Etched diffraction grating demultiplexer with distributed Bragg reflector facets on Silicon-on-insulator

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Abstract

Multiplexers and demultiplexers are essential components of a wavelength division multiplexing (WDM) system which allows for the multiplication of data transmission capacity based on existing telecom infrastructure. In this master thesis, a distributed etched diffraction grating (DEDG), which finds its application as the wavelength demultiplexer, is studied. The device is designed and built based on the platform of silicon on insulator (SOI). A center-fled reflective grating configuration is used for the design of the layout. Distributed Bragg grating reflectors are incorporated at the back of the diffraction grating facets for the purpose of enhancing the Fresnel reflection, as the insufficient reflectivity is the general problem encountered by this type of devices. Taking advantage of the high refractive index contrast of the SOI, the Bragg reflectors are fabricated with shallow etching, greatly easing the fabrication difficulty while preserving the reflectivity performance.

The device is first designed with several layout and modeling software. As for a CWDM design, 4 output channels with a 20nm wavelength spacing centered at 1550nm are proposed. By simulation the inter-channel crosstalk is less than -30dB. Furthermore, 8 output channels with 10nm wavelength spacing centered at 1550nm are proposed and simulated as well. Then a bi-layer lift off fabrication process is designed and. Electron beam lithography (EBL) is used for defining the patterns of the input/output waveguides, with a width of 500nm, and the first order Bragg grating reflectors, which have features as small as 100nm. The choice of incorporating first order Bragg reflector is to maximize the reflectivity performance and minimize the device footprint. Reactive ion etching (RIE), which has the capability of providing near vertical sidewalls, is used for the etching process.
Sommaire

Les multiplexeurs et les démultiplexeurs sont des composantes essentielles pour les systèmes à multiplexage par répartition en longueur d'onde qui permettent de multiplier la capacité de transmission de données sur les infrastructures de télécommunication existantes. Dans cette thèse de maîtrise, un réseau de diffraction gravé et réparti servant de démultiplexeur à longueur d'onde est examiné. Le dispositif est conçu et fabriqué sur une plateforme de silicium sur isolant. Une configuration de réseau réflecteur est utilisée pour la conception du plan d'ensemble. La faiblesse des réflexions sur les réseaux de diffraction étant un problème connu et important, des réflecteurs de Bragg distribués sont incorporés à l'arrière des facettes du réseau afin d'augmenter les réflexions de Fresnel. Les réflecteurs de Bragg sont fabriqués par une gravure peu profonde grâce au large contraste de l'indice de réfraction du silicium sur isolant ce qui permet de diminuer les difficultés lors de la fabrication tout en préservant la performance du dispositif.

Le dispositif est d'abord conçu selon plusieurs plans par l'entremise d'un logiciel de modélisation. Pour le multiplexage par répartition approximative en longueur d'onde, nous proposons quatre canaux espacés par 20 nm en longueur d'onde et centrés à 1550 nm. Par simulation de la diaphonie inter-canaux est inférieur à -30dB. De plus, nous proposons et simulons 8 canaux de sortie espacés par 10 nm en longueur d'onde et centrés à 1550 nm. Par la suite, nous élaborons un procédé de fabrication de soulèvement par bi-couche. Nous utilisons la lithographie par faisceau d'électrons pour créer les guides d'onde d'entrée et de sortie avec une largeur de 500 nm ainsi que les réflecteurs de Bragg de premier ordre qui ont des éléments aussi petits que 100 nm. Les réflecteurs de Bragg de premier ordre sont incorporés afin de maximiser la réflexion tout en minimisant la surface utilisée par le dispositif. La gravure par ions réactifs est utilisée pour la gravure puisqu'elle permet la fabrication de murs quasi verticaux.
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### Glossary of Terms and Acronyms

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<th>Description</th>
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<tr>
<td>WDM</td>
<td>Wavelength division multiplexing</td>
</tr>
<tr>
<td>CWDM</td>
<td>Coarse wavelength division multiplexing</td>
</tr>
<tr>
<td>DWDM</td>
<td>Dense wavelength division multiplexing</td>
</tr>
<tr>
<td>FTTH</td>
<td>Fiber to the home</td>
</tr>
<tr>
<td>TFF</td>
<td>Thin film interference filter</td>
</tr>
<tr>
<td>AWG</td>
<td>Arrayed waveguide grating</td>
</tr>
<tr>
<td>EDG</td>
<td>Etched diffraction grating</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon on insulator</td>
</tr>
<tr>
<td>FSR</td>
<td>Free spectral range</td>
</tr>
<tr>
<td>DBR</td>
<td>Distributed Bragg reflector</td>
</tr>
<tr>
<td>FPR</td>
<td>Free propagation region</td>
</tr>
<tr>
<td>PDL</td>
<td>Polarization dependent loss</td>
</tr>
<tr>
<td>TIR</td>
<td>Total internal reflection</td>
</tr>
<tr>
<td>RTL</td>
<td>Round trip length</td>
</tr>
<tr>
<td>EBL</td>
<td>Electron beam lithography</td>
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<tr>
<td>EMT</td>
<td>Effective medium theory</td>
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<tr>
<td>EIM</td>
<td>Effective index method</td>
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<tr>
<td>TMM</td>
<td>Transfer matrix method</td>
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<tr>
<td>FDTD</td>
<td>Finite difference time domain</td>
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<tr>
<td>BPM</td>
<td>Beam propagation method</td>
</tr>
<tr>
<td>DUV</td>
<td>Deep UV lithography</td>
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<tr>
<td>DEDG</td>
<td>Distributed etched diffraction grating</td>
</tr>
<tr>
<td>DEMUX</td>
<td>Demultiplexer</td>
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<tr>
<td>DG</td>
<td>Diffraction Grating</td>
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<tr>
<td>IPA</td>
<td>Isopropyl alcohol</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------</td>
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<tr>
<td>EL 6</td>
<td>EBL copolymer resist</td>
</tr>
<tr>
<td>PMMA</td>
<td>Poly(methyl methacrylate)</td>
</tr>
<tr>
<td>NPGS</td>
<td>Nanometer Pattern Generation System</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
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</table>
1. Introduction

1.1 Overview

We are living in an information age now, with abundant publication, consumption and manipulation of information heavily affecting and shaping our economic, social and cultural activities. Among all the information media, computers and computer networks (the Internet) play a vital role. From the computer microminiaturization as early as from the 1950s, to the introduction of personal computers in the 1970s, and to the massive spanning of Internet in the 1990s and the new century, and up to the current wide adoption of mobile devices (Smartphones, PDAs, tablets), evolution of technologies have reached an unprecedented speed. Of all the 7 billion population globally, one third of them uses Internet as a communication tool. In North America this number reaches almost 80%. Global communications have never been so easy with ways such as simple clicks and touches. Our modern society is reshaped by the technologies we develop.

The information is processed, organized and structured from data. By CISCO’s Visual Networking Index (VNI), ten years ago in 2001, the global Internet data transfer was 197 petabyte/month. In 2011, this number reached 27,483 petabyte/month, an almost 150 fold increase. The Internet continues to grow, driven by ever-greater amounts of online information, such as knowledge, commerce, entertainment and social networking. Such an exponential increase in usage drives the need for more computer network infrastructure to be put into use. Moreover, researchers are coming up with new ideas of maximizing the utilization of existing equipment for efficient data transfer.
1.2 Fiber Optic System

Fiber optic system provides by far the fastest transmission speed. Intercity and transoceanic fiber communication lines have been connected. Google has started a “Google Fiber” project, beginning with Kansas City, Kansas, to build a broadband Internet network infrastructure using fiber-optic communication, and deploy a 1 Gbit/s-speed network to the homes. The current state of art technology is the fourth generation fiber-optic communication system. Compared to the previous 3rd generation system, the 4th generation system used optical amplification to reduce the need for repeaters and wavelength division multiplexing (WDM) to increase data capacity. The two improvements lead to a revolution resulting in doubling of

Figure 1 Trend of global Internet data transfer CISCO’s Visual Networking Index (VNI)
system capacity every 6 months starting in 1992 till 2001, reaching a speed of 10 Tbps. In 2006, the rate reaches 16 Tbps over a single 160km line. The speed continues to exponentially grow, reaching a speed as fast as 73.7 Tbps in research lab this year through coherent optical communications, which allow many channels to be transmitted simultaneously over the same fiber by frequency-division multiplexing (FDM) [1].

Technology companies are continuously making efforts to replace the traditional copper wire networks with optical fibers. Compared to copper wires, optical channels have a much broader bandwidth. It is capable of transmitting a huge amount of signals (audio, video, microwave) directionally over one optical fiber simultaneously. In contrast, one needs thousands of electrical links to replace a single high bandwidth fiber cable. Optical fiber communications systems are immune to electromagnetic interference due to the properties of fiber materials. The attenuation loss in various transmission windows, especially in the currently used C-band, is very low. In the development of fifth generation optical fibers the focus is put on extending the low-loss wavelength range well beyond C-band. Last but not the least, due to the insulator property of silica glass, from which optical fibers are made, there are no ground loops and leakage of any type of current. Thus, large capacity, low distortion, low loss and great safety make optical fibers an ideal choice for networks.

On the other hand, fiber optic systems suffer the disadvantage of its complexity and high cost to install and operate. Therefore, optical fiber is generally chosen for systems requiring higher bandwidth or spanning longer distances than electrical cabling can accommodate. And considering budget and profits, companies are more willing to maximize the utilization of existing systems rather than building up new ones. Wavelength Division Multiplexing (WDM), which allows the expansion of capacity of the network without laying more fibers, comes to researchers’ attentions.
1.3 Wavelength Division Multiplexing

WDM enables bidirectional communications over one strand of fiber. It multiplies the existing capacity of optical fibers through parallel channels, with each channel on a dedicated wavelength. There are multiplexers at the transmitter end to combine a number of optical signals onto a single fiber and demultiplexers at the receiver end to separate the signals. The capacity of a given system could be expanded by simply upgrading the multiplexers and demultiplexers at each end only. Moreover, an optical add-drop multiplexer does both multiplexing and demultiplexing simultaneously, adding or dropping channels at any point of the network. Modern fiber optic systems could handle up to 160 signals and expand a basic 10 Gbit/s system over a single fiber pair to over 1.6 Tbit/s. Thus WDM is a powerhouse driving the network capacity and speed up.

![Figure 2 A typical add-drop wavelength multiplexing system](image)

\[
\begin{align*}
\lambda_1 & & & \lambda_1 \\
\lambda_2 & & & \lambda_2 \\
\lambda_3 & & & \lambda_3 \\
\lambda_4 & & & \lambda_4 \\
\lambda_5 & & & \lambda_5 \\
\lambda_6 & & & \lambda_6 \\
\lambda_7 & & & \lambda_7 \\
\lambda_8 & & & \lambda_8
\end{align*}
\]

Transmitters \hspace{1cm} Add-Drop Multiplexer \hspace{1cm} Receivers

Add \(\lambda_9\) \hspace{1cm} Drop \(\lambda_8\)
WDM systems are divided into two wavelength patterns, Coarse WDM and Dense WDM. Standardized by International Telecommunication Union (ITU), CWDM refers to those systems with $20\text{nm}$ channel spacing covering from $1270\text{nm}$ to $1610\text{nm}$. On the contrary, channel spacing of DWDM could be as small as 0.4 or $0.8\text{nm}$ ($50 \text{GHz}$ / $100 \text{GHz}$ in terms of frequency). Thus small channel spacing allows more information to be transmitted simultaneously. DWDM is suited for long-haul transmission with tightly packed wavelengths. CWDM, on the other hand, does not span long distances due to the non-amplification of the signals. Compared to CWDM, DWDM technology is more expensive because of the requirement of sophisticated transceiver designs.

CWDM, due to its cost-effectiveness and power consumption, finds its applications in many fields, such as business customers in metropolitan areas, and cable TV networks. Many manufactures are promoting passive CWDM, which consumes no electrical power, to deploy fiber to the home (FTTH). DWDM tends to be deployed at a higher level in the communications hierarchy than CWDM, such as Internet backbone.

Several technologies have been considered for WDM at the various input and output channels, including thin film interference filters (TFF), Mach-Zehnder-type devices, and planar spectrograph type devices such as Arrayed Waveguide Gratings (AWG) [3] [4] and Etched Diffraction Gratings (EDG) [5] [6]. Earlier, TFF type devices were adopted. Their ultra flat transmission passbands with low insertion loss over very wide free spectral range are proved successful. However, this requires labor-intensive assembly and once assembled, cannot be reconfigured for demultiplexing a different set of channels. Moreover as the requirement for number of channels increases, TFF seems to be less cost-effective. Planar spectrograph devices (AWG and EDG), on the other hand, emerge as the leading technology.
1.4 AWG and EDG

Both AWG and EDG devices have been demonstrated in various material systems, including Silica-on-silicon, III-Vs and Silicon On Insulator (SOI). In common, they require no intervention in assembly or alignment, have footprints smaller than TFF (and EDGs could be much smaller than AWG), can be mass-produced with current developed semiconductor fabrication techniques, and additionally, be easily integrated with other optical components.

![Arrayed Waveguide Grating](image)

*Figure 3 Arrayed waveguide grating*

AWG was historically more popular due to its simple and tolerant fabrication requirements, which could be easily realized with conventional fabrication techniques. EDG, on the other hand, if to perform as well as AWG, requires deeply etched grating facet walls. This is very difficult, considering that the roughness and inclination of the wall become serious as the etch depth increases. Various methods have been tried to eliminate the requirement of deep etching. The following paragraphs will address these attempts.

1.4.1 Enhancements of Fresnel reflection for EDG

One common method is to coat the back of the grating facets with a thin layer of metal with high reflectivity. Researchers in [24] [26] took this approach. Choice of metals include Al and Au, all of which are highly reflective. In [26] they chose
Ti / Au. Though Fresnel reflection loss will be reduced by doing this, it poses other problems to the system. First, metallic coating on the grating facets means a separate fabrication procedure. Since metallic coating will not be the last step of the process flow, it will make the entire fabrication procedure more complex. Second, due to the induced surface current of the metal, metallic coating will yield high polarization dependence loss (PDL), highly undesirable for polarization independent design.

A second approach is by replacing the regular grating facets with retro-reflecting facets. It is based on the principle of total internal reflection (TIR). This design is proposed in [14] [25] [28]. Figure 4 is a reproduced picture from [14]. As can be observed, it is a V-shape grating. Light is incident on each grating with about 45 degrees, producing TIR. This leads to a huge improvement on reflection efficiency. In [14], the device with retro-reflecting grating facets provided a total on chip loss of 10 dB and a crosstalk of -25 dB between channels, while the device with everything exactly same but flat regular facets produced 4 dB more loss, a significant improvement. However, there are some problems associated with this approach. The requirements for sharp corner design along with deep etching make the device difficult to fabricate. And when there is fabrication imperfection such as round corner phenomenon, device performance deteriorates. Moreover, there is sidewall non-verticality problem associated with every etching process, especially those deep ones. Tilt of sidewall gives additional loss. And when it is TIR design where there are two reflection surfaces, the loss will double. Furthermore, retro-reflecting grating facet can also increase grating loss by introducing local image error, or field noise at the facets.
While most designs, regardless of if it is metal-coated or TIR equipped, come with flat facets, the researcher in [19] proposed elliptical facets to reduce aberration, and demonstrated that the improvement is significant. However, fabrication of very tiny (on the order of $10 \, \mu m$ or smaller) and curved facets requires very advanced fabrication techniques. This will significantly increase the fabrication difficulty.

1.4.2 Advantages of EDG

As can been seen from the previous section, all the approaches to enhance the Fresnel reflection have their drawbacks. However, irrespective of these facts, EDG has gained a lot of research attention. This is primarily due to the rapid development of semiconductor fabrication technology and adoption of new high refractive index contrast materials. The attractiveness of EDG will be listed below.

1. The increasing popularity of high refractive index material, especially SOI, paves the road for EDG to attract research attention. The high refractive index contrast allows the realization of a high Fresnel reflection with a
much shallower etch depth. This alleviates the difficulty of fabrication greatly.

2. The rapid development of semiconductor fabrication technology allows for fabrication of EDG with smaller and finer features. Better photolithography techniques and e-beam lithography make device features down to a few hundred nanometers fully possible. Better etching techniques, especially reactive ion dry etching, allow for smoother and more vertical grating walls even if the etch depth is not shallow.

3. The device dimension of EDG is smaller than AWG, despite that a lot of AWG already achieve very compact feature sizes. This is an advantage of EDG for some packaging requirements.

4. Aside from those approaches to reduce the Fresnel loss discussed above, another approach, which is to replace the grating facets with Bragg reflectors, fully utilizes the advantage of fabrication development, i.e., very low order of Bragg reflectors could be readily fabricated to provide very high reflection response. More importantly, incorporation of the DBR at the back of the grating facets decouples the reflection and diffraction functionalities. The device is therefore suitable for spectral response engineering.

On the other hand, AWG has its limitation as well. First, AWG is mostly and only suited for DWDM applications because the devices have very limited free spectral range. Second, AWG is more sensitive to environmental perturbations than EDG devices. Third, in SOI and other high refractive index contrast platforms, AWG does not perform as well as silica-based AWG. It suffers the problems such as high waveguide propagation loss, limited spectral range, strong polarization dependence and poor optical crosstalk.

In a short conclusion, the desire to produce ultra compact devices, the ability to apply advanced semiconductor fabrication technology and the willingness to fabricate device on new materials have brought new research focus to the EDG.
There are several contributions made by this master thesis. First, the first order distributed Bragg reflectors (DBR) are incorporated at the back of the diffraction grating facets. Dr. Amir Jafari had a similar design in his PhD thesis but with a 3rd order DBR [8]. It is demonstrated that 1st order facets provide higher reflectivity and larger bandwidth compared to the 3rd order counterpart. The first order facets are realized by EBL. Second, a polarization independent design is proposed. It is realized by placing two diffraction gratings side by side, each reflecting waves of a specific polarization state while transparent to the other. Moreover, several DWDM versions of the device are designed, with the number of output channels up to 10 and wavelength spacing down to 4nm.
2. Diffraction Grating Demultiplexer

2.1 Overview

This chapter focuses on the introduction of diffraction grating demultiplexer. To begin with, the principle of diffraction phenomena will be explained first. The diffraction equation will be analyzed in detail, and a variety of properties regarding diffraction equation will be discussed. Then the diffraction gratings and its application as a wavelength demultiplexer will be introduced. Several major aspects will be addressed in detail, including the design of the geometrical configurations and enhancements of diffraction efficiency by Bragg reflector. Peer research progress will also be discussed.

2.2 Principle of Diffraction

Diffraction arises due to the nature in which waves propagate, and happens when waves encounter obstacles. It is well described by the Huygens-Fresnel principle and the principle of superposition of waves. The former principle states that each point on advancing wavefronts act as a source of secondary outgoing wavelets. Waveforms at a later time are determined by the vector sums of these secondary wavelets. The later one states that the summation of waves is determined by the phase and amplitude differences of each individual wave. Therefore, the summation could result in zero amplitude (destructive interference), or addition of each individual wave (constructive interference).

A diffraction grating is a structure that separates polychromatic light into its constituent monochromatic components. The grating has a periodic structure, usually with a shape of rectangle or triangle, and the groove period on the scale of the wavelength of interest. In this situation, the refractive indices along the
periodic surface encounter a periodic modulation. Electromagnetic waves that incident on the grating surfaces will have its field amplitude and phase modified in a predictable manner upon diffraction: Light diffracted by the grooves combines to form a wavefront, and there exist a unique set of discrete directions that the diffracted light from one groove is in constructive interference with the light diffracted from any other grooves.

James Gregory, a Scottish mathematician, was among the earliest scientists to discover the diffraction grating effect as early as in the 17th century. He made this discovery by passing sunlight through a bird feather and observing the diffraction pattern produced. David Rittenhouse, an American scientist, succeeded in assembling the first man-made diffraction grating in late 18s century with hairs between two finely threaded screws. In 1821 and not aware of the progress of David Rittenhouse, Joseph von Fraunhofer, a German scientist, made his parallel contribution by manufacturing a wire diffraction grating. H.A.Rowland, a professor of physics at the Johns Hopkins University, established the grating as the primary optical element of spectroscopic technology in 19th century.

Diffraction gratings have found many applications, including astronomical gratings, gratings as filters, grating for electron microscope calibration, gratings for laser tuning, and grating as beam dividers [10] [11] [12].

2.3 Diffraction Equation

The equation governing the diffraction grating is

\[ d (\sin \alpha + \sin \beta) = m \lambda_{eff} \]

In this equation, \( d \) represents the grooving period. \( \alpha \) and \( \beta \) are the incident and diffracted angles, respectively. \( \lambda_{eff} \) is the effective wavelength of light in the propagating media, such that
where $\lambda_0$ is the wavelength of light in free space, and $n_{\text{eff}}$ is the effective refractive index of the propagating media. This equation is explained with the visual help of Figure 5.

![Figure 5 Principle of diffraction](image)

When the path difference between two waves diffracted from adjacent grooves equals to half $\lambda$, the waves will be out of phase and interfere destructively, according to the wave theory of light. Contrary, when the difference equals a multiple integers of $\lambda$, the phases will add together and a maximum will occur. As can be observed from the graph, the path difference between the adjacent grooves equals to $d (\sin \alpha + \sin \beta)$. Thus it easily leads to the statement of the equation.

$m$ is the denotation for diffraction order, due to the case that there are multiple directions where the diffracted waves interfere constructively to form maxima. It is therefore clearly seen from the equation that when other parameters are fixed, a specific diffraction order gives a specific diffracted angle. Gratings can be made reflective or transmissive. When grating order $m$ is 0, there is no diffraction, and the light waves behave exactly based on principle of reflection and refraction. Thus the diffraction grating acts like a mirror or a lens, respectively. In addition to the zero-order mode, $m$ could be both positive and negative integers, leading to
diffracted waves on both sides of the zero-order ray. Whether it is positive or negative depends on whether the waves are advanced or retarded as one moves from groove to groove. Solely positive or negative, the larger the absolute value of the grating order reaches, the further the specific diffracted ray deviates from the zero-order ray.

From another perspective, in a given grating order \( m \), a beam of light with different wavelengths incident on the grating with angle \( \beta \) will be diffracted with diffraction angle

\[
\beta(\lambda) = \arcsin\left(\frac{m\lambda_0}{n_{eff}d} - \sin\alpha\right)
\]

The wavelength dependence relation shows that diffraction grating act as a dispersive element. This is similar to the operation of a prism, although the working mechanism is very different.

Regarding diffraction grating, there are multiple aspects that need to be discussed, and they are listed in the following paragraphs.

### 2.3.1 Limited Number of Diffraction Orders

Observing the diffraction grating equation carefully, one realizes that, since the absolute value of \((\sin\alpha + \sin\beta)\) must be less or equal to 2, rearranging the term it leads to the conclusion

\[
|m| < \frac{2d}{\lambda_{eff}}
\]

Thus, though zero-order ray always exists because the right term of the above equation is always non-zero, there is a restriction preventing light of a specific wavelength from being diffracted into more than a finite number of orders.
2.3.2 Dispersion

One primary function of the diffraction grating is to spatially disperse light by its wavelength. Dispersion is the effect that the velocity (phase or group) of light is dependent on its frequency. It is a measure of the separation between diffracted lights of different wavelengths. Angular dispersion measures this spectral range per unit angle. It equals to the rate of change of the diffracted angle with respect to the change of wavelength. Differentiating the grating equation, one obtains the angular dispersion strength

\[ D = \frac{\partial \beta}{\partial \lambda} = \frac{m}{d \cos \beta} = \frac{\sin \alpha + \sin \beta}{\lambda_{\text{eff}} \cos \beta} \]

Observing the equation, one can realize that although when the groove density increases (period \( d \) decreases) the dispersion strength increases, the value of \( m/d \) could not be chosen irrespective of other parameters. Re-writing the angular dispersion expression in terms of \( \alpha \), \( \beta \) and \( \lambda \), as shown on the right hand side, and given a specific wavelength, it is seen that \( D \) is a function solely dependent on the incident and diffraction angles. It is thus inferred that once the diffraction angle \( \beta \) has been decided, \( m/d \) need to be chosen proportionally: either a small period \( d \) with a low operating order, or a large period \( d \) on a high operating order.

In addition, linear dispersion is the product of angular dispersion and the effective focal length of the system. It expresses the spectral range per unit length.

2.3.3 Free Spectral Range

For a given set of incident and diffraction angles, the diffraction grating equation is satisfied for a different wavelength for each diffraction order \( m \). Therefore there could be light of different wavelengths diffracted along a same direction. For example, light of wavelength \( \lambda \) diffracted in \( m \) order will superimpose with light
of wavelength $\frac{1}{2} \lambda$ in the $2m$ order, for all $m$. This overlapping of diffracted spectra is undesired, and must be prevented by a careful grating design or by suitable filtering technique.

The largest wavelength range in a specific spectral order for which light from adjacent orders does not overlap is called the free spectral range (FSR). The expression for FSR is directly derived from the definition: let $\Delta \lambda$ be the spectral range. If a light with wavelength $\lambda$ is diffracted into order $m$ and $m + 1$, To prevent spectral overlapping the following relation need to be satisfied

$$m(\lambda + \Delta \lambda) = (m + 1)\lambda$$

Thus, the FSR is

$$FSR = \Delta \lambda = \frac{\lambda}{m}$$

As can been seen, higher diffraction order leads to small FSR, which is unwanted. Therefore, FSR comes as a very important concern when designing specialized gratings, such as Echelle gratings, because they function at very high operating orders.

2.3.4 Chromatic Resolving Power / Spectral Resolution

The term chromatic resolving power and spectral resolution are used interchangeably to describe the ability of the diffraction grating to distinguish between adjacent spectral lines with an average wavelength of $\lambda$. It is expressed as

$$R = \frac{\lambda}{\Delta \lambda}$$

In this expression, $\Delta \lambda$ is called the limit of resolution, the smallest resolvable wavelength difference. This value is determined by the Rayleigh criterion applied to the diffraction maxima, i.e., two adjacent wavelengths are resolved if the maxima of one wavelength lies at the first minimum of the other.

Suppose the grating has $N$ grooves, then the spacing between maxima will be
broken up at most into \( N - 2 \) subsidiary maxima. The distance to the first minimum is \( \frac{1}{N} \) times the separation of the main maxima. This leads to a resolving power of

\[
R = \frac{\lambda}{\Delta \lambda} = mN
\]

Here \( N \) is the total number of illuminated grooves while \( m \) is the diffraction order. Replacing the diffraction order \( m \) with its expression from the grating equation, one obtains

\[
R = mN = \frac{d(sina + sin\beta)N}{\lambda_{\text{eff}}}
\]

From another perspective, chromatic resolving power could be considered as being determined by maximum phase retardation of the extreme rays diffracted from the grating illuminated. First, the optical path difference between waves diffracted from the two extreme ends of the grating gives the maximum phase retardation. Then this value is divided by the average wavelength \( \lambda \) to provide the quantity of resolving power.

### 2.3.5 Grating Efficiency

The total power of incident wave will be partitioned into various spectral orders upon diffraction. The proportionality of power distribution is dependent on wave polarization status, incident and diffraction angles, the refractive index of the grating materials, and the groove period. While the polarization status and the refractive index of materials may not be modified due to a certain design / application requirement, the incident / diffraction angles and the groove period could obviously be manipulated to produce a higher grating efficiency, i.e., to modify the default power distribution so that a maximum achievable portion of power is concentrated in a single diffraction order. The method of implementation
is to modify the cross-sectional profiles of the grooves, usually as the triangular profile as shown below. This technique is called the blazing. Since via blazing, the grating efficiency is optimized for one wavelength, that wavelength is denoted blaze wavelength and must be clearly specified. Blaze angle indicates the sharp angle of the triangular profile (indicated in the graph) under maximum grating efficiency, and is closely related to the blaze wavelength and diffraction order.

In order to calculate the grating efficiency in detail, one has to solve Maxwell’s equations rigorously to find the solutions. Fortunately, thanks to technology, commercial software is available that accurately calculates grating efficiency for a wide variety of groove shapes over a wide spectral range. On the other hand, a special setup called the Littrow configuration, under which maximum grating efficiency is achieved, is discussed in detail in the following section.

### 2.3.6 Littrow Configuration

The Littrow configuration is a special grating profile. By properly selecting the blaze angle, the incident angle and diffraction angle are identical. *Figure 6* shows a diffraction grating under Littrow configuration. In this situation, the light is diffracted back toward the direction from which it is incident from. Expressed from the grating equation

\[ \alpha = \beta = \theta_B \]

\[ m\lambda_{eff} = 2dsin\alpha = 2dsin\theta_B \]

Several features of Littrow configuration are worth noting, and they are related to the previous discussion. Most importantly, the maximum grating efficiency for a specific wavelength is achieved under Littrow configuration. Moreover, for the angular dispersion under Littrow configuration,

\[ D = \frac{d\beta}{d\lambda} = \frac{2tan\beta}{\lambda} \]

This equation makes the point clearer that the angular dispersion is solely
dependent on the incident and diffraction angles, while the two are the same in Littrow mount.

Second, maximum chromatic resolving power also occurs under the Littrow configuration.

\[ R = \frac{Nd(sina + sin\beta)}{\lambda_{eff}} \]

\[ R_{max} = \frac{2Nd}{\lambda_{eff}} \]

\( R_{max} \) occurs when incident and diffraction angles are equal and are approximately 90 degrees, which is the grazing condition. However, this maximum resolving power is theoretical, and is dependent on the optical quality of the grating surface and the uniformity of grooves periods. Deviation from ideal condition will result in a reduction of resolving power.

![Figure 6 Littrow configuration](image-url)
2.4 Concave Diffraction Grating Demultiplexer

A concave diffraction grating could be modeled as a concave focusing mirror that meanwhile disperses light. It is capable of reflecting and focusing light because of the concavity, and dispersing light due to the functioning of grating. The focusing functionality, without making the flat diffraction grating concave, could otherwise only be provided by inserting separate, bulk optical elements into the setup, which cause a significant increase of the device footprint. It was Henry Augustus Rowland, a physicist at Johns Hopkins University, who lead the revolution of the diffraction grating by eliminating the bulk focusing optical devices and fabricating the concave diffraction gratings with extremely high accuracy.

One of the major applications of the concave diffraction gratings is to function as a wavelength demultiplexer due to its strong dispersing ability. In recent years, much effort has been invested into researching various grating geometrical configurations, enhancement of the grating efficiency, and realization of the device in various material systems. The following paragraphs will review works on this topic.

2.4.1 Grating Geometrical Configurations

The most important aspect leading to a successful design is the grating geometrical configuration. One of the earliest developed, also one of the most successful and popular designs is Rowland configuration proposed by Henry Augustus Rowland. Figure 7 shows Rowland configuration.
The ports of the input and output waveguides are positioned on the Rowland circle with radius $R$. A curve with radius $2R$ touches the Rowland circle at the pole, shown on the drawing. This is the concave grating curve, where the grating facets are located. The coordinates of the grating facets are determined such that if each mid-point of grating facets are projected against the tangential line of the Rowland circle at the pole, they are equally spaced apart by a distance of $d$, the design grating period.

After having emerged from the input waveguide, light propagates and expands freely in the free propagation region (FPR), hits the grating facets, then diffracts and focuses back to the arrays of output waveguides, following the diffraction grating equation

$$d(\sin \alpha + \sin \beta) = m\lambda_{eff}$$

in which $\lambda_{eff}$ is the effective center-design wavelength.
The proposal of Rowland configuration was originally intended for bulk optics, but has been proven successful with miniaturization. The diffraction demultiplexers proposed in [13] [14] [15] [18] [26] are designed solely based on Rowland configuration. On the other hand, researches on other possible configurations have been ongoing. One of the successful designs comes with two stigmatic reference points, which enables compact geometries with reduced aberrations. *Figure 8* shows such a configuration.

*Figure 8 Concave grating based on confocal ellipses*

According to the property of an ellipse, light from one focus point of the ellipse, upon reflection from a point on the ellipse, passes through the other focus point. Thus the design starts by selecting the position of input waveguide port $I$ and the position of one output waveguide port $O_1$ as the stigmatic points of a series of concentric ellipses. The grating facets, therefore, will locate on the concentric ellipses, with their respective distances determined by the size of the ellipses such that the optical path length difference from $I$ to $O_1$ is equal to $\frac{mN\lambda_1}{n_{eff}}$, where $\lambda_1$ is the designed wavelength at port $O_1$, $m$ is the grating order, $n_{eff}$ is the effective refractive index of the propagation region, and $N$ is an integer. Next, the design is
repeated by treating $I$ and $O_2$ as the two stigmatic points, leading to another series of centric ellipses. In order to satisfy both design criteria, the grating facets need to be sitting on the respective intersections of the two series of concentric circles. As shown in the figure, points $M_1, M_2.. M_N$ are the locations of the grating facets. With this design, one can achieve the same optical performance as with a Rowland configuration, on a much smaller footprint. Diffraction demultiplexers designed in [25] [28] are based on this two astigmatic point design.

It is interesting to point out here that in [22], the author proposed a design that incorporates Rowland configuration with one stigmatic point correction. In that design, the stigmatic points are located at the input waveguide port and the central waveguide of the 21-output waveguide array. Then the parameters for Rowland configuration are correspondingly chosen so that the location of grating facets calculated from Rowland design coincides with the concentric ellipses. In this paper they demonstrated a grating WDM with 21 channels, 1 nm channel spacing with crosstalk better than -10 dB. Moreover, their design resulted in a free spectral range of more than 100 nm.

McMullin proposed a different approach in [27], in which the grating facets are reflective arcs of concentric circles centered at the port of the input waveguide. The difference between radii of adjacent arcs is an integer multiple of the half wavelength in order to obtain constructive interference. Each facet, by calculation, subtends an equal angle corresponding to the input point. From this approach, the output waveguides, along with the input waveguide, are placed equidistantly along a line. This approach exhibits less aberration than Rowland. Jafari in his paper [21] adopted this approach and showed a good result. In this thesis, this flat-field configuration is applied. Further detail on the design configuration will be discussed in the following chapter.
2.4.2 Enhancement of Grating Facet Reflection Efficiency

Several methods to reduce reflection losses have been discussed in the first chapter. In addition to those, Bragg reflectors has become a popular way to enhance Fresnel reflection efficiency, as detailed in [16] [20] [26]. This is realized by replacing each grating facets with a Bragg grating reflector with a certain number of periods. Since designed and fabricated together with other parts of the device, it eliminates the additional fabrication process that is required by metallic coating. It eases the fabrication difficulty by eliminating sharp corners, which is unavoidable in TIR design. Moreover, though in some of the previous literatures the Bragg reflector required a deep etching, it is fully possible and has been realized by shallow etching the Bragg region. Thus, problems such as fabrication imperfections or sidewall non-verticality are greatly alleviated. It is necessary to point out that the largest source of loss for a Bragg reflector is the scattering loss when light passes through the air slot. Nonetheless, Bragg reflector is proven to be a highly efficient, while fabrication-error tolerant method to enhance the reflection efficiency of the facets. In this thesis, a shallow etching Bragg grating reflector is adopted to the design. The detail, including the design, simulation and fabrication, will be discussed separately in the following chapters.
2.4.3 Materials

Etched diffraction grating demultiplexers have been realized in various material platforms, including silica-on-silicon, III-Vs, InGaAs/InP and recently, Silicon-On-Insulator (SOI) [29] [30]. The SOI platform has drawn a lot of recent research attentions primarily due to its high refractive index contrast: SOI consists of a top silicon layer with a thickness of 220 nm - 350 nm and a refractive index of 3.45-3.47, an underlying silicon dioxide layer with a thickness of 1 µm - 2 µm and a refractive index of 1.45-1.47, and a thick substrate silicon layer. The high refractive index contrast provides the possibility of shrinking the size of the device while preserving the performance [31] [32]. Demultiplexers based on etched diffraction gratings with size of 280 µm by 150 µm have been successfully demonstrated. It allows for the reduction of the fabrication difficulty of many silicon photonics devices such as Bragg grating reflectors, because the etching is not needed to be deep due to the high refractive index contrast. Many problems such as sidewall non-verticality and rough surfaces can thus be greatly alleviated. In addition, semiconductor fabrication technologies are well developed at this age to cater the need to incorporate photonics circuit with electronics circuits and the
There, however, exist several challenges associated with SOI platform. Similar with silica platform, SOI suffers polarization birefringence. This is due to the fact that the effective refractive indices of TE and TM light propagating in SOI are different. This deteriorates when the thickness of the top silicon layer increases. In addition, when high refractive index is an advantage when referring to device design, it comes as a disadvantage when coupling light into and out of SOI. Traditional vertical grating couplers come at the cost of high coupling loss and polarization selective coupling. Other coupling schemes such as butt coupling suffer even higher losses and require very complex design and fabrication procedures.

Nevertheless, due to the various attractive properties of SOI, it is a very popular and preferred platform for photonics integration. In this thesis, the etched diffraction grating demultiplexers are fabricated on SOI platform.

### 2.4.4 More Peer Research Progress

There are a few additional research papers with their design approaches and results that are worth noting. Brouckaert in [15] designed and fabricated a 4 channel CWDM etched diffraction grating demultiplexer on SOI. They achieved a record small footprint of 280 $\mu m$ by 150 $\mu m$. The design configuration is based on Rowland mount. All the grating facets are individually blazed to maximize the reflection at the blazing point. The output channel spacing is 20 $nm$. The on chip loss is 7.5 $dB$ with a crosstalk better than -30 $dB$. Horst in [25] designed an 8-channel DWDM demultiplexer with 3.2 $nm$ channel spacing. They showed by this design an ultra compact footprint of 250 $\mu m$ by 200 $\mu m$ could be realized. The design was based on two stigmatic aberration-free points configuration. They introduced retro-reflecting corner mirrors to enhance the reflectivity at the facets. The results showed a theoretical 2.5 $dB$ loss and a crosstalk of better than -19 $dB$, with a variation of 0.5 $dB$. 

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3. Design

3.1 Overview

In this chapter, all of the design factors for this thesis are discussed. First, the geometrical configuration of the etched diffraction grating is explained in detail. After that the enhancement of reflectivity with the aid of Bragg reflectors is addressed. A practical issue regarding the continuity of Bragg reflectors is extensively considered. Further discussions in this chapter involve the design of input/output vertical grating couplers, polarization independent grating couplers and finally, a proposal of a polarization independent diffraction grating demultiplexer.

3.2 Flat Field Design

The design principle applied in this thesis is adopted from the one in [27] proposed by McMullin. He introduced a center-fled reflective grating configuration. In this configuration, the input waveguide and all the output waveguides are placed equidistantly along the vertical direction. The diffraction grating is positioned with respect to the input waveguide. Due to the special configuration, the wavelength of design will be reflected back to the input waveguide. The rest of wavelengths will be reflected back to both sides of the input waveguide, with higher wavelengths on the left side and lower ones on the right. Therefore, if the design wavelength falls in the middle of the desired spectrum, there will be a hole in the output. To avoid this, the wavelength of design is chosen to be located at one side of the desired output spectrum. For example, in this thesis, the output spectrum falls between 1500 nm and 1580 nm, so the wavelength of design is chosen to be at 1500 nm. Figure 10 shows the schematic diagram of the layout. I denotes the input waveguide port; O denotes one of the output waveguide ports. By ray theory,
facets reflecting all rays from input waveguide back on themselves should be reflective arcs of concentric circles centering at the input point. Therefore, grating facets \((F_1, F_2, \ldots)\) are arcs located on a series of concentric circles with origins at \(I\), the port of input waveguide. Furthermore, by wave theory, rays reflected from different facets need to interfere constructively at designed output waveguides. This can only be satisfied if the radius of successive concentric circles differs by

\[
\frac{N\lambda_d}{2n_{eff}}
\]

This is the expression of path length difference, in which \(N\) represents grating order, \(\lambda_d\) represents the wavelength of design, and \(n_{eff}\) represents the effective wavelength in the free propagation region (FPR).

![Figure 10 Center-fed reflective grating design](image)

**Figure 10 Center-fed reflective grating design**

There are two further design specifications with respect to this configuration. First, the lateral spacing between each adjacent output waveguide is equal, denoted as \(d\). The spacing between the input waveguide and the innermost output waveguide is
also equal to \( d \). Therefore the waveguides are evenly distributed on one side of the free propagation region. Second, the diffracted output wavelengths are also evenly distributed along the output waveguides, with a same value of channel spacing \( d\lambda \). For example, with a designed channel spacing of 20 nm and 4 output channels covering 1500-1580 nm wavelength spectrum, the output wavelength at the 4 evenly distributed output waveguides will be 1520 nm, 1540 nm, 1560 nm and 1580 nm.

To further explore the geometrical specification of this configuration, a few algebraic calculations are needed. Let

\[ \lambda_j = \lambda_d + j d\lambda \]

be the \( j^{th} \) output wavelength, with \( j \) an integer, positive for wavelengths longer than \( \lambda_d \) and vice versa. Let \( d_j = jd \) be the \( j^{th} \) position of the output waveguide laterally with respect to the input waveguide, where \( d \) is the spacing between adjacent waveguide, as shown in the figure. \( D \) denotes the position of the outermost output waveguide, \( O \) as the port of this waveguide. Two facets are marked as \( F_1 \) and \( F_2 \) for convenience. Let \( T_1 = |IF_1|, T_2 = |IF_2|, R_1 = |F_1O| \) and \( R_2 = |F_2O| \). The round trip length (L) from input to one facet, and to the output is

\[
L_1 = T_1 + R_1 = T_1 + \sqrt{T_1^2 + (D)^2} - 2D(T_1)\sin\theta_1 \approx 2T_1 - D\sin\theta_1
\]

\[
L_2 = T_2 + R_2 = T_2 + \sqrt{T_2^2 + (D)^2} - 2D(T_2)\sin\theta_2 \approx 2T_2 - D\sin\theta_2
\]

Notice that the subscript could be generalized as \( T_m \). The approximation in this equation is derived by the fact that while \( D \) is usually 30 to 50 \( \mu m \), \( T_m \) is on the order of several hundred micrometers, much larger than \( D \). Furthermore, \( T_2 \) is further than \( T_1 \) by an amount

\[
T_2 = T_1 + \frac{N\lambda_d}{2n_{eff}}
\]

Thus, round trip length for facet \( F_2 \) could be rewritten as
This could be rewritten as

\[
\sin\theta_1 - \sin\theta_2 = \sin\theta_{m+1} - \sin\theta_{m+2} = \frac{N\lambda_d}{n_{eff}d}
\]

as can be seen in the equation, this relation could also be generalized for any facet \( m \).

Since all grating facets are close to the virtual line extending from the input waveguide, especially compared with the distance from input to each facet, a paraxial approximated could be applied.

\[
\sin\theta_m - \sin\theta_{m+1} \approx \theta_m - \theta_{m+1} = \theta = \frac{N\lambda_d}{n_{eff}d}
\]

Therefore, the statement is that each grating facet subtends a same angle at the input point, with the angle proportional to the grating order, the wavelength of design, the effective index in FPR, and the waveguide spacing. Facets, however, subtend different widths with values of \( T_m \theta \). Ideally, facets should be arcs to provide perfect wave phase fronts. However in reality they are designed as straight lines. This is because even the size of the largest facet does not exceed a few micrometers. There is trivial difference between an arc and a straight-line segment. Moreover, designing the facets to be straight line segments also make the fabrication easier, especially at the layout stage, because the software fragments a straight line and an arc very differently, while a straight line design achieves an intuitively higher resolution and leads to a better fabrication accuracy.

Another design consideration is the free spectral range: the non-overlapping output spectrum, briefly discussed in the previous section. If the design grating order is \( N \), the spectrum of grating order \( N + 1 \) should not interfere with the design grating order. This is to say that the FSR of the device should exceed \( N_{ch} d\lambda \). Put into this center-fled configuration, the position of constructive interference for a specific wavelength lambda in \( N - 1 \) diffraction order, denoted as \( X \), should be larger than
the aggregate lateral distance of the output waveguides.

\[ X > D = N_{ch}d \]

The round trip length between input, facet \( m \) and \( m + 1 \), and \( X \) is

\[ L_{X,m} \approx 2T_m - Xsin\theta_m \]

\[ L_{X,m+1} \approx L_{X,m} + \frac{(N - 1)\lambda_d}{n_{eff}} = 2(T_m + \frac{N\lambda_d}{2n_{eff}} - Xsin\theta_{m+1}) \]

Further formatting the two equations, one obtains

\[ X = \frac{\lambda_d}{n_{eff}\theta} \]

Combining this with the previous inequality equation, it is stated that in order for the adjacent order to not overlap in the output spectrum, the diffraction order \( N \) should satisfy the following relationship

\[ N < \frac{\lambda_d}{d\lambda N_{ch}} \]

This is a crucial design restriction, and should be considered first and foremost when initializing every new design.

### 3.3. Enhancement of Reflectivity with Bragg Reflectors

As has been discussed in the literature review sections, a lot of thought have been put into enhancing the Fresnel reflectivity at the grating facets. In this thesis each grating facet is replaced by a certain number of Bragg grating reflectors. The front surface of the first Bragg layer acts as the grating facet, and the layers behind that are used to enhance the reflectivity by the distributed Bragg reflectors.

Bragg grating is designed to reflect particular wavelengths of light and transmit the rest. This is achieved by creating periodic varying structures at the local Bragg region, modifying the refractive indices. At each change of refractive index a reflection takes place. The repeated variation of refractive indices causes multiple reflections from multiple interfaces. At the design wavelength, the Bragg
wavelength, all reflected waves are in phase and add constructively to form the back reflected signal.

The system of equations expressing the working principle of Bragg grating reflectors is listed as follows:

\[ N\lambda_B = 2n_{avg}\Lambda \]

\[ n_{avg} = (1 - D)n_{eff1} + Dn_{eff2} \]

\[ D = \frac{w_u}{w_e} = \frac{w_u}{\Lambda} \]

In these equations \( \lambda_B \) represents the design Bragg wavelength. \( N \) represents the Bragg order. Lower order Bragg grating, though resulting in more fabrication challenges, gives better spectral performance. \( \Lambda \) is the total period length of one period, consisting of etched width \( w_e \) and unetched width \( w_u \). \( D \) stands for duty cycle, the proportion of the unetched width with respect to the period length. \( n_{avg} \) is the averaged effective refractive index between the etched and unetched regions. 

*Figure 11* shows the layout of Bragg grating and the respective symbol designations.
Shallow etching is chosen for the trench of the Bragg reflectors in order to reduce the fabrication difficulty. This is because generally, deeper etching causes problems such as sidewall non-verticality and larger area of surface roughness. Moreover, larger bottom width to sidewall depth aspect ratio is always preferred due to fabrication difficulty concern. There is a minor drawback, however, that the 3 dB bandwidth will shrink due to shallow etching. But since we are operating at very low grating order bandwidth should not be a big concern. In addition, a shallow etching reduces reflectivity. Increasing the number of periods can compensate this.

3.3.1 Continuity Issue of Bragg Reflectors

A practical concern arises here, that since a large number of grating periods is required, the Bragg grating layers from adjacent facets will overlap with successive ones, creating a discontinuity. This is highly undesirable because first, this discontinuity on such nanoscopic level is technically unfabricatable. Not only the fabrication technology will possibly ignore such a positional difference, but also that unpredictable and undesirable fabrication results will occur by leaving such a discontinuity design in the mask layout. Second, structural discontinuity within the Bragg grating region leads to additional scattering loss. The solution to this problem is to manipulate various parameters somewhat so that the radial difference $\Delta R$ between adjacent facets equals to integer multiple of the period length of the Bragg grating reflector. The expression is listed as follows:

$$\Delta R = \frac{N_D \lambda_D}{2n_D}$$

$$\Lambda = \frac{N_B \lambda_B}{2n_B}$$

$$\frac{\Delta R}{\Lambda} = \frac{N_D \lambda_D n_B}{N_B \lambda_B n_D}$$
The purpose is to make $\frac{\Delta R}{\Lambda}$ as close to an integer as possible. $N_B$ is fixed as 1\textsuperscript{st} or 2\textsuperscript{nd} order by design rules. $N_D$ is the diffraction order, which could be changed accordingly. However as explained previously, one has to keep in mind that there is an upper limit for this value so that the output spectrum does not overlap. $\lambda_D$ and $\lambda_B$ are fixed by design rules. Typical values in this research thesis would be 1500\textit{nm} and 1550\textit{nm} respectively. $n_B$ is dependent on the etch depth and duty circle. While the etch depth is fixed according to fabrication process, the duty cycle could be flexibly changed within fabrication-tolerable range (for high accuracy, minimum width 100\textit{nm} with EBL). $n_D$ is dependent on the design wavelength of diffraction, which is then fixed. In conclusion, two parameters, $n_B$ and $N_D$ could be manipulated to produce an almost integer value of $\frac{\Delta R}{\Lambda}$.

There is a general drawback about changing $n_B$. That is, by changing the duty cycle the Bragg reflectors will not stay at optimal performance. However, subsequent simulation shows that by using the values obtained in this research thesis, the effect of manipulating the duty cycle on the performance of the Bragg reflectors is minimal.

### 3.4 Vertical Grating Coupler

A vertical grating coupler is designed to generate a phase matching condition between an input wave that is obliquely incident on the waveguide surface and a specific waveguide mode, in this case, the fundamental mode. Figure 12 shows the layout of the vertical grating coupler.
The periodic nature of the grating causes the perturbation of the waveguide modes in the propagation region, leading to a set of spatial harmonics with propagation constants along the direction of propagation given by

$$\beta_m = \beta_0 + \frac{m2\pi}{\Lambda}$$

in which $m$ is an integer set and $\Lambda$ is the periodicity of the grating. Due to the negative values of $m$, the phase matching condition can be satisfied so that

$$\beta_m = kn_1 \sin \theta_m$$

The grating coupler can be used to selectively transfer energy of specific wavelengths from an optical beam light to a particular waveguide mode by choosing the right angle of incidence. Moreover, this process can be reversed, so that the grating can also be used as an output coupler. Grating coupling, compared to other coupling methods such as butt coupling, has the advantage of easy fabrication with traditional semiconductor technology and relatively simple fabrication process. Under proper construction, grating coupling achieves high coupling efficiency. In [34], the fiber-to-chip grating couplers on SOI show a coupling efficiency of -1.6dB and a 3dB bandwidth of 80nm.

However, grating couplers suffer a big disadvantage that it is strongly polarization dependent. In 1D grating typically, TE mode effective index is larger than that of the TM mode due to the larger confinement factor. Therefore the grating period
for TE mode coupling is always smaller than that required for TM mode. Thus for a polarization independent grating demultiplexer, a traditional 1D grating coupler cannot couple light of both polarization into the waveguide simultaneously.

### 3.5 Polarization Independent Grating Coupler

For wave coupling to a polarization independent design, several coupling schemes have been considered, such as butt coupling and polarization-beam-splitting grating couplers [35]. The former one, though offers a true polarization independent coupling, has low coupling efficiency. The later one has the disadvantage of doubling the footprint of the device and place stringent requirement on the fabrication process to make sure that the two sets of circuits are identical.

Special attention has been paid to 2D polarization-independent grating couplers. In [36], the polarization independency is achieved by applying subwavelength microstructure to the original 1D grating couplers so that the effective indices of TE and TM modes become identical. In the design, the subwavelength dimension of the holes are smaller than the wavelength of propagating light, so that effective medium theory (EMT) at the 0th (approximation) and 2nd (more accurate) orders could be used to approximate the subwavelength structure by a traditional 1D structure with a modified effective indices for each polarization mode. They achieved an optimized condition that with over 64% coupling efficiency for polarization independent coupling between single-mode fiber and SOI waveguides.
3.6 Polarization Independent Diffraction Grating Demultiplexer

The factor that makes the diffraction grating demultiplexer polarization dependent is the reflecting behavior of the Bragg grating reflectors: while designed for one polarization state, it does not efficiently reflect the wave with another polarization state. This is due to the strong difference of effective refractive indices between TE and TM mode in SOI material. Figure 13 shows the effective refractive indices of TE and TM mode with different top silicon thickness of SOI. By calculation the average difference of the effective index between two modes is 38% with the thickness of top silicon layer up to 220nm.

![Figure 13 n eff difference between TE mode and TM mode](image)

In this research thesis, the polarization independent design is achieved by having two etched diffraction gratings operating side by side, all designed with the flat field design principle introduced previously, each reflecting wave of a specific polarization state while being transparent to the other. Figure 14 shows the layout of this 2-layer polarization independent design scripted and drawn in dw-2000.
**Figure 14** Layout of polarization independent diffraction grating demultiplexers

The design parameters are listed in *Table 1*.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period length</td>
<td>450.81 nm</td>
</tr>
<tr>
<td>Number of output channels</td>
<td>4</td>
</tr>
<tr>
<td>Waveguide Spacing</td>
<td>7 μm</td>
</tr>
<tr>
<td>Center design wavelength</td>
<td>1500 nm</td>
</tr>
<tr>
<td>Wavelength spacing</td>
<td>20 nm</td>
</tr>
<tr>
<td>Diffraction order</td>
<td>7</td>
</tr>
<tr>
<td>Etch depth</td>
<td>100 nm</td>
</tr>
<tr>
<td><strong>TE Bragg Reflector</strong></td>
<td></td>
</tr>
<tr>
<td>Bragg order</td>
<td>1</td>
</tr>
<tr>
<td>Period length</td>
<td>308.98 nm</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.44</td>
</tr>
<tr>
<td>Distance of central facet to input</td>
<td>410 μm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>18</td>
</tr>
<tr>
<td><strong>TM Bragg Reflector</strong></td>
<td></td>
</tr>
<tr>
<td>Bragg order</td>
<td>1</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.63</td>
</tr>
<tr>
<td>Distance of central facet to input</td>
<td>310 μm</td>
</tr>
<tr>
<td>Number of periods</td>
<td>18</td>
</tr>
</tbody>
</table>

*Table 1* Design parameters for polarization independent diffraction gratings
The TM Bragg reflector facets are placed on the left of the TE Bragg, closer to the input waveguide. This is because TM Bragg reflector, due to the smaller effective refractive index, always has larger geometrical size than the TE counterpart. This is true for both the period length of the Bragg grating and the arc width because of their inverse proportions with respect to the effective refractive index. It could also be visually justified from the layout that TM Bragg reflector has larger geometrical size than TE Bragg, despite the fact that the distance of central facet to input waveguide is a lot smaller for TM Bragg.

The various modeling and simulation regarding the design, including the wave propagation inside the waveguides, the Fresnel diffraction through the free propagation region and the Bragg grating reflectors will be done in the following section.
4. Modeling and Simulation

4.1 Overview

This chapter introduces all the modeling methods used in this thesis and the corresponding simulation results. Effective index method (EIM) is used for effective refractive index calculation. Fresnel diffraction integral is used for predicting the demultiplexing output spectrum within the free propagation region. Beam propagation method is used for tracing the pattern of the input wave in the free propagation region after coming out of the input waveguide. Transfer matrix method is used for approximately calculating the response of the Bragg grating reflectors, while FDTD is used for accurately predicting the performance. Moreover, FDTD is also used for calculating the spectrum of vertical grating couplers.

4.2 Calculation of Effective Refractive Index of Waveguide

The effective index method (EIM) is applicable to solve complex waveguide problems such as those associated with ridge waveguides or strip waveguides. These waveguides are difficult to deal with if analyzed by Marcatili’s method [38] or Kumar’s method [39]. Effective index method converts a 3D problem into a 2D problem, facilitating the numerical analysis of the complicated waveguide structure that usually requires Finite Difference Time Domain (FDTD) method or so. Reducing the problem from 3D to 2D will significantly reduce the time of calculation, while the accuracy of calculation is well preserved.
When applying EIM, the operating modes of waveguides are assumed to be almost TE or TM like. Figure 15 shows the cross section of a ridge waveguide. $n_1$, $n_2$ and $n_3$ represent refractive indices for cladding, core and substrate regions. With EIM, the ridge waveguides are firstly divided into three regions vertically, i.e., left, middle and right parts. They respectively are treated as a 2D slab waveguide and the corresponding TE/TM effective refractive indices are calculated, represented as $n_{left}$, $n_{mid}$ and $n_{right}$. $b-V$ curve method is used here. The normalized frequency $V$ is calculated from the operating wavelength. $b$ is obtained from interpolating the $b-V$ curve, followed by the calculation of effective index. Second, the equivalent structure from first step will be again treated as a slab waveguide, and the effective index ($n_{eff}$) will be calculated. This effective refractive index determines the propagation constant within the waveguide.

If the wave is TE polarized in 3D, then in 2D it is TM polarized. If the wave is TM polarized in 3D, then in 2D it is TE polarized. This is because in 2D, TE means the electric field is transverse to the direction of propagation, and TM means the magnetic field is transverse to the direction of propagation. In 3D however, there are no waves that are true TE or TM, but quasi-TE or quasi-TM, which is when one longitudinal component of one field is much larger than that of the other. TE is when the electric field is predominantly along the horizontal transverse direction. Thus this corresponds to the TM mode when it is in 2D.
EIM is written in MATLAB and used for calculating effective refractive indices of all the components in this design, including the waveguides, the grating couplers and the Bragg reflectors. These calculation results are used to construct the circuit in a 2D manner in other analyzing software such as RSoft and Lumerical. This step of calculation is important for reducing the time of further analysis and well preserving the accuracy.

4.3 Calculation of Output Field Profile

Fresnel diffraction integral is an approximation of Kirchhoff-Fresnel diffraction equation that could be used to calculate the propagation of electromagnetic waves in the near propagating field. The near field regime applies for where the square of the size of the aperture is a lot great larger than the product of wavelength of light and distance of the observation point from the center of aperture. In contrary, Fraunhofer diffraction deals with propagation in the far field.

Providing an initial electrical field $E(x', 0)$ in 2-D, the 2-D diffraction pattern at specified points will be

$$E(x, z) = \int E(x', 0) h(x - x', z; k_{\text{eff}}) dx'$$

in which $h(x - x', z; k_{\text{eff}})$ is the 2-D Fresnel diffraction operator

$$h(x - x', z - z'; k) = \sqrt{\frac{jk}{2\pi(z - z')}} \exp(-jk(z - z') - \frac{jk(x - x')^2}{2(z - z')}}$$

and $k$ is the effective wavenumber at a specified wavelength.

$$k = \frac{2\pi}{\lambda}$$

To calculate the electrical field profile, the locations of the grating facets are first calculated with a program written in dw-2000, a physical layout design software. The grating facets are then discretized and represented by consecutive points in Matlab, with all points carrying the coordinates information of the grating facets. The electrical field distribution pattern is obtained by numerical integration at
these points. To obtain the field distribution at the output waveguides, the same integral is applied by assuming the results from forward propagation calculation as the initial field and the calculation is taken at the opposite direction. The code for Fresnel diffraction integral is written in MATLAB.

A four-output design is first simulated. The design parameter is listed in Table 1.

The calculated output spectrum is plotted in Figure 16, neglecting all forms of losses. The 4 output positions are at 7, 14.1, 21.2 and 28.5 μm. However, this is not the actual output position, because this result is obtained by solely using the effective refractive index of the design wavelength (1550 nm) for the entire spectrum (1500 nm – 1580 nm). The four output wavelengths are 1520, 1540, 1560 and 1580 nm instead. Under TE and TM polarization, the effective refractive indices corresponding to these wavelengths are different. Their values are listed in Table 2.
Therefore, slightly deviating from the original layout, all the output waveguides are placed further from the input waveguide due to the modified effective refractive indices corresponding to each output wavelength. Under TE polarization, the modified output spectrum is plotted in Figure 17.

![Figure 17 Modified output spectrum under TE polarization](image)

The modified output positions are now at 8.9, 17.9, 27.2, and 36.6 μm. It is seen that a refractive index value change from 2.8297 to 2.7905 can lead to an output position change from 28.5 to 36.6 μm for the outermost output wavelength, an
almost 8 $\mu m$ displacement. Thus if this condition is not considered, the output waveguide will receive undesired output wavelength or a lot of noise.

There are two directions one can go with to deal with this problem. The first method is straightforward: displace the output waveguide position laterally to the newly calculated coordinates. Second, start with a design waveguide spacing slightly less than the desired one. After the modification of the effective refractive indices, the spacing will be displaced almost to the desired spacing.

*Figure 18* shows the simulation with modification of effective refractive indices considered, but with a design waveguide spacing of 5.6 $\mu m$ instead of 7 $\mu m$. The output positions are at 7.1, 14.3, 21.6 and 29 $\mu m$. This is almost same as the one coming from an original waveguide spacing but without modification of refractive indices. Also as can be seen from all the figures, there is an approximately 3$dB$ non-uniformity across the spectrum, due to the envelope function. In addition, the channel crosstalk is less than -30$dB$. Since what truly matters is the actual waveguide spacing, the latter approach is more desired, because the closer the output waveguide from the input, the less non-uniformity there is. The optimized output waveguide positions should be those as close to the input as possible, meanwhile not too close so that interference take place from adjacent outputs.

*Figure 18 Modified output spectrum under TE polarization with smaller waveguide spacing*
With TM polarization, the effective refractive indices will be completely different from the TE case, generally with smaller values. To make the design polarization independent, one has to play with the design waveguide spacing for both cases so that the outputs fall on the same lateral positions.

*Figure 19* and *Figure 20* show output spectrums of a 4-output and an 8-output design respectively, both polarizations independent. The design parameters of 4-output version is the same as listed in Table 1, as the 8-output version employs most same design parameters, but increase the number of output channels while decreasing wavelength spacing from 20nm to 10nm. These are achieved by adjusting the design waveguide spacing for each polarization respectively. For the 8-output design, it could be seen that for the furthest output on the right, the spectrums for TE and TM are slightly out of superposition. It is because the TM mode effective refractive index changes more rapidly than the TE case as wavelength changes. When the number of output channel increases, the output channels will be displaced more, leading to this result. This displacement is acceptable as long as both output spectrums from different polarization states fall within the spatial location of the corresponding output waveguide.

*Figure 19 Output spectrum of a 4-output polarization independent design*
4.4 Calculation of Beam Propagating in Free Space

The forward propagating wave in the input waveguide could be written in the form of Helmholtz equation if the field is assumed scalar.

\[ E(x, y, z, t) = \phi(x, y, z)e^{-i\omega t} \]

\[
\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} + k(x, y, z)^2 \phi = 0
\]

\[ k(x, y, z) = k_0 n(x, y, z) \]

In these equations scalar electrical field is represented as a product of spatial component and time component. \( k \) is the wavenumber at the calculated wavelength and is spatially dependent. \( N \) is the refractive index of the waveguides and surrounding environment. The geometry of the waveguides in the computation is defined by the refractive index distribution.

The beam propagation method is a computational technique used to solve the Helmholtz equation indicated above. \( \phi(x, y, z) \) here, is further represented as product of a slow varying field and a rapid varying field.
\[ \phi(x, y, z) = u(x, y, z) e^{i k z} \]

where \( k \) represents the average phase variation of the field. In this case, if the quickly varying term along the major propagation direction is neglected, the original Helmholtz equation could be re-written into

\[ \frac{\partial u}{\partial z} = \frac{i}{2k} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \left( k^2 - k^2 \right) u \right) \]

With an input wave \( u(x, y, z) \), the field distribution could be obtained by solving the above equation.

In this project, the field distribution emerging from the input waveguide is calculated and displayed. Since there is a large dimensional mismatch between the input waveguide and the free propagation region, significant amount of diffraction is anticipated. The output wave from the input waveguide will quickly spread out along the transverse direction in the FPR as wave propagates forward. If the diffraction gratings on the far end of the FPR are not wide enough to catch up all the waves, there will be significant loss. The function of the BPM is to simulate this effect and determine up to which position the wave will spread out along the transverse direction. The diffraction gratings are correspondingly placed based on the simulation result.

Moreover, BPM method is also used to determine the spacing between two waveguides that crosstalk can be avoided. To achieve this, wave is propagated through the input waveguide, and the power level at the adjacent output waveguide is monitored. As long as the power is below a threshold level, that waveguide spacing is good for avoiding crosstalk.

Beamprop from RSoft is powerful commercial software that utilizes the principle of BPM to solve problems relevant to waveguides. Figure 21 shows the field profile calculated by Beamprop. In this case, the waveguide has a width of 500 nm and tapered to 5 \( \mu m \) at the edge of the FPR. The tapering length is 150 \( \mu m \). The initial input to center facet distance is designed to be 410 \( \mu m \). Waveguide with a width of
500 nm ensures a single-mode waveguide operation. Tapering length and the input-to-center-facet-distance are optimal values decided by simulation.

Along Z coordinates (the propagation direction), waveguide is from 0 to 150 μm and FPR is from 150 to 560 μm. As can be seen from the simulation, it will be a safe design if the grating facets cover up to 90 μm from input, laterally along the x direction. The importance of tapering is demonstrated by comparing this design with a less-tapered design. Figure 22 shows the field profile of the design with a taper width of 2 μm. The input wave displays much greater divergence. This not only requires more grating facets along the X direction to catch all the light, but also means that the size of the FPR will be larger.
Figure 22 Field profile out of the input waveguide, with reduced tapering width

Figure 23 shows the simulation result demonstrating the importance of placing the waveguide arrays a certain distance apart. An input wave is propagated from the tapered part of the waveguide back to the non-tapered part, simulating the case that the light is reflected back from the grating facets to the output waveguides. The upper right one shows the crosstalk effects when adjacent waveguides are placed too close to each other. The lower right one has a spacing of 7 \( \mu m \), the parameter used in the design. The output, as can be seen, is well isolated.
4.5 Performance Calculation of Distributed Bragg Reflectors by Transfer Matrix Method (TMM)

The wave reflection from an interface between two media is expressed by Fresnel reflection equations.

\[ r_s = \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \]

\[ r_p = \frac{n_t \cos \theta_i - n_i \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \]
In these equations, \( r_s, r_p \) represent the reflection coefficients of \( s \)-polarized and \( p \)-polarized input waves respectively. \( n_i, n_t \) stand for the refractive indices of input and transmitting mediums, while \( \theta_i, \theta_t \) are the input and transmitting angles.

If there are multiple reflecting interfaces, each reflection and transmitting beam will undergo a series of partial reflection and transmission. These beams will interfere constructively or destructively. Thus the overall reflection/transmission coefficient will be difficult to calculate. Transfer Matrix Method (TMM) is used to calculate the reflection / transmission coefficients when electromagnetic waves are propagated through multiple-layers of media. Based on Maxwell’s equations, there are simple continuity conditions for the waves across boundaries from one medium to the next.

Assume the input wave hit the systems of layers with normal incidence and represent the wave as a superposition of forward and backward travelling waves with wavenumber \( k \).

\[
E(z) = E_1 e^{ikz} + E_2 e^{-ikz}
\]

\[
H(z) = iKE_1 e^{ikz} - iKE_2 e^{-ikz}
\]

Propagating through a medium with a thickness of \( L \) can thus be represented as a matrix \( M \),

\[
M = \begin{pmatrix}
\cos kL & 1 \\
\frac{1}{k} \sin kL & \cos kL
\end{pmatrix}
\]

and the \( E, H \) pair at the end of the medium can be represented as

\[
\begin{pmatrix}
E(z + L) \\
H(z + L)
\end{pmatrix} = M \begin{pmatrix}
E(z) \\
H(z)
\end{pmatrix}
\]

For a stack of \( N \) layers, each layer has a transfer matrix, and the systematic transfer matrix is

\[
M_{\text{system}} = M_N M_{N-1} \ldots M_2 M_1
\]

The system reflection and transmission coefficients can be extracted from the transfer matrix.
In this thesis, TMM is used to initialize the design and performance evaluation of diffraction Bragg reflectors. The TMM code is written using Matlab. Figure 24 shows several reflectivity plots of a 1st order Bragg reflector. The period of the Bragg grating is 308.98nm, a duty cycle of 0.44, a 100nm etch on a SOI with a 220nm top layer Silicon. The number of period is 6, 12 and 18 in order. The central wavelength of design is 1550nm. The choice of these design parameters echoes the concern about the continuity of DBR address in previous section. By choosing these parameters the Bragg facets behind adjacent grating facets are continuous. As shown, as number of period increases, the reflectivity reaches its maximum over a very wide band covering the entire wavelength of interest (1500nm – 1580nm). On the other hand, the reflectivity drops more sharply at the band-pass edge when the period is large, resembling a more square-shaped band-pass.
Figure 24 Reflectivity plots of 1st order Bragg reflectors with varying number of periods
In terms of practical issues, such 1\textsuperscript{st} order Bragg grating reflector requires fabrication techniques of very high accuracy: with a period of around 300\textit{nm} and a duty cycle of 0.44, that means 132\textit{nm} ridge and 168\textit{nm} trench. This high accuracy fabrication has not been practically realized, and only been achieved with E-beam lithography (EBL) mostly in the research lab. In certain situations when there is no access to EBL, one has to relax the fabrication requirement by increasing the Bragg order. This means the device could be easily fabricated by common photolithography techniques, but also means the reflectivity of the Bragg reflectors is compromised. Figure 25 shows the reflectivity plots of 2\textsuperscript{nd} order Bragg reflectors, with design concept similar to the 1\textsuperscript{st} order counterparts previously. They have period numbers of 12 and 18, for the convenience of comparing with the 1\textsuperscript{st} order ones. It is observed that the reflectivity decreases, though not that much, compared with the 1\textsuperscript{st} order counterparts. However, the reduction of the bandwidth is significant, especially if one tries to increase the number of periods in order to increase the reflectivity. Therefore reflectivity and bandwidth are trade-off with one another, especially with higher order Bragg reflectors. The trench and ridge width are both at the 300nm range, which could be readily realized by Deep UV Lithography (DUV).
For the polarization-independent design, it is expected that TE Bragg reflectors reflect back all TE-polarized waves, and let through all the TM-polarized waves, while TM Bragg reflectors have the opposite function. 1\textsuperscript{st} order TE and TM Bragg reflectors are designed and simulated for both TE and TM waves. The TE Bragg has a period of 308\textit{nm} with a duty cycle of 0.44, while the TM one has a period of 450\textit{nm} with a duty cycle of 0.63. It is worth noting that TM Bragg reflectors, under similar design principle, always have a larger period length, resulting in a
more relaxed fabrication requirement. This is due to the significant smaller effective refractive index value of TM wave propagating in the SOI. Moreover, the grating facet width for TM reflector will be larger as well. This is because the facet width is proportional to the equivalent angle spanning by each facet, while the angle is inversely proportional to the effective refractive index. Therefore when designing a polarization independent device, it is beneficial to always consider the TE case first, because the TM case will always be realizable if TE case is.

Figure 26 Reflectivity plots of polarization independent design
Both designs are functional as expected as observed from the simulation results shown in Figure 26: while dedicated on reflecting one polarization wave, they act like being virtually transparent to the other polarization.

Although TMM gives a reliable evaluation on the performance of the grating, this method is not capable of estimating the scattering loss because it is a 2D simulation. Therefore the actual performance of the device would deviate from what TMM predicts. Finite Difference Time Domain method (FDTD), which is a 3D simulation and able to predict the scattering loss, is introduced to further calculate the device behaviors.

4.6 3-D Simulation of Distributed Bragg Reflectors and Vertical Grating Coupler

Finite Difference Time Domain (FDTD) method is a rigorous, direct solution to Maxwell’s curl equation. It is one of the grid-based differential time-domain numerical methods. The partial differential equations are solved in a leapfrog manner, i.e., the electrical component is solved at one time, and the magnetic field component is solved at the next instant time. This process is repeated until the results reach a steady state. FDTD is a powerful tool, which covers a wide range of frequencies and can treat the nonlinear properties of material.

Maxwell’s curl equations, assuming written in Cartesian coordinates, can be written as

\[
\frac{\partial H_x}{\partial t} = -\frac{1}{\mu} \left( \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} \right)
\]

\[
\frac{\partial E_y}{\partial t} = -\frac{1}{\varepsilon} \left( \frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} \right)
\]

These are two of the six scalar equations derived from Maxwell’s curl equations. The other four are determined by cyclically exchanging the \( x, y, z \) subscripts and
derivatives. The six equations are discretized by central difference method in time and space and FDTD is used to solve them. Based on Yee’s mesh [37], one of the common approaches to solve the equation, the electrical and magnetic components of the field are calculated at grid points spaced by $\Delta x, \Delta y, \Delta z$. Time is further divided into discrete steps of $\Delta t$. The electrical field component is computed at $t = n\Delta t$, then the magnetic field component is computed at $t = (n + \frac{1}{2})\Delta t$. $N$ here is an integer representing the computing step. These computations are repeated iteratively in the leapfrog manner, alternating between $E$ field and $H$ field at subsequent $\frac{\Delta t}{2}$ time interval.

FDTD has the big advantage of solving almost any electromagnetic problems regardless of the complexity of the problem. However, it suffers a disadvantage that the computation time for a single run is very large, especially if the device is relatively large. Ideally, FDTD can simulate the entire process of the wave propagating in the DEDG device. But in reality, the computational demand is so high that the simulation process freezes at the initial meshing stage due to the complexity of the structure and the insufficient memory of the computer.

In this project, two parts of the device are designed with the assistance of FDTD. Commercial software from Lumerical called FDTD solutions is used. First, the Bragg grating reflectors, which is preliminary designed with TMM method, is constructed in Lumerical FDTD. Since the model constructed is 3D, the accuracy of modeling is greatly improved. Moreover, the dimension of one Bragg grating reflectors is about 2 by 2 $\mu m$ and 220 $\mu m$ high, the simulation time will be less than 15 minutes, providing a fine meshing density. Figure 27 shows the reflectivity plots of the 1st order Bragg reflectors with number of periods 12 and 18 respectively, and the design parameters exactly the same as that used in TMM calculation. By overlapping the spectrum with different number of periods, it is clearly seen that increasing the number of periods increases the reflectivity while reducing the bandwidth, i.e. a design trade off. In addition, the bandwidth and
reflectivity simulated with FDTD are significantly smaller than the one predicted by simple TMM method. By careful observation, the 1st order Bragg reflectors simulated with FDTD almost resemble the spectrum of 2nd order Bragg reflectors simulated with TMM, one grating order larger. Further looking into the cross section of the Bragg reflectors with a TE wave propagating through, as shown in Figure 28, it is seen that the incoming waves are partitioned into reflected waves, transmitted waves and scattered waves, upon engaging with the periodic structures. The scattered waves, especially the one leaking to the underlying SiO$_2$ layer, accounts for a large portion of the loss. However, though the bandwidth is truncated, it still fully meets the bandwidth requirement of this design (1500-1580 nm). Increasing the number of periods could enhance the reflectivity. When the number is 18, the reflection loss is quite trivial.

![Figure 27 FDTD result of 1st order Bragg reflectors with varying number of periods](image)

*Figure 27 FDTD result of 1st order Bragg reflectors with varying number of periods*
The second application of FDTD simulation in this thesis is to design the input and output grating couplers. The working principle of vertical grating coupling has been discussed in detail in previous sections. By principle of reversibility of light wave, an input coupler could be used as an output coupler without design modification. Therefore the light is coupled by one input grating coupler, propagated through the demultiplexing structure, and coupled out of the SOI by a series of grating couplers connected with output waveguides. The approximate design of the grating coupler is based on the equation

\[ k_0 n_{avg} = k_0 n_c \sin \theta + \frac{2\pi}{\Lambda} \]

Assume the etch depth and a 0.5 duty cycle, so that \( n_{eff,avg} \) is known. Further assuming an input angle of 15 degree, which is typically a good starting choice for vertical grating coupler setup, one can calculate the period length of the grating. In reality however, the optimal incidence angle may deviate slightly from the design angle. Moreover, the input position along the propagation direction should also be optimized. Therefore there are two parameters, input angle and input position, which need to be scanned to find the optimal values. Figure 29 shows the transmission spectrum of the optimized grating coupling condition, in which the center of input beam is 2 \( \mu m \) from the edge of the grating to the right, and the
incident angle is 15 degrees to the normal direction. The length of the grating is 680 nm. The maximum coupling efficiency is 45% for the center wavelength. In the wavelength of interest, i.e., 1500-1580 nm, the coupling efficiency is above 30%.

![Figure 29 Transmission spectrum of optimized grating coupler, TE mode](image)

As discussed, due to polarization dependence, TE grating coupler cannot be readily used for coupling TM wave. Therefore a customized TM coupler, which has the same design principle but with a different effective refractive index, should be made to accommodate TM DEMUX design.

For polarization independent design, the coupler should be capable of coupling both TE and TM waves. The design, which was discussed before, that employs subwavelength structure to modify the effective refractive indices of TE and TM modes is constructed and simulated here. The material platform used is SOI with 220 nm silicon on top of oxide.
For a specific traditional grating coupler, the coupled TE wavelength range will be higher than the coupled TM wavelength due to the larger effective refractive indices. Adding the subwavelength structure, i.e., modifying the refractive indices aims to bring the two wavelength ranges closer, eventually together. Figure 30 shows the best-case scenario with the 220 nm top silicon SOI. It is seen that the TE and TM spectrums are not properly superimposed, not to mention that the coupling efficiency is only above 20%. The later case is due to that great amount of design compromise has been made to bring the wavelength ranges as close as possible first. The non-superposition of spectrum is due to the 220 nm top silicon SOI. In the original literature as shown previously, the top silicon is a lot thicker, making it more flexible to manipulate the effective refractive indices. Thus in this thesis, this subwavelength structure grating coupler may not be a good choice for polarization independently coupling the light wave.

With the available fabrication resources at hand, the following method for testing a polarization independent diffraction grating demultiplexer is proposed: the exact same polarization independent DEMUX is fabricated twice on the same SOI chip. One is connected to TE grating couplers, and the other connected to TM grating
couplers. The device is tested for its TE and TM behavior respectively, and the result is superimposed to give a full version of performance of the device.
5. Fabrication

5.1 Overview

The fabrication process of the diffraction grating demultiplexer was implemented at the Nanotools Microfab of McGill University. Electron Beam Lithography (EBL) is used as the primary patterning tool, due to the fact that the smallest feature size of the chip is in the 100 nm range. Compared to photolithography, which is more popular for industrial fabrication, EBL has the advantage of realizing the fabrication of feature sizes down to tens of nanometers. It actually is one of the finest methods for nanofabrication with the highest accuracy and resolution. The resolution of photolithography, on the other hand, is limited by the wavelength of light used. Current state of the art tools use Deep UV Lithography (DUV) at the wavelengths of 248 nm and 193 nm, while for EBL, the fabrication resolution could be down to 10 nm or less. One disadvantage of EBL method, however, is its low throughput, i.e., the long time it takes to write on the wafer. For instance, the single patterning time with EBL for the device in this thesis is 2 hours. The device need 2 similar etch processes repeatedly, each associated with a patterning process with EBL. Therefore 4 hours solely for EBL writing are required.

Hitachi SU-70 is the EBL machine used here, with Schottky field emission source, and a typical working voltage of 20 kV. Briefly speaking, the machine scans electrons across a surface covered with resist films sensitive to electrons, depositing energy on the resist film in a designed pattern. The exposed/unexposed pattern can be removed from the development process. The finest resolution achieved by this machine is 1 nm. The primary electrons from the emission source hitting the resists experience inelastic scattering and collisions with other electrons. Electrons scattered at angles less than 90 degrees are called forward scattering, while those scattered at angles more than 90 degrees are backward.
scattering. The feature resolution is limited by the forward scattering, while the pitch resolution is determined by secondary scattering from adjacent feature. Higher energy electrons or thinner photoresist could reduce forward scattering. Thus typical PMMA resist thickness is in the tens of nanometers range for a more precise result.

### 5.2 Process Flow

A well-developed bi-layer lift off process is used here for the formation of the patterns. Two etch processes are required because the patterns are associated with two etch depths, i.e., 220 nm for waveguides and free propagation regions, and 100 nm for Bragg reflectors and vertical grating couplers. *Figure 31* shows the process flow. And the following paragraphs will, referring to the number in the figure, address the procedures in detail.

![Fabrication process](image)

*Figure 31 Fabrication process*
5.2.1 Pre-handle

The SOI wafer is cut into 1 by 1 cm piece by the wafer-dicing saw. To thoroughly clean the sample, it is immersed in 60-Celsius acetone solution, and placed in ultrasonic bath for 10 minutes. Then it is cleaned with Isopropyl alcohol (IPA) and water subsequently. After blowing drying with nitrogen gun, SOI sample is subsequently pre-baked on 180-Celsius hot plate for five minutes. The purpose of prebaking is to dehydrate the sample. A better-dehydrated sample allows a better adhesion of coated resist.

5.2.2 Resist coating

Copolymer EL6 and resist PMMA A2 are spin-coated onto the SOI in order. To obtain a good lift-off quality, the copolymer EL6 is first coated in order to create an undercut in the pattern. With this undercut and subsequent chromium evaporation, a shadowing effect will occur, creating a discontinuity in the metallic film, which eases the lift-off process. PMMA is a positive photoresist, indicating that the exposed portion will become soluble in the resist developer. PMMA is closely associated with EBL process, for the reason that it allows ultra-high pattern resolution to be achieved. The processing parameters are typically 4000 rpm for 45 seconds for both EL6 and PMMA A2. This gives a theoretical PMMA thickness of about 60 nm. In principle, the thickness of the resists needs to be 1X to 5X thicker than the smallest feature size wanted. Thus in this case, a 60 nm PMMA thickness means that features down to 10-20 nm could be achieved. A 90sec post-baking is followed after each of the coating step for better adhesion purposes. The baking temperature is 150 Celsius for EL6 and 180 Celsius for PMMA.
5.2.3 EBL writing

EBL is a maskless process, with beam of electrons directed to the resist-coated surface. The layout is first created in dw-2000 with scripting, then transferred to NPGS designCAD. With NPGS designCAD, different patterns could be set as different colors, each one associated with a specific dose, which determines the quantity of electrons hitting the surface. A dose test needs to be implemented so that the ideal dose is found. Typically, wide patterns such as free propagation region need relatively low dose, while thin pattern and isolated patterns such as 500 nm-wide waveguides need relatively high dose.

In addition to the fixed amount of dose for a pattern, the electron speed can be changed by varying the condense lens. For example, condense lens 10 provides an emitting current of about 20 pico-ampere (pA), and a relatively fast exposure time. Thus it is used for wide patterns such as the waveguides and free propagation region. Condense lens 16, on the other hand, provides emitting current of 9 pA. It takes longer time to satisfy the dose requirement, but provides a higher writing precision. It is used for the 150 nm Bragg reflectors.

As for the free propagation region, an area dose of 35 $\mu Cm^{-2}$ is applied. The optical microscopic view of the region is shown in Figure 32.

Figure 32 Optical microscopic view of the FPR region and waveguides
For the 500 nm wide waveguides and taper waveguides that range from 500 nm to 5 μm, a test of the right doses are investigated together. Figure 33 shows the 5 μm side and 500 nm side when the dose is 50 μCcm⁻². It is observed that the wide side dose is appropriate while the narrow side is too small. Fig shows the 500 nm waveguide side when the dose increases to 60 μCcm⁻², indicating that the dose is correct. Thus the dose will be set to 60 μCcm⁻² for the 500 nm waveguides and gradually be decreased to 50 μCcm⁻² heading to the 5 μm taper ends. Figure 33 also shows the bending parts of the waveguides.

*Figure 33 SEM images of tapered waveguides*

For the Bragg reflectors and grating couplers, since PMMA is positive photoresist so that non-exposed areas will be etched away subsequently with the bi-layer lift-off method, the almost entire region need to be exposed to electrons again in the second process as in the initial one.

Another different process design was evaluated. In that early design, the first etch process was not bi-layer lift-off. Instead only the Bragg reflectors were exposed
and etched directly without the coating of a protective layer. The PMMA photoresist here was used as the etching mask. PMMA has poor resistivity against dry etching, so that a significant large thickness is needed for protecting the etching gases from reaching the silicon surface. By spin-coating the photoresist at low speed, a PMMA thickness of 250 nm is on top of the SOI as the protection layer. However, this process tends to be not working well by various dose and etching process tests. As can be seen in Figure 34, which is the best scenario gotten, the pattern is ill defined. There are two problems associated with it. The etching is not smooth and non-uniform at the central region and the edge. With a fixed amount of dose the central region tends to be over-etched while the edges tend to be under-etched. Second, under the observation of optical microscope, there are resist residues left on the sample that cannot be removed by resist remover. This is attributed to the large thickness of the PMMA, causing too many electrons scatterings and the subsequent degradation of the feature resolution.

Figure 34 SEM images of Bragg reflectors with PMMA as etch protecting layer

Therefore the first etch process is modified to be similar as the second one, i.e. a bi-layer lift-off process. The entire layout except for the Bragg reflector lines is exposed. The pattern of the Bragg reflectors is shown in Figure 35. The green areas surrounding the center structure are part of the free propagation region. They act as a buffer region since the doses between the FPR and the reflectors region are significantly different. Moreover, the pattern for free propagation region is bulk, while for the Bragg region it is fine and therefore sensitive. Buffering the dose in
between will make the Bragg pattern not affected by the possible over-dose of the FPR with respect to the central structure.

Figure 35 Design of Bragg reflectors pattern with buffer region surrounded

With other parameters being fixed, Figure 36 shows the fabrication results of a segment of the Bragg reflectors, with the dose of the buffer region to be 25 $\mu C cm^{-2}$, 30 $\mu C cm^{-2}$ and 35 $\mu C cm^{-2}$ respectively. Clearly observed from the first picture, a dose of 25 $\mu C cm^{-2}$ is too small as the buffer region barely forms a defined shape. A dose of 35 $\mu C cm^{-2}$ gives an over-exposed buffer region. Though the shape of the buffer region is well defined, the dose is too large that the shape of the Bragg reflectors is affected and in some way twisted. This effect is especially significant for the peripheral part of the Bragg as shown in the picture, which is less clustered. For the dose of 30 $\mu C cm^{-2}$, it is shown from the picture that the shape of the Bragg pattern is well defined, not affected by the buffer region. The buffer region itself is not as well defined as when there is larger dose applied. However this will be well compensated when the entire device is written by EBL, i.e., there will be free propagation region before and behind the Bragg grating reflectors region, and the doses from those region will make compensation for the buffer region.
Due to the fact that a certain level of magnification is necessary for fine e-beam writing resolution, the magnification in this design is set as 800X or larger in order for a well-defined pattern. In this case the maximum single exposure field area is 100\(\mu\)m by 100 \(\mu\)m. Thus proper field stitching/alignment techniques need to be implemented. There are three sets of axis that need to be aligned, i.e., the sample axis, controlled by how one places the sample on the platform and the global rotation matrix from NPGS interface, a stage axis, a default setup which could not be changed, and a field axis, the axis of the microscope which could be adjusted relative to the stage axis by changing the raster rotation alignment parameter. If there are no previous patterns on the sample, there is no sample axis. Only the stage and field axis need to be aligned. Else, all three sets of axis need alignment. In this design, the first bi-layer lift off process need only align stage and field axis,
while the second process need align all three. Figure 37 shows the relative placement of all three sets of axis.

Figure 37 Relative placement of three axes

Trying different raster rotation alignment value and observing the pattern mismatch achieves the alignment of field and stage axis. With the value set to 0.9 degree, the pattern is best aligned. Figure 38 shows the alignment before and after the raster rotation option is activated.
For the alignments of three sets of axis, NPGS has a built-in function called global rotation correction. By default, sample axis and stage axis are aligned if global rotation correction is not activated. If the option is activated and several points representing the coordinate system of the sample are recorded, NPGS will calculate the angle between the sample axis and stage axis. Subsequent commands will then follow the newly calculated coordinates, rather than the default stage axis.

A registration mark is created along with the first lift-off process as the reference for alignment. Figure 39 shows the registration mark. The coordinates of points A, B, and C will be recorded. Vector AB indicates the positive $x$ direction of sample, while vector AC indicates the positive $y$ direction. Each vector has an absolute value of 100 $\mu m$ and 50 $\mu m$ respectively. These will all be recorded by NPGS and used for calculating the rotated coordinates. Moreover, the experimentally determined 0.9 degree axis mismatch between the field and stage axis will be
corrected here. Thus all three sets of axis are aligned. Moreover, the registration mark is the general original point (0,0) of first process pattern and second process pattern. Therefore the patterns will be aligned both angularly and spatially.

![Figure 39 Layout of the device in dw-2000 and registration mark](image)

**5.2.4 Development 150μm**

In EBL, resist behavior such as sensitivity, contrast, exposure dose latitude, roughness and resolution are affected by the developer type and composition, and the development technique. A mixture of IPA: H2O (9:1) is prepared. This mixture of solution is very suitable for developing PMMA, especially for high-resolution feature compared with another typical developer such as MIBK: H2O (1:3). The sample is immersed in the developer solution for 100 seconds, and thoroughly rinsed with water. Given appropriate developing time, EL6 and PMMA A2 resists that are exposed previously become soluble and are removed. Samples are usually observed under optical microscope at this stage. If the patterns are found to be well defined, they will be brought to Chromium mask evaporation.
5.2.5 Chromium deposition and resist removal

To achieve selective etching, certain regions of the sample need to be protected by etching mask. A variety of materials could be chosen as the etching mask, as long as they show strong resistance to the etchant. For reactive ion etching method with mixture of gases, such as $HBr/Cl_2$, as the etchant, metallic materials such as gold, silver or chromium could all be used as the etching mask. Chromium, among all of the materials, provides an ultra high feature resolution, and is very popular in the electron beam lithography process. Moreover, due to the high resistance of the chromium to gas etchant, a thickness of a few nanometers is sufficient to protect the samples under. Thus, chromium is the material of choice here and a thickness of 20 $nm$ is sufficient as the protecting layer. Temescal BJD1800 EBeam Evaporator is used here. The evaporator uses high voltages to accelerate electrons toward the sample. First the working chamber is pumped down to reach 2e-6 Torr or lower. This is important, especially for chromium deposition, which may possibly cause sudden pressure rise and filament shut down during Cr sublimation. Thus manual operation of deposition is reserved for chromium. The applying voltage is gradually increased so that the deposition rate reaches 0.2 $nm/second$. Given reaching this rate, it takes less than 2 minutes for 20 $nm$ deposition.

After the deposition is finished, the sample is immersed in resist remover. Resists that are not previously exposed in EBL will be removed, together with the deposited Cr. Thus these areas will not be protected and will be etched afterwards. For this project Remover PG from MICROCHEM is used as the solvent stripper, Remover PG is based on $N$-Methyl-2-pyrrolidone (NMP) and is efficient for removing PMMA. It takes 5 to 10 minutes with a 50 Celcius Remover PG solution to remove the resist completely.
5.2.6 Reactive Ion Etching and Chromium Removal

As the waveguides and FPR regions are protected by chromium, and the rest silicon parts are exposed, it is ready to treat the sample with dry etching. These exposed areas are attacked by plasma of reactive gases, and this etch process is directional and anisotropic, meaning that the verticality or near verticality of the waveguide sidewalls or gratings sidewalls could be realized. The cluster system Applied Materials Precision 5000 is used for the etching. The recipe for silicon etching includes the usage of $\text{HBr}/\text{Cl}_2$ mixture and the following stages: Stabilization, Breakthrough, Stabilization, Main etch and Pump-out. The parameters for the process are listed below in Table 3.

<table>
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<tr>
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<td>Pressure</td>
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<td>Power</td>
</tr>
<tr>
<td>Mag Field</td>
<td>0</td>
<td>Mag Field</td>
</tr>
<tr>
<td>Gas</td>
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<td>Gas</td>
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<tr>
<td>Duration</td>
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<td>Duration</td>
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<table>
<thead>
<tr>
<th>4. Main Etch</th>
<th>5. Pump out</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<td>Pressure</td>
</tr>
<tr>
<td>Power</td>
<td>300 W</td>
<td>Power</td>
</tr>
<tr>
<td>Mag Field</td>
<td>75 G</td>
<td>Mag Field</td>
</tr>
<tr>
<td>Gas</td>
<td>$\text{Cl}_2$: 30 sccm $\text{HBr}$: 15 sccm</td>
<td>Gas</td>
</tr>
<tr>
<td>Duration</td>
<td>40 sec</td>
<td>Duration</td>
</tr>
</tbody>
</table>

*Table 3 Dry etching parameters*
To measure the etch rate of the recipe for silicon, a fixed amount of etch time is settled, in this case, 40 seconds, and the etch depth is measured with Ambios XP200 Profiler. As can be seen in Figure 40, the 40 seconds etch give an etch depth of approximately 220 nm. (There is a 20 nm chromium mask that has not been removed) That, after several repetitive experiments, indicates that with this recipe the etch rate is about 330 nm/min. Therefore, first process requires 40 seconds to etch thoroughly the 220 nm silicon. In the second process, 18 seconds is required to etch 100 nm for the grating couplers and the Bragg reflectors.

![Etch depth profile](image)

**Figure 40 Etch depth profile**

### 5.3 Progress Discussion

The realization of fabrication of the etched diffraction grating demultiplexer depends primarily on the E-beam lithography machine: the Hitachi SU-70. Not only the Bragg reflectors require line resolution of down to 100 nm, but also that
the input and output waveguides have widths of 500 nm which could not be fabricated by the photolithography machine at McGill Microfab. The machine requires very stable operation environment: any minor external disturbance would seriously degrade the performance. Due to this reason the Hitachi SU-70 machine is placed at the basement of Wong Building at McGill University.

A very unexpected and serious accident, however, took place during January 2013, that the entire McGill campus was flooded due to a ruptured water main break. The Wong building was among the most affected and damaged buildings, especially for its basement. The Hitachi SU-70 was unfortunately not available since then. According to the most up to date announcement, the machine won’t be back before December 2013. Because of the malfunction of the EBL machine, the fabrication of the device desired this thesis has not been completed. However, all of the necessary recipes and procedures have been well developed. The final fabrication of the device should be completed soon after the restoration of the Hitachi SU-70 machine.
6. Conclusion

As information technology quickly evolves, the requirement of large volume data transmission leads to the fast development of fiber-optic telecommunication technologies. Wavelength division multiplexing (WDM) allows for the multiplication of data transmission capacity based on existing infrastructure, and becomes one of the predominant technologies currently deployed. Historically, technologies that are considered for WDM include TFF, Mach-Zehnder-type devices, and planar spectrograph type devices such as AWG and EDG. Among all of them, EDG was less popular despite its smaller footprint and better integration potential with electric circuit, because it requires deeply etched vertical grating facet walls. This makes the fabrication of EDG more difficult than the rest of the devices.

On the other hand, semiconductor fabrication technology has been quickly developing. The realization of nanoscale patterns become fully possible with the help of electron beam lithography (EBL) or deep UV lithography (DUL). Reactive ion etching allows for a better defined deep, vertical sidewalls. Moreover, new materials, due to distinctive advantages of each of them, are brought to focus and treated as promising alternatives to the traditional silicon platform. With respect to EDG, silicon on insulator (SOI) is favoured in this thesis due to its high refractive index contrast, which not only makes the footprint of the device smaller, but also provides a high Fresnel reflection at the grating facets with a much shallower etch depth. Overall, the desire to produce device with ultra compact size, the capability of applying semiconductor fabrication technology extensively developed by the industry, and the possibility of chip massive production are the attractive factors that eventually lead to the research focus in this master thesis.

This thesis starts with the modelling and layout of the etched diffraction grating demultiplexer. The design principle is based on a center-fled reflection
configuration. Diffraction Bragg reflectors are incorporated at the back of the grating facets to enhance the Fresnel reflectivity. By combining with the design principle of the center-fled configuration, the Bragg reflectors behind each facet can be positioned continuously with respect to their adjacent ones, which eliminates additional scattering loss and eases the fabrication difficulty greatly. By building the demultiplexer on top of a SOI platform which has high refractive index contrast, very high reflectivity performance could be achieved by simply shallow etching the Bragg grating reflectors, greatly reducing the fabrication difficulty. As for this thesis, the first order Bragg reflectors are designed and used. First order Bragg reflectors have the highest reflection efficiency and provide the largest bandwidth, but they have the smallest feature size and are the most difficult to fabricate. This challenge is solved by electron beam lithography at McGill’s Nanotools Microfab. Furthermore, since the refractive indices in SOI platform differ significantly for TE and TE modes, the performance of the demultiplexer is strongly polarization dependent due to the polarization dependency of Bragg grating reflectors. Therefore a polarization independent design is proposed in this thesis. Two curves of Bragg grating reflectors are placed and operated side by side, each reflecting wave of a specific polarization state while being transparent to the other.

A bi-layer lift off recipe is developed at the McGill Nanotools Microfab, with electron beam lithography techniques and reactive ion etching. In this recipe, the SOI chip is exposed under EBL twice, first time for the pattern formation of the waveguides and FPR, second time for the DBR and vertical grating couplers. By using EBL, first order DBR, which have feature sizes down to 130 nm, are successfully fabricated. The first etch process defines the 220nm deep waveguides and FPR, and the second etch process defines the shallow etched (60nm - 100nm) DBR and vertical grating couplers. Several fabrication challenges are solved during the development of the recipe, including the alignment of the three axes, the alignment of first process and second process by registration marks, the right
dose for the DBR and the etch recipe of reactive ion etching.
Unfortunately, the fabrication has not been completed due to the flood which affected McGill campus and the subsequent malfunction of the Hitachi SU-70 EBL machine. Future work towards this research topic I suggest is to finish the fabrication of the EDEG at McGill Nanotools Microfab once the EBL machine is brought back online. This includes the polarization dependent and polarization independent versions, because they share the same fabrication principle. This process should be successfully completed since the recipe for the fabrication is well developed. The device could then be brought to McGill’s photonics lab to have its performance tested. In addition, Dr. Amir Jafari designed a methodology to engineer the output spectral response of the DEDG demultiplexer [8], which is based on tailoring the reflectivity of the DBR. This method can be readily applied thereafter to enhance the output uniformity of the DEDG demultiplexer.
References


