas were also done on the etch recipe to arrive at the optimal value. The etch recipe was therefore modified to 20 sccm C_4F_8 , 60 sccm O_2 (to scavenge the carbon atoms), 75 W Bias (which was found to be quite sufficient for the etch), and loop count increased to 18 loops (enough to etch the entire SiO₂ layer). The resulting etch is shown below:



Figure 3.13: Side view of SEM image of 50% duty cycle SiO₂ grating



Figure 3.14: SEM images of SiO_2 grating showing uniformity across grating length

At this point a thick resist is applied on the grating to serve as a protective layer. After which the end facets of the sample is polished before testing. In this case I used NR9-3000 with a spin recipe of 3000 rpm, 1000 rev/s, for 60 seconds and baked at 150°C for 60 seconds.

3.4.2 Gold Grating

With Silicon dioxide I was unable to achieve a sufficient index contrast that is enough to realize a substantial reflection. My next attempt was to try a different approach - Plasmonic waveguide. Plasmonics involves the study of the interaction between an electromagnetic wave (light) and the free electrons in a metal. When a photon interacts with the surface of a metal, there is a possibility of both elastic scattering (Rayleigh scattering) and inelastic scattering (Raman scattering). In elastic scattering, the scattered photons have the same energy (frequency and wavelength) as the incident photon. When photons are inelastically scattered from a metal, there is a shift in frequency/wavelength of the scattered photon from the incident photon – this amounts for a small fraction of the scattered photon. This difference in wavelength is equivalent to a change in energy that gives rise to the excitation of the free electrons in the metal (localized surface Plasmon). When the Plasmon frequency is in resonance with the radiation, there is field enhancement due to Plasmon oscillation. It is this field enhancement that magnifies the intensity of the incident light. The caveat for this enhancement is the ability to engineer metallic nanoparticles or roughened surfaces because those surfaces provide an area on which localized collective oscillation can occur. In Plasmonics, the emphasis is on metallic nanostructures that can support electromagnetic oscillations (surface plasmon polaritons) at their interfaces [27].

In this approach, I fabricated a set of gold grating on Ti diffused LiNbO₃ waveguides. The fabrication process was similar with silicon dioxide grating but with a little tweaking of the process. The pitch of the grating was still a couple of

nanometers so electron beam lithography was used for defining the pattern. Electron beam resist (PMMA) is first deposited on a Ti Diffused LiNbO₃, and then a thin layer of gold (10 nm) is deposited on it using the resistive boat of the evaporator. As explained previously, this 10 nm Au functions to reduce space charge effect that causes drifting of the sample when view with the scanning electron microscope (SEM). The sample at this point is exposed using the e_LiNE and developed as before using iodine solution, MIBK+IPA, IPA, and Ethanol

At this point, we have a set of PMMA grating on Ti diffused LiNbO₃ waveguide. The sample is then placed in the evaporator and 5 nm of Titanium with 30 nm of gold is deposited using the electron beam crucible. The titanium layer serves as an adhesion layer. Next we use lift-off technique to remove the PMMA thereby transferring the pattern to the gold layer. After applying acetone, methanol and isopropanol on the spinning sample, a 10mins ultrasound is then carried out to achieve a complete lift-off. The sample is then coated with a resist protective layer using NR9-3000 or a similar thick resist. The resist is spun at 3000 rpm, 1000 rev/s for 60 seconds and baked at 150°C for another 60 seconds. After this, the end facets are polished and the device is tested.



Figure 3.15: Gold grating on LiNbO₃ waveguide

With the gold grating, the depth and quality of the grating was adequate for a 50% duty cycle but the reflection spectrum was still not adequate for the application. On the positive side though, we noticed for the first time a weak transmitting signal at the same wavelength as the reflecting signal.

3.4.3 Amorphous Silicon Grating

Our move to Silicon was informed by the results we achieved through simulation. Silicon is known to have a higher index of refraction when compared to silicon dioxide and this translates to a higher index contrast for a lower amount of Silicon when used in place of Silicon dioxide. By making use of silicon, I reverted back to the principle of reflection from planar boundaries as against plasmonics.

As was expected, early simulation results showed that with as low as 60nm Silicon, a high index contrast can be achieved. Some of the these early simulations were carried out in collaboration by Dr. Shouyuan Shi using a set of code he developed that runs on Matlab. This suggested silicon as a viable option to replace silicon dioxide but more simulations has to be done to verify the optimum thickness that is sufficient to achieve the index contrast.

The initial simulation used Silicon but the growth process in the PECVD yield amorphous silicon which would show significant differences in the performance of the material. This was accounted for by running more simulations and shooting for an index contrast that is higher than the required value of $\Delta n = 2.5 \times 10^{-4}$.

Another challenge I experienced was the weak adherence of the amorphous Silicon on the LiNbO₃ substrate. The amorphous Silicon holds fairly okay after the growth process but starts peeling off during further processing. The first approach I employed to eliminate this problem was to dice the LiNbO₃ waveguide prior to the amorphous silicon deposition. Initially this turned out right but after a number of processes (like lift-off, ultrasound etc.) the peeling off of the amorphous silicon layer resumed.



Figure 3.16: a) Amorphous silicon peeling off the surface of LiNbO₃ after dicing. b) LiNbO₃ sample diced before amorphous silicon growth.

The next approach was to introduce an adhesive layer between the LiNbO₃ surface and the amorphous silicon. A suitable candidate for this task is silicon dioxide because it is compatible with LiNbO₃ (as was shown with SiO₂ grating) and Silicon (or aSi in this case). By depositing a thin layer of silicon dioxide (about 30 nm thick) before depositing the amorphous silicon, I was able to prevent the amorphous silicon from peeling off so that the grating can withstand all the processes. Figure 3.18 shows the insignificant differences that exist between the samples after silicon dioxide/amorphous silicon deposition and the sample that has undergone 4 minutes of ultrasound.



Figure 3.17: LiNbO₃ samples with SiO₂ and aSi deposited. a) Just after SiO₂/aSi growth on LiNbO₃ b) After 4 minutes ultrasound

At this point I proceeded to defining the grating pattern as before using electron beam lithography since the grating structure still remains the same. Below are the two fabrication approaches I came up with to achieve the amorphous silicon grating.

The first approach involves patterning PMMA on a LiNbO₃ waveguide, depositing the require thickness of amorphous silicon and then using lift-off technique to transfer the pattern from the PMMA to the amorphous silicon layer. These steps are synonymous to the ones used above to fabricate the SiO₂ grating. The spin recipe for PMMA is still the same, the exposure parameters for the e_LiNE are equally the same, a thin layer of gold (about 10 nm) is also deposited on the resist before electron beam lithography to prevent space charge effect. After the electron beam lithography, the sample is developed as before using gold etch, MIBK+IPA, IPA and ethanol in the right order. The differences in the two approaches I mentioned lies with the way amorphous silicon is deposited. In this case the aSi is deposited using a tantalum crucible (which is able to withstand the high temperatures required to melt silicon) with the electron beam evaporation system. This fabrication approach is expected to yield high quality silicon having smooth side walls because this method is devoid of any etch process. The downside with this approach arises from the poor feasibility of achieving a uniform deposition throughout the tiny openings of the PMMA graded regions (which are about 180 nm). Also, the order of fabrication steps here eliminates the possibility of incorporating the SiO₂ adhesive layer. The SiO₂ layer is usually grown in the PECVD at 300°C at which temperature the PMMA grating that is earlier formed will decompose. This leaves us with the same adhesion problem that we started out with.



Figure 3.18: Fabrication step involving e_beam evaporated Silicon

The second approach involves depositing PECVD grown silicon dioxide and amorphous silicon in turns, patterning and developing PMMA on top of these layers and then using the ICP to transfer the grating pattern by an etch process. Depending on the etch recipe and process that was used, I was able to arrive at two similar etch profiles that are suitable for achieving the required index contrast. The parameters for the oxide growth are 6 sccm SiH₄, 120 sccm N₂O, 300°C, 67 Pa, 50 W RF for 30 seconds. This will deposit 30 nm of SiO₂ on the LiNbO₃ wafer. After this the recipe for growing amorphous silicon is run immediately with the following parameters -4.5sccm SiH4, 52 sccmAr, at 67 Pa, 300°C, 30 W RF for 5 minutes. This will deposit 60 nm of amorphous silicon on the silicon dioxide layer at a rate of approximately 12 nm/min. After this PMMA is spun on the sample and patterned using electron beam lithography as before. There is no need to deposit a thin layer of gold in this case as the silicon layer is sufficient to prevent the sample from charging. The sample is then placed in the e LiNE for electron beam exposition using the same exposure parameters. After the electron beam lithography, the sample is developed as before using gold etch, MIBK+IPA, IPA and ethanol in the right order. At this point we have a sample with PMMA gratings on top of layers of amorphous Silicon and SiO₂ as shown below.



Figure 3.19: PMMA grating on a-Si and SiO₂ adhesion layer

The sample is then etched in the ICP using fluorine based etch recipe that etches both amorphous silicon and silicon dioxide similarly. A total of 60 nm etch depth is achieved at the rate of about 15 nm every loop for 4loops.



Figure 3.20: Fabrication step involving ICP etch of PECVD grown a Si and SiO $_2$

The parameters for the etch process consist of 90 sccm Ar, 5 sccm SF₆, 5 sccm C_4F_8 , 500 W ICP, 150 W Bias, at a pressure of 1.5 Pa. This recipe produces a decent etch through the amorphous silicon and silicon dioxide layers but after about 60 nm etch, the resist (which in this case acts as the etch mask) is virtually etched away. Which would mean that for an increased amorphous silicon etch, a harder etch mask will be required. Introducing an etch mask, - say Nickel will involve the addition of a new fabrication step which is not desirable. To prevent this, the etch recipe was changed to Bosch process (time multiplexed etching) which allows me to etch a much thicker layer of amorphous silicon with a near-vertical sidewalls structure. Bosch

process involves the alternation of two processes – a passivation layer deposition using Octafluorocyclobutane, C_4F_8 to prevent lateral etching and an isotropic etch using Sulphur hexafluoride, SF_6 .



Figure 3.21: Illustration of a time multiplexed etch - Bosch process

The parameters for the etch process includes 20sccm C_4F_8 at 450W ICP and 150W Bias; 25sccm SF₆ at 500W ICP and 100W Bias, with 5sccm Ar to vent the chamber. This etch recipe will only etch silicon but not silicon dioxide so the structure after the etch process will have an amorphous silicon grating on top of a silicon dioxide adhesive layer. The only down side to this approach is the decrease in index contrast as compared to the previous etch process that allows etching through amorphous silicon and silicon dioxide simultaneously. This is compensated for by the fact that much thicker amorphous silicon layer can be grown and etched using this etch recipe. After 4 loops of the Bosch process, we get a structure that is represented by Figure 3.22:



Figure 3.22: Expected grating structure after 4loops of Bosch process



Figure 3.23: Etch profile of aSi grating on a 30 nm SiO₂ adhesive layer

3.5 Conclusion

In this section I have described the different materials that were used to fabricate the grating structure on the Ti-diffused LiNbO₃ waveguide – silicon dioxide, gold and amorphous silicon. I had also outlined the various approaches and techniques that were considered during the fabrication and their merits or demerit as the case may be. I mentioned the reason for having a thin layer of gold coating prior to electron

beam lithography and the factors affecting my choice of thermal deposition crucibles. SEM images of the grating were also shown and discussed.

In the following chapter I will proceed to discuss some of the result I got and how they informed my next line of action.

Chapter 4

DEVICE TESTING

4.1 Introduction

The device testing that was carried out at this point was mainly to ascertain the strength of the reflecting and transmitting signal and the wavelength at which the peak or dip is predominant for different grating width. It is worth noting that this test is not related to actual modulation as that would involve the incorporation of an electrode structure. The experimental setup for this testing is shown below.



Figure 4.1: Test setup for measuring the reflection and transmission

As shown above, the test setup uses an optical power meter to generate laser beam that is coupled to the sample through v-grooves at both ends of the mounted sample. The sample was diced earlier on at 7° to allow for this alignment with the vgroove. A circulator is incorporated to measure the reflecting signal. The circulator is a three port ferromagnetic device that allows energy flow in one direction i.e. from port 1 to 2, port 2 to 3 and port 3 to 1. If a signal is placed at port 1, and port 2 is well matched, the signal will exit at port 2 with very little loss (usually about 0.4 dB). If there is a mismatch at port 2, the reflected signal from port 2 will be directed to port 3. Circulators are non-reciprocal. In a reciprocal device the same fraction of energy that flows from port 1 to 2 would result to energy flowing in the opposite direction, from port 2 to port 1. This idea is utilized here to measure the reflecting signal by connecting port 3 to the Optical spectrum analyzer (OSA). To measure the transmitting signal, a v-groove mounted at the other end of the sample is used to couple light into a fiber connected to the OSA.



Figure 4.2: Circulator connection for measuring the magnitude of reflected and transmitting signal.
The piezo controller allows for the adjustment of the stage with the sample on it while the motion control enables the motion of the infra-red (IR) camera. The IR camera is used to observe the incident light at longer wavelengths and together with the monitor screen is used to align the fiber to the waveguides before testing. The OSA gives a graphical representation of the signal strength with regards to wavelength in dBm (in reference to 1mW of input power).

4.1.1 Result with Silica Grating

The Silica grating structure consists of 800 nm thick silicon dioxide grating with a width of 180 nm and a pitch of 360 nm (50% duty cycle). With this grating structure, the index contrast that was achieved was $\Delta n = 2.5 \times 10^{-5}$ which is an order of magnitude lower that the index contrast required. Very weak reflections were observed which were insufficient to create a dip in the transmitting signal.



Figure 4.3: Reflection signal from 800 nm SiO₂ grating.

Figure 4.3 shows a reflecting signal with a peak of -65.26 dBm at 1622 nm. This is less than 1 in a million part reflection. The reflection above was measured from one end facet that was polished. I noticed a 13 dBm drop in reflectivity after polishing the other end facet. This can be attributed to degradation of the grading due to multiple processing. With this in mind, both end facets of subsequent samples were polished prior to testing and efforts were made to reduce the number of processes involved in the fabrication.



Figure 4.4: A change in the reflection signal with a 13 dBm drop in reflectivity after polishing

Based on the weak reflecting signal, there was no noticeable transmission signal corresponding to the reflection rather what was observed was some kind of rippling effect at the output.



Figure 4.5: Rippling signal in place of transmission

Despite the fact that the reflection from the silicon dioxide grating was very weak, we were able to observe a close match between the experimental plot and the simulation.



Figure 4.6: Simulation plot of the reflection spectrum



Figure 4.7: Experimental plot of the reflection spectrum

4.1.2 **Result with Gold Grating**

The gold grating structure consists of 30 nm thick gold grating on a 5 nm titanium adhesion layer with a width of 180 nm and a pitch of 360 nm (50% duty cycle).



Figure 4.8: Reflection from 30 nm thick gold gratings, 12 µm wide



Figure 4.9: Transmission from 30 nm gold gratings, 12 µm wide

With the gold grating, the reflectivity was greatly improves about a thousand times and for the first time I observed a transmitting signal at the same wavelength as the reflection signal.



Figure 4.10: Reflection from 30 nm thick gold gratings, 5 µm wide



Figure 4.11: Transmission from 30 nm thick gold gratings, 5 µm wide



Figure 4.12: Reflection from 30 nm thick gold gratings, 3 µm wide



Figure 4.13: Transmission from 30 nm thick gold gratings, 3 µm wide

A recurring feature of all three transmission signal is the huge loss that is observed close to the actual transmission wavelength. Initially this was assumed to have originated from coupling. Which informed my decision to use an index matching fluid to improve coupling but that didn't seem to reduce the loss. Another possible explanation that readily comes to mind is that the loss could have been due to reflection from the shiny gold surface.

4.1.3 **Result with Amorphous Silicon**

The amorphous silicon grating structure consists of 60 nm thick amorphous silicon grating on a 30 nm silicon dioxide adhesion layer with a width of 180 nm and a pitch of 360 nm (50% duty cycle).



Figure 4.14: Reflection from 60 nm thick amorphous silicon gratings, 12 μ m wide

With this grating structure, the index contrast that was achieved was $\Delta n = 1.2 \text{ x}$ 10⁻⁴ which is about half the magnitude of the index contrast required. With this grating structure, the width of the reflection signal was greatly narrowed, though no transmission was observed due to weak reflection that peaks at about -55 dBm at 1588 nm. For the 5 µm and 3 µm grating, similar reflection of about -57 dBm at 1582 nm was observed but with a broader peak.



Figure 4.15: Reflection from 60 nm thick amorphous silicon gratings, 5 μ m wide



Figure 4.16: Reflection from 60 nm thick amorphous silicon gratings, 3 μm wide

Chapter 5

OPTICAL SIMULATIONS

In various science and engineering fields, simulations are extensively used to depict the characteristics and response of a test sample. Simulating an optical device helps to understand how it would behave when fabricated. Giving the time and resources required to fabricate an actual device, simulation becomes very useful as it saves time and resources that could have been expended on trials and errors.

5.1 Lumerical Simulation Tool

The optical simulations that were performed were done alongside the device fabrication and testing to confirm the optical response that was observed. The mode profile was computed using Lumerical Mode Solution which gives a sense of the mode confinement in the Ti-diffused LiNbO₃ waveguide. The waveguide supports two modes – one fundamental TE mode and one fundamental TM mode. For the purpose of this device characterization, quasi-TM optical mode propagation was used because of the crystal orientation of the LiNbO₃ substrate (z-cut) so as to utilize its dominant electro-optic coefficient.



Figure 5.1: Mode confinement within a Ti-diffused LiNbO₃ waveguide

Lumerical Finite Difference Time Domain (FDTD) solution was used to analyze the propagation of light through the device. FDTD is a numerical analysis method that is used to model computational electromagnetics problem. The main property that was analyzed is the change in index (resulting from the presence of the grating) that the light experiences as it goes through the device.



Figure 5.2: Mode propagation profile without any grating



Figure 5.3: Mode propagation profile with 800 nm SiO₂

From this simulation, the effect of adding 800 nm Silicon dioxide grating resulted in an index contrast of $\Delta n = 2.5 \times 10^{-5}$. This explains the weak reflectivity that was observed with this grating as the required index contrast is about $\Delta n = 2.5 \times 10^{-4}$.

Another possibility of improving index contrast was to etch some part of the LiNbO₃ substrate which would introduce a rather aggressive process to the already

lengthy fabrication process. Etching 3 μ m LiNbO₃ (which in itself is a lot) was found not to be sufficient to achieve the required index contrast.



Figure 5.4: Mode propagation profile with 3 µm LiNbO3 etched

At this point Silicon was considered for use as possible grating material given its high refractive index value. This turned out right as simulation results showed that at 60 nm thickness silicon grating was able to produce an index contrast of $\Delta n = 1.2 \text{ x}$ 10^{-4} which is half the required index contrast.



Figure 5.5: Mode propagation profile with 60 nm silicon grating

Thus with increased thickness, I would anticipate a higher index contrast but at the same time increasing the thickness of the silicon layer could lead to losses as most of the mode would be couple into the silicon (higher index material) at some point. Thus there has to be an optimal value at which the index contrast is maximized while the mode is still confined in the waveguide.



Figure 5.6: Optimal silicon height for mode confinement



Figure 5.7: Plot of index contrast against silicon thickness

h _{si}	20	40	60	80	100	110	120
Δn	4x10 ⁻⁵	9.68x10 ⁻⁵	1.75x10 ⁻⁴	3.14x10 ⁻⁴	6.70x10 ⁻⁴	1.20x10 ⁻³	2.74x10 ⁻³

Table 5.1: Change in index contrast with silicon thickness

This simulation was done using silicon but during fabrication, the material that is grown in the PECVD is actually amorphous silicon which had device properties that are substantially different from crystalline silicon. So the result from the amorphous silicon grating was not expected to match perfectly with this simulation result.

5.2 Optimal Thickness for Amorphous Silicon Grating

Apart from having different material properties from crystalline silicon, the actual amorphous silicon grating will have a silicon dioxide adhesive layer underneath as explained in section 3.4.3. This was also incorporated into the simulation for the optimal thickness. Simulations were done for the two different structures of figure 3.20 and figure 3.22.



Figure 5.8: Effective index across SiO₂/Si grating

With 30 nm SiO₂ + 60 nm Si grating, $n_{eff2} = 2.140630$, so that $\Delta n = 1.67 \times 10^{-4}$. i.e. $\Delta n = n_{eff2} - n_{eff1}$ (5.1)

With only 60 nm Si, $n_{eff2} = 2.141121$ such that $\Delta n = 6.58 \times 10^{-4}$. Thus the addition of the 30 nm SiO₂ adhesive layer reduces the effective index as was expected.

With 30 nm SiO2 + 100 nm Si grating, $n_{eff2} = 2.140954$, so that $\Delta n = 4.9 \times 10^{-4}$. This exceeds the index contrast that is needed ($\Delta n = 2.5 \times 10^{-4}$) but amorphous silicon will be used instead of crystalline silicon.



Figure 5.9: Mode profile with 30 nm $SiO_2/100$ nm Si grating

The other configuration (which is easier to fabricate) involves silicon grating on top a continuous layer of silicon dioxide.



Figure 5.10: Effective index across silicon grating on SiO₂ adhesion layer

With 60 nm Silicon grating, $n_{eff2} = 2.140630$, so that $\Delta n = 8.2 \times 10^{-5}$ which is approximately half the previous result with the same amount of silicon.

With 100 nm Silicon grating, $n_{eff2} = 2.140957$, so that $\Delta n = 4.1 \times 10^{-4}$. This also exceeds the index contrast that is needed but since amorphous silicon will be used instead of crystalline silicon the effective index will be lower.



Figure 5.11: Mode profile with 100 nm Si grating on 30 nm SiO_2 adhesion layer

h _{si}	60	100	130	135	140
Δn	8.2x10 ⁻⁵	4.1x10 ⁻⁴	7.4x10 ⁻⁴	9.1x10 ⁻⁴	1.6x10 ⁻²

Table 5.2: Change in index contrast with silicon thickness in the presence of SiO_2 adhesion layer.

Table 5.2 shows the relationship between the thicknesses of the Si-strip loaded on $LiNbO_3/SiO_2$ substrate to the index contrast attainable. As was expected, the index contrast in Table 5.2 is lower when compared to the same silicon thickness in Table 5.1.



Figure 5.12: Mode profile for 130 nm silicon height



Figure 5.13: Mode profile for 135 nm silicon height



Figure 5.14: Mode profile for 140 nm silicon height

From the simulation results, it was shown that 130 nm of silicon is the optimum height that can be accommodated for the application. At 135 nm, a significant amount of the mode starts coupling into silicon and at 140 nm, the entire mode is coupled into silicon as illustrated above.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

A detailed approach to fabricating Distributed Bragg Gratings (DBGs) of different sizes and with different materials on lithium niobate (LiNbO₃) waveguide has been outlined. The devices were fabricated in two phases. First was the fabrication of Ti-diffused lithium niobate waveguide, which has been previously established. The techniques applied here include sample cleaning and preparation, UV lithography, material deposition using the Angstrom electron beam evaporator, lift-off and diffusion in the furnace. The other phase is the fabrication of the Distributed Bragg Gratings. The gratings were fabricated using electron beam lithography to expose the pattern, PECVD to grow the grating materials (silicon dioxide and amorphous silicon), Angstrom electron beam evaporator to deposit gold and ICP to etch amorphous silicon.

The materials that were utilized in this research work includes silicon dioxide, gold and amorphous silicon. The initial challenge, which was to develop a repeatable process for fabricating high quality gratings on lithium niobate base material with a pitch of only a few hundred nanometers, has been met. Despite this success, we have continually been plagued with low index contrast, which has a huge implication on the operation of the recycled carrier modulator. Much of the future effort in this work will be geared towards achieving higher index contrast.

6.2 Future Work

As was stated in chapter 5, the simulation results for an increased height of silicon shows the possibility of achieving an index contrast higher than the required value. Future endeavors in this regard will involve the establishment of a growth process for the exact thickness of the respective materials (30 nm SiO_2 and 100 nm or more of aSi as the case may be). The etch process (specifically the time) will have to be tweaked coupled of times to ascertain the optimal etch rate.

More effort will be devoted to analyzing the PECVD grown material. As at the time of writing this thesis manual, all the simulations that were done used crystalline silicon as the grating material in the simulation. The Lumerical database does not include a template for amorphous silicon but has the capability of accepting refractive index values and assigning them to layers within the simulated structure. More work will have to be done to ascertain the refractive index of the amorphous silicon layer using the Spectroscopic Ellipsometer (SE). Spectroscopic ellipsometry is a technique that is based on the measurement of the relative phase change of reflected and polarized light in order to characterize thin film optical functions and other properties [27]. The SE will avail us with more optical properties of the film like thickness (or height), refractive index and loss which will result in better simulation results and optical characterization of the film. Further studies will also be carried out to determine other materials with optical properties that could be useful for this application.

Another area that will be developed during the course of future work will be the incorporation of electrodes for the application of electric (RF) signal. The crystal orientation of the LiNbO₃ substrate (z-cut) suggests that we use ground-signal-ground (GSG) electrode structure with the Ti diffused region directly beneath the signal electrode. Quasi-TM optical mode propagation will be used so as to utilize the dominant electro-optic coefficient.

This device will be attractive for any application requiring signal modulation at high speed with high efficiency. It will find useful application in RF signal generation. The improved efficiency would be useful in millimeter-wave imaging systems such as those pursued in collaboration with Phase Sensitive Innovation. Higher efficiency from the RCM will increase the power in the modulated output signal. Other useful application will be in RF photonics – for remoting high frequency RF signals using optical fibers.



Figure 6.1: Integrated source using RCM with a GSG electrode structure.

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