Flat Spectral Response Arrayed Waveguide Grating (AWG) in Silicon-on-Insulator (SOI) via Ion Implantation

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This thesis proposed and demonstrated a flat-spectral response Arrayed Waveguide Grating (AWG) in Silicon-on-Insulator (SOI). The response exhibits a flat spectral of approximately 0.5nm with a crosstalk level of round -3dB. The high crosstalk is due to the phase errors as a result of fabrication tolerance and errors. Two main errors were identified. Firstly, the systematic errors of waveguide rib width and etched depth and secondly, the random variation of photomask resolution which was subjected to fabrication equipment in Southampton University. These errors have been investigated and the observations of the analysis were consistent with the experimental result.

The AWG is designed to operate at a centre wavelength of 1.55μm at a grating order of 52 with path length differences of 23.62μm. The rib waveguides of the array are designed to operate as singlemode waveguides and to exhibit minimum polarisation dependence.

As this thesis is to proof of principle, additional optimisation of the AWG is not carried out. The main ideology of the design method is to introduce free carriers to parts of the waveguides across the grating arms to induce absorption. This will modify the shape the field distribution across the array waveguides from a Gaussian to a SINC function. By applying Fourier optics to the free space region of the AWG, this field profile is the inverse Fourier transforms of the required output field of the AWG, which is the flat spectral response. This method gives the robustness of tailoring the optical field distribution across the AWGs by the appropriate choice of net doping concentration, and hence gives room for design flexibility without increasing the physical dimension of the AWG significantly. The potential of achieving a smaller SOI AWG device with the use of higher net dosage and the realisation of achieving a uniform doping concentration through multiple implantations has been discussed.

Keywords: Arrayed Waveguide Gratings (AWG), Flat-spectral response, Ion Implantation, Rib waveguides, Silicon-on-insulator (SOI), Silicon photonics.
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PUBLICATIONS

Parts of this work have been published elsewhere.


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Figure 7.57(d) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide has variation of $0.038 \mu m$ on the rib width and $0.059 \mu m$ on the etch depth.

Figure 7.58(a) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide has a rib width of $0.419 \mu m$ and etch depth of $0.362 \mu m$.

Figure 7.58(b) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide has a rib width of $0.443 \mu m$ and etch depth of $0.359 \mu m$.

Figure 7.58(c) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide has a rib width of $0.644 \mu m$ and etch depth of $0.368 \mu m$.

Figure 7.59 Cumulative phase error due to waveguide geometry and path length deviation

Figure 7.60 Simulated and measured transmission spectrum of the AWG with high sidemode due to phase error

Chapter 8

Figure 8.1 Proposed experimental setup for measuring $e_\phi(\sigma)$ and $P_\phi(\sigma)$; PC: polarisation controller
CHAPTER 1
Introduction

Do not fear to be eccentric in opinion, for every opinion now accepted was once eccentric.

Bertrand Russell

Silicon based photonics, especially based upon silicon-on-insulator (SOI), is interesting for a combination of technological and cost reasons. The cost issues are related to the absolute cost of silicon and SOI wafers as compared to materials such as the III-V compounds or the insulator lithium niobate, as well as to the cost of processing the wafers, and to the packing density that can be achieved. Silicon is a well understood and robust material, and the processing of silicon has been developed by the electronics industry to a level that is more than sufficient for most integrated optical applications. Furthermore, any technological development in either silicon or in the associated electronics industry can readily be transferred to silicon based integrated optics.

Since the early investigation of propagation loss and polarisation dependance of silicon waveguides, the interest for SOI devices has increased enormously. Today, research activities in SOI range from the study of basic building blocks such as waveguides and couplers, to more complex devices such as modulators and Bragg gratings, through to larger and more complex circuits such as Arrayed Waveguide Gratings (AWGs).

In recent years, Arrayed Waveguide Gratings (AWGs) have increasingly become more important in Wavelength Division Multiplexing (WDM) systems. An AWG in SOI takes advantage of some of the unique optical properties of SOI, such as the high refractive index of silicon (~3.5) and the large index difference between silicon and silicon-dioxide (~1.5), to produce a relatively small device as compared to some other technologies. However, the spectral response of the SOI AWG still typically exhibits a Gaussian response, which restricts the wavelength selectivity of the devices due to the wavelength
drift caused by the laser diode and the AWG, and therefore a flat spectral response is desirable to ease the wavelength selectivity of the WDM system.

The slab region within the AWG can be regarded as a Fourier plane; hence the focused beam profile at output waveguides is the spatial Fourier transform of the optical field profile at the output array-slab interface. It is convenient to specify a rectangular function of the output field in terms of the spatial harmonics of the array waveguides (AWs). An inverse Fourier transform can be performed to achieve a $\sin(x)/x$ field distribution across the output of the AWs. The optical field distribution at the input/slab interface, according to Fraunhofer diffraction, is a gaussian field. In order to shape the Gaussian field distribution at the input of the AWs to a SINC field distribution at the output, free carrier doping is introduced, which alters the intensity field distribution within the AWs through absorption. The introduction of free carriers to the array waveguides will not only cause absorption of the optical field of the AWs but at the same time change the refractive index of the material. This change in refractive index will cause a change in phase since the phase of the optical field in the AWs is dependent upon the propagation constant, $\beta$. However, it is crucial to maintain the $2m\pi$ (where $m$ is an integer) phase difference between adjacent waveguides to enable constructive interference at the output slab. Thus, an additional optical path length is needed to compensate for such difference and this leads to a change in the conventional geometry of the AWG. It is also essential to achieve a uniform doping concentration throughout the guiding region to avoid any phase errors resulting from the injection of free carriers. This can be achieved using multiple ion implantations.

In chapter 2, Literature Review, the chapter begins with an introduction of the Arrayed Waveguide Gratings (AWG) technology which includes a brief history of AWG evolution. The topic of flat-spectral response AWG is addressed with ideologies proposed and demonstrated by many experts in the field. The chapter also studies the subject of Silicon-on-Insulator (SOI) technology, which is of central importance to the treatment of SOI waveguides. It then reviews the literature of the SOI structure from many authors, one of which is the treatment of singlemode rib waveguide which exhibits very low loss.
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In Chapter 3, various theories related to the design and modelling for both the conventional and flat spectral SOI AWG are presented. These include waveguide theory, losses inherent in SOI due to (1) absorption, (2) scattering, and (3) radiation. Also, this chapter discusses the phenomenon of light propagation within the AWG. It presents a treatment to the subject of interference, Fraunhofer diffraction and the principle of the AWG. Lastly the chapter will touch on the topics of simulation techniques, which comprises of two main methods; (1) Effective Index Method (EIM) and (2) Beam Propagation Method (BPM). Chapter 4 presents the design and modelling of the SOI AWG and a theoretical analysis of the flat-spectral AWG is discussed, together with AWG design and simulation results.

In Chapter 5, Fabrication, a summary of fabrication procedures is presented. The chapter describes various types of fabrication methods, specifically for this work, and contains a detailed description of each fabrication process and discusses the choices of some of the fabrication methods selected. Chapter 6 deals with the experimental techniques employed in this work. This includes the study of one of the main commonly used techniques involving sample preparations. Also, the experimental setups prepared for various measurements are considered. Lastly, the chapter will discuss various losses associated with coupling, which are presented in an optical experiment.

Chapter 7 provides a discussion of the experimental results obtained in this work. Based on these results, an analysis is performed to identify some of the parametric influences that change the transmission spectrum of the AWG. Finally, the research covered in this thesis is concluded in chapter 8. A summary of achievements is given and ideas for future research work areas are suggested.
CHAPTER 2
Literature Review

Arrayed Waveguide Gratings (AWG) can perform wavelength routing for a large number of optical channels and provides a high level functionality on an integrated chip. It is likely to have an increasing role in Wavelength Division Multiplexing Systems.

- Kenneth A. Mcgreer
  University of Manitoba and TRLabs

2.1 Introduction

The growth of the internet at the end of the 20th century has led to an explosion of bandwidth and revolutionised the photonic communication industry. Wavelength Division Multiplexing (WDM), which forms the back-bone of photonic communication networks, has played a key role in meeting the enormous demand for high bandwidth and large number of channels. Different technologies have been implemented to deliver WDM capability, particularly, the Thin-film Multi-Layer Interference Filter [2.1], the Fabry-Perot Tunable Filter [2.2] and the Arrayed Waveguide Grating [2.3]. With diverse applications in WDM, the choice of technology is crucial. The choice is greatly influenced by the type of material and design used in each technology.

Today, the rapid progress of photonic networks has led to an increasing demand for more channels at a reduced cost. It is understood that a WDM multi/demultiplexer can be formed by a cascading series of thin-film filters or Fabry-Perot filters operating at different wavelengths. However, these technologies have their disadvantages. It is difficult to reduce channel spacing and increase the number of channels simultaneously. These difficulties can be overcome but at a cost and high accumulation of insertion losses. With the advent of AWGs, this problem can be solved. AWGs offer long term stability, reduced insertion loss and mass productivity.

The AWG is designed and fabricated in the platform of planar lightwave circuits (PLC). PLC technology is a combination of optical fiber fabricating technology and large-scale integrated circuit patterning technology, which provides low-loss characteristics and high
productivity [2.4]. From the material and optical point of view, PLC devices can match very well with the single mode fiber. Furthermore, they allow the use of hybridisation that may result in manufacturing flexibility, reduced cost and high performance, because the best combination of materials and devices can be used. Hence, the AWG offers an alternative solution for the future of photonic communication networks.

This chapter is intended to give the reader a review of the literature and provide the background of the technologies in the WDM and related domains. It is divided into two main sections; the Arrayed Waveguide Grating (AWG) Technology and the Silicon-on-Insulator (SOI) Technology.

Section 2.1, is intended to give the reader a brief introduction to wavelength division multiplexing (WDM) systems, together with the International Telecommunications (ITU) grid that defines the operating standards of the AWG. In Section 2.2, Arrayed Waveguide Technology, the evolution of the AWG will be discussed. Also, different characteristics such as the flat spectral response, polarisation independence and low-loss AWGs will be looked into. Section 2.3, Silicon Photonics, discusses the impact that silicon has on the photonics industry and its development. Also, the optical properties of silicon; mainly the absorption and refractive index change due to free carrier injection effect, which is the main mechanism that is responsible for the alteration of optical field within the array of waveguides in the AWG. In Section 2.4, Silicon-on-Insulator (SOI) technology, the emphasis is on the various SOI technologies that are used in SOI wafer fabrication; namely, Separation by Implanted Oxygen (SIMOX) and Smart-Cut (UNIBOND). This is particularly important because the advances in the quality and availability of SOI substrates provided the necessary impetus for the development of silicon photonic devices. We will then review the extensive optical devices that have been proposed and demonstrated in SOI in recent years. This is relevant because the realisation of basic devices such S-bends, Y-junction power splitters, directional couplers and other passive devices can then lead to more useful integrated devices such as an AWG.
2.1.1 Wavelength Division Multiplexing (WDM)

In order to appreciate the usage of AWGs in WDM, it is useful to understand the basic technology involved in a photonic network. Hence a brief introduction to WDM will be given. However it is not the intention of the author to give a comprehensive review of photonic networking systems.

Wavelength Division Multiplexing (WDM) is the basic technology behind photonic networking. It utilises a significant portion of the bandwidth available in the optical fibre by allocating many independent signals to be transmitted simultaneously on the same fibre [2.5]. These wavelengths can be visualised as “different colours”, illustrated in figure 2.1. To be able to combine these wavelengths from the different sources, a multiplexer is needed. At the receiver end, different signals are routed to different locations; hence a demultiplexer is required. It is during this multi/demultiplexing that the AWG comes into play. There are different varieties of WDM; DWMD (Dense Wavelength Division Multiplexing) and CWDM (Coarse Wavelength Division Multiplexing). The word Dense and Coarse in the context of WDM is relative. These are only qualitative measures and the technologies differ primarily in the spacing of the wavelength and numbers of channels.
2.1.2 International Telecommunication Union (ITU) Grid

The International Telecommunication Union (ITU) has defined a number of standards for the operations of WDM links and of optical networks covering approximately the 1330nm to 1600nm wavelength range. This is due to the availability of commercial fibre, with two low attenuation domains around the 1300nm and 1550nm wavelengths. Standard singlemode fibre exhibits a null dispersion (where material dispersion and waveguide dispersion cancel each other out). This happens at a wavelength of 1330nm. However, there are good reasons for photonics engineers to take into account the use of a 1550nm wavelength [2.6];

1. Fibre attenuation is much lower in the 1550nm band
2. Erbium Doped Fibre Amplifiers (EDFAs) operate in the 1550nm band. Although, Praseodymium (Pr) Doped Amplifiers are available which operate in the 1300nm band, their quality is not as good as EDFAs.
3. WDM systems require a large amplified bandwidth which is compatible with the use of 1550nm band, together with EDFAs.

The main drawback in using the 1550nm band is the dispersion characteristic of the singlemode fibre, which is very large (around 17ps/nm.km). This has lead to the development of a fibre that has its dispersion minimum set at 1550nm. This type of fibre is generally referred to as a Dispersion Shift Fibre, which can be fabricated by manipulating the core profile to introduce dispersion in the opposite direction from the direction in which chromatic dispersion operates. Hence, the ITU has defined four WDM frequencies Grids, to date;

- 100GHz grid in the frequency range 186-200.9THz (covering S, C and L bands in the wavelength range 1492.25nm – 1611.79nm).
- 50GHz grid in the frequency range 186-200.95THz covering wavelength range from 1491.88nm – 1611.79nm.
- 2.5GHz and 12.5GHz, which is based on 193.1THz.
The S band covers the wavelength range from 1491.88nm – 1529.55nm, C band covers from 1529.94nm – 1569.59nm, whereas the L band covers from 1570.1nm – 1611.79nm. Standards, such as the one described above are important because of cost and technological reasons. WDM technology is in its early phase, hence it is important to ensure the required devices for such technology are supplied as regular components rather than a very expensive made-to-order device and standards are required to make this happen. Also, in a longer term, the aim of such technology is to allow the use of equipment from many different suppliers to facilitate the operation of WDM. Thus, this equipment needs standard to allow interoperation.

2.2 Arrayed Waveguide Grating (AWG) Technology

2.2.1 History of Arrayed Waveguide Grating (AWG)

Arrayed Waveguide Gratings (AWGs) were first demonstrated by Dragone [2.7], who described an integrated N x N multiplexer capable of simultaneously multi/demultiplexing a large number of input and output channels based on the generalisation of a 2 x 2 Mach-Zehnder multiplexer. The invention of such a device went back to 1988 when M. Smith presented a novel method involving a focusing and dispersive component operating in the 0.63μm wavelength band, which was based on a phased array of bent optical waveguides as illustrated in figure 2.2 [2.8] He explained, when a broad parallel beam impinged on an array of concentric planar optical waveguides, part of the incident rays will be coupled into the array of waveguides, hence having a phase distribution:

$$\phi_i = \beta \psi R_i + \phi_0$$  \hspace{1cm} (2.1)
where $\beta$ is the propagation constant of the waveguide, $\phi_0$ is the phase at the input plane, $\psi$ is the sector angle of the concentric array, and $R_i$ is the bending radius of the $i^{th}$ waveguide. If the concentric arrays are chosen, such that, $\beta \psi R_i = 2\pi n$, this distribution will yield a focusing operation. Because of the operating wavelength and limited path difference in the geometry of the concentric bent waveguides, the wavelength resolution is limited to several nanometres.

Therefore, H. Takahashi et al [2.9] proposed a diffraction grating, operating at 1.3μm in the communication wavelength, based on arrayed waveguides with nanometre resolution as shown in figure 2.3. He showed that by designing two adjacent array waveguides to have the same length difference, $\Delta L$, a phase difference of $2\pi n_c \Delta L/\lambda$ occurs, where $n_c$ is the effective refraction index of the waveguides. By placing an objective lens at the output of the array waveguides, the light beams will focus into a focal point. This gives a wavelength resolution which is proportional to $\Delta L$. Therefore he concluded, in order to have a better wavelength resolution, a large $\Delta L$ is required.
However, a major problem was yet to be solved, that is replacing the bulk-type input/output lenses with a waveguide type. The invention of a multi-efficient star coupler, as shown in figure 2.4, by C. Dragone [2.10] was the solution. This coupler as shown in figure 2.4 is constructed in free space having two arrays each consisting of $N$ elements.
HISTORY OF ARRAYED WAVEGUIDE GRATING

When light is coupled into any of the $2N$ ports, the fundamental mode is excited. The resulting radiation pattern in the free space region is determined by the Fourier transform of the fundamental mode. A fraction of the radiated power is intercepted by the receiving array and its value is determined by the angular aperture $2\alpha$ of the receiving array and is shown to be 60% under optimised conditions. However the efficiency, $\varepsilon$, is substantially lower than the radiated power since the fundamental mode of a receiving element accepts a fraction of the incident power illuminating the element aperture. $\varepsilon$ depends on two factors; the distribution of the fundamental mode and the space-bandwidth product determined by the element width, $a$, and the array angular width $2\alpha$ given as:

$$w_a = \frac{\pi \cdot a \cdot \sin \alpha}{\lambda} \quad (2.2)$$

As a consequence, Dragone showed that the highest possible $\varepsilon$ using uniform array is 0.34 and the efficiency of such a coupler is approximately wavelength independent. He also showed that it is possible to increase $\varepsilon$ with the use of non-uniform arrays giving a value of 0.438. This planar coupler is the only known geometry that is realisable for large $N$ in integrated form suitable for use with singlemode fibres. Hence, extensive research was done to integrate such elements with that proposed by H. Takahashi et al which was a diffraction grating based on a series of array waveguides. [2.9].

In the meantime, A. R. Vellekoop proposed a four-channel integrated-optics wavelength demultiplexer, which adopted the concept of array waveguides proposed by both Smith [2.8] and Takahashi et al [2.9]. In his work, he described that in order to counter the loss caused by the multiple foci in the focal plane, the array waveguides can be placed more closely with a smooth connection between the concentric section and the coupling section shown in figure 2.5 [2.11].

However, a major deficiency in transmission efficiency occurs, due to the free radiating region. This was finally overcome by Dragone [2.7].
The first AWG in silica-on-silicon was reported by Dragone [2.12]. He had proposed a 7 channel NxN multiplexer fabricated using SiO\textsubscript{2}/Si waveguides as shown in figure 2.6. These multiplexers employed a correction scheme to reduce aberration caused by mutual coupling of the adjacent waveguides in the array. Mutual coupling between the input waveguides will affect the phases of these signals, thus resulting in phase errors. These phase errors can be minimised by optimising $F_1$ (see figure 2.6). The optimum value of $F_1$, also known as the phase centre of the array, can be obtained by varying the distance $d$. Consequently by exciting the centre port of the first couplers, the minimum phase error given as $\delta\phi = k\delta l(\alpha' s)^2 / 2$ can be located. Dragone showed that the effect of mutual coupling can be considerably reduced if the distance $d$ is given as $d = 30\beta(\alpha' s)$ [2.13], where $\beta$ is the propagation constant of the free-space region. However, there is a trade-off between the efficiency of the array waveguides and the effect of mutual coupling. Thus, with the deployment of Rowland Circle geometry [2.14] within the free space region, optimisation can be achieved without the tedious procedure of locating $F$ and $d$. 

Figure 2.5 Layout of a four-channel integrated optics wavelength demultiplexer with weak polarisation dependence [2.11]
Continual research in silicon-based AWG has gained an increasing amount of interest from researchers developing various Si-based AWGs. An example is the silicon-on-insulator (SOI) AWG [2.15-2.17], which has shown to be a promising technology for guided wave photonics; also for its well-understood optical properties and existing technology. P. D. Trinh et al [2.15] proposed and demonstrated the first SOI AWG operating at 1550nm wavelength, having a channel spacing of 1.9nm with insertion loss below 6dB with a TE-TM shift less than 0.04nm without any compensation. With the advances of SOI technology, high quality SOI wafers are now readily available at a low cost, which has resulted in an on-going research effort in producing smaller, low loss AWGs. Hence a much smaller device having a rib width of 1.3μm with a typical waveguide array of a few square millimetres was developed [2.16].
2.2.2 Flat Spectral Response AWG

The spectral response of the AWG plays an important role in an optical network because it determines the maximum number of channels, the minimum channel spacing separation and the level of isolation between channels. Ideally, a flat spectral response is generally preferred, for it reduces the need for accurate control of the transmitted wavelengths. However, the spectral response of a conventional AWG usually takes the form of a ‘peak’ with significant sidelobes. This is due to the dispersive properties of a singlemode input to singlemode output waveguides. This deficiency posed a problem in WDM networking system for the following reasons:

1. Small fluctuations in the wavelength of the laser source causes a great loss.

2. The transmission loss of a convention AWG monotonically increases at both sides of the transmission spectrum from the centre channel due to the effect of Fraunhofer diffraction. This places tight restrictions on the wavelength tolerance of laser diodes and requires accurate temperature control for both the AWGs and the laser diode.

3. Due to multiple uses of AWGs in WDM ring/bus networks, the cumulative passband width of each channel becomes much narrower than that of a single stage AWG filter. Hence there is a need to broaden the spectral response for AWG multi/demultiplexers.

Various methods have been proposed and also demonstrated to achieve a flat spectral response within an AWG. An early version is the use of wide multimode output waveguides, which is a common technique used in bulk-optic demultiplexers, proposed by M. R. Amersfoot et al in 1994 [2.18], which is shown in figure 2.7.
This technique allows the realisation of a flat spectral response at the expense of coupling efficiency. The transmitted light may not be taken off-chip into a conventional single-mode fibre, as the subsequent fibre coupling is both inefficient and unpredictable. If they are, however coupled to detectors, the advantages of the flattened response can be fully exploited.

K. Okamoto et al proposed an interesting approach based on the principle of a Discrete Fourier Transform (DFT) [2.19]. In accordance with his method, the field distribution of light incident to the second slab waveguide has the form of a SINC function. A diffraction phenomenon occurring in the second slab waveguide can be regarded as a Fourier Transform of the incident light occurring at the output plane. In order to obtain a flat spectral response, accordingly, his method is adapted to adjust the profile of incident light to have the form of a SINC function corresponding to an Inverse Fourier Transform of a desired output. Consequently, their methodology involves some alteration of the core aperture width and the path length difference by means of a thermo-optic effect to achieve the required optical field intensity. However, this methodology displayed a significant challenge both to the design and fabrication.
The idea of the DFT is further exploited by Dragone et al [2.20]. In his work, he uses the concepts explained in [2.19], however he introduced a new coefficient $c(u)$ with two zeros and multiplied this new coefficient by the aperture distribution, hence resulting in a distribution with two negative lobes at the output array/slab interface as shown in figure 2.8. He further explained that the coefficient $c(u)$ can be realised by expressing $c(u)$ as the product of its magnitude $|c(u)|$ and its sign $\text{sig}(u)$. This sign distribution can be realised by changing the appropriate arms, which are responsible for the negative lobes of the filtered distributions. The magnitude distribution can then be obtained by introducing a lateral offset to the appropriate array, characterised by $|c(u)| < 1$.

![Figure 2.8 Aperture distribution (i) is produced in conventional router, product of $c(u)$ gives the filtering distribution of (ii). [2.19]](image)

Another approach that has been looked at by a number of researchers is the integration of other photonics components, such as Multimode Interference Couplers (MMI) and Mach-Zehnder (MZ) Filters etc, to the AWG on a single substrate. A MMI is integrated at the input section of the star coupler [2.21 -2.23]. By adjusting the width and length of the MMI, a partially resolved two fold image is produced at the MMI output as shown in figure 2.9; hence the spectral responses of the AWG may be broadened and flattened.
However, this comes at the cost of precision tailoring of the images at the MMI output to match the optical mode at the output waveguides so that, as the refocused image of the former is dispersed across the latter, their mutual overlap gives the desired transmission function, which is a flat spectral response.

On the other hand, the asymmetrical Mach-Zehnder filter is connected to each AWG output waveguide to introduce a spectral loss corresponding to the peak of the AWG response [2.24]. Hence, in order to obtain the flat spectral response AWG, the spectral characteristics of the asymmetric MZ filter should be exactly the opposite to that of AWG and also the maximum loss wavelength of each asymmetrical MZ filter should coincide with the corresponding channel centre of the AWG. However due to the variation in the effective index, precise tuning of the MZ filter is necessary to adjust the maximum loss wavelength of each MZ filter corresponding to the channel centre of the AWG.

Figure 2.9 Array waveguide grating with MMI input section; Schematic diagram of filter imaging using an MMI input section and associated transmission function. [2.21]
An alternative approach to achieve a flat spectral response AWG is the modification of the components within the AWG such as its input waveguides, free space region or array waveguides. Two different processes are reported in the literature; first the modification of the input/output waveguides as proposed by K. Okamoto et al [2.25-2.26] and second, the use of several focal points in the input and output star coupler using multi-grating methods [2.27] and the multiple Rowland circles [2.28].

The first methodology involves the reshaping of a typical input straight waveguide into a parabola. This will create a slightly double-peaked rectangular optical field at the interface of the input waveguide and slab region, which is similar to the methodology that has been proposed in [2.25]. This parabolic horn waveguide utilizes the characteristics of the wavelength demultiplexer allowing the double-peaked mode profile at the first slab input plane to be reconstructed at the output image plane of the second slab waveguide. This in turn forms a flat spectral response using overlap integration for the double peak profile. However such methodology restricts the versatility of the AWG as a multiplexer since the parabolic horn is fixed at the input waveguides and it introduces loss inevitably resulting from the fact that the double-peak image at the output image plane does not correspond to the local mode of the output waveguide.

The second methodology is the use of a multigrating method consisting of several interleaved sub-gratings of monomode waveguides each having its own path length increment and central wavelength as shown in figure 2.10, as disclosed in U.S Pat. No. 5,978,532 entitled “Spectrographic Multiplexer Component having an Array of Waveguides” by Ringy et al [2.29].
The sub-gratings formed by the array of waveguides are divided into two. They are carefully selected so that their spectrum responses are offset in wavelength, with the difference between the peaks of the two Gaussian spectrums interleaved with each other, and hence generating a flat response when they are fused together. By appropriately selecting this offset between the two Gaussian responses, it is possible to widen the spectrum response so as to make it more than three times as wide as the Gaussian response of either one of the arrays.

Also, the use of multi-Rowland circles can help widen the channel pass-band. This approach tailors the focused image by varying the ending positions of the array waveguides so that superposing of the multiple spatially separated images at the output waveguides can occur to form the desirable images.
2.2.3 Polarisation Independent AWG

The output polarisation of the optical field from a circularly symmetric optical fibre is generally unpredictable and changes with time. Hence, it is essential for most optical devices, in particular, the AWG that uses its dispersive property to differentiate the different wavelengths, to maintain their polarisation independence. It is known that the phase of the optical field is dependent upon the propagation constant $\beta$, which relates to the effective index of the waveguiding structure. Therefore the difference in polarisation in the AWG will each associate with a unique effective index number, i.e $N_{TE}$ and $N_{TM}$. This will result in a wavelength shift $\Delta \lambda$ between the TE and TM spectra of the AWG, and is given as [2.30]:

$$\Delta \lambda = \lambda_0 \frac{N_{TE} - N_{TM}}{N_{TE}^g}$$ (2.3)

where $\lambda_0$ is the centre wavelength, $N_{TE}$ and $N_{TM}$ are the effective indices of TE and TM polarisation respectively, and $N_{TE}^g$ is the group index of the TE mode. Thus from the equation (2.3), it can be noted that in order to achieve non-birefringence, the most obvious answer is to have similar $N_{TE}$ and $N_{TM}$.

Different techniques have been employed to nullify this phenomenon and they can generally be classified into two categories: (1) modification of the array waveguides and (2) modification of the star couplers.

In the first category; modification of the array waveguides, H. Takahashi et al [2.31] had proposed an elegant method by inserting a quartz $\lambda/2$ plate, at a principal optical axis set at $45^\circ$ to the waveguide surface in order to change the polarisation direction from TE and TM and vice versa as shown in figure 2.11.
The centre wavelengths for TE and TM incidence can be equalized as follows:

\[ \lambda_0 = \frac{(n_{TE} \Delta L / 2 + n_{TM} \Delta L / 2)}{m} \]

\[ = \frac{(n_{TM} \Delta L / 2 + n_{TE} L / 2)}{m} \]  \hspace{1cm} (2.4)

where \( n_{TE} \) and \( n_{TM} \) are the effective indices of the waveguide for the TE and TM modes, respectively. Thus the polarisation dependence of the centre wavelength is completely eliminated. The advantage of this method is that it does not require the elimination of waveguide birefringence through proper design of the waveguiding structure; however inserting the quartz plate increases fabrication complexity of the AWG. The \( \lambda/2 \) plate must also be inserted exactly midway along the waveguide lengths.

Also, M. Zirngibl et al [2.32] had presented a method, which involved incorporating an additional path length, \( \Delta l \), to each of the array arm having a different index, \( n \). In his argument, he pointed out that if two waveguides were taken into consideration, and the first waveguide being \( \Delta L \), shorter than the second waveguide, and a path length of \( \Delta l \) is
added to both waveguides having different birefringence, then the phase difference between the two waveguides is given by:

$$\Delta \phi = 2\pi [\Delta L + \Delta l(N-n)] \lambda$$ \hspace{1cm} (2.5)

They then proved that if $\Delta \phi$ is to become independent of polarisation, the optical path difference, $\Delta l$, has to satisfy:

$$\Delta l = \frac{\Delta L}{\left(\frac{\Delta n}{\Delta N} - 1\right)}$$ \hspace{1cm} (2.6)

where $\Delta n = \Delta n_{TE} - \Delta n_{TM}$ and $\Delta N = \Delta N_{TE} - \Delta N_{TM}$. They further demonstrated the above theory on an InP AWG and they showed that both the TE and TM modes overlap almost completely. However, such methodology inevitably increases the device dimension and requires additional fabrication steps.

Several other approaches had also been developed and demonstrated to compensate for the polarisation sensitivity on silica and InP AWG. These include the matching of thermal coefficient of expansion of the overcladding layer to the silicon substrate [2.33], the appropriate choice of process parameters such as top cladding stress, grating waveguide width and core density [2.34] and the used of the stress release grooves to control the birefringence of the waveguides in the array [2.35]. However, the above methodologies may only applied to the material in question, thus they might not be suitable for polarisation compensation in SOI AWG.

In the second category, J. -J. He et al [2.36-2.37] and P. Cheben et al [2.38] have demonstrated a technique for polarisation compensation by integrating a prism-like polarisation compensator in the slab waveguide region. This technique is first demonstrated on an etched grating waveguide demultiplexer [2.36] and is further extended to the InP based AWG as illustrated in figure 2.12 [2.37].
In the analysis of such methodology, J. -J. He et al [2.37] proposed that the shape of the polarisation compensator has to satisfy the following criterion:

$$\gamma = \frac{\Delta L_c}{\Delta L} = \frac{\Delta n}{2(\Delta n'_c - \Delta n'_s)}$$  \hfill (2.7)

where $\Delta L$ is the path length difference of any two waveguides in the AWG. $\Delta L_c$ is the corresponding path length difference within the slab compensator region, and $\Delta n$, $\Delta n'_c$ and $\Delta n'_s$ are the effective index differences between TE and TM modes for the arrayed waveguide, the slab waveguide and the etched slab waveguide respectively. The factor 2 denotes a compensator is incorporated in both the input and output couplers.

One of the main contributors to the polarisation effect is due to the modal solution of the TE and TM eigenvalue equations. Hence, it is possible to minimise this polarisation by careful selection of the rib waveguide geometry.
Pearson et al showed that by varying the SOI waveguide width to height ratio it is feasible to design waveguides with zero birefringence [2.39]. They modelled a 1.5mm Si-overlayer with two fabrication processes; Wet-Etch/Chemical-Etch and Reactive Ion Etching (RIE), using a finite-difference method. They found that waveguide birefringence is larger for a wet-etched waveguides and is not as sensitive to etch depth or ridge width. This design works relatively well for large dimension AWGs, but it is more difficult to suppress higher order modes and birefringence using ridge dimension alone in smaller waveguides. Furthermore, their design results in a multimode SOI waveguide, which will affect the AWG performance.

Hence, in order to compromise between singlemode and zero birefringence, P. Cheben et al [2.39] adopted a similar technique to that in [2.37] and further exploit its analysis in SOI AWG due to its fabrication simplicity and compensation reproducibility.

According to them, an etched region as shown in figure 2.13 is required in order to create a difference in the effective index within the slab region, thus assuring that the wave fronts corresponding to both TE and TM slab modes have the same tilt in the output coupler. This will lead to both modes converging at the same position of the focal line.

![Etched Compensator Region](image)

Figure 2.13 Etched compensator region within the slab region of the AWG [2.39]
APPLICATION OF THE AWG TO WDM SYSTEM

If the difference between the total optical phases is identical for both TM and TE polarisations, they derived a relationship between the compensator shapes given by \( d_i - d_o \) and the effective index difference. Hence defining the condition for compensation as:

\[
d_i - d_o = \frac{1}{2} \frac{im\delta\lambda}{\delta n_y - \delta n_z}
\]  

(2.8)

where \( d_i \) is the distance between the end of the array waveguide \( i \) and the point where the compensator boundary intersects a line joining the end of waveguide \( i \) and the beginning of the central output waveguide and the factor \( \frac{1}{2} \) account for splitting the compensators equally on both slab region. With this technique, the etch depth of the compensator region has to be carefully controlled.

2.2.4 Application of the AWG to WDM Systems

The demand for high functionality components such as the optical add/drop multiplexers, optical cross-connects, and the wavelength routers have lead to the integration of AWGs with other active/passive components. These technologies are critical to ensure the flexibility and survivability of the systems.

An example of such integration is the optical add/drop multiplexer (OADM) as illustrated in figure 2.14. This device has the ability to select a particular wavelength for removes within a series of wavelengths that are multiplexed on an incoming fibre. At the same time, add the same wavelength to other data content along the transmission. An effective way for implementing an OADM is to integrate the entire component onto a single substrate. Of course, the general design of an OADM as shown in figure 2.14 can be implemented using different configurations of the AWGs, such as the use of two AWG [2.40-2.41], a single double AWG, with a static router [2.42] or with a single AWG in double pass [2.43].
One unique configuration is the use of an AWG, together with thermo-optic switches [2.44] which consist of four AWGs, and sixteen double-gate thermo-optic (TO) switches as shown in figure 2.15.

The outputs of the AWG(1) and AWG(2) are connected to the input of AWG(3) and AWG(4). Therefore, when the TO switch is “on”, the optical signal demultiplexed by AWG(1) and AWG(2) goes to the AWG(4) and AWG(3) respectively. On the other hand, when the TO switch is “off”, the optical signal goes to AWG(3) and AWG(4). In this way, any specific wavelength can be identified for “add/drop” by changing the switching condition.
An AWG can also be implemented as an optical cross-connect (OXC). An optical cross-connects is an $N \times N \times M$ component with $N$ inputs, $N$ outputs and $M$ wavelength channels. A $2 \times 2 \times 8$ OXC using TO switches and two AWGs has been demonstrated [2.45]. The OXC was designed for a channel spacing of 200GHz. The first AWG functions as a demultiplexer and has two inputs, $P(1)$ and $P(2)$ with 16 outputs, $q$. The even $q$ ports carry signals from the $P(1)$ port and the odd $q$ ports carry signals from the $P(2)$ port. The second AWG functioning as the multiplexer, is the mirror image of the first and is interconnected to the first by 12 Mach-Zehnder interferometer (MZI) TO switches as illustrated in figure 2.16. Alternatively, a $2 \times 2 \times 4$ OXC can be implanted with 4 MZI and only one AWG in loopback configuration, as shown in figure 2.17. In this configuration, each wavelength passed through the AWG twice in the same direction. In the first pass, the AWGs act as demultiplexers; in the second pass the AWGs act as a
multiplexer [2.45]. The advantage of such configuration is to avoid wavelength misalignment that could cause a power and crosstalk penalty. On the other hand, it might be prone to coherent crosstalk.

Figure 2.16 An OXC constructed with two AWGs. The wavelength channels interleave because the input and output fibres are at adjacent ports [2.45]

Figure 2.17 A 2 x 2 x 4 OXC constructed with single AWG in loopback configuration [2.45]
Another application of the AWG in WDM is in the areas of wavelength monitoring and stabilizing [2.46]. Figure 2.18 shows the schematic diagram of a multiwavelength simultaneous monitoring (MSM) device using an AWG. The AWG is configured to exhibit 8 input signal ports and 8 input monitoring ports. On the outputs, there are 8 signal output and 2 monitor ports. Each of these ports is independent of one another; therefore, the device can also function as a multi/demultiplexer as well.

![Figure 2.18 Multi-wavelength simultaneous monitoring device using an AWG [2.46]](image)

In DWDM systems where smaller channels are required to improve the data capacity, dispersion-shifted fibres and high wavelength filters are mandatory. The use of the dispersion-shift fibres near zero cause a non-linearity effect known as four wave mixing (FWM) [2.47]. Unfortunately, the ITU standard sets a grid of frequencies with constant channel spacing. Hence all the products generated by FWM in the bandwidth of the system fall at the channel frequencies and thus cause crosstalk degradation. It is possible to minimise FWM by using unequally spaced channels selected in the ITU grids. Therefore, an unequal-channel-spacing AWG can be fabricated by appropriate allocation of the output waveguides, which are separated at different distances at the output slab [2.48].
2.3 Silicon Photonics

In the future, Silicon photonics will play a crucial role in the field of opto-electronics due to several important developments in silicon technologies, such as the development of silicon-on-insulator (SOI) as a platform for photonic integrated circuits (PLC's), epitaxial growth of silicon based alloys with tailored optical properties, and scaled CMOS technology, which offers low cost lightwave circuits with gigabits per second speed and low noise performance.

With the emergence of modern telecommunications applications, such as fiber to the home, integration of both electronic devices and optical (photonic) devices into one large device appears imminent. The main reason for such integration is to drive the telecommunications market, in which opto-electronic (OE) components will be playing an important role. Today, work on Si OE is emphasised, particularly on developing waveguides and components such as directional couplers, photodetectors, modulators and arrayed waveguide gratings. Silicon, which is relatively inexpensive compared to GaAs or InP, offers a very attractive platform for device integration. It also has a mature low-cost very large scale integration (VLSI) microelectronics technology that has the potential of substantial improvement [2.49]. Silicon is transparent at the standard telecommunication wavelength range 1.2\(\mu\)m - 1.6\(\mu\)m. It exhibits very low loss and the losses of bulk Si for \(\lambda = 1.3\mu m\) are \(\approx 0.1dB/cm\) [2.50], which is mainly due to free carrier absorption in doped Si-material. Silicon does not exhibit the Pockels effect, also known as the linear electro-optic effect present in lithium niobate. This is due to the inversion symmetry of silicon's diamond lattice. However, injected charge carriers can cause a change in the refractive index of crystalline silicon. This characteristic led to the development of silicon modulators.

Research in photonics began in the 1950s and 1960s. Then the emphasis was on solar cells, light emitters, field-effect modulators and light-infrared photo-elastic modulators. In the 1970s, research moved to developing charge-coupled device imagers, optical-absorption modulators and infrared detectors. Research work on SiGe/Si optics was carried out in the 1980s leading to the development of first SiGe/Si photodetectors. In the
80s and 90s, silicon photonics research progressed into silicon-based waveguides, guided photodetectors and silicon microphotonics [2.51]. Today, one of the challenge facing researchers is to demonstrate optical components in much smaller dimensions.

2.3.1 Optical properties of Silicon

The optical properties of silicon referred to here are the index of refraction and optical absorption, first studied by Fan et al [2.52] in 1954. The absorption band edge was well described by his experimental data. Very little data about the background or residual absorption in silicon was reported for the near infrared, for $\lambda > \lambda_g$ at that time. Swimm [2.53] improved this situation by performing calorimetric measurement of absorption, $\alpha$, on single crystal silicon sample. Promising results were obtained showing the absorption at 1.32μm wavelength is $10^{-3}$ dB/cm. Soref et al [2.50] further calculated the free carrier absorption over the spectral range of communication wavelengths at 1.2μm – 1.6μm using a p-type crystal containing $10^{16}$ impurities/cm$^3$. Figure 2.19 shows the resulted plot, it is clear that the free carrier absorption loss, $\alpha$, was less than $5 \times 10^{-3}$ cm$^{-1}$, which translate to 0.02 dB/cm at the wavelength of 1.3μm – 1.5μm.

Figure 2.19 Wavelength dependence of optical absorption for high-resistivity single crystal Si (10$^6$ impurities/cm$^3$) over the infrared wavelength range 1.2μm – 1.6μm [2.50]
The optical properties of silicon are greatly affected by the change in free carriers; either from residual impurities present in silicon or by deliberate injection/depletion of charge/free carriers into silicon. Those carriers can alter the real and imaginary parts of the silicon dielectric constant. Optically, the refraction and absorption indexes will change by $\Delta n$ and $\Delta \alpha$ respectively, and is described by the well know Drude-Lorenz equation [2.54]:

$$\Delta \alpha = \frac{\varepsilon^2 \lambda_0^2}{4\pi^2 c^3 \varepsilon_0 n} \left( \frac{N_e}{\mu_e (m_{ce}^*)^2} + \frac{N_h}{\mu_h (m_{ch}^*)^2} \right)$$

$$\Delta n = -\left( \frac{q^2 \lambda^2}{8\pi^2 c^2 n \varepsilon_0} \right) \left( \frac{N_e}{m_{ce}^*} + \frac{N_h}{m_{ch}^*} \right)$$

where $q$ is the electronic charge, $\lambda$ is the optical wavelength, $n$ is the refractive index of pure silicon, $\varepsilon_0$ is the permittivity of free space, $N_e$ is the free electron concentration, $N_h$ is the free hole concentration, $m_{ce}^*$, is the conductivity effective mass of electrons ($m_{ch}^*$ for holes), $\mu_e$ is the electron mobility, and $\mu_h$ is the hole mobility.

Soref and Bennet [2.55] used a numerical Kramers-Kronig analysis to predict the refractive index perturbations produced in crystalline silicon by charge carriers. They compared the predictions of Drude model of c-Si to the $\Delta n$ results and to experimental $\Delta \alpha$ data. They reveal that the $\Delta \alpha$'s predicted are approximately 0.5 of the experimental values for holes, and are approximately 0.25 of the experimental values for electrons, as shown in figures 2.20 – 2.23.
Figure 2.20 Absorption in c-Si at $\lambda = 1.3\mu$m as a function of free electron concentration [2.55].

Figure 2.21 Absorption in c-Si at $\lambda = 1.3\mu$m as a function of free hole concentration [2.55].
Figure 2.22 Absorption in c-Si at $\lambda = 1.55\mu m$ as a function of free electron concentration [2.55]

Figure 2.23 Absorption in c-Si at $\lambda = 1.55\mu m$ as a function of free hole concentration [2.55]
Then they concluded that the $\Delta n$ results of figures 2.24 - 2.27 were in good agreement with the classical Drude-Lorenz model, for electrons. For holes they noted a $(\Delta N)^{0.8}$ dependence. They produced an extremely useful expression for silicon to evaluate changes due to injection or depletion of carriers in silicon in a subsequent publication [2.56] and is used almost universally:

At 1.55$\mu$m:

\[
\Delta n = \Delta n_e + \Delta n_h = - [8.8 \times 10^{22} \cdot \Delta N_e + 8.5 \times 10^{-18} \cdot (\Delta N_h)^{0.8}] \tag{2.11}
\]

\[
\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h = 8.5 \times 10^{-18} \cdot \Delta N_e + 6.0 \times 10^{-18} \cdot \Delta N_h \tag{2.12}
\]

At 1.33$\mu$m:

\[
\Delta n = \Delta n_e + \Delta n_h = - [6.2 \times 10^{22} \cdot \Delta N_e + 6.0 \times 10^{-18} \cdot (\Delta N_h)^{0.8}] \tag{2.13}
\]

\[
\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h = 6.0 \times 10^{-18} \cdot \Delta N_e + 4.0 \times 10^{-18} \cdot \Delta N_h \tag{2.14}
\]

where:

$\Delta n_e$ = change in refractive index resulting from change in free electron carrier concentrations.

$\Delta n_h$ = change in refractive index resulting from change in free hole carrier concentrations.

$\Delta \alpha_e$ = change in absorption resulting from change in free electron carrier concentrations.

$\Delta \alpha_h$ = change in absorption resulting from change in free hole carrier concentrations.
Figure 2.24 Refractive-index perturbation of c-Si (versus $\lambda$) produced by various concentrations of free electrons [2.56].

Figure 2.25 Refractive-index perturbation of c-Si (versus $\lambda$) produced by various concentrations of free holes [2.56].
Figure 2.26 Carrier refraction in c-Si at $\lambda=1.55\mu m$ as a function of free carrier concentration ($\Delta n$ determined from figure 2.24 and 2.25) [2.56].

Figure 2.27 Carrier refraction in c-Si at $\lambda=1.3\mu m$ as a function of free carrier concentration ($\Delta n$ determined from figure 2.24 and 2.25) [2.56].
2.3.2 Silicon Based Optical Waveguides

The optical waveguide is the most fundamental optical component in integrated optics that interconnects the various devices of the optical integrated circuits. The most basic waveguide configuration is the slab waveguide; where light is guided between two parallel cladding layers by making use of multiple total internal reflections in the vertical direction. However, in a true optical link, a two dimensional guiding structure is usually required. Hence, the formation of channel and rib structures gave rise to a new era of integrated optical technology. Generally, two main types of silicon based waveguides are available; the Epitaxial silicon germanium (Si$_{1-x}$Ge$_x$) and silicon on insulator (SOI) as shown in figure 2.28. Waveguide designs and fabrications for Si/Si$_x$Ge$_x$ optical components require a thorough understanding of its material and optical properties. While material and optical properties of silicon-on-insulator waveguides are well understood, the design of single mode waveguides in SOI is somewhat more complex due to the strong confinement in these structures and this will be explained in greater detail in the later sections of this thesis.

![Silicon -Germanium on Silicon](image1)

![Silicon-on-Insulator (SOI)](image2)

Figure 2.28 Two main types of silicon based optical waveguide
2.4 Silicon-on-Insulator (SOI)

Silicon-on-insulator (SOI) (where we consider Si-on-SiO\textsubscript{2} as shown in figure 2.29), possess unique optical properties due to the large refractive index difference between silicon ($n_1 = 3.45$) and SiO\textsubscript{2} ($n_2 = 1.46$). The silicon-guiding layer is typically of the order of a few micrometers in thickness, and the buried silicon dioxide is typically about half a micron, which is enough to prevent the optical field from penetrating the silicon substrate below in large waveguides.

![Figure 2.29 SOI planar waveguide](image)

In the early 90s, researches in low loss SOI waveguides have been based on two processes: Bond and Etch Back (BESOI) [2.57] and Separation by Implantation of Oxygen (SIMOX) [2.58].

BESOI involves the use of two oxidised silicon wafers to form the basis for wafer bonding process. Once a permanent bond is developed between the initial two wafers, etching of the silicon wafer took place to obtain the required Si-overlayer thickness. The first loss measurement in BESOI optical waveguides is reported by Evans et al [2.59]. They recorded loss measurement for TE\textsubscript{0}, TE\textsubscript{01} and TM\textsubscript{01} modes at the operating
wavelength of 1330nm and the lowest losses documented were 2.6dB/cm for TE_0 and 2.0dB/cm for TM_0. Even though their waveguides were multimode, they provided early evidence that low loss waveguides are feasible in SOI. This led to the investigation for such SOI optical waveguides from various researchers including Reed et al [2.57], who reported a loss of 0.27dB/cm at a wavelength of 1523nm.

Another form of silicon-on-insulator technology resulted form the use of oxygen-ion + implantation into device grade silicon is known as *Separation by Implanted Oxygen* (SIMOX). SIMOX technology makes use of a single crystal layer separated from a conventional silicon substrate by a thin layer of silicon dioxide. The buried layer of silicon dioxide is created by implanting a high dose of oxygen ions (~10^{18} \text{ cm}^{-2}) at energies in the range of 150 – 200keV into a silicon substrate, which is held at 450 – 600°C [2.58] to maintain the crystallinity of the silicon overlayer. The wafer is then annealed at high temperature to form the buried silicon dioxide beneath the wafer surface.

The first SIMOX optical waveguide was demonstrated by Soref et al [2.60] in 1989. He used an oxygen-implanted SIMOX wafer consisting of a 3.15\mu m core, which comprised 0.3\mu m crystal-silicon and a 3\mu m epitaxial-crystalline-silicon layer, with a 0.4\mu m oxide layer operating at a wavelength of 1330nm. He demonstrated the technique of optical induced attenuation in modulating light at 1330nm using a square-wave modulated 800nm light. His technique did not prove to be an efficient intensity modulator at 1330nm, however his results proved to be useful in designing SOI mode-extinction modulators and optically controlled directional coupler switches.

In 1991, Weiss et al [2.61] showed both experimentally and theoretically that a low loss single mode planar waveguide is made possible in SIMOX structure at a wavelength above 1.15\mu m with a minimum propagation loss of 8 dB/cm for TE_0 mode. They further investigated the propagation loss of different silicon overlayer thickness, ranging from 0.12 to 0.25\mu m using standard SIMOX wafers. Promising results were obtained and waveguide loss at wavelength 1.523\mu m was reported to be 0.14dB/cm [2.62]. Their results highly suggested that SIMOX planar waveguides could be produced with losses
low enough for optical applications. However, one of the disadvantages of SIMOX is the lack of flexibility in controlling the thickness for both the oxide layer and the guiding layer, which is crucial to prevent the evanescent field from penetrating the silicon substrate.

The planar waveguides discussed above are usually in their multimode configuration. In order for a 3 layer silicon on SiO$_2$ planar waveguide to be in singlemode, in accordance to the solution of a symmetrical planar waveguide eigenvector equation, which is given as [2.63]:

For TE polarisation:

$$\tan\left[\frac{k_0 n_1 h \cos \theta_1 - m \pi}{2}\right] = \frac{\sqrt{\sin^2 \theta_1 - \left(\frac{n_2}{n_1}\right)^2}}{\cos \theta_1}$$  \hspace{1cm} (2.15)

For TM polarisation:

$$\tan\left[\frac{k_0 n_1 h \cos \theta_1 - m \pi}{2}\right] = \frac{\left(\frac{n_1}{n_2}\right) \sin^2 \theta_1 - 1}{\left(\frac{n_2}{n_1}\right) \cos \theta_1}$$  \hspace{1cm} (2.16)

The singlemode SOI planar waveguide is predicted to be in sub-micron dimensions. Soref et al [2.64] have shown that for a simple air-clad planar waveguide at 1.3\(\mu\)m, the Si guiding layer thickness for TE\(_0\) and TM\(_0\) modes has to be smaller than 0.22\(\mu\)m and 0.3\(\mu\)m respectively. In the early 1990s, Petermann et al [2.65] showed that even a rib waveguide with large cross section dimensions could behave as a singlemode structure. This led to a great interest in researching low loss, singlemode rib waveguides that is important for integrated optics devices, in particular, the AWG, which has a dispersive property.
Singlemode propagation is an important requirement for optical waveguide devices for use with singlemode fibre. A rib structure with large cross-sectional area, as shown in figure 2.30, possesses this unique quality with the appropriate choice of rib width to height ratio.

![Cross-section of an SOI (silicon-on-insulator) optical waveguide](image)

Figure 2.30 Cross-section of an SOI (silicon-on-insulator) optical waveguide

Following the analysis of Petermann [2.65], Soref et al [2.66] investigated the singlemode condition on silicon and restricted their consideration to rib guides with $0.5 < r < 1.0$. They demonstrated that if a large cross section rib guide with vertical sidewalls satisfied the condition in equation 2.17, the singlemode condition could be achieved. This is based on the fact that the effective index of the ‘vertical mode’ in the planar regions on either side of the rib is higher than the effective index of all vertical modes in the rib, other than the fundamental mode and hence, all other higher modes will be not be guided.

$$2b\sqrt{n_1^2 - n_2^2} \geq 1$$ (2.17)

Hence they analysed the limiting condition such as EH$_{01}$ and HE$_{01}$ modes, and hence higher order modes, just failed to be guided. This resulted in a condition with an aspect ratio as follows:

$$\frac{a}{b} \leq 0.3 + \frac{r}{\sqrt{1-r^2}}$$ (2.18)
Then they used a Beam propagation method (BPM) to investigate the stability of the singlemode condition by launching a beam off axis purposely, to excite the higher order modes and after 2mm it was observed that the higher order mode leaks out laterally along the slab. However, their analysis does not take into consideration polarisation which is another important parameter in the design of an AWG which we will discuss in later sections. (Soref’s formula).

Many papers have reported losses on SOI rib structures following the above analysis [2.67-2.72]. Schmidtchen et al [2.68] had demonstrated a large rib structure with 7.5μm Si-overlayer with etch depth of 2.2μm and rib width of 7μm. They performed a series of experiments based on different rib width, ranging from 2μm-12μm. They noted that losses for waveguides having rib width greater than 3μm were below 0.5dB/cm.

Zinke et al [2.70] further verified the singlemode assumption by Soref. They fabricated the SOI rib waveguides based on two different processes; SIMOX (Si-overlayer; 7.5μm) and BESOI (Si-Overlayer 4.2μm). Their experiment agreed considerably well with equation (2.10) and losses of both rib waveguides shown be as low as 0.5dB/cm for rib width greater than 4μm.

Also, Fischer et al [2.72] have shown that waveguide losses as low as 0.1dB/cm can be achieved in SOI rib waveguides. They fabricated their SOI rib based on BESOI, with a large cross sectional Si-overlayer of 11μm, which allow maximum coupling efficiency to a standard singlemode fibre.

In 1998, Pogossian et al [2.73] employed the effective index method (EIM) to investigate the singlemode condition as proposed by Soref [2.66] with experimental data obtained from Rickman et al [2.71]. Their theoretical formula is almost identical with equation 2.10, except the constant of 0.3 in Soref’s formula is zero in the EIM, hence providing a more restrictive criterion for singlemode behaviour.
2.4.1 Smart-Cut Technology

With the advances in SOI technology, a new process in wafer processing known as "Smart-Cut" has been developed in the mid 1990s [2.74-2.75]. This "Smart-cut" process combines the techniques of wafer bonding and ion implantation to produce a high quality SOI wafer with low intrinsic defect densities and thickness homogeneity. It was then adopted by a French company, SOITEC to produce high quality SOI wafers, with the trade name 'Unibond'. The originality of the smart cut process is the use of the phenomenon of blistering and microcavities grown in a low temperature thermal treatment to induce a splitting effect, leading to a SOI structure. This structure offers great potential for the fabrication of photonics integrated circuits since it has the flexibility to enable fabrication a variety of silicon guiding layers and buried SiO₂ layer thickness with high precision. The uniformity of the surfaces roughness is of the order of ±120 Å RMS. Therefore, it gives great flexibility in the design of optical waveguiding devices. For the first time, propagation loss in Unibond SOI was measured by T. W. Ang et al [2.76]. They reported a loss of 0.15 ± 0.005 dB/cm that is comparable to the loss of SIMOX waveguides.

Smart-cut technology, was introduced in the mid nineties by M. Brue1 [2.74]. It makes use of wafer bonding and ion implantation techniques to get good uniformity and high quality for both the SOI and the buried oxide layer. The Smart-cut process can be described in six steps as illustrated in figure 2.31.

1. Thermal oxidation takes place on the first wafer, referred to as wafer A. This is a crucial step where the thickness and thickness uniformity of the oxide layer are defined.

2. Ion implantation of hydrogen ions, usually with dose ranging from 2 x 10¹⁶ to 1 x 10¹⁷ cm⁻², in wafer A to define the region, located at a depth corresponding to the projected range, where the silicon wafer is split in the later stage.
3. Hydrophilic bonding at room temperature of wafer A to wafer B. A modified RCA cleaning process is used to ensure that no particles of size bigger than 0.3µm is trapped at the bonding interface. Wafer B acts as a stiffener and provides the bulk silicon under the buried oxide in the SOI structure.

4. A first thermal treatment is used to split both the wafers to form the SOI structure. The bonding strength between both wafer A and wafer B must be strong enough to allow splitting of the implanted wafer, A, to occur. During the annealing process, there will be an interaction between cavities inside the implanted wafer, resulting in a formation of cracks which propagate parallel to the bonding surfaces.

5. A second thermal treatment is performed at high temperature to stabilize the bonding interface.

6. A final step, Polishing is needed to smooth the structure surfaces. It removes a few hundred Angstroms from the top silicon layer thickness. Using a simple polish step, wafer A can be reused as a new handle wafer.
2.4.2 Active and Passive Optical Components in SOI

The successful demonstration and fabrication of very low loss optical waveguides in SOI led to the development of a number of technologically important optical devices. Over the years, an extensive library of low loss optical devices has been fabricated, ranging from simple devices such as Y-Junctions and Bends to the more complicated ones, such as Modulators, Bragg Gratings and Arrayed Waveguide Gratings.
Optical devices can be classified as passive or active. The first passive directional couplers in SOI were demonstrated by P. D. Trinh [2.77] with low insertion loss of 1.9 dB and excellent uniformity. Star couplers fabricated in large cross section rib structures were also demonstrated [2.78]. The star coupler consists of one input waveguide and $N$ output waveguides with a radiative slab waveguide region represents a key component for realisation of silicon photonic circuits. Asymmetric Mach-Zehnder type wavelength filters with a channel spacing of 4nm and free spectral range of 8nm have also been reported [2.79]. Periodic waveguides structures, such as Bragg Gratings [2.80] and Grating Couplers [2.81] have been realised in SOI due to the ultra compact dimension and potentially low cost. Multi/Demultiplexing devices used in optical networking, such as Multimode interference (MMI) couplers and AWG have also been demonstrated in SOI [2.82] and have gained significant popularity among academics and industrialists in recent years.

Active devices in SOI are made possible by applying injected carriers or the use of thermo-optics. Optical phase modulators based on thick silicon-overlays have been demonstrated [2.83], and the modulation bandwidth was until recently limited to the order of 10-20 MHz. In order to achieve a higher modulation, smaller dimensions usually in the sub-micron range, are required. Extensive research into this has been done in University of Surrey and with excellent results [2.84]. Recently, a high speed modulator was demonstrated by Liu et al [2.85] operating at 19GHz.

Phase modulators can also be achieved in SOI using thermo-optics. Clark et al [2.86] have investigated a series of low-power thermo-optics phase modulating devices fabricated in SOI suitable for use in distributed sensing or as optical variable attenuators. The future potential of silicon-on-insulator (SOI) in photonics is extremely promising and bright!
2.5 Summary

In the review of Arrayed Waveguides Technology, we have discussed the developments of the Arrayed Waveguide Gratings (AWGs). The invention of the AWGs started in 1988 by M. Smith, where he developed dispersive and focusing arrays having low wavelength resolution. Throughout the course of finding a suitable device that allowed the handling of large number of channels to be used in WDM systems, many researchers have improved and incorporated different optical components. Finally the AWGs were developed in 1991 by C. Dragone. The AWGs operate according to the ITU specifications. Such specifications were still in early stages of development; nonetheless it provided the elementary guidelines for both the components and systems designers, as well as the end-users. Besides wavelength specifications, effects of polarisation and cross-talk have to be taken into consideration. Hence these lead to the different design variations of AWGs which include the flat-top and polarisation independent implementations. An extensive review has been done on designing a flat spectral response AWG, however most of the improvements were proposed and demonstrated in silica. Some of these methodologies might be applicable to our SOI structures; nevertheless, each method has its drawbacks. We have also discussed the effect of polarization variation within the AWG, where it is particularly important to achieve birefringence free AWGs since such devices exhibit a dispersive property that could lead to the misalignment of the focusing beam (TE or TM) at the output waveguides.

In the review of silicon photonics, it has been shown that silicon is an interesting material for optical waveguiding due to it transparency at standard communications wavelength (1.2µm – 1.6µm). Also for its mature processing technology in electronic industry that allows the viability of most integrated optical components. Silicon also has proven to be attractive because of its low losses ~ 0.5dB/cm. The quality of commercial Si-material is sufficient to realised low loss optical waveguides, in material such as Silicon-on-insulator, when we considered Si-on-SiO$_2$ where the refractive index difference is high. It is possible to realise optical components with relatively small dimensions due to its high optical confinement and also the possibility of increased integration density. One other
significant technological issue is the change of refractive index via the use of free carrier injection, which has proven to be efficient in the realisation of optical phase modulators. If this phenomenon is further exploited, it can have different optical applications, such as the use of free carrier injection to shape the optical field distribution to the intended profile that form the methodology of this project (details will be explained in Chapter 4). Singlemode Unibond SOI waveguides exhibit losses as low as 0.1dB/cm have been demonstrated and a library of optical components such as Directional Couplers, Grating, Bends, Y-junctions and Star couplers have been demonstrated. Even though very few papers have reported AWGs in SOI. With the realisation of different optical components, AWGs in SOI are possible.

Hence, in this work, we have chosen SOI as our fabricating materials. The SOI rib design exhibits singlemode behaviour and near zero birefringence. We exploit the free carrier injection phenomenon to introduce absorption to shape our optical field distributions across the array waveguides to the intended profile, hence producing a flat spectral response AWG in SOI.
References:


REFERENCES


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CHAPTER 3
Theory

Silicon has numerous qualities that make it a desirable material for constructing small, low-cost, optical components: it is relatively inexpensive, plentiful and well understood material for producing electronic devices. In addition, due to the longstanding use of silicon in the semiconductor industry, the fabrication tools by which it can be processed into small components are commonly available.

Dr Mario Paniccia
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3.1 Introduction

This chapter discusses some of the important theories, which help facilitate the understanding of the arguments used and their physical bases throughout the work of this thesis. However, the singlemode condition and the free carrier dispersion effect have been discussed in chapter 2, hence they are not included in this chapter.

In section 3.2, waveguiding theory will be explained; in particular, reflection and refraction, reflection and transmission coefficients, planar waveguides, propagation constant, complex refractive index and complex propagation constant etc, which together formed the basic principles behind the propagation of light in an optical waveguide.

Section 3.3, highlights the loss contributions originated from a series of sources that affect the mode intensity as the light beam propagates along the waveguiding structure. It is important to understand their origin since these losses need to be sufficiently low so that the optical mode initially launched into the waveguide will be available to perform the function for which the device was designed.

In section 3.4, addressing coupling, the discussion will focus on the different methods of getting light into and out of the waveguide, which is essential for determining the optimum method for light coupling. Each method has its advantages and difficulties and
the optimum method depends greatly on the structure of the device and its intended application.

In Section 3.5, two light phenomenon will be explained, the interference of light and Fraunhofer diffraction, which will then lead to the discussion of the principle and operation of AWGs (section 3.6). Finally, in section 3.7, theories that governed some of the simulation techniques, which help acquire a better understanding of the intended device, will be explained.

### 3.2 Waveguide Theory

The most fundamental optical structure of an integrated optical circuit is its straight waveguide. A waveguide is a structure that allows light to be guided by making use of the multiple total internal reflections from two or more surfaces. In its simplest forms, light is guided between two parallel plates forming the structure known as the slab waveguide. If the light is further confined in an additional dimension by more surfaces, which in our case, is a rib structure, light is confined in two dimensions which may truly represent a realistic optical link. Hence, to understand how a waveguide works, it is essential to understand some of the waveguiding theories, which govern the behaviour of a wave at an interface and its propagation. Hence, a comprehensive discussion on simple optical waveguides using the ray optical model, without the rigours of Maxwell’s equations, is introduced through the approach of both Zappe et al [3.1] and Reed et al [3.2].

#### 3.2.1 Angles of Reflection and Refraction

When a light beam is incident at a particular angle on a reflecting surface, it will be reflected at the same angle. This effect is expressed mathematically as:

\[
\theta_1 = \theta_2
\]  

(3.1)
where $\theta_i$ is the angle of incidence and $\theta_r$ is the angle of reflection. If the surfaces is not completely reflective, then a portion of the incident waves will be transmitted from the region with refractive index $n_1$ to that with a refractive index, $n_2$ as illustrated in figure 3.1 [3.1] This relation of the transmitted angle, $\theta_t$, to the incident angle, $\theta_i$, is given by Snell’s law as:

$$n_1 \sin \theta_i = n_2 \sin \theta_t \quad (3.2)$$

Equation (3.2) has an interesting implication. If the refractive index, $n_1$ is greater than $n_2$, when the light beam is transmitted from a high refractive index region to a low refractive region, it is implicit that the angle $\theta_t$ must be greater than $\theta_i$ so that $\theta_t$ will approach 90° for some smaller value of $\theta_i$. If $\theta_t = 90^\circ$, none of the beam is transmitted into the material of lower refractive index, hence Snell’s law is simplified to:

$$\sin \theta_i = \frac{n_2}{n_1} \quad (3.3)$$

which allows the critical angle, $\theta_c$, to be defined.
Therefore the critical angle is given as:

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

(3.4)

For angles of incidence greater than this critical angle, \(\theta_i > \theta_c\), the incident beam experiences total internal reflection and no light is transmitted across the boundary. This phenomenon is what makes an optical waveguide possible.

### 3.2.2 Reflection and Transmission Coefficients

When we considered light propagation within the waveguides, it is beneficial to use electromagnetic theory to understand the behaviour of the optical waveguide. The electric and magnetic fields of electromagnetic waves are orthogonal to one another, and both are orthogonal to the direction of propagation. Hence propagating electromagnetic waves are also referred to as Transverse Electromagnetic Waves, or TEM waves. By reducing an arbitrary TEM wave to its electric and magnetic field components, its behaviour can be calculated by applying the boundary conditions (see Appendix A). Hence, two general configurations can be solved, namely Transverse Electric (TE) and Transverse Magnetic (TM), since any arbitrary wave may always be reduced to these two cases.

The TE condition is defined as the condition when the electric fields of the waves are perpendicular to the plane of incidence as illustrated in figure 3.2. The electric field can be written as:

$$E_i + E_r = E_i$$

(3.5)
This TE wave has the electric field transverse to the plane of incidence, hence the tangential components of its magnetic field are given by $\cos(\theta) H$ yielding:

$$H_{it} + H_{rt} = H_{rt}$$  \hspace{1cm} (3.6)

$$H_{i} \cos \theta_{i} - H_{r} \cos \theta_{r} = H_{i} \cos \theta_{2}$$ \hspace{1cm} (3.7)

The electric field and magnetic fields are related by the impedance, hence:

$$E = \frac{1}{\sqrt{\varepsilon_{m} \mu_{m}}} B = \sqrt{\frac{\mu_{m}}{\varepsilon_{m}}} H$$ \hspace{1cm} (3.8)

when $\varepsilon_{m}$ is the permittivity [F/m] and $\mu_{m}$ is the permeability [H/m]. $B$ is the magnetic flux density. Equation (3.7) then can be re-written as:

$$\sqrt{\frac{\varepsilon_{i}}{\mu_{i}}} E_{i} \cos \theta_{i} - \sqrt{\frac{\varepsilon_{r}}{\mu_{r}}} E_{r} \cos \theta_{r} = \sqrt{\frac{\varepsilon_{r}}{\mu_{r}}} E_{r} \cos \theta_{2}$$ \hspace{1cm} (3.9)
For nonmagnetic materials, such as semiconductor, \( \varepsilon_l = \varepsilon_r \), and \( \mu_l = \mu_r = \mu_t = \mu_m \), and \( n = \sqrt{\varepsilon} \) for \( \varepsilon_m = \varepsilon \varepsilon_0 \). This allows equation (3.9) to simplify as:

\[
n_1 \cos \theta_1 (E_l - E_r) = n_2 \cos \theta_2 E_r
\]

(3.10)

Hence by manipulating equations (3.5) and (3.10), the reflection coefficient, \( r_{TE} \) is defined as:

\[
r_{TE} = \frac{E_r}{E_l} = \frac{n_1 \cos \theta_1 - n_2 \cos \theta_2}{n_1 \cos \theta_1 + n_2 \cos \theta_2}
\]

(3.11)

Similarly, for TM polarisation, which the magnetic field is always transverse to the plane of incidence, the tangential magnetic fields are continuous as illustrated in figure 3.3. We can hence solve the \( r_{TM} \) in the same way as previous. I.e. equation 3.6 is reproduced here:

\[
H_r + H_{rt} = H_{rr}
\]

(3.12)

Figure 3.3 Orientation of magnetic and electric fields for TM incidence [3.1]
Using the relationship between $E$ and $H$ equation (3.8) becomes:

\[ n_i E_i + n_r E_r = n_i E_i \]  

(3.13)

Since the tangential components of the electric fields are also continuous, this implies:

\[ E_i \cos \theta_1 - E_r \cos \theta_1 = E_i \cos \theta_2 \]  

(3.14)

Hence, the reflection coefficient is:

\[ r = \frac{n_2 \cos \theta_1 - n_1 \cos \theta_2}{n_2 \cos \theta_1 + n_1 \cos \theta_2} \]  

(3.15)

Using Snell's law, given in equation (3.2), the reflection coefficients, $r_{TE}$ and $r_{TM}$ of equations (3.11) and (3.15) can be rewritten as:

\[ r_{TE} = \frac{n_2 \cos \theta_1 - \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_2 \cos \theta_1 + \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}} \]  

(3.16)

\[ r_{TM} = \frac{n_2^2 \cos \theta_1 - n_1 \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}}{n_2^2 \cos \theta_1 + n_1 \sqrt{n_2^2 - n_1^2 \sin^2 \theta_1}} \]  

(3.17)

Whilst not intending to complicate our model mathematically, it is necessary to evaluate these equations. Once the critical angle is reached, it is important to note that total internal reflection occurs, together with a phase shift on reflection. The set of equations (3.16) and (3.17) are known collectively as the Fresnel equations and define the so-called Fresnel reflection coefficient of a surface.
Consider the situation where the refractive index $n_j$ is greater than $n_2$, and the incidence angle $\theta_i$ is greater than $\theta_c$, which is the usual scenario of a waveguide. The square root terms in equation (3.16) and equation (3.17) yield a negative sign. This implies that a phase shift is imposed on the reflected waves, where the phase, $\phi_{TE}$ and $\phi_{TM}$ are given by:

$$\phi_{TE} = 2\tan^{-1}\sqrt{\frac{\sin^2 \theta_i - \left(\frac{n_2}{n_1}\right)^2}{\cos \theta_i}}$$

$$\phi_{TM} = 2\tan^{-1}\sqrt{\frac{n_2^2 \sin^2 \theta_i - 1}{n_2 \cos \theta_i \cdot \frac{n_2}{n_1}}}$$

### 3.2.3 Power Reflection

Thus far, the discussion is based on the reflection coefficient where it relates to the relative amount of fields which are reflected. Usually, a measurable quantity is desired; therefore, the magnitude of power reflected at a boundary needs to be considered. The propagation of power in a wave is given by the Poynting vector $S \ [W/m^2]$, which can be described as the vector product of both the electric and magnetic field given as:

$$S = E \times H$$

and is commonly expressed in its impedance form:

$$S = ZH^2 = \frac{1}{Z} E^2$$
where $Z$ is the impedance, $H$ and $E$ are the magnetic and electric fields respectively. Thus, the reflectance, $R$, which relates to the incident and reflected powers, is given as:

$$R = \frac{S_c}{S_i} = \frac{E_r^2}{E_i^2} = r^2$$  \hfill (3.22)

### 3.2.4 Propagation Constant

The general form of expressing a propagating optical wave is:

$$E = E_0 \exp[j(kz + wt)]$$  \hfill (3.23)

and the argument of the exponential is the phase $\phi \,[rad]$ of the electromagnetic wave, namely:

$$\phi = (kz + wt)$$  \hfill (3.24)

Taking its time derivative yields:

$$\left| \frac{\partial \phi}{\partial t} \right| = \omega = 2\pi f$$  \hfill (3.25)

for angular frequency $\omega \,[rad/s]$ or frequency $f \,[Hz]$. Then its spatial derivative is:

$$\frac{\partial \phi}{\partial z} = k$$  \hfill (3.26)

where $k$ defines the wavevector, or propagation constant $k \,[m^{-1}]$, and relates to wavelength $\lambda \,[m]$ and frequency as:

$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$  \hfill (3.27)
v represents the wave velocity and w represents the change in phase of a wave as a function of time, and k represents the change of phase as a function of its position. The propagation constant is a vector and, in general complex, defining the propagation direction and velocity of a wave. If we refer the phase change, $\phi$, over a distance $z$, we can evaluate this phase change as the product of the propagation constant and the distance given as:

$$\phi = k \cdot z$$ (3.28)

This propagation constant, $k$, relates the phase change propagating in the waveguides in its $z$ direction. However, in reality, the wave is propagating in a ‘zigzag’ manner. Therefore it is appropriate to describe the equivalent propagation constants both across and down the waveguide, which shall be discussed in the next section.

3.2.5 Planar Waveguide

Up till now, the discussion of light phenomenon at interface has been resolved using the ray optics model. If this model is extended a bit further, this could help enhance the understanding of the propagation of light in a planar waveguide. Consider figure 3.4, a planar waveguide, which consists of a waveguiding layer (core), having an index $n_1$, a low cladding with index $n_2$ and an upper cladding with index $n_3$, where it is bound in the $y$ direction and infinite in the $x$ and $z$ directions.

Figure 3.4 Schematic diagram of a planar waveguide [3.3]
If ray optics model is used in this instance, it can be shown that the wave is propagating in the y-direction, and only a portion is directed down the waveguide as illustrated in figure 3.5. Hence, by simple trigonometry:

\[ k_z = n_1 k_0 \sin \theta_1 \]  \hspace{1cm} (3.29)

and

\[ k_y = n_1 k_0 \cos \theta_1 \]  \hspace{1cm} (3.30)

Two propagation constants are acquired; first, \( k_y \), the propagation constant across the waveguide and second, \( k_z \), the propagation constant along the waveguide. \( k_z \) can also be referred to as the propagation constant, \( \beta \), and is generally referred to as the propagation
constant of the waveguide. It defines the changes in phase as the wave propagates along the waveguide. Hence, equation (3.28) can be rewritten, in this case as:

\[ \phi = \beta \cdot L \]  

(3.31)

where \( L \) is the waveguide length. The propagation constant can be expressed as:

\[ \beta \equiv k_z = N k_0 \]  

(3.32)

by introducing a new parameter, \( N \), known as the effective index. The above equation means that the mode in the waveguide thus sees an effective index of \( N \), which means that all zigzagging can be ignored and the wave is thought to propagate straight down a waveguide with index \( N \). Thus, the effective mode propagation constant is then given by \( \beta \).

### 3.2.6 Modes in the Planar Waveguide

From the previous section, the discussion of light reflected upon an interface has been examined and a phase shift is introduced upon the reflection. Also, the wavevector, \( k \), can be decomposed into two components; \( k_y \) and \( k_z \). If light propagation in the \( y \)-direction is considered, there will be a potential standing wave across the \( y \)-direction of the waveguides. Hence, the total phase shift can be derived by summing the ray propagating across the waveguides and back again. This phase shift has to be a multiple of \( 2\pi \) in order to maintain the phase matching condition. Hence the total phase shift can be given as:

\[ 2k_y n_1 \cos \theta_i - \phi_i - \phi_i = 2m\pi \]  

(3.33)

where \( \phi_i \) is the phase shift introduced upon reflection at the upper cladding, \( \phi_l \) is the phase shift introduced upon reflection at the lower cladding and \( m \) is an integer. From equation (3.26), it can be noted that for each value of \( m \), there will be a corresponding
value of $\theta$ that satisfies this equation. Therefore, there will be an equivalent propagation constant in the $y$ and $z$ direction for each polarisation (TE or TM). Each of the allowed solution is referred as a *mode*, and the *mode number* is given by the value of integer $m$. The characteristics of the mode depend not only on $m$ but also on the reflection phase shift resulted from TE and TM polarisation. This argument will be study further in the next few sections when the symmetrical and asymmetrical planar waveguides are taken into account.

3.2.7 Symmetrical Planar Waveguide

In accordance with figure 3.4, where a planar waveguide consists of the upper cladding and the lower cladding, if both their refractive index are equal, which is $n_2 = n_3$, the waveguide is regarded as the symmetrical planar waveguide. Hence, the boundary conditions will apply on both the upper and lower interfaces, so that $\phi_u = \phi_l$. By substituting equations (3.29) and (3.30) into (3.33), we can rewrite the phase matching conditions for the symmetrically planar waveguides for TE and TM polarisation. Assuming TE polarisation for this particular instance, the phase matching condition is given as:

$$2k_0n_1h \cos \theta_l - 4\tan^{-1}\frac{\sqrt{\sin^2 \theta_l - \left(\frac{n_2}{n_1}\right)^2}}{\cos \theta_l} = 2m\pi$$  (3.34)

It is useful to rearrange the above equation into the form of:

$$\tan\left[\frac{k_0n_1h \cos \theta_l - m\pi}{2}\right] = \frac{\sqrt{\sin^2 \theta_l - \left(\frac{n_2}{n_1}\right)^2}}{\cos \theta_l}$$  (3.35)
where it yields an eigenvalue equation, which the only variable is $\theta_i$, which can be solved either numerically or graphically. In the case of the TM polarisation, the equivalent TM phase shift is used. Thus, the corresponding TM eigenvalue equation is:

$$\tan\left[\frac{k_{\phi}n_1h\cos\theta_i - mx}{2}\right] = \left[\frac{\left(\frac{n_1}{n_2}\right)^2 \sin^2 \theta_1 - 1}{\left(\frac{n_2}{n_1}\right) \cos \theta_i}\right]$$ (3.36)

Again, the above equation contains a single variable, $\theta_i$. Once $\theta_i$ is solved, the effective index and the propagation constant can be determined. If a particular mode has a value of $\theta_i$ equal to the critical angle $\theta_c$, which is the minimum value of $\theta_i$ to ensure total internal reflection. It is possible to analyse TE eigenvalue equation to determine the number of possible modes without actually solving it. If the term $(n_2/n_1)^2$ is replaced by equation (3.3), and $\theta_i=\theta_c$. Then the right hand side of equation (3.35) will reduce to zero. The lowest order mode has the largest $\theta_i$, $\theta_i$ decreases as $m$ increases. Thus, equation (3.35) can be simplified to:

$$\frac{k_{\phi}n_1h\cos\theta_c - m_{\text{max}} \pi}{2} = 0$$ (3.37)

I.e. the maximum value of $m$ is given by:

$$m_{\text{max}} = \frac{k_{\phi}n_1h\cos\theta_c}{\pi}$$ (3.38)

If the greatest integer value of the expression is taken, then the number of allowable modes is then given by $m_{\text{max}}+1$, which includes the mode, $m = 0$. This concludes that the both the TE and TM eigenvalue equations allow a solution for $m = 0$ which implies that
that the lowest order mode is always allowed. Thus, there is no cutoff for the lowest order mode in a symmetrical planar waveguide.

3.2.8 Asymmetrical Planar Waveguide

Earlier, the symmetrical planar waveguide is considered, which has the same refractive indices on the upper and lower cladding. If these indices are somewhat different, \( n_2 \neq n_3 \), an asymmetrical planar waveguide occurs. It can be analysed using the same approach as the symmetrical planar waveguide, however, this time there will be two different terms for the phase shift upon reflection since the phase change on reflection will not be the same on both the upper and lower boundary. Consequently, the eigenvalue equations for both TE and TM polarisation for the asymmetrical planar waveguide will take the form of:

For TE polarisation:

\[
[k_0 n_1 \cos \theta_1 - m \pi] = \tan^{-1} \left[ \frac{\sqrt{\sin^2 \theta_1 - \left( \frac{n_2}{n_1} \right)^2}}{\cos \theta_1} \right] + \tan^{-1} \left[ \frac{\sqrt{\sin^2 \theta_1 - \left( \frac{n_3}{n_1} \right)^2}}{\cos \theta_1} \right]
\] (3.39)

For TM polarisation:

\[
[k_0 n_1 \cos \theta_1 - m \pi] = \tan^{-1} \left[ \frac{\sqrt{\left( \frac{n_1}{n_3} \right)^2 \sin^2 \theta_1 - 1}}{\left( \frac{n_2}{n_1} \right)^2 \cos^2 \theta_1} \right] + \tan^{-1} \left[ \frac{\sqrt{\left( \frac{n_1}{n_3} \right)^2 \sin^2 \theta_1 - 1}}{\left( \frac{n_2}{n_1} \right)^2 \cos^2 \theta_1} \right]
\] (3.40)

The above equations can again be solve either graphically or numerically to obtain the propagation angle, \( \theta_1 \), for a given value of \( m \). It is important to note that the critical angle
for the waveguide as a whole will be determined by the larger critical angle of the two boundaries in order for the mode to be confined within the waveguide.

### 3.2.9 Propagation Constant and Effective Index of a Mode

Earlier, the propagation constant of a wave within the planar waveguide has been illustrated by disintegrating into two components in its $y$ and $z$ direction. As before, these two components are given as:

$$k_z = n_i k_o \sin \theta_i$$  \hspace{1cm} (3.41)

$$k_y = n_i k_o \cos \theta_i$$  \hspace{1cm} (3.42)

In this instance, the propagation constant in the $z$-direction $k_z$ representing the rate at which the wave transverses down the waveguide is of much interest. Hence, it can be denoted as:

$$\beta = k_z = n_i k_o \sin \theta_i = k_o N$$  \hspace{1cm} (3.43)

In a SOI structure, where the upper cladding usually has a lower refractive index than the lower cladding, and the minimum possible value of the upper cladding is air with a refractive index of 1. This suggests that the total internal reflection is governed by the lower cladding, which is the oxide layer having a refractive index of 1.5. Thus, $\theta_i \geq \theta_t$, which then allows to place restrictions on $\beta$. I.e.

$$\beta \geq n_i k_o \sin \theta_c = k_o n_2$$  \hspace{1cm} (3.44)

The upper cladding critical angle $\theta_c$ is clearly needed to be $90^\circ$. Hence, a range of allowable discrete effective propagation constants can be identified, yielding the condition of:

$$k_o n_1 \geq \beta \geq k_o n_2$$  \hspace{1cm} (3.45)
Similarly, a range of discrete effective indices, $N$ can be defined as:

$$n_1 \leq N \leq n_2$$

(3.46)

### 3.2.10 Complex Refractive Index and Complex Propagation Constant

Thus far, the refractive index discussed is regarded as a real quantity. In general, the refractive index is complex, having both the real and imaginary parts. The complex form of the refractive index, $n'$ is given by:

$$n' = n_R + jn_I$$

(3.47)

$n_R$ is the real component of the index of refraction; often referred to as the refractive index and $n_I$ corresponds to the imaginary component which defines absorption. The refractive index can be related to the propagation constant. Considering the general mathematical form of the electromagnetic waves equation (3.16) and the propagation constant, $k$, this is given as:

$$k = nk_0$$

(3.48)

The complex refractive index, $n'$ can be included to yield:

$$E = E_0 e^{j(kz - wt)} = E_0 e^{j(k_R n_R z + k_I n_I z)} e^{-jw t}$$

(3.49)

$$= E_0 e^{-k_R n_R z} \cdot e^{j(k_I n_I + k_R n_R)z} \cdot e^{-jw t}$$

(3.50)

The three exponential terms in equation (3.43) correspond to absorption, propagation, and time dependence of a wave in the waveguide. The significance of the real and imaginary parts should be obvious. The real part defines the propagation of a wave and the imaginary part defines the changes in intensity, or absorption. The time dependence is usually ignored since it is assumed that the wave oscillates at frequency, $w$, and does not change with time. Thus, the expression in equation (3.43) can be re-written as:
where $k_z$ is the propagation constant and is denoted as $\beta$, in the case of a waveguide. The term $\alpha$ is the loss coefficient. The factor of $\frac{1}{2}$ is included in the definition above because, by convention, $\alpha$ is the intensity loss coefficient. Hence, the intensity, $I$, decays with propagation through the material with refractive index, $n'$ and is given as:

$$I = I_0 e^{-\alpha z}$$ \hspace{1cm} (3.52)

Having defined the loss coefficient, $\alpha$, the different types of losses associated with an integrated optical waveguide should be considered to form a relationship between measurable properties. Whilst there is no absolute threshold that makes a particular material technology acceptable, the loss for a wave guiding material is set at a benchmark in the order of $1 \text{ dB/cm}$. The reason behind this assumption is due to the small scale of the integrated optical circuit, typically a few centimetres in length. A $3\text{dB}$ loss will correspond to a halving of the optical power, hence it is clear that a loss of more than a $\text{dB}$ will seriously deteriorate the signal to noise ratio at the detector. Losses for SOI waveguides are typically in the range of $0.1-0.5 \text{ dB/cm}$ [3.4-3.5].

### 3.3 Losses in Optical Waveguides

As from the previous section, it is clearly shown that a wave propagating through a material with initial intensity is attenuated with distance, $z$. This loss is often quoted in units of $\text{dB/cm}$ and is defined as the ratio of transmitted to incident intensity, or power given as:

$$Loss = 10 \log \left( \frac{I_{\text{out}}}{I_{\text{in}}} \right)$$ \hspace{1cm} (3.53)
The expressions of equations (3.52) and (3.53) for loss are then related as:

$$\alpha_{db} = \frac{10}{\ln 10} \alpha$$

(3.54)

where $\alpha_{db}$ has units of dB/cm and $\alpha$ has units of cm$^{-1}$. The total loss factor typically originates from a number of sources, namely scattering, absorption, and radiation the degree of which depends on the fabrication tolerances and material properties.

### 3.3.1 Scattering Loss

There are two types of scattering loss in an optical waveguide:

1. **Volume Scattering**
2. **Surface Scattering**

The imperfection within the volume of the waveguides, such as voids, contaminant atoms and crystalline defects are the main contributors to volume scattering. The loss per unit length due to volume scattering is proportional to the number of imperfections per unit length. Also, the volume scattering loss depends very much on the relative size of the imperfections, as compared to the wavelength of light in the material. One could reasonably be concerned that volume scattering could be the sole contributor to optical loss in SOI since the fabrication technique of achieving the flat spectral AWG via ion implantation, which will be discussed in a later section, contained the potential for the introduction of defects if the implantation parameters are not carefully selected.

The other form of scattering needed to be considered is the surface scattering. An uneven roughness at the waveguide surface or interface can lead to optical loss. However, in a good quality optical material, such scattering maybe found at the boundaries of the waveguide. At an uneven waveguide edge, the optical field will experience an irregular change in refractive index, and thus this could lead to a portion of the guided optical
mode being scattered out of the waveguide. One of the simplest ways to evaluate surface scattering is by following an approximate technique introduced by Tien [3.6]. The theory of his technique is based upon the specular reflection of power from a surface and it holds for long correlation lengths of the surface roughness, which is a reasonable assumption in most cases. If the incident beam has power $P_i$, the specular power, $P_s$, from a surface is given by: [3.3]

$$P_s = P_i \exp\left[-\left(\frac{4\pi \sigma n_l \cos \theta_i}{\lambda}ight)^2\right] \quad (3.55)$$

where $\sigma$ is the variance of the surface roughness (or rms roughness), $\theta_i$ is the propagation angle within the waveguide, and $n_l$ is the refractive index of the core. By considering the total power flow over a given distance, together with the loss at both waveguide interfaces based upon equation (3.55), Tien shows that a waveguide of index, $n_l$ with thickness variations $\Delta t$, has a scattering component given by:

$$\alpha_{sc} = \frac{\cos^3 \theta}{2t_{eff} \sin \theta} \left(\frac{4\pi \Delta t n_l}{\lambda_o}\right)^2 \quad (3.56)$$

$t_{eff}$ is the effective waveguide thickness and is given as:

$$t_{eff} = (t + k_{u}^{-1} + k_{l}^{-1}) \quad (3.57)$$

where $t$ is the physical width and $k_{u}$ and $k_{l}$ are the y-directed decay constants in the upper cladding and lower cladding respectively. It can be noted from equation (3.56) that scattering loss increases with larger roughness (with respect to wavelength), and also, higher order modes, with smaller incident angles $\theta_i$ are also more prone to scattering losses, which is expected since they interact more with the boundary than lower order modes.
3.3.2 Absorption

Absorption loss in a semiconductor is significant mainly due to the inter-band (band-edge) absorption and free carrier absorption. Photons with energy greater than the bandgap energy are strongly absorbed in order to raise their electrons from valence band to the conduction band. Hence, to avoid inter-band absorption, a wavelength which is longer than the absorption edge wavelength of the waveguiding material must be used. A classical example is the use of silicon, the band edge wavelength of silicon is approximately 1.1μm, above which silicon is used as a waveguide material. For wavelengths shorter than 1.1μm silicon absorbs very strongly, and is one of the most commonly used materials for photodetectors both in the visible and very short infra-red wavelengths.

The band edge absorption of silicon does not mark an abrupt transition from strong absorbence to transparence, at a wavelength of λ = 1.15μm, it suffers an attenuation of 2.83 dB/cm [3.7], if it shifts to a higher wavelength of λ = 1.52μm, the attenuation reduces to 0.004 dB/cm [3.8]. Thus, it can be concluded that, silicon waveguides should suffer negligible band edge absorption, providing a suitable wavelength of operation is chosen.

Free carrier absorption, sometimes called intraband absorption, occurs when a photon gives up its energy to an electron already in the conduction band, or to a hole in the valence band, thus raising it to a higher energy. This form of absorption may be significant in semiconductor waveguides. The concentration of free carriers will affect both the real and the imaginary refractive indices. In this project, for devices fabricated in silicon, alteration of an optical field in an AWG is done deliberately by the introduction of free carrier absorption to achieve a flat spectral response, an effect which forms the backbone of this thesis.
An expression for the absorption coefficient, $\alpha$, due to free carriers can be derived from classical electromagnetic theory. Changes in absorption in silicon can be described by the well-known Drude-Lorenz equation [3.9]

$$\Delta \alpha = \frac{e^2 A^2}{4\pi^2 c^3 \varepsilon_0 n} \left( \frac{N_e}{\mu_e (m^*_{ce})^2} + \frac{N_h}{\mu_h (m^*_{ch})^2} \right)$$

(3.58)

where $e$ is the electronic charge; $c$ is the velocity of light in a vacuum; $\mu_e$ is the electron mobility; $\mu_h$ is the hole mobility; $m^*_{ce}$ is the effective mass of electrons; $m^*_{ch}$ is the effective mass of holes; $N_e$ is the free electron concentration; $N_h$ is the free hole concentration; $\varepsilon_0$ is the permittivity of free space and $\lambda_o$ is the free space wavelength.

### 3.3.3 Radiation Loss

Optical energy can be lost from waveguide modes by radiation, in which case photons are emitted into media surrounding the waveguide and are no longer guided. Radiation loss from a straight optical waveguide should ideally be negligible. This type of loss implies coupling from the waveguide into the surrounding media, typically the upper or lower cladding, or for a rib waveguides, into the planar region adjacent to the guide. If the waveguide is well-designed, radiation loss will not normally be significant, however in some situations; scattering may lead to mode conversion, the transfer of energy from a lower to a higher order mode that is beyond cutoff, so that some modal energy can be lost by radiation. However, radiation losses can become significant for curved waveguides.

### 3.3.3.1 Radiation Loss from Curved Waveguides

In an integrated optical circuit, it is essential to interconnect various components via the use of optical waveguides to transmit information from point to point. The flexibility of this two-dimensional waveguide structure is maximised when they can be routed at will across the surface of the wafer. The ability to change the direction of the guided optical
mode is essential, and this is often accomplished by the use of a waveguide curve. Marcatili and Miller [3.10] have developed a convenient way of analysing radiation loss using the velocity approach, which stated that the tangential phase velocity of waves in the curved waveguide must be proportional to the distance from the centre curvature, otherwise the phase front would not be preserved. Consider figure 3.6, a curve with radius $R$, where it is assumed that a waveguide mode propagating in this circular bend, with a propagation constant, $\beta_z$. At a radius beyond $(R + X_r)$ the phase velocity would have to exceed the velocity of unguided light to preserve the phase front. As a result, the optical field loses energy to radiation. Based on considerations that the entire optical field, for all $R$, must rotate with the same $\frac{\partial \theta}{\partial t}$, consequently, producing the following two equations [3.3]:

\[
(R + X_r) \frac{d\theta}{dt} = \frac{w}{\beta_0} \tag{3.59}
\]

and

\[
R \frac{d\theta}{dt} = \frac{w}{\beta_0} \tag{3.60}
\]

where $\beta_0$ is the propagation constant of unguided light in free space, and $\beta_z$ is the propagation constant in the waveguide at radius $R$.

![Figure 3.6 Diagram illustrating the velocity approach to the determination of radiation loss [3.3].](image-url)
They demonstrated that the curvature radiation losses are of the form:

\[ \alpha = C_1 e^{(-C_2 R)} \]  

(3.61)

where \( C_1 \) and \( C_2 \) are constants that depend on the dimension of the waveguide, and on the shape of the optical mode given as:

\[
C_1 = \frac{\cos^2(k_x g w) \lambda_0 e^{2k_x g w}}{4k_x g n_{L2} w^2 \left[ w + \frac{1}{2k_x g} \sin(2wk_x g) + \frac{1}{k_x L} \cos^2(wk_x g) \right]} \]

(3.62)

and

\[
C_2 = 2k_x L \left( \frac{\lambda_0 \beta}{2\pi n_L} - 1 \right) \]

(3.63)

where the various parameters come from a two-dimensional solution of the waveguide; \( \beta \) is the z-directed propagation constant, \( k_x g \) is the x-directed propagation constant in the waveguide, and \( k_x L \) is the decay constant outside the rib, which has a width of 2\( w \). The loss coefficient, \( \alpha \), and radius, \( R \), have an exponential relationship, which implies a sensitive relationship of loss to radius. Thus a large value of \( R \) is usually chosen. The loss is also a critical function of \( k_x L \), which stipulates good lateral confinement and thus small lateral decay constant, for low curve losses. These two parameters; radius and confinement, can be traded off against one another; for example deeply etched waveguides result in a strongly guided mode that can be bent at smaller radii for equivalent losses.
3.4 Coupling

Once optical devices have been fabricated, it is understood that one must get light in and out of the device. Coupling of light to such devices is conceptually trivial, but in practice is a non-trivial problem. This is because the optical waveguides/devices are usually a few micrometers in either cross sectional dimension. The methods that are employed for coupling an optical beam between two waveguides are different from those used for coupling an optical beam in free space to a waveguide. Also, some couplers selectively couple energy to a given waveguide mode, while others are multimodal. Several methods are available, with the most common types being butt-coupling, end-fire coupling, and grating coupling. Each method has its own advantages and disadvantages; none is superior for all applications, hence knowledge of coupler characteristics is necessary to select the optimum approach for the intended applications.

For any coupler, the principal characteristics are its efficiency and its mode selectivity. Coupling efficiency is usually given as the fraction of total power in the optical beam, which is coupled into, or out of the waveguide. Coupling loss is usually specified in dBs. Therefore, the basic definition of coupling efficiency is given by:

$$n_{cm} = \frac{\text{power coupled into (out of) the } m^{th} \text{ order mode}}{\text{total power in optical beam prior to coupling}}$$

(3.64)

and the coupling loss (in dB) is defined as:

$$L_{cm} = 10\log\frac{\text{total power in optical beam prior to coupling}}{\text{power coupled into (out of) the } m^{th} \text{ order mode}}$$

(3.65)
3.4.1 Butt Coupling

The simplest form of coupling is the placement of the source as close as possible to the end of a waveguide as shown in figure 3.7 [3.1] below:

![Figure 3.7 Showing butt coupling between a semiconductor laser and a semiconductor waveguide](image)

The cleaved laser facet is placed in close proximity to a polished waveguide facet separated by distance, \(d \leq 1\mu m\). This approach is useful when two devices of similar structure, either two waveguides [3.11-3.12] or a semiconductor laser to a semiconductor waveguide, are required. Also, the involvement of small dimensions and the necessary lateral and transverse tolerance in the waveguiding structure usually required piezo-driven mounts in order to achieve higher efficiency. The efficiency of coupling a light source into a waveguide by this technique depends on numerous factors; firstly the spacing, \(d\), between the laser source and the waveguide, this must be minimised due to the uncollimated beam with a large divergence angle \(\approx 40^\circ\), emitted from the semiconductors laser and waveguides. Secondly, the precise control of the lateral and transverse position, since the SOI waveguide layers are often only a fraction of a micron thick. Thirdly, in the absence of anti-reflection coatings, the Fresnel reflectance at each surface presents a fundamental constraint, since only a small amount of the incident
power is transmitted into the waveguide. In addition, the reflected power from the waveguides might pose a problem to the laser sources stability. Finally, because of the two reflective surfaces, a Fabry-Perot cavity might form. The transmission will oscillate through minima and maxima as, $d$ varies. Hence, this places a further requirement on the physical positioning.

3.4.2 End-fire Coupling

End-fire coupling, involves the focusing of an external source by means of bulk optics onto the cleaved facets of a semiconductor, in our case, silicon. It has proven to be a practical technique of evaluating the waveguides structure in a laboratory environment. In practise, a microscope objective is often used to focus the external laser onto the waveguide facet; alternatively tapered fibres can also be used as illustrated in figure 3.8.

![Figure 3.8 End-fire coupling](image)

Figure 3.8 End-fire coupling; (a) External laser source to semiconductor waveguide; (b) Tapered fibre to semiconductor waveguide
End-fire coupling retains a good deal of flexibility because non-semiconductor laser sources can be coupled into waveguides. However, the optics must mount on the optical bench to eliminate vibrations. The transfer of beam energy to a given waveguide mode is accomplished by matching the beam-field to the waveguide mode field. The coupling efficiency can then be calculated from the overlap integral of the field pattern of the incident beam and the waveguide mode. Similar factors in determine the coupling efficiency for butt coupling needs to be considered for end-fire coupling. Again, Fresnel reflectivity constraints the maximum efficiency achievable; however the deployment of optical isolation technique might reduce both the problem of reflection into the laser source and the disturbance of Fabry-Perot oscillations.

3.4.3 Grating Coupler

An alternative way of getting light in and out of the waveguides is the use of grating coupler, which can be formed by etching the waveguides surface itself as illustrated in figure 3.9. In order to couple light into a waveguide mode, it is necessary to produce a phase matching condition between a particular waveguide mode and an unguided optical beam which is incident at an oblique angle to the surface of the waveguides (the components of the phase velocities in the direction of propagation must be the same).
Because of its periodic nature, the grating causes a periodic modulation of the effective index of the waveguide, hence, causing each of the waveguide modes in the region beneath the grating to have a set of spatial harmonics with z-direction propagation constants given by:

\[ \beta_p = \beta_n + \frac{2p\pi}{\Lambda} \quad (3.66) \]

where \( p = \pm 1, \pm 2, \pm 3, \ldots \) and \( \Lambda \) is the period of the grating. In order to satisfy the phase matching condition \[3.2\] given as:

\[ \beta = k_0 n_3 \sin \theta_a \quad (3.67) \]

It is clear that the propagation constants corresponding to positive values of \( p \) in the equation (3.66) cannot exist in the waveguides due to the fact the propagation constant \( \beta_p \) will be less than \( k_0 n_3 \). Hence, only the negative values of \( p \) can satisfy the phase matching condition. To date, very little work on grating couplers has been carried out in SOI, mainly due to the fabrication difficulties. The highest coupling efficiency gratings in SOI have been reported by Ang et al [3.13]. They showed that the coupling efficiency was approximately 70% and 84% for rectangular and blazed gratings respectively [3.14]. The advantage of such a coupler is that, once fabricated, it is an integrated part of the waveguide structure. Hence, its coupling efficiency remains constant and is not altered significantly by vibration or ambient conditions.
3.5 Arrayed Waveguide Grating (AWG) Theory

3.5.1 Phenomenon of Light Propagation

In the first part of this section, phenomena in the propagation of light are described in preparation for subsequent sections. Two important theories will be discussed; the theory of interference and the theory of Fraunhofer diffraction. These theories will help facilitate the understanding of the effect of light propagation within the free space region of the AWG. First, we will begin by describing Young’s experiment [3.15], the earliest arrangement for demonstrating the interference of light. Then with a more detailed description involving multiple interferences, we will see how the variation of different coherent sources and phases affects the interference pattern at an image plane. We will then look at a more complex theory, the Fraunhofer diffraction, which explains the limiting cases where light approaching the diffracting object is parallel and monochromatic, and where the image plane is at a large distance compared to the diffracting object. In general, interference and diffraction effects occur simultaneously when several wave systems propagate at the same time through the region of interest. Throughout our discussion, we assumed that the medium of propagation is in free space with refractive index, \( n = 1 \). In the case of an SOI slab region, this refractive index is simply replaced by the refractive index of silicon, \( n = 3.5 \).

3.5.1.1 Interference

Consider figure 3.10, where two monochromatic point sources, \( P_1 \) and \( P_2 \) are separated by a distance, \( d \) and are placed at a distance, \( a \), away from the image plane which is formed by the rectangular coordinate, \((x, y)\). For a point \( R(x, y) \) in the plane of observation, the optical path length of \( p_1 \) and \( p_2 \) are given as [3.15]:

\[
p_i = PR = \sqrt{a^2 + y^2 + \left(x - \frac{d}{2}\right)^2}
\]  

(3.68)
and

\[ p_2 = p_2R = \sqrt{a^2 + y^2 + \left(x + \frac{d}{2}\right)^2} \]  

(3.69)

Hence, the optical path length difference between \( p_1 \) and \( p_2 \) may then be expressed as:

\[ \Delta p = p_2 - p_1 = \frac{2xd}{p_2 + p_1} \]  

(3.70)

Figure 3.10 Young’s experiment; illustrating interference with two point sources [3.15]

If the distance, \( d \) is much smaller than the distance \( a \), and also provided that \( x \) and \( y \) are small compared to \( a \), then, the total path length of \( p_1 \) and \( p_2 \) can be approximated by \( 2a \).

\[ \Delta p = \frac{xd}{a} \]  

(3.71)

If the light is propagating in a medium with refractive index, \( n \), then the optical path difference between \( p_1 \) and \( p_2 \) is therefore given by:

\[ \Delta P = n\Delta p = \frac{nxd}{a} \]  

(3.72)
with the corresponding phase difference given as:

\[ \Delta \phi = \frac{2 \pi \, n x d}{\lambda_0 \, a} \]  \hspace{1cm} (3.73)

If we now consider these two sources, represented by their electric vector \( E_1 \) and \( E_2 \), when these waves interfere after travelling along different paths, at some general point \( R \), the waves intersect to produce a disturbance whose electric field, \( E_p \), [3.16] is given by the superposition of these waves, thus:

\[ E = E_1 + E_2 \]  \hspace{1cm} (3.74)

If \( E_1 \) and \( E_2 \) are represented by:

\[ E_1 = A_1 \sin(wt - k z + \phi_1) \]  \hspace{1cm} (3.75)

\[ E_2 = A_2 \cos(wt - k z + \phi_2) \]  \hspace{1cm} (3.76)

Hence, the sum of \( E_1 \) and \( E_2 \) is given as:

\[ E_1 + E_2 = A_1 \sin(wt - k z + \phi_1) + A_2 \sin(wt - k z + \phi_2) \]  \hspace{1cm} (3.77)

If the above equation is rearranged into:

\[ E = (A_1 \cos \phi_1 + A_2 \cos \phi_2) \sin(wt - k z) \]

\[ + (A_1 \sin \phi_1 + A_2 \sin \phi_2) \cos(wt - k z) \]  \hspace{1cm} (3.78)

This equation of (3.77) will yield the form of:

\[ E = E_p \sin(wt - k z + \phi) \]  \hspace{1cm} (3.79)
only if:

\[ E^2 = (A_1 \cos \phi_1 + A_2 \cos \phi_2)^2 + (A_1 \sin \phi_1 + A_2 \sin \phi_2)^2 \]  \hspace{1cm} (3.80)

or

\[ E^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\phi_2 - \phi_1) \]  \hspace{1cm} (3.81)

Equation (3.81) shows that resultant is not just the sum of the amplitude of the two waves, but with an interference term that depends on the phase of \( \phi_1 \) and \( \phi_2 \). This resultant can be represented by its radiant power density, or intensity, \( I \) (W/m\(^2\)), which measures the time average of the square of the wave amplitude, \( I = E^2 \). I.e. equation (3.81) can also be expressed as:

\[ I = I_1 + I_2 + 2\sqrt{I_1I_2} \cos \Delta \phi \]  \hspace{1cm} (3.82)

By equation (3.82), it is noted that there will be a maxima of intensity when the phase difference, \( |\Delta \phi| \), is a multiple of \( 2m\pi \), where \( m \) is an integer, and can be extended for \( n \) coherent sources, and the final intensity can be shown as [3.17]:

\[ I_p = \sum_{h=1}^{n} I_h + \sum_{k=1}^{n-1} \sum_{n=k+1}^{n} \sqrt{I_kI_m} \cos \Delta \phi_{mn} \]  \hspace{1cm} (3.83)

where \( I_p \) is the total intensity at point \( p \) on a parallel virtual screen, a fixed distance from the sources of intensity \( I_1...I_n \) and \( \Delta \phi_{mn} \) representing the phase difference between the sources of intensities \( I_k \) and \( I_m \) evaluated at the point \( p \) as illustrated in figure 3.11, below. Based on this model, we developed a 2-D computer model to calculate the interference intensity for five and ten coherent sources respectively. The interference pattern is shown in figure 3.12.
Figure 3.11 Illustrating interference pattern for multiple sources [3.17]

Figure 3.12 Interference patterns of 5 and 10 coherent sources
It is noted that the principal peaks increase in intensity with the square of the sources as expected, when the phase difference, $\Delta \phi$, is equal to $2\pi n$. If we introduced an additional phase shift between adjacent sources equivalent to a fixed change in path length, $\Delta L$, then the phase shift will vary with wavelength of operation. Since the phase shift is given by the propagation constant, $\beta$, multiplied by the path length which is given as:

$$\Delta \phi = \beta \cdot \Delta L$$  \hspace{1cm} (3.84)

Consider the effect of interference patterns of an array of 10 coherent sources as illustrated in figure 3.13. Assuming that the intensity is constant for all sources and a phase difference is introduced between the adjacent sources. Imagine that each phase difference is caused by the different in path length, $\Delta L$, as in the case of the AWG. Hence, the principal peaks will steer along different positions of the virtual screen. In conclusion, the AWG makes use of this property of light to differentiate the wavelengths being transmitted in the system.

![Figure 3.13 Principal peaks steered with the variation of phase](image)
3.5.1.2 Fraunhofer Diffraction

In the preceding section, the principle mechanism of the AWG has been discussed, which exploits the interference property of light. However, the focal length of the slab region is usually designed to be much larger than the array waveguides separation. Hence, a 'far-field' diffraction occurs, namely, Fraunhofer diffraction.

Consider the coordinate system as shown in figure 3.14 where the endface of the waveguides is located at $z = 0$ and the radiation field is propagating through the free space with a refractive index $n$.

The radiation pattern $f(x, y, z)$ is related to the endface $g(x_0, y_0, z_0)$ by Fresnel-Kirchhoff [3.18] diffraction as:

$$f(x, y, z) = \frac{jk n}{2\pi} \int \int \int g(x_0, y_0, 0) \frac{1}{r} e^{-j kr} dx_0 dy_0$$

(3.85)

where $k$ is given as $2\pi/\lambda$ and $r$, the distance between $Q$, the location of source point, and $P$, the point where the field is observed (see figure 3.14), given as:
when the distance of the observation plane \( z \) is very large compared with \(|x - x_0|\) and \(|y - y_0|\). Then equation (3.86) can be approximated by:

\[
r = z \left[ 1 + \frac{(x - x_0)^2 + (y - y_0)^2}{z^2} \right]^{1/2}
\]

\[
= z + \frac{(x - x_0)^2 + (y - y_0)^2}{2z} + \ldots
\]

The fourth terms on the RHS can be neglected because the optical field is confined in a small area of the order < 10\(\mu\)m, and the distance of \( z \), which in the case of the AWG represents the focal length of the free space region is 1500\(\mu\)m. When we apply the Fraunhofer approximation to \( r \), equation (3.85) reduces to:

\[
f(x, y, z) = \frac{jkn}{2\pi z} \exp \left\{ -jkn \left[ z + \frac{x^2 + y^2}{2z} \right] \right\} \times \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(x_0, y_0, 0) \exp \left\{ jkn \frac{(xx_0 + yy_0)}{z} \right\} dx_0 dy_0
\]
diagram below is considered and the distance $D$ is much larger than the aperture width $a$, then the Fraunhofer criterion is then given by:

$$D \gg a^2/\lambda$$  \hspace{1cm} (3.89)

![Figure 3.15 Single slit Fraunhofer diffraction](image)

If the Fraunhofer criterion is met, the angle $\theta = \theta$ and using small angle approximation, where $\tan \theta \approx \sin \theta \approx \theta$. This yields the following condition.

$$\theta = \frac{y}{D}$$  \hspace{1cm} (3.90)

According to Huygens assumption, each wavefront element behaves like a point source, hence each amplitude displacement has a constant phase displacement from the next. Imagine these point sources advancing in some direction making an angle $\theta$. The path length difference between the top and the bottom elements of the slits is $a \sin \theta$. Hence the phase difference between the extreme edge rays is given as:

$$\delta = 2\pi \frac{a \sin \theta}{\lambda}$$  \hspace{1cm} (3.91)
Imagine the slit to be divided, parallel to its length, into a large number of narrow strips, all of the same width. The whole slit is uniformly illuminated; the strips are of equal area, so the amplitude of the contribution from each strip in a given direction $\theta$ is the same. The amplitude contribution of each point source can be easily calculated using the phase-amplitude diagram as shown in figure 3.16. At this point, it is convenient to use the point $C$ as illustrated in figure 3.15 as the reference baseline for the phasor. In figure 3.16(a) the phasor for the light from this strip is labelled $C'$. The phase of the light from the adjacent strip below $C$ in figure 3.15 lags behind that from $C$, and that from the adjacent strip above $C$ is ahead of that from $C$. In the phasor diagram these are added to $C'$ accordingly, as are pairs from strips further and further away from $C$, until the contributions from all the strips have been included. $R$ is the resultant given by this construction, but to obtain an accurate value we need a phasor diagram which represents the limit when the strips become infinitesimally narrow. The transition is easily made. First we note that the present phasor diagram resembles part of a regular polygon because the phasors are of equal length, and they rotate through equal angles. As previous discussed, the phase difference between the extreme edge rays is given by $\delta$. Thus, the light from $A$ has a phase ahead of that from $C$ by an amount of:

$$\alpha = \frac{\delta}{2}$$  \hspace{1cm} (3.92)

and the phase from $B$ lags behind $A$ by $\alpha$. Therefore, it is clear that if the light leaves half way between $C$ and $B$, the phase lag is $\alpha/4$ and so on. In the limit when the strip widths are reduced to zero the phasors form an arc of a circle with radius $r$, as shown in figure 3.16(b) and the resultant amplitude, $R_1$, is given by:

$$R_1 = 2r \sin \alpha$$  \hspace{1cm} (3.93)

The arc $A'B'C'$, of length $r\cdot\delta$, is equal to the total length of all phasor elements stretched out in a straight line, as in figure 3.16(c). This straight line represents the phasor diagram.
FRAUNHOFER DIFFRACTION

for $\theta = 0$ direction. There will be no path differences and all the contributions are in phase with that from C. I.e:

$$R_r(0) = r \cdot \delta$$  \hspace{1cm} (3.94)

Substituting the above equation into equation (3.93) yields:

$$R_r = R_r(0) \left[ \frac{\sin \alpha}{\alpha} \right]$$  \hspace{1cm} (3.95)

Figure 3.16 Single slit diffraction: Phasor diagrams [3.19]

In the propagation of light, both the interference and Fraunhofer diffraction will occur concurrently, if these phenomena are combined, under the Fraunhofer conditions specified earlier, the resultant intensity for multiple coherence sources will be the interference pattern multiplied by the single slit diffraction enveloped as shown in figure 3.17, and intensity for multiple coherent sources can be obtained by:
where \( m \) is the grating order, \( N \) is the number of sources.

Figure 3.17 Multiple slits diffraction patterns
3.5.2 Principle of Arrayed Waveguide Gratings

The Arrayed Waveguide Gratings (AWG) is used in Wavelength Division Multiplexing (WDM) optical communications systems. In such systems, different wavelengths are transmitted on a single optical fibre, hence the need to multi/demultiplex multiple wavelengths has gained the AWG significant popularity due to its low insertion loss, high stability, high wavelength selectivity and good mass producibility. The AWG has proven itself to be very flexible, being utilised in a number of configurations. The generic schematic diagram of the AWG is shown in figure 3.18 and the principle of operation is outlined as follows.

An AWG comprises two slab regions (planar waveguides), which acts as passive star couplers, and an array of rib waveguides, of progressively increasing length. The increasing lengths typically introduce phase differences between adjacent waveguides of $2\pi n$ at the centre wavelength.

![Figure 3.18 Schematic Diagram of AWG [3.18]](image-url)
The first planar region is to excite the array of waveguides, and the second planar region is to allow multiple beam interference from the outputs of the array waveguides. If a single wavelength is introduced into one of the input waveguides, this wavelength is distributed to the array of rib waveguides via the first planar region. The purpose of the array rib waveguides is simply to add incremental phase shifts to each ray emerging from successive waveguides. This is achieved because each of the array waveguides is slightly longer than its neighbour. Therefore, the increasingly longer waveguides in the AWG introduce increasingly greater phase shifts. The difference in length between adjacent waveguides is kept constant, so that the phase shift 'added' to each successively emerging ray of light is also constant. Hence our wavelength propagates through these waveguides, each ray emerging with the incremental phase shift due to length of the waveguide in question.

In the second planar region, the beams emerging from the array waveguides interfere to produce a pattern with a single principle peak that spatially coincides with one of the output waveguides. If the second wavelength is introduced into the same input waveguides, it will also be distributed to the array of waveguides in the same way as the first wavelength. It will pass through the array of rib waveguides, but will experience a different phase shift through these waveguides, due to the slightly different propagation constant associated with each wavelength. Once again the various components of the second wavelength will interfere in the second planar region resulting in another interference pattern. Due to the slightly different amount of incremental phase for the second wavelength, the interference pattern will have a peak that will occur at a different output waveguide, separating the two wavelengths. Multiple wavelengths can be separated in this way, producing a wavelength demultiplexer, placing each wavelength at a different output waveguide.

Now, consider figure 3.19, an enlarged version of the slab region within the AWG. Assume that both the input and output slab regions within the AWG have the same configuration. If two light beams pass through the (i-1)\textsuperscript{th} and i\textsuperscript{th} array waveguides. The total phase delay of these two light beams must be an integer of $2m\pi$ in order for
constructive interference to take place (section 3.5). Hence this interference condition can be written as [3.18]:

\[
\beta_s(\lambda_o)\left(R_m - \frac{d_{in}x_{in}}{2R_m}\right) + \beta_{aw}(\lambda_o)(L_c + (i-1)\Delta L) + \beta_s(\lambda_o)\left(R - \frac{dx}{2R}\right) = \\
\beta_s(\lambda_o)\left(R_m + \frac{d_{in}x_{in}}{2R_m}\right) + \beta_{aw}(\lambda_o)(L_c + i\Delta L) + \beta_s(\lambda_o)\left(R - \frac{dx}{2R}\right) - 2m\pi
\]

where \(\beta_s\) and \(\beta_{aw}\) are the propagation constant of the slab and the waveguides, respectively. \(\lambda_o\) is the centre wavelength, \(d_{in}\) and \(d\) are the separation of the input Array Waveguides (AW) and output AW respectively, and \(x_{in}\) and \(x\) are the separation of the input waveguides and output waveguides. \(R_m\) and \(R\) are the focal length of the input and output slab.

![Figure 3.19 Enlarged view of the slab region [3.18]](image-url)
The above equation can be further simplified by subtracting the common terms, hence this yields:

\[
\beta_z(\lambda_0) \frac{d_{in} x_{in}}{R_{in}} - \beta_z(\lambda_0) \frac{dx}{R} + \beta_{aw}(\lambda_0) \Delta L = 2m\pi
\]  

(3.98)

If the condition of \( \beta_{aw}(\lambda_0) \Delta L \) is equal to a multiple of \( 2\pi \), we can rearrange equation (3.98) as:

\[
\lambda_0 = \frac{n_{aw} \Delta L}{m}
\]

(3.99)

where \( m \) is an integer, usually referred to as the diffraction (grating) order and \( n_{aw} \) is the effective index of the AW. If the above condition holds, light emerging at \( x \) can be determined by the position of \( x_{in} \), simply by:

\[
\frac{d_{in} x_{in}}{R_{in}} = \frac{dx}{R}
\]

(3.100)

### 3.5.2.1 Dispersive Characteristic of AWG

Another characteristic of AWG is its dispersive property. According to figure 3.20, the dispersion angle, \( \theta \), resulting from a phase difference, \( \Delta \phi \), between adjacent waveguides can be described by [3.20]:

\[
\theta = \sin^{-1} \left[ \frac{\left( \Delta \phi - 2m\pi \right) / \beta_{aw}}{d} \right] = \frac{\Delta \phi - 2m\pi}{\beta_{aw} d}
\]

(3.101)

This means, the angular dispersion, \( \delta \theta \), of the AWG can be obtained by differentiating equation (3.101) with respect to \( \lambda \), thus:

\[
\frac{\delta \theta}{\delta \lambda} = -\frac{m}{n_{aw} d}
\]

(3.102)
$n_{aw}$ is the effective index of the array waveguides. The angular dispersion can be described as the lateral displacement of the focal spot along the image plane, as a function of dispersion angle, per wavelength change.

The dispersion of the focal point $x$ with respect to wavelength $\lambda$ for the fixed light input position is given by differentiating equation (3.98), hence:

$$\frac{\Delta x}{\Delta \lambda} = \frac{N_{aw} R A L}{n_s d \lambda_o} \tag{3.103}$$

Likewise the dispersion of the 1st slab region at position $x_{in}$ with respect to the wavelength is given by:

$$\frac{\Delta x_{in}}{\Delta \lambda} = \frac{N_{aw} R_{in} A L}{n_s d_{in} \lambda_o} \tag{3.104}$$

where $N_{aw}$ is the group index and is given by $N_{aw} = n_{aw} - \frac{\lambda}{d} \frac{dn_{aw}}{d \lambda}$, and $n_s$ is the effective index of the slab. If the input and output waveguides separations are given as $|\Delta x_{in}| = D_{in}$.
and $|\Delta x| = D$, then the channel spacing of the AWG can be obtained by substituting these relations in equations (3.103) and (3.104), thus:

$$\Delta \lambda_{\text{out}} = \frac{n_i d D \lambda_0}{N_{\text{aw}} R \Delta L}$$

(3.105)

and

$$\Delta \lambda_{\text{in}} = \frac{n_i d_{\text{in}} D \lambda_0}{N_{\text{aw}} R_{\text{in}} \Delta L}$$

(3.106)

3.5.2.2 Transmission Coefficient of AWG

The operation of AWG can also be understood by its transmission coefficient, which can be described as [3.21]:

$$E_i = \sum_{i=1}^{N} E_o \exp(j\phi_i)$$

(3.107)

$\phi_i$ is the phase of each array waveguide and can be expressed as:

$$\phi_i = \frac{2 \pi n_{\text{aw}} i L}{\lambda_0}$$

(3.108)

where $n_{\text{aw}}$ is the effective index of the array waveguide, $L$ is optical path length and $\lambda$ is the centre wavelength. Equation (3.107) can be expanded into the form below:

$$E_i = E_o \exp(j\phi_1) + E_o \exp(j\phi_2) + ... + E_o \exp(j\phi_n)$$

(3.109)

Substitute equation (3.108) into (3.109)
\[
E_i = E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw} \cdot L}{\lambda} \right) + E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw} \cdot 2 \cdot L}{\lambda} \right) + \ldots \ldots + E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw} \cdot N \cdot L}{\lambda} \right)
\]

\[
E_i = \left[ E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw}}{\lambda} \right) \right] \cdot \left[ 1 + \exp(j \cdot L) + \exp(j \cdot 2 \cdot L) + \ldots \right] \tag{3.110}
\]

The term in the second brackets can be further simplified using geometric series, hence;

\[
E_i = \left[ E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw}}{\lambda} \right) \right] \cdot \left[ \frac{\exp(j \cdot N \cdot L) - 1}{\exp(j \cdot L) - 1} \right]
\]

\[
= \left[ E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw}}{\lambda} \right) \right] \cdot \left[ \frac{\exp \left( \frac{j \cdot N \cdot L}{2} \right) - 1}{\exp \left( \frac{j \cdot L}{2} \right) - 1} \right]
\]

\[
= \left[ E_o \exp \left( \frac{j \cdot 2 \cdot \pi \cdot n_{aw}}{\lambda} \right) \right] \cdot \left[ \frac{\exp \left( \frac{j \cdot N \cdot L}{2} \right) - 1}{\exp \left( \frac{j \cdot L}{2} \right) - 1} \right] \cdot \left[ \frac{\sin \left( \frac{N \cdot L}{2} \right)}{\sin \left( \frac{L}{2} \right)} \right] \tag{3.111}
\]

The intensity at point \( t \), which is the square of \( |E_i|^2 \), is given by;

\[
|E_i|^2 = \left[ \sin^2 \left( \frac{N \cdot L}{2} \right) \right] \cdot \left[ \frac{\sin^2 \left( \frac{L}{2} \right)}{\sin^2 \left( \frac{L}{2} \right)} \right] \tag{3.112}
\]
Assuming all array waveguides have a path length increment of $\Delta L$, which is proportional to the $2m\pi$ phase difference with $N$ equal to the number of array waveguides, the expression of equation (3.113) is obtained:

$$L = \Delta L + (d \cdot \sin \theta) \tag{3.113}$$

From equation (3.98) $\Delta L$ is given as;

$$\Delta L = \frac{m \cdot n_{\text{eff}}}{\lambda} \tag{3.114}$$

Assuming the intensity is distributed equally among each array waveguide, thus $|E_d|^2 = 1$ and together with equation (3.112), (3.113) and (3.114). The total intensity at point $t$ can be expanded into:

$$|E_t|^2 = \left[ \sin^2 \left( \frac{N \cdot \frac{m \cdot n_{\text{eff}}}{\lambda} + (d \cdot \sin \theta)}{2} \right) \right]$$

$$\left[ \sin^2 \left( \frac{\frac{m \cdot n_{\text{eff}}}{\lambda} + (d \cdot \sin \theta)}{2} \right) \right]$$

$$\quad \sin^2 \left( \frac{\frac{m \cdot n_{\text{eff}}}{\lambda} + (d \cdot \sin \theta)}{2} \right)$$

If we now consider a conventional AWG fabricated in SOI having the following parameters [3.22]: $N = 100$, $n_{\text{eff}} = 3.4378$, $\lambda_o = 1.55\mu m$, $d = 4\mu m$ and $\theta = 0^\circ$, the transmission spectrum of such device can be calculated using equation (3.115) and it is noted that such response will exhibit a Gaussian-like response as shown in figure 3.21.

If the above response is projected across a wider range of wavelengths, it can be noted that the AWG holds a periodic property as shown in figure 3.22. In another words, the optical field undergoes a $2m\pi$ phase change and will focus at a different wavelength. This is known as the Free Spectral Range (FSR), and it governs the number of channels which are allowed in an AWG.
Figure 3.21 Typical response of an AWG with 3-dB bandwidth (BW), crosstalk and 20 dB BW

Figure 3.22 Periodicity of an AWG spectral response
At this point, it is worth mentioning that due to this useful property (periodicity) of the AWG, an interesting device known as the Cyclical Wavelength Router can be obtained by designing an AWG with \( N \) input waveguides and \( N \) output waveguides with a free spectral range (FSR) equal to \( N \) times the channel spacing [3.23].

Next, if we vary the grating order, \( m \), a change in the FSR can be observed as illustrated in figure 3.23. It is interesting to note that for \( m = 50 \), resulted in FSR of 30nm and when \( m = 30 \), the FSR = 50nm. Hence, it can be concluded that the greater the grating order, \( m \), the smaller the FSR. Thus, the relationship between the FSR and grating order, \( m \), can be defined by:

\[
FSR = \left\lfloor \frac{\lambda}{m} \right\rfloor
\]  

(3.116)

Figure 3.23 Spectral response of different \( m \)

Thus, the principle and operation of the AWG has been discussed. However, the importance of flat spectral response, polarisation independence and loss has led to the variations in different design consideration.
3.6 Simulation Methods

The fundamental component in SOI is a rib waveguide structure, which requires some effective methods to analyse its optical performance, e.g. singlemode behaviour and birefringence properties. In an SOI AWG that comprises different sub-components; curvilinear, tapered and bent waveguides are indispensable. Light coupling in different regions of the AWG should be taken into account so as to evaluate the propagation characteristics precisely. Two simulation methods will be briefly discussed, which will equip the reader with a basic knowledge behind the theories of the simulated results.

Firstly, the Effective Index Method (EIM) which breaks down a 3-D structure, in this case a rib waveguide, into a 2-D structure to obtain its propagation constant and efficiency when incorporating the Beam Propagation Method (BPM). Secondly, the BPM, which is a powerful tool to investigate lightwave propagation phenomena in axially varying waveguides, such as tapered waveguides, bends and rib waveguides.

3.6.1 Effective Index Method (EIM)

The effective index method is used to find an approximate solution for the propagation constants of two-dimensional waveguides. In this section, we will refer the EIM with a specific example, in this particular case, a rib structure and discuss its methodology.

The previous chapter showed that a rib waveguide structure can be represented by its cross-sectional areas as shown in figure 3.24 with refractive indices \( n_1 \) (overlayer), \( n_2 \) (substrate) and \( n_3 \) (cover), waveguide height \( h \), slab height \( r \) and rib width \( w \). The approach in finding the propagation constants for this waveguide structure is to regard the rib structure as a combination of planar waveguides in their horizontal and vertical direction as shown in figure 3.25. Because of the inconsistency in refractive indices between the height and sides of the core, it is necessary to find the effective index, not only the core but also in the slab regions at either side of the core in the x-direction, prior to solving the decomposed planar waveguide in it verticals direction. However, care must
be taken to consider the polarisation involved. In which, when solving for the decomposed vertical planar structure as shown in figure 3.25a, TE eigenvalue equation has to be used. This will yield effective indices of $n_{effp}$ and $n_{effg}$ for the height of $h$ and $r$ respectively. Likewise for solving for the decomposed horizontal planar structure as shown in figure 3.25b, the TM eigenvalue equation is used. This is best illustrated with a numerical example following the approach of Reed [3.2]
In order to find the effective index $N_{ng}$ of the fundamental mode for the rib waveguide used in this project for the following parameters, assuming TE polarisation.

Table 3.1: Parameters of a SOI rib waveguide.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rib width, $w$</td>
<td>1.1$\mu$m</td>
</tr>
<tr>
<td>Silicon overlayer, $h$</td>
<td>1.5$\mu$m</td>
</tr>
<tr>
<td>Slab height, $r$</td>
<td>0.62$\mu$m</td>
</tr>
<tr>
<td>Refractive index of air, $n_3$</td>
<td>1</td>
</tr>
<tr>
<td>Refractive index of silicon, $n_1$</td>
<td>3.5</td>
</tr>
<tr>
<td>Refractive index of silicon dioxide, $n_2$</td>
<td>1.5</td>
</tr>
<tr>
<td>Operating Wavelength, $\lambda$</td>
<td>1550nm</td>
</tr>
</tbody>
</table>

Firstly, the rib structure is decomposed into its vertical and horizontal planar waveguides as shown in figure 3.25(a) and 3.25(b). Since the polarisation is TE, the asymmetrical TE eigenvalue equation of equation (3.39) has to be used and is given as:

$$[k_o n_1 h \cos \theta_1 - m \pi] = \tan^{-1} \left[ \frac{\sin^2 \theta_1 - \left( \frac{n_3}{n_1} \right)^2}{\cos \theta_1} \right] - \tan^{-1} \left[ \frac{\sin^2 \theta_1 - \left( \frac{n_3}{n_1} \right)^2}{\cos \theta_1} \right]$$  (3.117)

This eigenvalue equation can be solved in a number of ways and is more informative to solve it graphically. The terms of the left hand side and the right hand side are plotted separately as shown in figure 3.26. Solving the above equation yields for $m=0$ yields a propagation angle of 1.434 radians. In section 3.2.9, equation (3.43), the propagation constant, $\beta$, is reproduced here as:

$$\beta = n_t k_o \sin \theta_1$$  (3.118)
Thus, the effective index, \( n_{\text{eff}} \), of the waveguides region is given by:

\[
\frac{\beta}{k_0} = n_i \sin \theta_i \\
= 3.4673
\]  

(3.119)

Now, we need to solve the second decomposed planar waveguides, this time for a waveguide height of \( r = 0.62\mu m \) using the asymmetrical TE eigenvalue equation and is shown in figure 3.26. This gives us a propagation angle of 1.282 radians, and an effective index, \( n_{\text{eff}} \), of 3.3551.

---

**Figure 3.26 Solution of the TE eigenvalue equation for \( m = 0 \)**
Having obtained both the effective indices for the decomposed planar waveguides in figure 3.25(a), we can now solve the vertical planar waveguide as illustrated in figure 3.25(b). This time, we need to use the symmetrical TM eigenvalue equation for the fundamental mode given as:

\[
k_0 n_{\text{eff}} \cos \theta_{wg} = 2 \tan^{-1} \left[ \frac{\sqrt{\left(\frac{n_{\text{eff}}}{n_{\text{dir}}}\right)^2 \sin^2 \theta_{wg} - 1}}{\frac{n_{\text{eff}}}{n_{\text{dir}}} \cos \theta_{wg}} \right]
\]

Again this is solved graphically and term on the RHS and LHS are plotted separately as shown in figure 3.27.

![Graph showing solution of the TM eigenvalue equation for m = 0](figure3.27.png)

Figure 3.27 Solution of the TM eigenvalue equation for m = 0
Hence, this gives a solution of $\theta_{wg} = 1.432$ radians, which correspond to an effective index of $N_{wg} = 3.466$.

The EIM is only an approximation and it has shown to be in good agreement with the SOI rib structure, since the fundamental mode of the optical field within our rib waveguide is well confined yielding the effective indices very close to the refractive index of silicon (3.5).

### 3.6.2 Beam Propagation Method (BPM)

The basis of the BPM revolves around the three-dimensional scalar (i.e. neglecting polarisation effects and time-dependence) wave equation (Helmholtz equation) [3.18] which can be expressed as

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} + k^2 n^2(x, y, z) E = 0$$  \hspace{1cm} (3.121)

where $E$ is the electric field $E(x, y, z)$ and describing the optical field having components in the $x$, $y$ and $z$ directions. The electric field $E(x, y, z)$ can be separated into two parts: the axially slowly varying envelope term of $\phi(x, y, z)$ and the rapidly varying term of $\exp(-jkn_0z)$. $n_0$, in this instance it represents the refractive index in the cladding, hence $E(x, y, z)$ is represented by:

$$E(x, y, z) = \phi(x, y, z) \exp(-jkn_0z)$$  \hspace{1cm} (3.122)

Substitute equation (3.122) into equation (3.121)

$$\nabla^2 \phi - j2kn_0 \frac{\partial \phi}{\partial z} + k^2(n_0^2 - n^2)\phi = 0$$  \hspace{1cm} (3.123)

where

\[ n^2 \]
In BPM, weakly guiding condition is assumed, however it show good agreement with some of the SOI waveguiding applications, such as the straight waveguide, tapered waveguides and bends etc [3.24-3.25]. The terms \( (n^2 - n_0^2) \) in equation (3.123) can be approximated as \( 2n_0(n - n_0) \), hence equation (3.123) can be rewritten as:

\[
\frac{\partial \phi}{\partial z} = -j\frac{1}{2kn_0} \nabla^2 \phi - jk(n - n_0)\phi
\] (3.125)

The first term on the right hand side of equation (3.125) represents free space light propagation in the medium having a refractive index \( n_0 \), if the condition of \( n = n_0 \) is fulfilled. The second term of the equation (3.125) represents the guiding function or influence of the region which has a refractive index \( n(x,y,z) \). Both of the terms will have an effect on the light propagation simultaneously. However, in BPM analysis, it is assumed that the two terms can be computed separately, and each of these terms will affect the light propagation separately and alternately in the axially small distance, \( h \). To further illustrate the BPM analysis, a useful example is a tapered waveguide to demonstrate the assumption mentioned above. Figure 2.28a taken form [3.18] shows the actual light propagation in a tapered waveguide over a small distance, \( h \), and figure 2.28b shows the separation of free-space propagation and the wavelength effect in BPM analysis. In the analysis, first the electric field, \( \phi(x,z) \), is propagated in the space over a distance of \( h/2 \), then the phase retardation of the entire length, \( h \), (which corresponds to the shaded area in figure 2.28(a), is taken into consideration at the centre of propagation. This electric field is then further propagated along the next free space with distance \( h/2 \) to obtain the electric field, \( \phi(x,z+h) \). The principle of the BPM is to formulate over the small distance, \( h \), so as to relate the transmitted field \( \phi(x,z+h) \) to the initial field \( \phi(x,z) \).
Figure 3.28 Schematic illustration of BPM analysis: (a) Light propagation in the tapered waveguide and (b) Separation of free-space propagation and the waveguide effect in BPM [3.18]
3.7 Summary

In summary, we have described some of the basic theories that will be used extensively throughout the course of this work. We began by introducing the waveguiding theory where some of the physics behind the propagation of light was discussed. This formulated a general knowledge of the operation of an integrated optical waveguide. We then discussed some of the loss factors primarily; scattering, absorption and radiation, which allowed us to consider the implication that they have on our intended device in order to make it feasible. Given that the principle idea behind this work is to introduce free carriers into our AWG to achieve our intended application (Flat Spectral Response), and also due to the immersive use of curvilinear waveguides in our AWG structure. We also discussed the different methods in ‘coupling’, which will be considered later in the experiment section to determine the best and optimum method of achieving a greater coupling efficiency. Next we introduced two light phenomena and associated them with the principle of a conventional AWG. It can be shown that with the correct phase and propagation, a constructive interference can be achieved by producing a principal peak at the image plane and also this principal peak will steer accordingly to the difference in wavelengths. Subsequently, we described the basic operational principles of the AWG, how to calculate the basic properties such as dispersion etc., and also provide a comprehensive description of its transmission coefficient. Finally the chapter concluded with the discussion of two simulation theories, EIM and BPM. These simulation techniques will be used widely throughout the next chapter to provide detailed characteristics of the intended photonic devices prior to fabrication.
References:


CHAPTER 4
Design and Simulation

Mistakes are the portals of discovery.

James Joyce

4.1 Introduction

In the previous chapters, SOI has been shown to be a promising waveguiding material and the successful demonstration of AWG has also provided the fundamental grounds in which to introduce a novel method of achieving a flat spectral response. However, to date, very few references in the literature have reported on AWGs in SOI. However, it is still feasible to design a small dimension AWG based on the extensive library of optical devices that have been proposed and demonstrated.

Computer aided design is very commonly used in design and simulation. It provides a detailed description of the waveguides or device characteristics prior to fabrication. Hence in this chapter, several software packages such as Beamprop™, Matlab™ and SILVACO etc are used. These simulation packages will provide the fundamentals of the design process in this work.

In section 4.2, the design procedure of SOI waveguides will be discussed. Two important characteristics, namely; zero birefringence and singlemode propagation will be taken into consideration. We will investigate the variation that rib width and etch depth have upon on the optical properties within our SOI rib waveguide. Finally, we will come to the conclusion on the optimum rib structure that is to be used in our AWG design.

In section 4.3, Arrayed waveguide Gratings Design, the design strategy of a 1x8 demultiplexer AWG in SOI will be discussed. First, we define our AWG specification according to the ITU grid. Following the approach in chapter 3; AWG theory, we are able to calculate the necessary physical parameters of our AWG. We then determined the mandatory parameters, such as the coupling distance and taper which are necessary to incorporate into our AWG design.
In Section 4.4, we will demonstrate our design methodology for our flat spectral AWG in SOI using the introduction of free carriers via ion implantation with illustrative examples, specifically using n-type dopants at concentration level of $9 \times 10^7 \text{cm}^{-3}$, $1 \times 10^8 \text{cm}^{-3}$ and $2 \times 10^8 \text{cm}^{-3}$. We compare and contrast how different net concentrations will affect our design. Finally, due to addition optical path length required for phase compensation as a result of ion implantation, a modified AWG geometry is proposed.

### 4.2 Waveguide Design

The most fundamental structure of an integrated optical circuit is its straight waveguide. Here, we will look at the design principle governing some of the important characteristics in determining an SOI rib waveguide supporting only a singlemode and exhibiting zero birefringence. From chapter 2, we know that a relatively large dimension rib structure, $\approx 5 \mu \text{m}$ Si-overlayer, is possible for singlemode propagation if it satisfies the condition of the rib aspect ratio given by (4.1):

$$\frac{a}{b} \leq 0.3 + \frac{r}{\sqrt{1 - r^2}}$$

(4.1)

It is important to design a singlemode AWG because each waveguide mode has its own effective index. When more than one of these modes propagates down the AWG, the interference pattern of each mode will focus at slightly different positions at the image plane. Hence, wavelength resolution will be limited by the spread in wave vectors of the supported modes. Also, if the mode effective indices are widely spaced, light propagating in different modes can contribute to device crosstalk by coupling into adjacent waveguides. Similarly, different polarisation modes with different propagation constants will focus at different points on the image plane. Therefore, it is crucial for the AWG to maintain both its singlemode condition and polarisation independence. However, with the advances of SOI integrated optics, small devices are required. Hence, this translates into a move from large waveguides to smaller waveguides. With such advances, issues regarding polarisation dependence become much more significant.
Our SOI wafer was acquired from SOITEC, and has a Si-overlayer of 1.5μm and a small variation of ±1.5nm in thickness uniformity. It has P-type (boron) doping with a concentration level of $10^{15} \text{cm}^{-3}$ and a buried oxide (SiO$_2$) of 3μm, which is sufficiently large to prevent any evanescent fields from leaking into the silicon substrate layer. Due to the small dimension of our rib waveguide, polarisation dependence potentially increases as a result of the difference in mode shapes of TE and TM modes. It is difficult to determine a suitable geometry for the rib structure by following the analysis of Soref and Petermann [4.1-4.2], which satisfy both conditions. Nevertheless, waveguide birefringence can be removed with an appropriate choice of etch depth and rib width [4.3] since it is well-known that silicon does not inherently suffer from material birefringence. It is this formation of the rib geometry, in order to provide a two dimensional optical confinement, that leads to the modal birefringence. Throughout this thesis we will refer to the ‘modal birefringence’ as birefringence.

4.2.1 Birefringence Simulation

First let us consider the degree of influence that the rib width and etch depth have upon the modal birefringence for a given Si-overlayer, which in our case, is 1.5μm thick. The birefringence can be defined as the difference between effective indices of TE and TM fundamental modes, $(N_{TE} - N_{TM})$. Then we can evaluate the effective indices of both TE and TM fundamental modes using semi-vectorial Beam Propagation Method (BPM) through the use of commercial software, RSoft™. If we model our rib waveguide at an operational wavelength of 1550nm, we can show that for some geometries, it is possible to achieve birefringence free waveguides when a deep etch is employed. However, this might come at the expense of the singlemode operation due to the alteration of the modal field profile.

Figure 4.1 shows the effective index plot of differences between the rib widths for a series of etch-depths ranging from 900nm to 850nm taken from [4.4]. The etch-depth was increased gradually with the variation of rib width, in order to show the effect that both have on the birefringence. The curves with an etch depth ≥ 880nm cross the axis where
the effective index is the same for fundamental TE and TM modes, \((N_{TE} - N_{TM}) = 0\). This suggests that it is necessary to achieve a relatively deep etch to minimise the effect of modal birefringence in SOI waveguide, however the singlemode condition specified in equation (4.1) could be violated. Hence, in order for us to specify our waveguide dimension, we have to take into consideration; fabrication tolerance, which is expected to have a variation of \(\pm 10\%\). For this reason, our choice centred on the 880nm etch-depth with a rib width of 1.1\(\mu m\).

![Figure 4.1 Effective index difference plotted against rib width for various etch depths](image)

Based on our rib specification as shown in figure 4.2, it is necessary to investigate the modal behaviour of this structure.
4.2.2 Singlemode Condition Simulation

In order to ensure that the rib waveguide geometry in figure 4.2 satisfies the singlemode condition (to avoid modal interference or modal conversion) it is necessary that our waveguide only supports the fundamental mode. We performed a 3D mode-field calculation in which the cut-off point for mode 0 (fundamental mode), mode 1 and mode 2 (higher modes) are determined. We performed a scan on the effective refractive index in conjunction with the variation of rib width and a plot of effective index, $N_{TE}$ (assume TE polarisation) against rib width which is shown in figure 4.3.
According to the plot in figure 4.3, it can be observed that when the rib width is greater than 1.45\(\mu\)m, higher order modes start to appear, \(m=1\) and \(m=2\). This, consequently, will set the upper limits for the rib width to ensure that the waveguide operation satisfies the singlemode condition. However, to further verify our rib structure, we can follow the approach of Soref et al. [4.1] as illustrated in figure 4.4. They used a simulation to show that higher order modes leaked out of a correctly designed rib waveguide.
Figure 4.4 BPM simulations showing higher order mode leaking out from the rib waveguide to maintain its singlemode condition after propagating for 90µm.

The above simulation was conducted with the design value of the rib waveguides used in this work. First, a Gaussian field is deliberately launched off-axis to excite the higher order modes. When this Gaussian field is guided through the rib waveguide, the higher order modes are seen to be leaking out from the slab region on both sides of the rib. When this field propagates a distance of 90µm along the z-direction, only the fundamental mode remains confined in the rib core. Hence, it shows the design structure is singlemode and has near zero birefringence characteristics.
4.3 Arrayed Waveguide Grating Design

There are numerous ways of designing an AWG and these have been illustrated and explained by a number of authors [e.g 4.5-4.7]. However, these illustrations only provide a general guideline in the design methodology without looking at the various components, such as tapered or curved waveguides and coupling within the AWG. In this section, the design procedure of a relatively small dimension AWG in SOI will be explained following the approach of M. Amersfoort [4.7].

The SOI AWG is designed as a demultiplexer which consists of one input waveguide and eight output waveguides. Also, our design strategy pays particular attention to various SOI components, such as tapered structures and curves etc. The design strategy starts with a given waveguide structure, which in this case, is the designated rib geometry as mentioned in figure 4.2 that exhibits only a singlemode and minimum birefringence. Based on this waveguide geometry, the physical parameters of the AWG can be calculated. For a complicated device like the AWG, it is advisable to perform the simulation on each component within the AWG separately; once again Rsoft software is used. The following outlines the design and simulation procedure:

1. Define AWG parameters, for example:

   • *Wavelength Channels* — set the number of channels that the design of the AWG is based on.
   
   • *Centre Wavelength* — set the centre wavelength that the design of the AWG is based on.
   
   • *Channel Spacing* — set the channel spacing that the design of the AWG is based on.

2. Perform coupling simulation based on the rib geometry obtained in previous section. Thus, locating the minimum spacing between adjacent waveguides where coupling is at its lowest.
3. Design of tapered waveguides for improved coupling between the slab/arrayed waveguide interface.

4. Calculate the physical dimension of the AWG using the parameters defined in (1). Design the input and output Star Coupler.

5. Perform numerical simulation on the intended AWG.

6. Design the Layout Geometry for the AWG.

Each step is described in detail in the subsequent sections.

4.3.1 Defining AWG parameters

The first step in designing AWG is to define parameters based on user specifications. These specifications provide the foundation in the calculation for the rest of the AWG design variables, such as the Free Spectral Range (FSR), focal length ($R$), and the path length difference ($\Delta L$). As the aim of this project is a proof of principle (design for flat spectral response), the AWG is modelled in its simplest form. To use the RSoft simulation package, the user defined parameters are listed below.

1. Number of channels, $N$ - The AWG is designed for 8 outputs; hence $N = 8$.

2. Centre wavelength, $\lambda_c$ - 1550nm

3. Channel Spacing, $\Delta \lambda$ - The choice of the channel spacing, $\Delta \lambda$, is selected according to the ITU grid given as 200GHz, which can be translated into 1.6nm in wavelength terms.

Recall that the channel spacing, $\Delta \lambda$, given in equation (3.75) is given as:

$$\Delta \lambda = \frac{n_c S_{in} S_{out} \lambda_c}{N_c R \Delta L}$$  \hspace{1cm} (4.2)
and

\[ \Delta L = m \cdot \frac{\lambda_0}{n_{\text{eff}}} \]  \hspace{1cm} (4.3)

Hence, we can rewrite equation 4.2 as:

\[ \Delta \lambda = \frac{n_s S_{\text{arr}} S_{\text{out}}}{m R} \]  \hspace{1cm} (4.4)

where \( n_s \) is the effective index of the slab, \( S_{\text{arr}} \) is the array waveguides separation, \( S_{\text{out}} \) is the output waveguides separation, \( N_c \) is the group index of the array waveguides given as

\( N_c = n_{\text{eff}} - \frac{\lambda}{\lambda} \frac{\partial n_{\text{eff}}}{\partial \lambda} \),

which is approximately to the waveguide index. \( R \) is the focal length of the star coupler, \( m \) is the grating order and \( \Delta L \) is the path length difference. The FSR, which determines the allowable number of channels, according to equation (3.86) is given as:

\[ \text{FSR} = \frac{\lambda_0}{m} \]  \hspace{1cm} (4.5)

From a design perspective, it is convenient to combine and rearrange the equation (4.4) and (4.5) to determine the required grating order for a given channel spacing, \( \Delta \lambda \) and number of channels, \( N \). Thus if the FSR is given a value of 30nm, then by rearranged equation (4.5), we can calculate the grating order, \( m \) using:

\[ m = \text{round} \left( \frac{\lambda}{\text{FSR}} \right) \]  \hspace{1cm} (4.6)

Thus, this will give a value of \( m = 52 \).
4.3.2 Design and Simulation for Coupling and Tapered Waveguide

From earlier section 4.2, the rib width \( w \) had been predetermined to be 1.1\( \mu \)m. The next step is to fix the spacing of the arrayed waveguides, \( S_{aw} \), as shown in figure 4.5. In order to achieve sufficient isolation (minimum coupling from adjacent waveguides) between adjacent waveguides, this spacing has to be adequately large.

To determine the spacing, \( S_{aw} \), a BPM simulation was performed to distinguish the minimum coupling between the adjacent waveguides. Two waveguides are placed at a distance, \( S_{aw} \), and the fundamental mode of the optical field for the rib structure (refer to earlier section 4.2) is launched into the first waveguide centre at \( x=0 \). By allowing the optical field to propagate for a distance of 180\( \mu \)m, we can then observe the optical power in both waveguides and monitor their optical intensity. The choice of this distance is chosen to be sufficiency long to allow higher order modes to leak out of the core to both sides of the slab regions to maintain singlemode propagation.

This simulation is performed over a range of spacing, \( S_{aw} = 1.5\mu m, 1.6\mu m \ldots \ldots 3\mu m \) and a plot of intensity against spacing, \( S_{aw} \) is shown in figure 4.7. Also from figure 4.6, it can be noted that the waveguide separation will achieve complete isolation if this spacing is set at least two times the width of our rib waveguides. Consequently, \( S_{aw} \) is fixed at 4\( \mu \)m for this particular design.

Figure 4.5 Diagram illustration of the spacing between adjacent output waveguides of the AWG
Figure 4.6 Coupling against adjacent waveguide for spacing $S_{aw}$

The simulation only evaluates $S_{aw} \geq 1.5 \mu m$, for $S_{aw}$ smaller than this value, it is obvious that the structure will behave as a directional coupler as shown in the simulation in figure 4.7 for a $S_{aw}$ of 1.1 $\mu m$.

Figure 4.7 $S_{aw}$ is smaller than 1.5 $\mu m$, the waveguides acts a directional coupler
The optical mode in the free space region within the star coupler is confined in the lateral direction. Hence to avoid abrupt transition between the slab modes to the fundamental mode of the rib waveguide, tapered waveguides that adiabatically increase the waveguide width have been proposed [4.8] to reduce the coupling loss between the slab region and the array waveguides, due to mode mismatch. Figure 4.8 shows the structure of the tapered waveguide.

where $S_{aw}$ is the tapered width or the array waveguides separation. $L_{taper}$ is the length of the tapered section, $L$ is the length of the straight waveguides, and $w$ is the rib width. Previously, we have determined the dimension of $S_{aw}$ and $w$, leaving the two unknown variables, $L_{taper}$ and $L$. However, the value of $L$ does not affect the tapered structure; $L$ is chosen to be sufficiently long to allow singlemode propagation. In order to reduce radiation loss, the taper structure needs to have a smooth transition. Thus, to obtain a feel of a permissible tapered ratio, theoretical calculations were carried out by applying a BPM simulation on a fixed $S_{in}$, together with a fixed $L_{taper}$. $L_{taper}$ is chosen to be 210μm.
so that the angle $\theta_{\text{taper}}$ is $\leq 1^\circ$. Figure 4.9 shows the BPM simulation of the tapered structure and it can be observed that the total loss is approximately 10% of the normalised transmitted power.

![Figure 4.9 BPM simulations showing the tapered structure with less than 10% losses](image_url)

Similarly, the choice of output waveguides spacing, $S_{\text{out}}$, can be determined by the plot in figure 4.6. The choice of this spacing has again to be twice the width of the selected rib waveguides. However, the choice of the array waveguides separation must be chosen to be sufficiently to allow the occurrence of Fraunhofer diffraction at the image plane of the slab region of the AWG, since the focal length, $R$, is proportional to the relative dispersion, $\delta$. Therefore, $S_{\text{out}}$ is chosen to be $8.8\mu m$, because the core of the typical lensed fibre is approximately $4\mu m$ in diameter. Hence sufficient space should be allowed between the neighbouring waveguides so that the fibre will pick up the optical power from the adjacent crosstalk.
4.3.3 Design for Input and Output Star Coupler

In order to design the star couplers, the parameters are set based on the relative dispersion, $\delta y$, given as:

$$\delta y = \frac{S_{\text{out}}}{\left(\frac{\Delta \lambda}{\lambda_c}\right)}$$  \hfill (4.7)

According to section 4.3.1, $\Delta \lambda$ and $\lambda_c$ are given as 1.6nm and 1550nm respectively. Also the output spacing, $S_{\text{out}}$, has been determined in previous section 4.3.2. Hence, we can equate $\delta y = 8.525 \times 10^{-3}$. Once $\delta y$ is solved, together with the grating order $m$, and the array waveguides separation $S_{\text{in}}$, the focal length, $R$, can be established by rearranging equation (4.4) and is given below as:

$$R = \frac{S_{\text{in}} \delta y}{r m \lambda_g}$$ \hfill (4.8)

where $r = \beta_s/\beta_f = 1$ with $\beta_s$ and $\beta_f$ are the propagation constant of the slab and array waveguide respectively. $\lambda_g$ is the wavelength measured in the material given as:

$$\lambda_g = \frac{\lambda_s}{n_{aw}}$$ \hfill (4.9)

and $n_{aw}$ is the effective index of the array waveguide. Hence, the focal length, $R$, for our design is 1500$\mu$m. It is interesting to note that, from equation (4.4), $R$ is dependent upon the input and output waveguide separations, $S_{\text{in}}$ and $S_{\text{out}}$. The smaller these separations are, the more coupling between the array/input guides, and the larger these separations are the longer the star coupler region.
Another important variable within the AWG design which is not part of the star coupler is the path length difference, $\Delta L$, and can be determined by rearranging equation (3.99) in terms of the grating order $m$, thus yielding:

$$
\Delta L = m \cdot \frac{\lambda_c}{n_{aw}}
$$

(4.10)

Here, $\lambda_c$ is the centre wavelength and $n_{aw}$ is the effective index of the array waveguides. Hence this will give us a value of 23.62μm. The parameters for both the input and output star coupler should be identical for self consistency purposes and for most basic AWG design. Hence by default, the two star couplers are symmetric except for the number of input and output ports.

### 4.3.4 Numerical Simulation of AWG

Numerical simulation is performed based on the parameters derived from earlier sections, using the transmission coefficient as described in equation (3.85), which is reproduced here as equation (4.6):

$$
|E_i|^2 = \begin{vmatrix}
\sin^2 \left( \frac{N \cdot m \cdot n_{aw} + (S_{out} \cdot \sin \theta)}{\lambda} \right)
\end{vmatrix}^2
$$

(4.11)

The simulation is based on a numerical recipe written in MATLAB, a technical computing application which allows the handling of numerical computing and mathematical modelling. To enable the modelling of the AWG, a list of parameters is required as shown in Table 4.1.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Number of arrayed waveguides</td>
<td>100</td>
</tr>
<tr>
<td>m</td>
<td>Grating order</td>
<td>52</td>
</tr>
<tr>
<td>$n_{aw}$</td>
<td>Effective index of the arrayed waveguide</td>
<td>3.41</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Centre wavelength</td>
<td>1550nm</td>
</tr>
<tr>
<td>$S_{aw}$</td>
<td>Separation of the output waveguides</td>
<td>8.8μm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Dispersion angle</td>
<td>0.34°</td>
</tr>
</tbody>
</table>

*The dispersion angle can be calculated by $\sin^{-1}(R/S_{out})$ in degree.

Table 4.1 Parameters require for numerical simulation of the AWG.

The plot in figure 4.10 shows the spectral response of two inner channels, which is equivalent to channel 4 and 5 in the AWG. The responses are centred at 1449.2nm and 1550.8nm respectively, and they are separated by a channel spacing, $\Delta \lambda$, of 1.6nm.

Figure 4.10 Spectral response of the two most inner channels of the AWG; centred at a wavelength of 1449.2nm and 1550.8nm.
The above simulation regards the SOI AWG to be lossless and free from phase errors. However, this is not the case due to fabrication tolerance, which will be discussed chapter 7, section 7.5.

The entire demultiplexing properties of the 8 channel-1.6nm spacing AWG covering a wavelength range of approximately 16nm are shown in figure 4.11. The first channel is centred at a wavelength of 1544.4nm, and the subsequent channels are placed at wavelength spacing of 1.6nm. Also, the simulation showed that the device exhibits a crosstalk of -30 dB.

![Figure 4.11 Entire demultiplexing properties of 8 channels, 1.6nm channel spacing AWG](image)

To conclude, a summary of the various parameters needed for the construction of the AWG is listed in the table 4.2.
4.3.5 Array Waveguide Geometry Layout

Following the method of Ou et al [4.9], we can design the array waveguide geometry. A set of equations together with figure 4.12 shows greater detail and explanation. \( x(0) \) and \( r(0) \) have to be predetermined. The choice of \( x(0) \) is chosen to consist of the tapered structure and necessary minimum length (singlemode propagation). Thus, from figure 4.12, the angle \( a(0) \) can be given as:

\[
a(0) = 45^\circ - 7.92^\circ \\
= 37.08^\circ
\]  

(4.12)

The value of 7.92° can be calculated from the dispersion angle of the input slab region given by \( \sin^{-1}(R/S_{aw}) \) (degree) \*49 (half of the total number arrayed waveguides) + 0.08° (which is angle, of the 50th grating arm, from the normal)
Thus,

\[ x(0) + r(0) \cdot a(0) = z \]  \hspace{1cm} (4.13)

Hence \( z \) (millimetres) is the shortest grating arm within the arrayed waveguides. The choice of \( r(0) \) can be acquired by performing a "Bend Radius Simulation" to find the bend loss effective radius. The three dimensional rib structure is broken down into two dimensions using Effective Index Method (EIM) as in section 3.6.1. Thus, we obtained both \( N_{eff} \) and \( N_{effb} \) (see section 3.6.1), which are 3.47 and 3.39 respectively. Then we
used the simulated bend technique that makes use of the coordinate transformation to map a curved waveguide onto a straight waveguide, hence minimising the junction loss. This can be done by matching the modes at the junction [4.10], which can be achieved using RSoft. Figure 4.13 shows the loss induced by different values of bend radius, assuming an etch-depth of 0.88μm in a 1.5μm Si-overlayer.

![Graph showing excess loss vs. bend radius](image)

**Figure 4.13 Propagation losses for different values of bend radius**

From the above graph, it can be observed that the loss significantly increases for a bend radius below 300μm. Also, it has been demonstrated that the higher order modes effectively leak out of the waveguides if this radius is chosen appropriately [4.11]. Hence, our radius for the AWG design is decided on 1000μm, this would translate to a loss of around 0.04 dB/cm.
Once $r(0)$ has been determined, we can calculate $x(0)$ using equation (4.7). Since the shorter waveguide within the AWG is determined, we can proceed with the calculation for the rest of the array waveguides using the expression below.

\[ x(j) + r(j) \cdot a(j) = x(0) + r(0) \cdot a(0) + j \cdot \frac{\Delta L}{2} \]  

(4.14)

From equation (4.8), $x(j)$ and $r(j)$ are the only unknown parameters. Thus equation (4.8) can be re-written as:

\[ x(j) + r(j) \cdot a(j) = z(mm) + j \cdot \frac{\Delta L}{2} \quad j = 1 \sim M-1 \]  

(4.15)

Hence by defining $r(j)$ equal to 1000$\mu$m for all $j$, we can evaluate $x(j)$. We also need to calculate the separation between the slab regions of the AWG. Hence, we introduced new parameter, $L_{\text{slab}}$, and the basic equation was given as:

\[ [R + x(0)] \cos(a(0)) + r(0) \sin(a(0)) = \frac{L_{\text{slab}}}{2} \]  

(4.16)

We have determined the important parameters in designing the geometry of our AWG. Once, we have designed our conventional SOI AWG. We can implement our design methodology for achieving a flat spectral response through the introduction of free carriers.
4.4 Designs for Flat Spectral Response AWG

In this section, we are going to discuss a novel method of achieving a flat spectral response AWG in SOI using the injection of free carriers. It is well known that the focused beam profile at the output waveguides is the spatial Fourier transform of the optical field profile at the output array-slab interface. Hence in order to achieve a flat spectral response, theoretically, a rectangular function, a $sin(x)/x$ field distribution is required across the output of the array waveguides (AWs). The introduction of free carriers will cause absorption to the optical field of the AWs and at the same time, change the refractive index of the material. The phase of the optical field in the AWs is dependent upon the propagation constant, $\beta$, hence, a change in refractive index will cause a change in phase. However, it is crucial to maintain the $2\pi$ phase difference between adjacent waveguides to enable constructive interference at the output slab. Thus, an additional optical path length is needed to compensate for such a difference. This will lead to a change in the conventional geometry, as proposed in the previous section, of the AWG. The AWG is designed using 1.5μm Si-overlayer with 1.1μm rib width and 0.88μm etch-depth to facilitate singlemode, birefringence-free operation. It is also essential to achieve a uniform carrier concentration throughout the doped guiding region to avoid any phase errors resulting from the use of free carrier doping. This can be achieved using multiple ion implantations.

4.4.1 Discrete Fourier Transform Approach

The transmission function of the AWG of equation (3.77) is rewritten as:

$$E_i = \sum_{i=1}^{N} E_o \exp(-j\phi_i)$$  \hspace{1cm} (4.13)

$\phi_i$, the phase of $i^{th}$- array waveguide, can be written as:
\[
\phi_i = \frac{2 \cdot \pi \cdot n\text{_{avg}} \cdot i \cdot L}{\lambda_0}
\]  \hspace{1cm} (4.14)

Equations (4.13) and (4.14) describe a typical response of an AWG, where \(n\text{_{avg}}\) is the effective index of the array waveguide and \(L\) is the optical path length. The total optical path length, \(L\), through the slabs and the \(i^{th}\) waveguide, is the sum of the fixed path within the AWG and the contribution of the additional path length difference, \(\Delta L\) between adjacent waveguides. Hence \(L\) is given as:

\[
L = L_c + (i - 1) \Delta L
\]  \hspace{1cm} (4.15)

At the centre wavelength, the phase difference between adjacent waveguides has to be \(2m\pi\) in order to sustain constructive interference, hence:

\[
\frac{2 \cdot \pi \cdot n\text{_{avg}} \cdot i \cdot \Delta L}{\lambda_0} = 2m\pi
\]  \hspace{1cm} (4.16)

Rewriting the above condition yields a grating order, \(m\) given by:

\[
m = \frac{n\text{_{avg}} \cdot \Delta L}{\lambda_0} \cdot i
\]  \hspace{1cm} (4.17)

Hence, the Free Spectral Range (FSR) is related to the grating order, \(m\), as:

\[
FSR = \frac{\lambda_0}{m}
\]  \hspace{1cm} (4.18)

If we consider the approach of the Discrete Fourier Transform [4.12], the optical wavelength needs to be discretised and is given by:
where $M$ is the number of array waveguides, $q$ is the spatial harmonic number from $q = 1, 2, \ldots, M$ and $\lambda_0$ is the center wavelength. Thus, $\Delta \phi$ in its discrete form is given by:

$$\beta_{av}(q)\Delta L = 2\pi \left( m + \frac{q}{M} \right)$$

From equation (4.14), equation (4.15) and equation (4.20), the discrete optical phase, $\phi$, is:

$$\phi_l = \beta_{av}(q)L_c + (i-1)2\pi(m + \frac{q}{M})$$

Substituting equation (4.21) into equation (4.13) yields the $q$th component of the output electric field amplitude $E(\lambda_q)$:

$$E(\lambda_q) = E(q\Delta \lambda) = \exp[-j\beta_{av}(q)L_c] \sum_{i=1}^{M} E(i) \exp[-j2\pi \frac{(i-1)q}{M}]$$

If $(i-1)$ is replaced by $p$, equation (4.22) is therefore rewritten as:

$$E(q\Delta \lambda) = \exp(-j\beta_{av}(q)L_c) \sum_{p=0}^{M-1} g(p) \exp \left[ -j2\pi \frac{qp}{M} \right]$$

Where $g(p) = E(p+1)$. Hence, from equation (4.24), $g(p)$ indicates the optical field distribution across the arrayed waveguides, which is described by the inverse discrete Fourier transform of the output field.

$$g(p) = \frac{1}{M} \sum_{q=0}^{M-1} \left[ E(q\Delta \lambda) \exp \left[ j\beta_{av}(q)L_c \right] \right] \exp \left( j2\pi \frac{qp}{M} \right)$$
4.4.2 Optical Field Distributions of AWG

The optical field distribution across the input of AWs is obtained by performing a numerical simulation based on the Fraunhofer diffraction theorem [4.16] given by:

\[
I_{aw} = \left( \text{Sinc}^2(x) \right)^2
\]  \hspace{1cm} (4.25)

where

\[
x = \frac{\beta_{slab} \cdot w \cdot s_{aw}}{2 \cdot R}
\]  \hspace{1cm} (4.26)

and

\[
\beta_{slab} = \frac{2 \cdot \pi \cdot n_s}{\lambda}
\]  \hspace{1cm} (4.27)

where \(\beta_{slab}\) and \(n_s\) are the propagation constant and effective index of the star coupler respectively. \(w\) is the waveguide width, \(R\) is the focal length and \(s_{aw}\) is the separation between the array waveguides. Hence, the optical field intensity across each AW can be obtained and a Gaussian field distribution is noted as shown in figure 4.14. In order to design a flat spectral response at the output of the AWG, in an ideal case a rectangular function, it is important to specify the flat spectral region of the spectrum. It can be defined as:

\[
E(q \Delta \lambda) = \begin{cases} 
1 & (48 \leq q \leq 51) \\
0 & \text{elsewhere}
\end{cases} \hspace{1cm} q = 1, 2, 3, \ldots, N
\]

where \(q\) is given as the spatial harmonic number. By substituting this pre-defined waveguide number into equation (4.28), which is given by [4.12], the spectral width of the AWG can be specified as:

\[
\text{Spectral Width, } F_w = \text{FSR} \times \frac{q}{M}
\]  \hspace{1cm} (4.28)
Figure 4.14 Spectral response of a conventional AWG plotted against the number of arrayed waveguides

With the FSR fixed at 30nm and the number of arrayed waveguides fixed at 100, we would expect a spectral width of 1.2nm, because $\lambda(q) = 1$ over a range of $q = 4$.

If the FSR is fixed at 30nm and the number of array waveguides is 100, according to section 4.4.1, the optical field distribution across the output waveguides is the Discrete Fourier Transform of the field distribution across the output of the AWs. Thus, to obtain this optical field distribution, an Inverse Discrete Fourier Transform (IDFT) is performed on the $E(q\Delta\lambda)$ function, hence a $\sin(E(q\Delta\lambda)/E(q\Delta\lambda))$ distribution is obtained and is plotted against the number of AWs as shown in figure 4.15.
The optical field distributions at different points of the AWG have been defined. Thus, by following the approach of the IDFT, a SINC function is required at the outputs of the AWs. Hence, it is proposed to introduce absorption to parts of the AWs to shape the Gaussian field function to a SINC function by the use of free carriers. The disadvantage of this approach is that additional absorption introduces unwanted loss. However, the simplicity of the approach is much more attractive than some other more complex solutions. (e.g. [4.12-4.15])

Figure 4.15 Optical field distribution across the input of the AWs.
4.4.3 Free carrier Dispersion Effect

We recall in chapter 2, "Optical Properties of Silicon", the introduction of free carriers into silicon will affect both the real and imaginary refractive indices. The equations for changes in absorption coefficient and refractive index due to free electrons and holes at the communication wavelength of 1.55μm are replicated for reference in this section.

At 1.55μm:

\[
\Delta n = \Delta n_e + \Delta n_h \\
= -[8.8 \times 10^{-22} \cdot \Delta N_e + 8.5 \times 10^{-18} \cdot (\Delta N_h)^{0.8}]
\]

\[
\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h \\
= 8.5 \times 10^{-18} \cdot \Delta N_e + 6.0 \times 10^{-18} \cdot \Delta N_h
\]

where \( \Delta n_e \) is the change in refractive index resulting from the change in electron carrier concentration, \( \Delta n_h \) is the change in refractive index resulting from the change in hole carrier concentration, \( \Delta \alpha_e \) is the change in absorption resulting from the change in electron carrier concentrations and \( \Delta \alpha_h \) is the change in absorption resulting from the change in free hole carrier concentrations. An illustrative example using Phosphorous, with three different net peak atomic concentrations; 9 \( \times\) 10\(^{17}\) cm\(^{-3}\), 1 \( \times\) 10\(^{18}\) cm\(^{-3}\) and 2\( \times\) 10\(^{18}\) cm\(^{-3}\) will be discussed.

4.4.4 Design Methodology

In section 4.4.3, the effect of free carriers upon the absorption coefficient and refractive index of silicon was discussed. In order to shape the Gaussian distribution across the input of the AWs into a \( \sin(x)/x \) distribution, we introduce absorption through the introduction of free carriers into parts of the AWs. The absorption is implemented according to the intensity difference required for each AW that is associated with the difference between the two fields described in figures 4.15 and 4.16. The intensity difference is obtained by performing subtraction of one of the two fields from the other.
which is conveniently expressed in dB. The optical field of each AW is then evaluated individually as shown in figure 4.16.

The concentrations of free carriers to be introduced into each AW can be calculated using equation (4.30), and assuming a particular dopant type. Each individual AW will require a different doping length since the intensity required in each AW is unique. Thus, the doping length, $L_{\text{doping}}$, is given as:

$$
L_{\text{doping}} = \frac{\ln \left( \frac{\text{loss}}{10^{10}} \right)}{\Delta \alpha}
$$

(4.31)
The doping lengths have been investigated by changing the net doping concentration for different doses as shown in figure 4.17.

It can be deduced from the plot that a high concentration is needed to achieve a shorter doping length, thus a smaller device. If an attenuation of 20dB is required, doping lengths equivalent to 0.2cm, 0.5cm and 0.6cm are necessary for 2e18cm\(^{-3}\), 1e18cm\(^{-3}\) and 9e17cm\(^{-3}\) net concentration respectively. However the high concentration should not exceed the solid solubility limit. Hence, as a general rule it is best to keep the atomic peak in the order of 10\(^{17}\) ∼ 10\(^{19}\)cm\(^{-3}\). Figure 4.18 (a), (b) and (c) show the calculated doping length of each of the array waveguide for 9 \(\times 10^{17}\)cm\(^{-3}\), 1 \(\times 10^{18}\)cm\(^{-3}\) and 2 \(\times 10^{18}\)cm\(^{-3}\) respectively.
Figure 4.18(a) Calculated doping length of each array waveguide for $9 \times 10^{17} \text{ cm}^{-3}$ net concentration

Figure 4.18(b) Calculated doping length of each array waveguide for $1 \times 10^{18} \text{ cm}^{-3}$ net concentration
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Figure 4.18(c) Calculated doping length of each array waveguide for 2e18cm\(^3\) net concentration

Since the phase of the optical field in the AWs is dependent upon the refractive index of the material, one would expect a phase change resulting from the doping concentration. These phase changes are evaluated approximately from:

\[ \Delta \phi = \frac{2 \cdot \pi \cdot \Delta n \cdot L_{\text{doping}}}{\lambda} \quad (4.32) \]

According to equation (4.29), the introduction of free carriers will result in a change in the refractive index. Therefore for net n-type doping concentrations of 9e17cm\(^3\), 1e18cm\(^3\) and 2e18cm\(^3\), the refractive index changes are 7.92 x 10\(^{-4}\), 8.8 x 10\(^{-4}\) and 1.8 x 10\(^{-3}\) respectively. The expected change of phase resulting from the change in refractive index, \( \Delta n \), and the doping length, \( L_{\text{doping}} \), are shown in figure 4.19 for all three doping concentrations.
Figure 4.19 Phase changes due to the net concentration of $1e18\text{cm}^{-3}$ for each individual doping length

From the above figure, $L_{\text{doping}}$ and $\Delta \phi$ demonstrate linear relationships. These phases resulting from $\Delta n$ and $L_{\text{doping}}$ have to be evaluated for each AW and the results are presented in figure 4.20 (a), (b) and (c) for a doping concentration of $9e17\text{cm}^{-3}$, $1e18\text{cm}^{-3}$ and $2e18\text{cm}^{-3}$ respectively.

It is important to note the phase change caused by a change in $\Delta n$ for the individual AW, since a $2\pi$ phase difference is still required between the adjacent waveguides to enable constructive interference at the 2nd star coupler. To ensure this occurs, what is proposed is to have an additional optical path length for each AW to maintain the desired phase difference.
Figure 4.20(a) Calculated phase of each array waveguide for 9e17cm$^3$ net concentration

Figure 4.20(b) Calculated phase of each array waveguide for 1e18cm$^3$ net concentration
These excess optical path lengths are then calculated using equation (4.33) and the resultant plot is shown in figures 4.21 (a), (b) and (c) for $9 \times 10^{17}$ cm$^{-3}$, $1 \times 10^{18}$ cm$^{-3}$ and $2 \times 10^{18}$ cm$^{-3}$.

$$L_{\text{excess}} = \frac{\Delta \phi \cdot \lambda}{n_{\text{ew}} \cdot 2 \cdot \pi} \quad (4.33)$$

From the plots of figure 4.20 and figure 4.21 we can make an interesting observation. These plots are dependent upon one another, thus we have to calculate the relationship between the doping length and absorption coefficient as well as the change in refractive index due to free carriers. Subsequently, the phase change and the additional optical path length can be evaluated.
Figure 4.21 (a) Calculated additional path length for each AW that is needed to compensate the slight change in phase resulted from a net concentration of 9e17cm$^3$.

Figure 4.21 (b) Calculated additional path length for each AW that is needed to compensate the slight change in phase resulted from a net concentration of 1e18cm$^3$. 
4.4.5 Ion Implantation

Ion implantation is the introduction of ionised dopant atoms into substrate (silicon), with sufficient energy to penetrate beyond the surface. The depth of implantation, which is proportional to ion energy, can be selected to meet a particular application. Implantation offers clear advantages; as it can precisely control the number of implanted dopant atoms and the dopant depth distribution profiles [4.17]. Due to the confinement of the optical mode profile in the rib, it is essential to achieve a uniform doping distribution throughout the guiding region (1.5μm), hence multiple implantations are needed at different energies.

The Surrey University Sputter Profile Resolution from Energy Deposition Programme (SUSPRE) [4.18], together with SILVACO [4.19] have been used to simulate the penetration of dopants into silicon. Three different net concentration doses were considered for the doping ion phosphorus; 9e17cm\(^{-3}\), 1e18cm\(^{-3}\), and 2e18cm\(^{-3}\), all of
which require multiple implantations. The principle of multiple implantations of the rib structure using a specific example of $9 \times 10^{17} \text{cm}^{-3}$ net concentration will be explained for clarity purposes. Figure 4.22 shows the profile plot of a $9 \times 10^{17} \text{cm}^{-3}$ net concentration as predicted by SUSPRE.

These profiles will be named as 1 to 9, as in figure 4.22. Each profile is carefully chosen in order to achieve the targeted concentration.

These profiles are circumspectly selected for 2 reasons;

- Firstly, to achieve the required net concentration, e.g. $9 \times 10^{17} \text{cm}^{-3}$,
- Secondly, to ease the implantation process.
The optical mode field in the rib structure is shown in figure 4.23. This optical mode field is the fundamental mode of our designated rib structure and can be solved using BPM.

![Computed Transverse Mode Profile (m=0, n<sub>eff</sub>=3.422264)](image)

Figure 4.23 Optical mode field profile for the rib waveguide

Most of the optical mode intensity of the rib waveguide is confined within the region of 0.1μm-1.3μm in the vertical direction as shown in figure 4.23. Ideally, a uniform net concentration throughout the 1.5μm Si-overlayer is needed to prevent the slightest phase error caused by the injection of free carriers. However, because of the restriction of ion implantation, it is unrealistic to perform too many implants. Hence we define the areas of importance within the rib waveguides and deduce a more realistic number of implantations. 9 implantations are implemented and will be explained in conjunction with figure 4.24(a)–(d) showing step-by-step procedure and furthermore, explaining the need for doping profile 4, 6 and 8.
Figure 4.24 Step-by-step profile plots

Figure 4.24a shows the net field profile of two implants predominantly peaking at a depth of 1.5μm and 1μm at energies level of 1632 keV and 1060 keV respectively. However a notch is observed around 1.2μm depth which is caused by the net sum of both implantations, therefore, a small dosage of implantation is needed at energy of 1350 keV with a fluence of 0.12x10¹⁴ cm⁻² to flatten the profile at an approximate level of 9e17 cm⁻³ net concentration as in figure 4.24b. Figure 4.24c and 4.24d demonstrated the same principle where a notch is observed after a third predominant implantation at energy of 650 keV with fluence of 0.2x10¹⁴ cm⁻² and a compensating implantation at 850 keV with...
fluence of $0.1 \times 10^{14}\, \text{cm}^3$ to smoothen out the profile. This way, we can achieve a near uniform atomic profile throughout the region of importance within the guiding region as shown in figure 4.25 generated by SILVACO.

![Graph showing near uniform doping profile](image)

**Figure 4.25** Near uniform doping profile at the region of 0.4\(\mu\)m – 1.5\(\mu\)m

Annealing of the silicon is necessary after implantation because ion implantation causes degradation of the semiconductor parameters such as mobility and lifetime. To activate the implanted ions and restore the mobility and other silicon parameters, the silicon must be annealed at an appropriate combination of time and temperature. Rapid Thermal Annealing (RTA) is employed in this situation for the usual reason; to anneal out the damage in the substrate which has been caused by implantation, while at the same time minimising dopant diffusion. Figure 4.26 shows the temperature and anneal time required for RTA [4.20], for this kind of implantation process.
RTA is usually high in temperature and low in duration. This is because for a high temperature anneal, the significant percentage of the damage removal occurs in a fraction of a second and almost zero diffusion occurs at this instance. From figure 4.26, the RTA consists of a 6 seconds ramp up from the initial 700°C to 1000°C, followed by 60 seconds anneal, followed by a 9 seconds cool down.

Table 4.3 shows the energy level of each implant and the dose needed to achieve the required depth of penetration.
4.4.6 Modified AWG Geometry Layout

The AWG geometry for a flat spectral response can be designed with a certain degree of modification to accommodate the excess optical path length needed for phase compensation. From figure 4.12, \( x(0) \) and \( r(0) \) are predetermined. \( x(0) \) is given as 4.35mm, which took into consideration of the total path length, \( z(\text{mm}) \), in equation (4.13), in order to accommodate the maximum doping length. Figure 4.27 shows the general outline of the modified AWG.

A few geometrical equations based on figure 4.12 have to be confirmed before we introduce the design of the “modified” geometry. These equations are predetermined.

\[
L_1 = r(0)\sin(\alpha(0)) \quad (4.25)
\]

\[
L_2 = [R + x(0)]\cos \alpha(0) \quad (4.26)
\]
Figure 4.27 “Modified” geometry layout which includes the additional optical path length. Figure 4.27 shows the modified geometry and equation (4.28) is modified to include the $L_e$ into the equation, hence:

$$L_2 = [R + x(0) + L_e(0)]\cos\alpha(0)$$  \hspace{1cm} (4.28)

Combining equations (4.25), (4.27) and (4.28), the value of $L_{slab}$ can be obtained. The condition of equation (4.27) still holds because $L_e(0)$ is the excess optical path length. We can now solve for $x(j)$ and $r(j)$ in these modified equations. First we need to define two parameters, $A(j)$ and $B(j)$ which can be written as:
\[ A(j) = x(0) + r(0) \cdot \alpha(0) + j \cdot \frac{AL}{2} \quad (4.29) \]

\[ B(j) = \frac{L_{\text{int}}}{2} - [R + L_y(j)] \cos \alpha(j) \quad (4.30) \]

hence, \( r(j) \) and \( x(j) \) can be obtained, and are given by:

\[ r(j) = \frac{A \cos \alpha(j) - B(j)}{-\sin \alpha(j) + \alpha(j) \cdot \cos \alpha(j)} \quad (4.31) \]

\[ x(j) = A - r(j) \cdot \alpha(j) \quad (4.32) \]

For a detailed calculation of our AWGs geometry, both for the conventional AWG, as described in section 4.3.3, and the “modified” geometry due to ion implantation (9e17cm\(^{-3}\), 1e18cm\(^{-3}\) and 2e18cm\(^{-3}\) n-type dopants), refer to Appendix B.

### 4.5 Summary

Thus far, we have looked at the design methodology of achieving a flat spectral response AWG in SOI. We have considered the different design and simulation aspects when modelling an SOI AWG, such as singlemode and birefringence conditions. It is crucial to maintain these conditions since the AWG has a dispersive nature which means that all the different modes will result in different propagation constants, hence causing the principal peak of the AWG to focus at an incorrect position on the image plane, as well as significant crosstalk. We then described the basic layout which make up of a straight and curvilinear waveguides with minimum losses. This layout will provide a flexible solution to our design approach in achieving the flat spectral using the injection of free carriers. In our model, we illustrated our approach using three specific level of net concentration; 9e17cm\(^{-3}\), 1e18cm\(^{-3}\) and 2e18cm\(^{-3}\), all of which are n-type dopants (phosphorus).
In order to appreciate our design principles, first we need to understand the properties of a conventional AWG. By taking advantage of the small angle approximation within the AWG slab region, the focal length, $R$ is designed at a distance large compared to our waveguides separation, hence this allows Fraunhofer diffraction to occur. Due to this arrangement, we could employ the concept of Fourier optics. Consequently, a $\sin(x)/x$ function is required at the output of the array waveguides in order to produce a rectangular field distribution across the output waveguides, and hence a flat spectral response. It is well-known that the field distribution across the input of the array waveguides is a Gaussian distribution. Therefore, we need to shape this field distribution into a SINC distribution. This can be achieved by the injection of free carriers, in this particular work; phosphorus is used as the implantation dopant.

The principle behind our design approach is to introduce absorption to each of the array waveguides. Therefore, for each net concentration (cm$^{-3}$), the absorption coefficient, $\Delta \alpha$ can be determined. The loss due to absorption result from ion implantation depends on both $\Delta \alpha$ and the length of the doping region. i.e. having decided on a dopant type and concentration, we can evaluate this doping length, $L_{doping}$, for each of the array waveguides. As discussed in earlier sections, a high concentration of dopants will result in a shorter $L_{doping}$, which translates in to a smaller device. Again, due to the introduction of free carriers, there will be a change in the refractive index of the material, which inversely affects the phase of the optical field propagating through the waveguides. This change in phase needs to be evaluated, again, for all array waveguides, since the focusing of the AWG depends upon the interference condition, which is a $2m\pi$ phase difference between each adjacent waveguides. Hence, to compensate for this phase change, the geometry of our conventional SOI AWGs need to be modified. For simplicity, a straight waveguide is added to each of the array waveguide to accommodate such changes. Consequently, the constructive interference condition is maintained.

In conclusion, we have proposed and presented a novel method of achieving a flat spectral response AWG in SOI using the injection of free carrier. Different doping concentration levels could be used; however, we illustrated our design method using
specific examples for simplicity purposes, n-type phosphorus at $9 \times 10^{17} \text{cm}^{-3}$, $1 \times 10^{18} \text{cm}^{-3}$ and $2 \times 10^{18} \text{cm}^{-3}$. Although only an n-type dopant is used, it is understood that p-type can also be implemented. This method gives the robustness of tailoring the optical field distribution across the array waveguides by the appropriate choice of net doping concentration, and hence gives room for design flexibility without increasing the physical dimension of the AWG significantly.

We also have discussed the potential of achieving a smaller SOI AWG device with the use of higher net dosage and achieving a uniformity doping concentration through multiple implantations.
REFERENCES

References


[4.8] tapered structure


[4.18] Surrey University Sputter Profile Resolution from Energy Deposition Programme (SUSPRE), University of Surrey, Guildford, Surrey, GU2 7XH.

[4.19] SILVACO International, 4701 Patrick Henry Drive, Bldg 1, Santa Clara, California
CHAPTER 5
Fabrication

The attractive aspects of fabricating optical devices from silicon are the low primary cost of the material, the mature and well-characterised process techniques in the microelectronics industry and also, the potential for integration with the electrical components in the same substrate.

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5.1 Introduction

The purpose of this chapter is to introduce the reader to the fabrication and procedures to produce both the conventional and flat-spectral response Arrayed Waveguide Gratings (AWG).

This chapter, regarding the fabrication of the AWG, begins by introducing the general fabrication processes, describing the various types of fabrication methods, specifically for this work. The entire fabrication was conducted at Southampton University Microelectronic facility, except for high energy implantations, which were carried out at the University of Surrey. This section also contains a detailed description of each fabrication process and discusses the choice of some of the fabrication methods selected. However, it is not the intention of this section to give a comprehensive review of silicon processing but to cover the most important fabrication processes involved in fabricating the Silicon-on-insulator (SOI) AWG.

5.2 Fabrication

5.2.1 Introduction

The mature silicon microelectronic technology has benefited the fabrication of SOI integrated optical devices. The fabrication of such devices adopts similar procedures such as reticle writing, oxidation, photolithography, ion implantation and etching. As such, these are known as planar process in which all processes take place on or in the wafer surface. These processes are performed in a clean environment with precise control of temperature and humidity.
A straightforward waveguiding structure in SOI is a rib waveguide. This structure can be designed to exhibit qualities, such as singlemode and zero birefringence behaviours. The width of the rib is determined solely by the photolithography resolution. Hence it is important to control the photolithography process within ±5% tolerance to prevent the alteration of the optical properties within the waveguides. This ±5% tolerance is based on simulation results obtained from S. P. Chan et al [5.1] and is shown in figure 5.1.

In figure 5.1, both the singlemode condition for quasi-TE and quasi-TM for a waveguide height of 1.5μm are plotted together with the zero birefringence curves, as shown in figure 4.1. The purpose of figure 5.1 is to demonstrate that both conditions can be met under certain conditions. The areas below the quasi-TE and quasi-TM plots indicated the singlemode region; any points of the zero birefringence...
curve in this region will obviously suggest a waveguide geometry that satisfy both conditions.

Another process which requires tight control over the fabrication of the SOI rib waveguides is etching. As discussed in chapter 4, the rib width and etch depth of the SOI rib waveguide are inter-related, variations of these parameters will affect its singlemode and birefringence conditions. Hence it is important to control both parameters in order to achieve a good device.

5.2.2 General Process Flow

Our flat spectral SOI AWG was fabricated using a combination of processes as illustrated in the process flow diagram in figure 5.2. The fabrication process was conducted in two stages;

(1) Implantation and
(2) Fabrication of the AWG.

In the ion implantation stage, the fabrication process started with RCA Cleaning of the UNIBOND SOI wafer. The wafer was rinsed in Ammonia (NH₃) + Hydrogen peroxide (H₂O₂) for 10 minutes, followed by another 10 minutes rinse in Hydrochloric acid (HCL) + H₂O₂. This would remove any form of contamination before the various process steps.

This is followed by 500nm oxide deposited on top of the SOI wafer using the PECVD Dep 90 System. The purpose of the oxide layer was to provide a selective shielding mask for ion implantation. Before the oxide is etched, a mask was required to expose the selected regions of the design on the oxide layer.

This mask writing can be performed using the Leica-Cambridge 10.5 electron-beam direct write lithography tool. This lithographer is capable of a resolution of about 80 nm with placement and automated alignment accuracies of 100 nm over a 3 mm field.
The mask making in this particular stage applied negative resist, hence, in accordance to the system requirement, mask making was conducted on 5 inch chromium (Cr) plates with negative resist. Subsequently, the pattern on the reticle was transferred onto the wafer surface using photolithography, and the SiO₂ which is not covered with the photoresist was anisotropically etched (±10% uncertainty) using the Oxford RIE80+ Dry Etcher with a gas content of CHF₃+Ar.

The process is followed by a multiple implantation process of phosphorus to obtain a relatively uniform profile throughout the 1.5μm Si-overlayer. According to section 4.4.5, 9 implantations are needed, thus the first two implants, at a relatively low energy; 70keV with a dose of 0.2x10¹⁴cm⁻² and 150keV with a dose of 0.2x10¹⁴cm⁻² were conducted using a 200kV implanter from Danfysik A/S at Southampton University. The subsequent implants were conducted at Surrey University using the High Voltage 2MV implanter, details of the implantation energy and dose can be found in section 4.4.5, table II.

Following ion implantation, rapid thermal annealing (RTA) was carried out on the implanted wafers using the AG RTA 210 annealer, to reconstruct the silicon lattice to its crystalline condition and simultaneously position the dopant ions onto lattice sites. Finally, the deposited SiO₂ mask was removed.

In the second stage of the fabrication, the process started with reticles (masks) writing for the AWG pattern using the electron-beam pattern generator (Leica-Cambridge 10.5 electron-beam direct write lithographer). This time, the mask making applied positive resist and was conducted on 5 inch chromium (Cr) plates with positive resist.

Photolithography took place, where the AWG pattern on the reticle was transferred onto the wafer surface. Anisotropic etching of the silicon, with an uncertainty of ±10%, was performed by the Oxford RIE80+ Dry Etcher using a gas content of CF₄. This would create the desired AWG pattern onto the SOI wafer. Lastly, the resist was stripped.
The fabrication process flow is generally discussed in this section. In subsequent sections, detailed discussion about the technology of each process will be presented.

**Figure 5.2 Process flows of SOI AWG fabrications**

### 5.2.3 SOI WAFERS

The SOI wafers used in this project are fabricated by a combination of ion implantation and wafer bonding known as the Smart-cut process (see chapter 2). The UNIBOND SOI wafers are acquired from a French company called SOITEC. The wafer diameter is 100mm (4 inch) with a Si-overlayer of 1.5μm with a thickness uniformity of ±5nm. The buried oxide thickness is 3μm with thickness uniformity of ±15nm which is adequate to prevent the evanescent field from leaking into the silicon substrate. This wafer will form the basis of our flat spectral response SOI AWG.
5.2.4 Mask Patterning

One of the main processes in the fabrication of our AWGs is to identify the selected region on the wafer surface in which dopants are required to be implanted while protecting other regions of the wafer. This will induce free carrier absorption, which will alter the optical field within the array waveguides into a SINC distribution. Also, the formation of the rib waveguides within the AWG requires selected region of the wafer surface to be exposed to etching.

The mask production began with the drawing of the pattern with the aid of commercial software, L-Edit [5.2]. The finished layout was then transported to a pattern generator which drove the electron-beam (e-beam) to write on a glass plate covered with a thin layer of chromium film. This glass plate is generally referred to as the mask.

In this work, six different reticles were used. As mentioned in chapter 4, three different net doping concentrations are considered; 9e17cm⁻³, 1e18cm⁻³, 2e18cm⁻³ n-type (phosphorus) dopants. Each of these implantations will result in slightly different doping lengths (required to shape the Gaussian field distribution across the input of the AWs to a SINC field distribution at the output of the AWs).

For this reason, separate masks were needed. The introduction of the excess optical path lengths, required for the compensation for the phase differences as a result of ion implantation, also required additional masks for the AWGs, due to the fact that each set of AWs will require in a slight difference in length compensation. Also, a conventional SOI AWG was needed for performance comparison.
In figure 5.3, two AWG designs were included in one reticle. The top half of the first reticle contained the conventional AWG and the bottom half contained the flat spectral response AWG for a net concentration of $9 \times 10^{17} \text{cm}^{-3}$ phosphorus. Also, note that, on the bottom half, the blue line indicates a separate reticle is needed for ion implantation. The blue region in figure 5.3 also shows the areas needed to be implanted, since the mask was designed using negative resists.

Figure 5.3 Reticle 1; Mask layout for conventional AWG and mask layout for $9 \times 10^{17} \text{cm}^{-3}$ net concentration, n-type dopant.
Reticle 2

In figure 5.4, two AWGs were included. Both AWGs were designed for flat spectral response, with a net concentration of $1\times10^{18}$ cm$^{-3}$ phosphorus. Again, the blue region indicates a separate reticle needed for ion implantation.

Figure 5.4 Reticle 2: Mask layout for $1\times10^{18}$ cm$^{-3}$ net concentration; two devices in one reticle
Reticle 3

In figure 5.5, again, two flat spectral response AWGs were included. These AWG were designed for a net concentration of $2 \times 10^{18} \text{cm}^{-3}$ phosphorus. Again, the blue region suggested a separate reticle needed for implantation.

![Figure 5.5 Reticle 3: Mask layout for $2 \times 10^{18} \text{cm}^{-3}$ net concentration; two devices in one reticle](image)

Once the reticles were produced, manual inspection of the generated pattern was conducted to look for defects and faults within the design.
5.2.5 Oxidation

Oxidation is the process that consists of growing a thin film of silicon dioxide on the surface of the silicon wafer [5.3]. A silicon dioxide layer can provide a selective mask against the diffusion of dopants atoms at elevated temperature (annealing). Usually, a pre-deposition of dopants by ion implantation will result in a dopant source at or near the surface of the oxide. During the annealing process, the high-temperature must allow diffusion to occur much more slowly within the oxide compared to silicon itself. This will ensure that the dopants do not diffuse through the oxide in the masked region and reach the silicon surface. Typically, oxides used for masking common impurities, such as phosphorus has a diffusion constant of $2.9 \times 10^{-16}$ to $2.0 \times 10^{-13}$ at $1100^\circ$ [5.3], with a thickness of 0.5µm to 0.7µm, which make them compatible with oxide masking.

5.2.6 Photolithography

Photolithography is the process where the pattern on the reticle is transferred to the surface of the wafers [5.4] as illustrated in figure 5.6. To transfer the pattern, our SOI wafers were first coated with a light-sensitive photoemulsion, known as photoresist. A 1cm$^3$ of liquid photoresist was applied onto the wafer surfaces and the wafer was spun rapidly until a uniform 1µm thick layer of the photoresist was formed over the oxidised surface of our wafers. There are two types of photoresist [5.5]:

1. Positive resist
2. Negative resist

Accordingly to the approach of [5.5], an illustration of both types of resist is shown in figure 5.6.

For positive resist, the resist is exposed with UV light wherever the underlying material is to be removed. In these resists, exposure to UV light changes the chemical structure of the resist so that it becomes more soluble in the developer. The exposed
resist is then washed away by the developer solution, leaving windows of the bare underlying material. The mask, therefore, contains an exact copy of the pattern which is to remain on the wafer.

![Diagram of Resist Process](image.png)

**Figure 5.6 Pattern difference for positive and negative resist [5.5]**

Negative resists behave in just the opposite way. Exposure to the UV light causes the negative resist to become polymerised, hence becoming more difficult to dissolve. Therefore, the negative resist remains on the surface wherever it is exposed, and the developer solution removes only the unexposed portions. Masks used for negative photoresist, therefore, contain the inverse of the pattern to be transferred. It is worth mentioning here that the masks used for ion implantation applied negative photoresist whereas the mask used for the patterning the AWGs applied positive photoresist. This is due to the protocol used in Southampton University.
Once the wafer was coated with photoresist, the wafers were baked at 100°C to solidify the resist on the wafer. This process is known as soft-bake. Soft-baking plays an important role in photo-imaging because the photoresist coatings become photosensitive only after soft-baking.

![Alignment mark diagram](image)

Figure 5.7 Alignment mark on mask and wafer to achieve precise positioning.

The recticles produced in section 5.2.4 were then carefully aligned to our SOI wafers using alignment marks on the masks and the wafer to register the patterns prior to exposure. Normally, two alignment mark sets were required on the opposite sides of the wafer or the stepped region. This is best illustrated with a diagram as shown in figure 5.7. The opaque cross represented the alignment mark on the wafer created from prior processing steps and the white cross represents the alignment mark on the reticle, which is an open window in chrome which allows the mark to be seen on the wafer. The dimension of the alignment mark is approximate 1mm.

Once the mask had been accurately aligned with the pattern on the wafer’s surface, the photoresist was exposed through the pattern on the mask with a high intensity of UV light. Exposure methods are of three types; contact, proximity, and projection as shown in figure 5.8 below [5.6].
In contact aligners, the resist coated SOI wafer is brought into physical contact with the photomask in a vacuum chuck while the photoresist is being exposed with UV light. This allows very high resolution (eg. 1-micron feature in 0.5 micron of photoresist, however, due to the contact between the mask and the resist, debris trapped between the resist and the mask can damage the mask and cause defects in the pattern.

In proximity aligners, a small gap of 10μm to 25μm is maintained between the wafer and the mask during exposure. This gap minimises mask damage. 2μm to 4μm resolution is possible using this method.
In a Projection aligner, the mask and the wafer (usually a few cm away) are separated by imaging optics. Projection systems give the ability to change the reproduction ratio. An N:1 reduction allows larger size patterns on the mask, which is more robust to mask defects. Most wafers contain an array of the same pattern; hence only one cell of the array is needed on the mask. This cell is scanned or 'stepped' over the surface of the wafer and resolution of approximately 1μm can be achieved at Southampton. Hence, the projection aligner method was adopted, which used the GCA 6300 step and repeat projection printer providing a 5:1 reduction.

A Hard bake is the final step in the photolithography process. It is used to stabilise and harden the developed photoresist prior to processing steps that the resist will mask. It is carried out at a temperature of 90-140°C for several minutes. Any remaining traces of the coating solvent or developer will be removed. The exposed silicon dioxide is then etched away using hydrofluoric acid, which dissolves silicon dioxide and not silicon. The intended region required for ‘masking’ is still covered by silicon dioxide and the photoresist. Finally the photoresist is stripped and the silicon dioxide is exposed. The general steps in the photolithography process are shown in figure 5.9.

Figure 5.9 Steps in Photolithography [5.6]
5.2.7 Etching

Etching is the process of selective removal of the material in question. This has the effect of transferring the pattern to the oxide, creating barriers of oxide where we do not want subsequent processes to impact the silicon beneath. At this point, the photoresist has to be removed. The ‘stripping’ of the photoresist must be entirely complete because of its organic property which might cause defects if it is left on the wafer surface. There are two types of etching [5.7]:

- Wet etching where the material is dissolved when immersed in chemical solution.
- Dry etching where the material is sputtered or dissolved using reactive ions or a vapour phase element.

Wet etching is the simplest etching technology. It requires a container with a chemical liquid solution (etchants) that will dissolve the material in question. Wet etching falls into two categories; isotropic etching and anisotropic etching. Isotropic etching removes material for the target at the same rate in all crystallographic directions, but has the disadvantages that it etches horizontally under the etch mask (undercutting) at the same rate as it etches through the material. Anisotropic etching in contrast to isotropic etching means etching at different etch rates in different directions. The principles of anisotropic and isotropic wet etching are best illustrated in figure 5.10.

---

Figure 5.10 Differences between Anisotropic and Isotropic Wet Etching [5.7]
One of the most common techniques used in dry etching is the Reactive Ion Etching [5.8] (RIE). RIE is a combination of chemical and physical etching. During the chemical process of RIE, the substrate is placed inside a reactor in which several gases are introduced. An RF power source is used to strike plasma from the gas mixture, breaking the gas molecules into ions. These neutral or/and ionised atoms interact with the material's surface to form volatile products. The physical process of RIE which is similar to sputter deposition process uses high energy positive ions. These positive ions are accelerated and strike the substrate with high kinetic energy, hence transferring some of their energy to the surface atoms which then lead to the removal of the material. It is very complex to develop dry etch processes that balance chemical and physical etching. However if both of these etches are carefully controlled, it is possible to influence the anisotropy of the etching. This is because the physical process is anisotropic and the chemical process is isotropic as illustrated in figure 5.11.

![Reactive Ion Etching](image)

**Figure 5.11** Dry Etching using Reactive Ions; a combination of physical and chemical etching [5.8]

Figures 5.12 to 5.15 show Scanning Electron Microscopy (SEM) pictures of the component parts of the AWG. Figure 5.12 shows an SOI rib waveguide, figure 5.13 shows the array of waveguides, figure 5.14 shows a star coupler and finally figure 5.15 shows the star coupler/array waveguide interface.
Figure 5.12 An SEM picture of a SOI rib waveguides using RIE

Figure 5.13 An SEM picture of the array of waveguides within the AWG
Figure 5.14 An SEM picture of the input star coupler

Figure 5.15 An SEM picture of the interfaces between the star coupler and the array waveguides
5.2.8 Ion Implantation

In chapter 4, we have discussed ion implantation in its simulation terms. In this section we will look at ion implantation in terms of its system and relations with fabrication parameters. The ion implantation system comprises four major subsystems; the ion source, the magnetic analyser, the accelerator and the process chamber [5.9] as shown in figure 5.16.

In order to generate ions, the material source, typically in the form of gas such as phosphine (PH₃) is broken down into charged fragments. This can be achieved by creating a localised plasma driven by the acceleration of electrons provided by a tungsten filament. This ion plasma contains the desired ions together with many other species from other fragments and contamination. An extraction voltage, around 20 kV, causes the charged ions to move out of the ion source into the analyser. The magnetic field of the analyser is chosen such that only ions with the desired charge to mass ratio can travel through the accelerator without being blocked by the analyser walls.

![Figure 5.16 General schematic of an ion Implantation system [5.9]](image)
Upon entering the accelerator, the desired ions are subjected to an electric field, the magnitude of which determines the ions final energy and hence the ultimate depth in the silicon wafer.

In many applications, a single implantation step is insufficient to achieve the required doping distribution profile, in particular for this work, where ideally, a constant doping profile is required throughout the 1.5μm Si-overlayer. Thus, multiple implantations were implemented to form a flat doping profile [5.10]. This flat doping profile can be obtained by using various combination of implant dose and implantation energy as illustrated in section 4.4.5.

Ion implantation has the following advantages; (a) Doping levels can be precisely controlled since the incident ion beam can be accurately measured, (b) It is capable of variable penetration because the depth of the dopant is easy to regulate by the control of the incident ion velocity, (c) Extreme purity of the dopant is guaranteed, (d) Doping uniformity across the surface can be carefully controlled, (e) Doping can be clearly spatially controlled because the ions enter the silicon as a directed beam causing minimum spread.

However, this process does have one major shortcoming which is the crystal damage of the target due to the collision of high energy ions with the lattice. Such damage may result in inferior performance of devices made by this process. However, such damage can be substantially removed by the annealing process which restores the lattice structure.

5.2.9 Annealing

The most common type of annealing is known as Rapid Thermal Annealing (RTA), where annealing times are on the order of seconds. The annealing process was performed using the AG RTA 210 annealer. The RTA 210 is an alternative to conventional furnace systems. Its advantages include short annealing times (from 1 to 300 seconds) and precise control of the annealing profile. This annealer heats silicon
wafers in a quartz chamber to temperatures between 200 and 1200 degrees centigrade while flowing variable gas. It is a “clean” operation so care must be used to avoid contamination.

Figure 5.17 shows the ramping up and down times used for the annealing process. These times are characteristic of the annealing equipment at Southampton University, the AG RTA 210 annealer used in this work.

The initial temperature of the RTA process was at 750°C and was ramped to 950°C in 6 seconds. Then it was held at a constant temperature of 950°C for 60 seconds, followed by a uniform ramping down to 750°C in 9 seconds. The annealing process restores the Si-lattice to its crystalline condition and simultaneously positions the dopant ions onto its lattice sites.
5.3 Summary

In summary, the author has described the fabrication technology available which enables the realisation of SOI AWG. It has been shown that a combination of processes is necessary to achieve the resultant product and these processes are subjected to fabrication tolerances and errors.

The fabrication is divided into two major stages; firstly the implantation stage, where dopants are introduced to parts of the array waveguides and secondly, the patterning the AWG using the etching process. The implantation of the flat-spectral AWG were only conducted within a certain region of the grating arms, hence the alignment of masks within the two stages is particularly important. This is because the implantation has to be precisely doped within the rib of each of the array waveguides in order to introduce the required absorption to shape the optical field distribution at the output of the array waveguides.

The photomasks used in the fabrication consist of two types; (1) positive resist and (2) negative resist. The selection of mask is based on the specifications set in Southampton University.

In order to achieve a uniform concentration throughout the guiding region of the waveguides, 9 implantations were implemented, two of which consist of low energy is conducted in Southampton University and 6, which consist of high energy is conducted in Surrey University.

Each device is approximately 15mm x 15mm, and if this is translated to device per 4-inch wafer, 40 devices can be produced.
References:


CHAPTER 6
Experimental Techniques

When you make a mistake, don’t look back at it long. Take the reason of the thing into your mind and then look forward. Mistakes are lessons of wisdom. The past cannot be changed. The future is yet in your power.

Hugh White

6.1 Introduction

This chapter is intended to focus on the experimental techniques used for measuring the fabricated devices. In Section 6.2, the quality of the waveguide endface is discussed. It is well-understood that the waveguide endface is very dependent upon the preparation technique, hence, in this section, the author has paid particular attention to one of the most commonly used technique known as Facet Polishing. The author will discuss the polishing technique that is able to produce a sufficiently smooth facet that optical scattering is minimised.

Section 6.3, the author will discuss some of the main theory regarding the accuracy of the experimental techniques. These theories include propagation loss and insertion loss. Also, the author will describe several techniques available for waveguide loss measurement and selected an appropriate method for the SOI rib waveguide used in this work.

In section 6.4, the author discussed the losses inherent in coupling from the fibre to the waveguides and vice versa. These losses include overlap of excitation and waveguide endface and Fresnel reflection due to refractive index mismatch. Section 6.5, on the subject of experiments Setup, described two optical setups required for measuring the AWG. Each setup is carefully implemented to ease the process of measurement and to reduce the experimental errors inherent in most of the experimental work. Also, it provides a general review of the optical equipments used within the setups in section 6.6.

Finally in section 6.7, the characterisation of SOI straight waveguide is discussed and the measurement technique is explained.
6.2 Polishing

6.2.1 Introduction

The quality of the SOI waveguide facets plays an important role in determining its transmission characteristics. The imperfect surfaces of the waveguide facets create random surfaces, thus causing light to reflect off the waveguide interface. This will induce scattering losses and cause the excitation of higher order modes. Hence, it is vital to maintain a good quality facet to ensure the feasibility and reliability of the device.

The most fundamental step in preparation of such waveguide facets is polishing. The polishing technique in this work makes use of a METASERV 2000 grinder polisher as shown in figure 6.1.

The grinder polisher is a self contained unit that is designed for polishing and grinding samples for microstructural analysis [6.1]. It consists of a variable speed polishing wheel that allows a rotation speed of 50-500 rpm and a sample clamper to hold the sample onto the platen. A grit pad is then positioned on top of the platen and the endface of the sample is positioned on the pad under the sample clamper. A constant flow of water is required while the polishing takes place. The following grit pads were chosen for our polishing procedure: p600, p4000, 3μm, 1μm, and 0.3μm. Each grit pad plays an important role in determining our final polishing recipe in order to achieve mirror-like facets.

The final polishing recipe is derived through a series of repetitions based on a combination of polishing method and recipes. This final recipe has been tested on both dummy silicon and SOI chips, and it has proven to provide consistency in achieving mirror-like endfaces for different samples.
Before we begin our discussion on our polishing procedure and its recipe, it is worth reviewing the dimensions of our SOI AWG sample. The chip size of our sample is 15mm x 15mm and can hold up to two AWGs as shown in figure 6.2. The length of the AWG is 14mm, which gives an excess spacing of 0.5mm on both sides of the chip. This excess spacing has to be polished off, until the waveguides reach the edge of the chip, thus allowing light to be coupled in/out of the waveguides during experiment.
6.2.2 Sample holder

The METASERV 2000 grinder polisher is equipped with a sample clamper and provides a platform for semi-automatic polishing. However, before the sample can be placed onto the clamper, it has to be "waxed" onto a sample holder. A sample holder has been custom made for this project. This holder, as shown in figure 6.3 is specially designed to allow easy manipulation of the sample.
The sample holder consists of two parts;

(1) the holder, where the chips will be "waxed" against. This holder also contains two 4mm diameter holes, which fit the size of normal tweezers; hence, it can be easily taken off the polisher once the polishing has completed.

(2) the holder base, which is designed in a step fashion, will prevent the wax from dripping to the supporting base whilst making the holders for easy detachment from the holder base. It also helps align the edge of the device chip.

6.2.3 Polishing Procedure

6.2.3.1 Sample Preparation

Sample preparation is a critical element in achieving optimal flatness at the facet, where polishing takes place. Hence, the discussion will be based on a method to realise a good alignment between two samples that are "waxed" on both sides of the sample holder as shown in figure 6.4. The following preparation method is recommended:

![Sample preparations](image)
• Set the thermostat hotplate to around 100°C to 150°C, and allow it to heat for 10mins.
• Place the holder base and a glass plate on top of the hotplate, and melt some wax onto the top of the glass plate.
• Place the holder on top of the holder base. Apply wax to both sides of holder.
• Stick the samples onto the holder with the surface to be polished facing downward as shown in figure 6.4a. The base will provide a guideline for the alignment.
• Remove the base, together with the holder and samples from the hotplate and allow it to cool.
• Remove the holder from the base as shown in figure 6.4b. The samples are ready for polishing.

6.2.4 Polishing Recipe

Our polishing procedure begins with a p600 grit pad. This is the coarsest grit used in our polishing. This grit pad is useful in removing the excess spacing (between the sample edge and the waveguides) within the shortest possible time. However, due to the coarse grit, chipping can occur at the edge of the samples. Therefore, to prevent the waveguides from chipping, it is best to leave a very small gap, which serves as a guard line, between the chip edge and the waveguides.

Next, by changing the polishing pad to p4000 grit, the silicon was allowed to be slowly removed (to the point when the waveguides reach the edge of the sample) and thus minimising the chipping effect. Once the waveguides reach the edge, we replaced the P4000 grit pad with a 3μm grit pad. This step is particularly important, because of the large coarse grit used previously, the 3μm will have to remove the relatively deep scratches present on the surface, until a relatively smooth surface is observed under the optical microscope.
Subsequently, we replaced the polishing platen with a 1µm grit pad, which will eradicate the fine scratches produced in the previous step. Finally, a 0.3µm grit pad was used to polish the sample until a mirror-like surface was achieved at the facet. Because of the fragility of the waveguides, it is advisable to inspect the samples under a high power optical microscope for scratches after each polishing step. Table 6.1 gives a summary of our polishing recipe having parameters such as grits, polishing time and speed (rpm).

<table>
<thead>
<tr>
<th>Grits Type</th>
<th>Approximate Time</th>
<th>Speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P600</td>
<td>2 mins</td>
<td>50</td>
</tr>
<tr>
<td>P4000</td>
<td>3 mins</td>
<td>50</td>
</tr>
<tr>
<td>3µm</td>
<td>10 mins</td>
<td>50</td>
</tr>
<tr>
<td>1µm</td>
<td>10 mins</td>
<td>50</td>
</tr>
<tr>
<td>0.3µm</td>
<td>15 mins</td>
<td>50</td>
</tr>
<tr>
<td>0.05µm</td>
<td>10 mins</td>
<td>50</td>
</tr>
</tbody>
</table>

6.3 Silicon-on-Insulator (SOI) Optical Waveguide Measurements

6.3.1 Introduction

The optical waveguide loss is a primary aspect that needed to be addressed when developing an optical waveguide in the research discipline. Various methods of loss characterisation of an optical waveguide are available; however each measurement method depends on the information required.

When measuring an optical waveguide, the objective of the measurement must be comprehensible. Two types of losses, namely, insertion loss and propagation loss can somewhat be misinterpreted. Insertion loss generally takes into account the total loss associated with introducing a waveguide or device into a system and hence it deals with
both the inherent waveguide loss and the associated coupling losses. On the other hand, propagation loss is the loss related to propagation in the waveguide or device, which excludes coupling losses. In this work, propagation loss is of interest, since the loss linked with a particular waveguide in a research environment are associated with the design and material properties and fabrication quality.

There are three commonly used measurement methods for quantifying propagation loss; (1) Cut-back method, (2) Fabry-Perot (FP) Resonance Method and (3) Scattering light method. It is well-known that the scattering light method is useful for initial studies of the waveguide materials [6.4], when the scattering of light is high and relatively high power is propagating in the waveguide, and is ineffectual when optimisation of waveguide is required. Hence it shall not be contained in the scope of discussion in this chapter.

6.3.2 Cut-Back Method

Following the approach of Reed and Knights [6.2], the cut-back method is the simplest measurement technique of characterising the losses of an optical waveguide. This form of measuring technique involves the shortening of the waveguide length, \( L_1 \) to \( L_2 \) and recording the output power for both lengths, \( I_1 \) and \( I_2 \), while keeping the input power constant. Recall that, the intensity, \( I \), decays with propagation length through the material with refractive index, \( n' \) in equation (3.31) is given as:

\[
I = I_0 e^{-\alpha z}
\]  

(6.1)

Using the above equation, the ratio of \( I_1 \) to \( I_2 \) can be expressed as:

\[
\frac{I_1}{I_2} = \exp[-\alpha (L_1 - L_2)]
\]  

(6.2)

so that

\[
\alpha = \left( \frac{1}{L_1 - L_2} \right) \ln \left( \frac{I_2}{I_1} \right)
\]  

(6.3)
It is obvious that equation (6.3) is only taken from two data points, which assumed that the input coupling, the quality of the waveguide endfaces and the input power all remain constant, therefore the accuracy of such a measurement is jeopardised. In order to improve the accuracy of such technique, multiple measurements have to be performed, and the optical power is recorded and plotted against the waveguide length as illustrated in figure 6.5.

![Figure 6.5 Optical loss plot as a function of propagation length][1]

The optical loss in figure 6.5 suggests that, instead of the propagation loss being measured, the insertion loss is recorded since the coupling loss mechanisms are taken into consideration. It is obvious from the plot that an optical loss is associated with a zero propagation length and that loss is the coupling loss.

### 6.3.3 Fabry-Perot Resonace Method

As discussed in section 6.2, a commonly used technique for preparing the endface of an optical device is polishing. Two polished endfaces form a cavity which is similar to a laser cavity. Light reflected at either facet is determined by the refractive index of the waveguide material and the external media and described by the reflection coefficient. This reflectivity can be reduced using antireflection coatings. As the optical field

---

[1]: figure.png
propagates to and fro within the waveguide, it experiences multiple reflections, thus, this waveguide structure is regarded as a resonant FP cavity. The relationship between the transmitted optical intensity \(I_t\) and the incident light intensity \(I_o\) through such a cavity is given as [6.2]:

\[
\frac{I_t}{I_o} = \frac{(1-R)^2 e^{-\alpha L}}{(1-Re^{-\alpha L})^2 + 4Re^{-\alpha L} \sin^2 \left(\frac{\phi}{2}\right)} \tag{6.4}
\]

where \(R\) is the facet reflectivity, \(L\) is the waveguide length, \(\alpha\) is the loss coefficient and \(\phi\) is the phase difference between successive waves in the cavity. Following the approached of Reed and Knights [6.4], we see that equation (6.4) is periodic when the phase, \(\phi\), passes through multiples of \(2\pi\). Hence, equation (6.4) has a minimum value when \(\phi = \pi\), yielding:

\[
\frac{I_{\text{min}}}{I_o} = \frac{(1-R)^2 e^{-\alpha L}}{(1-Re^{-\alpha L})^2 + 4Re^{-\alpha L}} = \frac{(1-R)^2 e^{-\alpha L}}{(1+Re^{-\alpha L})^2} \tag{6.5}
\]

when \(\phi = 0\), then equation (6.4) will have a maximum value; that is:

\[
\frac{I_{\text{max}}}{I_o} = \frac{(1-R)^2 e^{-\alpha L}}{(1-Re^{-\alpha L})^2} \tag{6.6}
\]

Thus, we can evaluate the ratio of the maximum intensity to minimum intensity as:

\[
\zeta = \frac{I_{\text{max}}}{I_{\text{min}}} = \frac{(1+Re^{-\alpha L})^2}{(1-Re^{-\alpha L})^2} \tag{6.7}
\]

By rearranging equation (6.7), the loss coefficient, \(\alpha\), is given as:
Therefore, if the reflectivity, $R$, and the ratio of maximum intensity to minimum intensity, $\zeta$, can also be obtained, thus, the loss coefficient, $\alpha$, can be evaluated. Equation (6.7) describes the transfer function of the Fabry-Perot cavity, and is periodic when the phase, $\phi$, passes through multiples of $2\pi$, therefore, if the Fabry-Perot cavity is swept experimentally, either by varying the length of the waveguide or by varying the wavelength of the light source, through a few cycles of $2\pi$, $\zeta$ can be measured.

The transfer function in equation 6.4 is plotted in figure 6.6 for 3 different reflectivities by Reed and Knights [6.2]. The reflectivity values plotted were 0.1, 0.31 and 0.5, with $\alpha L = 0.023$ which corresponds to an approximate loss of 0.1 dB/cm. In accordance with figure 6.6, it can be observed that the transfer function has a near sinusoid response for a reflectivity $R=0.1$. As the reflectivity increases, the transfer function response exhibits sharper peaks.

![Figure 6.6 Fabry-Perot Transfer function for 3 different reflectivities [6.2]](image)
One main advantage of the FP resonance method is the determination whether the waveguide is singlemode or multimode. If the waveguide is singlemode, the FP cavity with approximately 31% reflectivity (for an air/silicon interface) will result in a solid curve as shown in figure 6.6. If the waveguide is multi-mode, then additional interference gives rise to distortion of the FP transfer function.

6.4 Coupling Loss

If an input fibre is perfectly aligned to a silicon waveguide, coupling loss can in turn be divided into three main factors; Fresnel Reflection loss, loss resulting from mode mismatch between the input and the guided modes, and scattering loss resulting from the end face roughness. Due to the small dimension of the waveguide (1.1μm in width), perfect alignment is difficult to achieve, thus, spatial misalignment of the excitation and waveguide fields is also taken into consideration. Among these factors, the Fresnel reflection loss is relatively insensitive to experimental conditions and is easily calculated for a given system. However, it is not easy to experimentally differentiate the loss caused by mode mismatching and scattering. The loss from mode mismatching can be calculated with the overlap integral between the excitation field and the waveguide field; hence we can deduce the scattering loss from the total coupling loss by subtracting the calculated losses. If the waveguide endface is prepared accordingly to section 6.2, a sufficiently smooth facet can be achieved where the optical scattering is minimised. Hence for the purposes of AWG measurements, the assumption is made that the polishing technique worked to a level that scattering is negligible.

6.4.1 Overlap of Excitation and Waveguide Endface

Mode mismatch calculation of the excitation and waveguide fields is usually carried out by performing the overlap integral between the two fields. As discussed in section 5.4.8, the lens fibre has a spot size of 2.5μm and is assumed to have a circularly gaussian profile, whilst the SOI rib waveguides structure has a width of 1.1μm and a etch depth of 0.62μm. Optical simulation using BPM was performed to study (a) the relationship
between the waveguide geometry and the launch field and (b) the launch position of the lens fibre with respect to the waveguide, hence establishing the mode mismatch loss due to the difference in the mode profile of the input beam and the mode profile of the SOI waveguide.

**Relationship between the Waveguide Geometry and the Launch field**

The plot in figure 6.7 gives a clear indication of the mode mismatch loss due to waveguide geometry. Two distinct scans were performed to monitor the optical power coupled into the waveguide. The first scan is carried out by varying the width of the waveguide and keeping the etch depth constant and the second scan is executed by varying the etch depth and keeping the rib width constant. A loss of -3.46dB is noted for our waveguide dimension. This loss can be translated to a coupling efficiency of 45.6%. Figure 6.7 also predicts that the variation of rib width within the waveguide structure results in a high coupling loss compared to the variation of etch depth.

![Figure 6.7 Coupling Loss due to (a) variation of rib width and (b) variation due to etch depth. An input beam of 4µm assuming to be circularly Gaussian.](image-url)
Launch Position of the Lens Fibre with respect to the Waveguide

Spatial alignment of the excitation and waveguide fields is critically important due to the small dimension of the SOI waveguide used in this work. If we follow the approach of Png [6.3], by performing two independent scans on both the variation of the x-position and y-position of the fibre with respect to the waveguide, we can predict the alignment tolerance where maximum coupling efficiency can be achieved. The maximum coupling efficiency for the waveguide structure in figure 6.9 indicated \( x = 0 \) and \( y = 0.72 \mu \text{m} \). If there is a variation on the optimum \( x/y \) position, the coupling efficiency can be significantly impaired.

![Diagram](Image)

Figure 6.8 Transmitted power (a.u) against the x-position of 4\( \mu \text{m} \times 4\mu \text{m} \) lens fibre with y-position at the waveguide centre and for y-position of 4\( \mu \text{m} \times 4\mu \text{m} \) lens fibre with x-position at the waveguide centre.
It is obvious in figure 6.8 that a maximum coupling efficiency is achieved when the variation of x-position, \( x' \), and variation of y-position, \( y' \), of the fibre with respect to the waveguide is equal to zero.

![Diagram showing maximum coupling efficiency at x=0 and y=0.72μm](image)

Maximum coupling efficiency
\( x=0 \) and \( y=0.72\mu m \)

Silicon

\( y=0 \)

Silicon dioxide

\( x=0 \)

Figure 6.9 Defining the origin of x and y position

However, if the \( x' \) and \( y' \) is shifted by ±0.1μm, a coupling efficiency of ~54% is still achievable. Hence, this eases the restriction of the positioning accuracy on the Melles Griot NanoMax-Hs x-y-z micropositioning stages, which has a resolution of 5nm. The above discussion accentuates the importance of a high efficient coupler for small devices [6.4].

6.4.2 Fresnel Reflection

When we consider an SOI waveguide having a high refractive index contrast between the Si/Air interfaces, these refractive indices will determine the reflection from the waveguide endface. This can be described by the Fresnel equations established in section 3.2.2, equation (3.11) and (3.15) for both TE and TM polarisation [6.5];

\[
    r_{TE} = \frac{E_L}{E_T} = \frac{n_i \cos \theta_i - n_f \cos \theta_L}{n_i \cos \theta_i + n_f \cos \theta_L}
\]  

(6.9)
Accordingly to the Fresnel formula, the angles of the incident wave, the reflected wave and the refracted wave can be depicted by Snell’s law. Hence the reflection coefficients can be described by the interface reflectivity, $R$, where $R = r^2$. Thus, $R$ is given as:

For TE polarisation:

$$R_{TE} = r_{TE}^2 = \frac{\sin^2(\theta_1 - \theta_2)}{\sin^2(\theta_1 + \theta_2)}$$  \hfill (6.11)$$

Similarly for TM polarisation:

$$R_{TM} = r_{TM}^2 = \frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)}$$  \hfill (6.12)$$

The dependencies for the reflection coefficients, $R$, are given in the diagram figure 6.10.

If we considered light propagation from air into silicon at the normal of incidence, thus, there is no difference between the TE and TM polarisation, since the angle of incidence is equal to zero. If we associated our experiment with end-fire coupling, where the light is introduced near normal incidence, we can rewrite equations (6.11) and (6.12) as:

$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$  \hfill (6.13)$$
Hence, the reflectance, $R$ is approximately 31%, which can be translated to an additional loss of 1.6dB per interface.

6.5 Experimental Setups

6.5.1 Introduction

A common test for measuring an optical device is the loss measurement. Loss is a stimulus-response measurement. Hence a light source is used as the stimulus to launch light into the device and an optical receiver measures the response, which is the light exiting from the device. For non-DWDM devices, where loss does not vary significantly with wavelength, the devices are often scrutinised under one or two fixed wavelengths – commonly at 1300nm and 1550nm. However, in DWDM devices, such as an AWG, where the loss is usually expressed as a function of wavelength, the spectral loss must be measured over the wavelengths in a “spectrally resolved” method, often called a “swept” loss measurement. This would generally require the source or receiver or both to be
wavelength selective. Hence, three common setups are available and are listed in table 6.2 [6,6]

<table>
<thead>
<tr>
<th>Source</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tuneable Laser</td>
<td>Broadband (Power Meter)</td>
</tr>
<tr>
<td>Broadband (EELED, ASE)</td>
<td>Tuned (Optical Spectrum Analyser)</td>
</tr>
<tr>
<td>Tuneable Laser</td>
<td>Tuned (Optical Spectrum Analyser)</td>
</tr>
</tbody>
</table>

The first setup consists of a Tuneable Laser source (TLS) paired with a broadband detector, such as a power meter, which can respond to a broad range of wavelengths as shown in figure 6.11.

This setup offers high wavelength accuracy since the resolution of the TLS and power meter is limited by the wavelength spacing of the samples of the power meter, which can be less than 0.001nm. Thus, a high accuracy wavelength meter can be used to monitor the tuneable laser during measurement. Simple, low-cost power meters make the best loss measurement and allow all outputs to be measured in parallel, making this the fastest solution for multiple outputs.

Figure 6.11 Swept wavelength loss solution; Tuneable laser paired with power meters [6,6]
The second setup consists of a broadband source and a tuneable receiver as shown in figure 6.12. The broadband source stimulates the devices with a broad continuous spectrum. Light leaving the device is shaped by its spectral loss and measured on a tuned receiver, usually an optical spectrum analyser.

Figure 6.12 Swept wavelength loss solution: Broadband source and optical spectrum analyser [6.6]

However, the use of the broadband source and optical spectrum analyser poses a major limitation in terms of its wavelength resolution [6.6] due to its bandwidth of the sweeping filter which is not narrow enough for today’s DWDM devices. Wavelength accuracy of an optical spectrum analyser has improved but that replies on a pre-calibration and repeatability. The complexity of the sweeping filter in the optical spectrum analyser also limits its loss (power) accuracy. When measuring DWDM devices, such as the AWGs, the strength of such a method, which is the fast sweep speed, is diminished, since a “switch” must be used to measure the output sequentially.

The third method, which is the most expensive and complicated method, is the use of a combination of both tuneable source and receiver. With the advances made in the tuneable laser, it is unnecessary to measure passive devices using the third method; hence, it shall not be included in our scope of discussion.
6.5.2 Criteria of Selecting the TLS and the Power Meter

As discussed in the comparison of test setups in the previous section, the TLS-power meter solution has the best potential in meeting the test requirement of the AWGs. The linewidth of the TLS is very narrow to provide the highest resolution while the power meter has the best power accuracy. However, for this setup to fully satisfy the measurement requirement, i.e. high wavelength accuracy, high resolution, high dynamic range and high speed, two critical performance limitations that TLS's have traditionally have to be overcome [6.7].

1. The poor wavelength accuracy, which affects the wavelength accuracy requirement of the measurement.

2. The spontaneous emission, which affects the dynamic range requirement.

The concept of measuring insertion loss against wavelength is to have the laser swept in wavelength while the power meter records the optical power. A swept measurement usually requires the proper synchronisation of the TLS and the power meter. One way of achieving this is to generate triggers at the set wavelength interval to the power meter which take a sample at each trigger. The sample rate of the power meter must be fast enough to accomplish small sample spacing at a reasonable sweep speed of the TLS. To illustrate the above point, for a continuous sweep of the TLS at a constant sweep rate of 10nm/s, the power meter takes a sample every 0.002nm, which is equivalent to 5000 samples/s. Sample spacing is an important aspect in determining the final resolution of the measurement. While the TLS linewidth may be narrow, tight sample spacing cannot be achieved meaning that details of the spectral shape of the device will not be resolved.

The second criterion is the dynamic range. Dynamic range is the difference between the largest and smallest loss value of an AWG that can be measured. The dynamic range in a TLS-power meter setup is generally limited by the output of the TLS, known as spontaneous emission (SE). SE is a continuous spectrum of light which surrounds the
signal, usually over the entire range of the TLS. To further explain the above point, it is best illustrated using the diagram as shown in figure 6.13.

Consider measuring the AWG with a transmission spectral, which possess a narrow, deep notch. If the TLS signal power is 0 dBm and the notch is 50dB deep, when the TLS wavelength is in the area of the notch, signal power out of the device is $0\text{dBm} - 50\text{dBm} = -50\text{dBm}$. However, the rest of the wavelength range of the device is so low loss, so almost all of the SSE passes through the device to the power meter. The power meter then receive the intended -50dBm signal, but also the higher power -30dBm of the SSE as shown in figure 6.13. Thus, the power meter measures the sum. Consequently, the dynamic range is limited to 30dB and the true depth of the AWG cannot be measured. Hence, a TLS with low-SSE, one with a high signal/total SSE ratio, provides the solutions, with typically a 60dB Signal/total SSE ratio.
6.6 Experimental Setups for Measuring AWGs

The experimental setup for measuring our SOI AWGs is shown in figure 6.14. The setup can be divided in three sections; input stage, middle stage and the output stage. Firstly, the input stage, which comprises an OZ Optics tapered lensed fibre, placed on top of the tapered grooved fibre holder. The holder is then mounted on top of the NanoMax-TS three axis stage which allows the manoeuvre of the fibre in its x, y and z directions. The NanoMax-TS three axis stage is then connected to the piezoelectric actuators for precision control. Subsequently, the lensed fibre is connected to the tuneable laser source (TLS).

The middle stage consists of the NanoMax-TS three axis stage where our AWGs or the device under test (DUT) will be placed. A microscope is situated above the DUT which allows movement in the x and z direction in order to locate the waveguides. The microscope is connected to a monitor, hence making the alignment of the fibre to the waveguides much easier.

In the output stage, we considered two different experiment setups; firstly the use of a focusing lens, which is mounted on top of the NanoMax-TS three axis stage, together with the new focus reflector which directed the beams to a MicroPhysic viewer. The MicroPhysic viewer is then connected to a computer to display the output waveguides and the optical output beam. Once this is accomplished, we have set the alignment between the input fibre and the input waveguide.

Secondly, an alternative setup that uses a singlemode fibre to replace the focusing lens as shown in figure 6.14. This singlemode fibre is mounted on top of the NanoMax-TS three axis stage to receive the optical output power from the devices. The optical fibre is then carefully aligned to the desired waveguides and a wavelengths scan is performed. The optical power from the different wavelengths is then received by the detector, which in turn is transferred to the computer for data acquisition.
The experiment setup as shown in figures 6.14 and 6.15 consist of the following optical equipment:

- Agilent Lightwave Optical Multimeter (8164A)
- OZ Optics Tapered Lens fibres
- NanoMax-TS: Three Axis stages By (Melles Griot) (x3)
- Tapered Grooves Fibre Holders (x 2)
- Focusing Lens
- New-focus Reflector (9891)
- Piezoelectric Actuators
EXPERIMENTAL SETUPS FOR MEASURING AWGS

- ElectronPhysic Micron Viewer
- Microscope
- Personal Computer (PC)
- Power supply
- Television

The next few sections will give a brief description of some of the most commonly used optical equipment in term of their functionality.

Figure 6.15 Experimental setup: replacement of the focusing lens with a Singlemode fibre for data acquisition
6.6.1 Lightwave Measurement Systems

The lightwave measurement system is a high performance optical multimeter for the characterisation and evaluation of optical components. With its modular format, it is flexible to meet changing needs when making a variety of optical measurement. In our experiment, the Agilent 8164A Lightwave Multimeter Mainframe is chosen. This Mainframe has one large and four slim module slots. The system could host one back loadable tuneable laser module and up to four front-loadable modules.

6.6.2 Laser Source

The laser source used in our experiment is the Agilent 81640A Fabry Perot (InGaAsP) tuneable laser, which is mounted on the Agilent 8164A Lightwave Multimeter as shown in figure 6.16.

![Figure 6.16 Agilent 81640A Tuneable Laser Module](image)

The laser source covers both C and L bands and is specifically designed for testing critical DWDM passive components such as the AWGs. It has continuous sweep through the full wavelength range, with maximum output power of 4dBm. The wavelength accuracy is ±0.015nm.
6.6.3 Nanopositioning

When singlemode fibres are coupled to our 1.5μm Si-ovelayer waveguides, lateral and axial misalignment will induce losses. To provide precise orientation of our AWGs, NanoMax-TS three axis stages (17 MAX 303) from Melles Griot are used. These stages facilitate the manoeuvre of the incoming fibre, the devices under test (DUT) and the outgoing fibre with nanometre resolution with the help piezoelectric actuators.

6.6.4 Optical head

One of the most versatile and accurate power meters come in the form of optical heads with analog output and optical input. The analog output is the BNC connector on the back of the optical head and it outputs a voltage, in a range of 0V to 2V, which is directly proportional to the strength of the optical signal. A number of optical heads are available, which use either germanium or InGaAs photo detectors. Germanium detectors offer excellent performance such as small wavelength dependence, for the 1330nm regime, at a low cost. On the other hand, InGaAs detectors have small wavelength dependence at both 1300nm and 1550nm, combined with better sensitivity, but at a higher price. Agilent 81624B optical head is used for our experiments simply because of it wavelength responsivity which allows the coverage of 800nm to 1700nm with a detector of 5mm in diameter.

6.6.5 Lensed fibre

The width of the SOI waveguides in our AWG is 1.1μm. The normal optical fibre core is around 9μm, which make coupling from fibres to the waveguides very inefficient. Hence, to improve the coupling efficiency, we employed a special fibre in our experiments known as Lensed fibre. Lensed fibre offers a convenient way to improve coupling between the optical fibres and waveguides devices. By drawing, tapering and shaping the fibre end, including the core, the light can be transformed to improve mode matching and coupling efficiency with the waveguide devices. Our lensed fibre is acquired from OZ
Optics. It has a spot size of 2.5 micron and is coated with an anti-reflectant coating. One end of the fibre is attached to an angled FC connectors, which make it compatible with the Agilent optical multimeter. The working distance is around 18μm which provide sufficient working spacing between the waveguides and the fibre.

6.7 Loss Measurements of SOI Straight Waveguide

As discussed in chapter 2, section 2.4, Silicon-on-insulator has been proven to be a low loss waveguiding material, which exhibited losses as low as 0.1dB/cm. In this work, waveguide propagation loss measurements are carried out using the Fabry-Perot Resonance method as described in section 6.3.3. The experimental setup for performing such technique is similar to that of measuring the AWGs as described in section 6.6. The measurement can be determined as follows:

1. The wavelengths of interest are scanned and the maximum output power from the Agilent InGaAs detector is recorded with no device present.

2. The output power with device under test (DUT) is recorded with the similar range of wavelengths as in (1). The device is accurately positioned in the beam axis by adjusting the micropositioners.

3. The output is first directed towards the MicroPhysic viewer with its output fed to a monitor to display the detected image. Fine adjustment of the fibre and DUT is performed using the micropositioner until the maximum output power is observed on the detector. When optimum waveguiding is achieved, the focusing lens is replaced by a lens fibre and the true output power is recorded for a range of wavelength.

4. Finally this output power is normalised to the laser power recorded in (1). To improve accuracy and maintain consistency in the measurement, the experiment is conducted at least ten times and average result is noted.
6.8 Summary

In summary, the author has described a polishing technique for endface preparation. This technique is probably the most common method of preparing a waveguide facet. The aim of such a technique is to produce a mirror-like surface for light coupling in the experimental stage of this work. This technique involves trials and error on both the dummy and SOI chips, which finally produce a “recipe” which allows repeatability on other samples. However, such a “recipe” is only applicable to the dimension of the chips described in this work.

Finally, two experimental setups are available for testing and measuring the SOI AWG. These setups have been carefully devised, so that the optimum method is used. With the help of some of the optical equipment such as the multi-lightwave meters, and nanopositioning stages, experimental errors such as, the losses due to lateral and axial misalignments can be greatly reduced.

The experimental results obtained are discussed in the next chapters.
References:


CHAPTER 7
Results and Discussion

After great pain, a formal feeling comes.

Emily Dickinson

7.1 Introduction

This chapter is intended to focus on the experimental results and discussion aspect of this work. We begin with a discussion of the results of the SOI straight waveguide using the Fabry-Perot resonance method to characterise the SOI waveguide. Then we proceed to discuss and analyse the experimental results obtained for our AWGs.

Two sets of AWG devices are fabricated, one with Gaussian-like transmission spectrum and one with flat-top transmission spectrum. The idea of these devices is to enable the author to make a comparison between both responses.

In section 7.2, the results for the SOI straight waveguides are presented. From the results, obtained through the Fabry-Perot Resonance method as described in section 6.3.3, the author is able to determine the propagation loss associated with the intended devices. In section 7.3, the author presents the measured results for the two different types of AWG; (1) the conventional AWG and (2) the flat-top AWG. The measurements are performed in a consistent experimental environment and the readings are taken for 8-channels per device.

In section 7.4, analysis and investigation is carried out to determine the parameters that influence the crosstalk on our fabricated devices. Simulations are performed based on the finding to verify such parametric variations.
7.2 Measured and Simulated Results of SOI Straight Waveguide using Fabry-Perot Resonance Method

The straight waveguides measured in this work are typically 725μm in length, which was measured using the Mitutoyo Series 500 Metric Caliper with an uncertainty of ±0.02mm. The length of the waveguide ranged between 705μm to 745μm. The optical power meter used to determine output power has an uncertainty value of ±0.1μW.

The waveguides were measured using the Fabry-Perot (FP) resonance method as described in section 6.3.3. A cavity was formed by polishing both the input and output ends of the waveguide. A constant power from the laser is coupled into the SOI straight waveguide through a tapered lensed fibre and the output power is detected via another tapered lensed fibre. The transmission spectrum was measured with changing λ as shown in figure 7.1. The propagation loss coefficient α is given by [7.1]:

\[
\alpha = \frac{1}{L} \ln \left( \frac{1}{R} \frac{\sqrt{I_{\max}/I_{\min}} - 1}{\sqrt{I_{\max}/I_{\min}} + 1} \right)
\]  

(7.1)

where \( L \) is the waveguide length, \( R \) is the facet modal reflectivity, \( I_{\max} \) and \( I_{\min} \) are the peak and trough intensity of each resonance respectively. Compared with the conventional cut-back method, this method yields a more accurate evaluation of such high index contrast waveguides, since the ratio of \( I_{\max}/I_{\min} \) is independent of the coupling condition of the input and output light. The reflectance \( R \) is 31% of the reflectivity, due to the index contrast between silicon and air, which is calculated in section 6.4.2.

In this experiment, the sample was prepared by polishing techniques and the measurement was conducted using the experimental setup as in figure 6.14. Figure 7.1 clearly indicated a Fabry-Perot response.
The theoretical transfer function of the FP response is plotted using the device parameters. The reflectance, $R$, is given as 0.31 for air/silicon interface and the length of the waveguide, $L$, is given as 725μm. The ratio of the maximum intensity to minimum intensity $\zeta$ can be obtained from the measured response in figure 7.1. Thus, using equation 7.1, the loss coefficient can be evaluated. Figure 7.2 shows the theoretical FP transfer function of the SOI waveguide, and it shows good agreement with the measured response with the transmission peaks falls approximately in the same wavelengths of interest.
If we record the average $I_{\text{max}}$ and $I_{\text{min}}$ values as in figure 7.1, this yields an average propagation loss of 1.4 dB/cm, which could be the result of scattering loss caused by the sidewall roughness [7.2-7.4].

Thus a Scanning Electron Microscopy (SEM) was performed on the SOI rib waveguides and a photograph of the sidewall is shown in figure 7.3. The qualitative agreement between the expected result from the literature of $\sim$ 0.5dB/cm and the SEM photograph indicated that the propagation loss was probably increased by the scattering loss. This is attributed to the E-beam photolithography and etching processes during fabrication.
7.3 Transmission Characteristics of the Arrayed Waveguide Gratings (AWGs)

The AWGs were measured using the experimental setups as described in section 6.6. Two fabrication runs were conducted, with two distinct devices on each run. The first fabrication run consisted of the conventional AWGs and the flat spectral width AWGs with $9 \times 10^{17}$ cm$^{-3}$ net doping concentration. The second fabrication run consisted of the flat-top AWGs with $1 \times 10^{18}$ cm$^{-3}$ and $2 \times 10^{18}$ cm$^{-3}$ net doping concentration respectively. The devices considered for measurement were selected from different areas of the wafers.

In the first fabrication run, 4 devices were fabricated and subsequently measured. Devices 1, 2 and 3 were selected around the centre of the wafer, while device 4 was selected near to the edge. The selection of devices near to the edge of the wafer is of particular importance, because of the occurrence of correlation errors in different positions on the wafer.
7.3.1 Measured Results of the Conventional AWG with Gaussian-like Transmission Peak

The transmission spectra for the 1x8 demultiplexer of the SOI-based 1.6nm spacing AWGs are shown in figure 7.4. The transmission spectra were measured at the central channel of the fabricated AWGs for Devices 1, 2 and 3. The sidelobe components produced in the transmission spectra ranging from -1.3dB to -4dB with respect to its peak. The central wavelength of the transmission peaks shows relatively good agreement with our simulated response, at 1550.8nm.

![Figure 7.4 Measured transmission spectra of the 1x8 demultiplexer SOI-Based AWG; responses indicated the measured transmission characteristics of 3 devices at a centre wavelength of 1550 nm](image-url)
However, in figure 7.4, it can also be noted that the transmission peak of device 1 differs from the designed value by 0.1nm. This may be due to the fact that, since the AWGs act as diffracting devices, which depend on the length and difference of the arrayed waveguides transmission paths, precise control must be exerted over the difference $\Delta L$ between the lengths of adjacent waveguides. In practice, however, the changes in the refractive index of the waveguide material caused by changes in temperature, together with thermal expansion and contraction of the substrate and waveguides [7.5], result in changes in both the length and the $\Delta L$ of the transmission path. This could cause a change in the focusing point at the output slab waveguides, as well as the wavelength entering the output waveguides. This change in effective index is governed by the thermal coefficient given as [7.6]:

$$\frac{dn}{dT} = 1.86 \times 10^{-4} / K$$  \hspace{1cm} (7.2)

Thus, this inevitable increase in temperature will cause a change in the effective index and ultimately introduce phase error as described in section 7.4.

Furthermore, with 100 waveguides in the grating, the waveguide geometry and refractive index may diverge from the design values. Also, even a minor discrepancy in the position of an output waveguide will cause the transmission spectrum to vary from the desired wavelength.

Figures 7.5 to 7.12 show the demultiplexing characteristics of all 8-channels of our fabricated AWGs. Each channel was separated with 1.6nm spacing and the transmission spectra exhibit a crosstalk value of approximately -3dB. This could be due to phase errors, which lead to destructive interference at the output slab, as a result of effective index variation; waveguides dimension variations, and/or path length deviation. The effect of such parametric influences shall be discussed further in 7.4.

In general however, all devices exhibit a clear peak in the spectral response, close to the expected wavelength.
Figure 7.5 Measured transmission spectra of channel 1 - centre wavelength at 1544.6nm

Figure 7.6 Measured transmission spectra of channel 2 - centre wavelength at 1547.2nm
MEASURED RESULTS OF THE CONVENTIONAL AWG WITH GAUSSIAN-LIKE TRANSMISSION PEAK

Figure 7.7 Measured transmission spectra of channel 3 - centre wavelength at 1547.9nm

Figure 7.8 Measured transmission spectra of channel 4 - centre wavelength at 1549.8nm
MEASURED RESULTS OF THE CONVENTIONAL AWG WITH GAUSSIAN-LIKE TRANSMISSION PEAK

Figure 7.9 Measured transmission spectra of channel 5 - centre wavelength at 1550.8nm

Figure 7.10 Measured transmission spectra of channel 6 - centre wavelength at 1552.2nm
MEASURED RESULTS OF THE CONVENTIONAL AWG WITH GAUSSIAN-LIKE TRANSMISSION PEAK

Figure 7.11 Measured transmission spectra of channel 7 - centre wavelength at 1554.1nm

Figure 7.12 Measured transmission spectra of channel 8 - centre wavelength at 1556nm
The transmission spectrum for device 4 is shown by the dotted line as in figure 7.13, where channel 5 is considered for the measurement. The device suffered a higher crosstalk of approximately 0.5dB compared to devices 1, 2 and 3. This is probably due to the phase error condition of the AWG. This phase error as described in [7.7] derives from of a spatial change across the wafers. Hence devices fabricated near the edge of the wafers would experience a greater variation, in terms of the path length deviation, waveguide geometry and effective index change.

Figures 7.14 to 7.21 show the measured wavelength response of the eight channels of device 4 at 1550nm wavelength. The dotted line represents device 4 and the solid line represents device 3 of the first fabrication run. The transmission peak of each channel of device 4 has the Gaussian profile, even though the channel crosstalk of approximately 0.5dB is much higher than in device 3. However, the responses still exhibited a channel spacing of 1.6nm.
MEASURED RESULTS OF THE CONVENTIONAL AWG WITH GAUSSIAN-LIKE TRANSMISSION PEAK

Figure 7.14 Measured transmission characteristics of channel 1 of device 4 from first fabrication run

Figure 7.15 Measured transmission characteristics of channel 2 of device 4 from first fabrication run
Figure 7.16 Measured transmission characteristics of channel 3 of device 4 from first fabrication run

Figure 7.17 Measured transmission characteristics of channel 4 of device 4 from first fabrication run
MEASURED RESULTS OF THE CONVENTIONAL AWG WITH GAUSSIAN-LIKE TRANSMISSION PEAK

Figure 7.18 Measured transmission characteristics of channel 5 of device 4 from first fabrication run

Figure 7.19 Measured transmission characteristics of channel 6 of device 4 from first fabrication run
It is clear from this data that the phase errors of device 4 are much larger than in the first run, resulting in poor resolution of the output channels.
7.3.2 Measured Results of the Flat-top AWG

An eight channel flat spectral response via ion implantation arrayed waveguide grating demultiplexer has been fabricated on an SOI platform. Three different n-type dopant concentrations were used; $9 \times 10^{17} \text{cm}^{-3}$, $1 \times 10^{18} \text{cm}^{-3}$ and $2 \times 10^{18} \text{cm}^{-3}$. The $9 \times 10^{17} \text{cm}^{-3}$ concentration devices were produced in the first fabrication run and the $1 \times 10^{18} \text{cm}^{-3}$ and $2 \times 10^{18} \text{cm}^{-3}$ concentrations were produced in the second fabrication run.

Figure 7.22 shows the measured flat-top transmission characteristics of channel 1 centred at 1554.2nm for both devices 1 and 2 in the first fabrication run.

![Figure 7.22: Measured flat-top response of channel 1 for device 1 and 2 of first fabrication run; channel 1-centre wavelength 1544.2nm](image)

The blue dotted line indicates the response for device 1 and the red solid line represents the response for device 2. Both responses show good consistency, having a flat-top with spectral range of approximately 0.5nm. The crosstalk level is in good agreement with the
conventional AWGs of the first fabrication run in the region of -3dB. The spectra exhibited phase error as expected, since these devices are fabricated on the same wafer as the conventional AWG having the same fabrication errors and tolerance. If we consider the crosstalk level on device 4 of the conventional AWG, we would anticipate similar level of sidelobes for the flat-top AWG fabricated on the same chip. The measured result is shown in figure 7.23.

Figure 7.23 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 1-centre wavelength 1544.2nm

The solid line represents the flat-top transmission characteristics of device 2 and the red dotted line represents the flat-top response of device 4. The sidelobe components of device 4 are approximately -0.5dB, which are nearly three and a half times higher than device 2. However in both cases there is a clear indication of a flat-top response within the wavelength range of around 1544.0nm to 1544.5nm.
Figures 7.24 to 7.37 show the transmission spectra of 8 channel flat-top AWG with 9e17 cm$^{-3}$ phosphorus net concentrations.

Figure 7.24 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 2-centre wavelength 1545.8nm

Figure 7.25 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 2-centre wavelength 1545.8nm
Figure 7.26 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 3-centre wavelength 1547.5nm

Figure 7.27 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 3-centre wavelength 1547.5nm
Figure 7.28 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 4-centre wavelength 1549.2nm

Figure 7.29 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 4-centre wavelength 1549.2nm
MEASURED RESULTS OF THE FLAT-TOP AWG

Figure 7.30 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 5-centre wavelength 1550.8nm

Figure 7.31 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 5-centre wavelength 1550.8nm
Figure 7.32 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 6-centre wavelength 1552.4nm

Figure 7.33 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 6-centre wavelength 1552.4nm
Figure 7.34 Measured result of device 1; showing a higher level of crosstalk as compared to device 2; channel 7-centre wavelength 1554.1 nm

Figure 7.35 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 7-centre wavelength 1554.1 nm
MEASURED RESULTS OF THE FLAT-TOP AWG

Figure 7.36 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 8-centre wavelength 1556.2 nm

Figure 7.37 Measured result of device 4; showing a higher level of crosstalk as compared to device 2; channel 8-centre wavelength 1556.2 nm
The transmission spectrum of each channel clearly shows a general trend, all indicate a flat-top response and bandwidth enlargement of 0.5nm. The crosstalk level, in the range of -2.5 to -4 dB, exhibited by each channel is in good agreement, for all three flat-top devices, as compared to the conventional AWG.

The experimental 1x8 demultiplexer AWGs on the second fabrication run were measured with 1e18cm\(^3\) and 2e18cm\(^3\) net concentrations based on phosphorus implant. Figure 7.38 to 7.45 show the demultiplexing properties of both implants.

![Graph showing measured transmission characteristics](image)

Figure 7.38 Measured transmission characteristics of 1e18cm\(^3\) and 2e18cm\(^3\) net concentration based on phosphorus implant from second fabrication run; channel 1
The blue dotted line indicated the 1e18 cm⁻³ net concentrations and the red dotted line indicated the 2e18 cm⁻³ net concentrations. Both responses show a flat-region within the wavelength of interest although the result is not as distinctive as for the previously repeated devices. The responses exhibited high sidelobe components compared to the devices measured in the first fabrication run. These sidelobe components are approximately 3dB higher compared to device 1, 2 and 3 of the 9e17 cm⁻³ devices and 0.2dB higher compared to device 4 of the 9e17 cm⁻³ device.

![Figure 7.39 Measured transmission characteristics of 1e18 cm⁻³ and 2e18 cm⁻³ net concentration based on phosphorus implant from second fabrication run; channel 2](image-url)
Figure 7.40 Measured transmission characteristics of 1e18cm\(^2\) and 2e18cm\(^3\) net concentration based on phosphorus implant from second fabrication run; channel 3

Figure 7.41 Measured transmission characteristics of 1e18cm\(^2\) and 2e18cm\(^3\) net concentration based on phosphorus implant from second fabrication run; channel 4
MEASURED RESULTS OF THE FLAT-TOP AWG

Figure 7.42 Measured transmission characteristics of $1e18\text{cm}^{-2}$ and $2e18\text{cm}^{-3}$ net concentration based on phosphorus implant from second fabrication run; channel 5

Figure 7.43 Measured transmission characteristics of $1e18\text{cm}^{-2}$ and $2e18\text{cm}^{-3}$ net concentration based on phosphorus implant from second fabrication run; channel 6
Figure 7.44 Measured transmission characteristics of $1e18\text{cm}^{-2}$ and $2e18\text{cm}^{-3}$ net concentration based on phosphorus implant from second fabrication run; channel 7

Figure 7.45 Measured transmission characteristics of $1e18\text{cm}^{-2}$ and $2e18\text{cm}^{-3}$ net concentration based on phosphorus implant from second fabrication run; channel 8
The difference in doping densities will not cause a large variation in phase error since the introduction of dopants is via ion implantation, a process which can be carefully controlled. However, it is important to note that a high doping concentration will result in a larger phase change due to the increase in effective index change. This increase in phase difference compared to low doping concentration will require longer path compensation. If the path compensation is not carefully fabricated, it will contribute to the total phase error experienced by the AWG.

However, the results obtained from figures 7.38 to 7.45 did not indicate a very distinctive error cause by higher densities. This is because the phase error is dominated by the fabrication errors as explained in section 7.5.

The insertion loss of the devices discussed above is approximately 15.28dB. This insertion loss is obtained by measuring the optical power without the DUT and output power from the devices using:

\[
IL(dB) = 10 \cdot \log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)
\]  

(7.3)

The high sidelobes are likely to be the result of phase errors in the grating waveguides due to fabrication imperfections. It has been shown by Y. L. Chu et al [7.8] that the physical character of the AWG is strongly dependent on the fabrication precision of the waveguide and any deviation of the fabricated parameters within the device to the design value will result in an additional phase error to the AWG, thereby increasing its loss and crosstalk.
7.4 Influence of Phase Error on Silicon-on-Insulator Arrayed Waveguide Gratings (AWG)

Phase error, a fundamental problem determining the performance of the crosstalk and insertion loss of an AWG has been investigated meticulously by a number of researchers in recent years [7.8-7.11]. The AWG demultiplexer mainly works on the principle of phase-front interference of light propagation. The passband spectrum of a particular output channel is simply the summation of the optical fields propagating along a series of waveguides, each with different path lengths and having different optical field amplitude with a constant phase change of $2m\pi$. Therefore, the crosstalk is directly affected by any deviation of the ideal design of the AWG during the fabrication process. Such deviation could be caused by (1) the material-index fluctuation within the SOI wafers, (2) the imperfections of waveguide geometry resulting from photolithography and the waveguide etching process and (3) the path length error caused by e-beam direct writing of the photomask.

This section, we will present a theoretical investigation of the phase error resulting from the above causes. Finally, we will relate such causes to our fabricated devices and make a comparison of the simulated result with the actual passband spectrum of our fabricated devices

7.4.1 Relation between Effective Index and Phase Error

The variation of waveguide geometry will cause a change in the effective index of the fundamental mode of a waveguide, thus resulting in phase errors within the grating arms of the AWG. However if the variation of the waveguide geometry remains constant across the grating arms as mentioned by Kamalaski et al [7.11], the value of the effective index change, $\Delta n_{eff}$, due to waveguide width, $w$, and etch depth, $h$, will have insignificant impact on the transmission spectrum of the AWG. If the waveguide geometry experiences an inconsistency variation, which results in a phase change, $\Delta \phi$, not equal to $2m\pi$ between the adjacent array-waveguides, phase errors between the different arms of
the grating occurs. This seriously affects the behaviour of the sidelobe level of a conventional AWG with a Gaussian passband.

In the following sections, two different possible situations will be discussed; (A) constant variation of waveguide geometry across the grating arms. (B) Random variation of waveguides geometry across the grating arms.

As mentioned in [7.12], for a given SOI rib waveguide structure, careful selection of the rib width and etch depth are required to enable the waveguide to function in its singlemode and zero-birefringence conditions. The following discussion will use a specified example, which corresponds to the SOI waveguide dimension used in this work. For a Si-overlayer of 1.5μm, a rib width of 1.1μm, an etch depth of 0.88μm is required to satisfy the singlemode and zero-birefringence condition. However any fluctuation in the fabrication process causes a variation in the rib dimension. This variation will cause a change in the effective indices of the SOI waveguides which in turn causes a change in phase of the AWG output. The plot in figure 7.46 shows the effective index variation for different rib widths corresponding to different etch depths. These effective indices are simulated using the BPM.

![Figure 7.46 Effective index variations for different waveguides geometry](image-url)
It can be observed that the effective index exhibits a near linear relation with increasing rib width. For clarity purposes, rib width and etch depth is chosen to demonstrate the effect upon the transmission characteristic of the AWG. Accordingly to figure 7.47, the ideal effective index is given as 3.41 by performing a BPM simulation based on the design waveguide, thus the difference in effective index for small variations in the rib width and etch depth can be calculated. The effective index difference will have an impact on the phase of the AWG. This phase change can be expressed as:

\[
\Delta \phi = \frac{2\pi \cdot (n_{\text{eff}} - \Delta n_{\text{eff}}) \cdot i \cdot L}{\lambda}
\]  

(7.4)

In figure 7.47, the transmission spectrum of the conventional AWG is plotted together with the transmission spectrum of -0.01μm and -0.1μm rib width variations. It is assumed, in both cases, that the variation is constant across the arrayed waveguides; hence each arrayed waveguide will have a constant deviation compared to its neighbour. This results in a constant change of effective indices, therefore, causing a phase change of 

\[(2\pi \cdot i) + \Delta n_{\text{eff}}\]

between adjacent waveguides.
This in turn results in a shift of wavelength without distorting the spectrum because the phase differences between the adjacent waveguide still maintain the $2m\pi$ condition. The direction of the transmission spectrum shift (in wavelength) depends on the value of the change in effective index. In this particular case, a negative value is chosen, thus resulting in a value less than the designed value. The peak, in this instance, will move in the negative direction. However, if a positive value is chosen, the peak will move in the opposite direction. It can be seen in figure 7.47 that the transmission peak is shifted by approximately 0.2 nm in wavelength for a change in 0.01 μm in the rib width. If we consider another situation, where the rib width is kept constant at 1.1 μm and the etch depth is varied by -0.01 μm and -0.1 μm respectively, it can be noted from figure 7.48 that the shift in wavelength is much smaller than the variation in rib width because the difference in effective index is smaller. Hence, it can be concluded that the tolerance of wavelength shift resulted from deviation of etch depth is much higher.

![Figure 7.48](image)

Figure 7.48 Transmission spectrum of AWG with constant etch depth variation within the grating arms
However, realistically it is not possible to achieve the "ideal" or the same variation of rib geometry across the grating arms due to variation in the fabrication process; hence a random variation of waveguide geometry is likely. If we impose a random variation of ±0.01\(\mu\)m both of the width and etch depth across the grating arms of our model as shown in figure 7.49, where the effective indices of each array waveguides fluctuated within ± 0.0002. We see an increase in sidelobe of the transmission spectrum from -27dB to -14dB due to the phase errors as in figure 7.50. If this fluctuation is further increased, the transmission spectrum will deteriorate further.

![Graph showing effective index variation](image.png)

**Figure 7.49** Random variation of ±0.01\(\mu\)m on both the width and etch depth of the rib waveguide
Figure 7.50 Increase of sidelobe due to random variation of rib geometry within ±0.01 µm on both the width and etch depth

7.4.2 Relation between Path Length Deviation and Phase Error

The phase of the optical field is also a function of the path length deviation, \( \Delta l \) within the array waveguides. This deviation results due to the resolution of the photomask and/or the fabrication tolerance and errors. The phase change, which includes the path length deviation, \( \Delta l \), is then given as:

\[
\Delta \phi = \beta \cdot [L + \Delta L + \Delta l]
\]  

(7.5)

where \( \beta \) is the propagation constant, \( L \) is the optical path length of the AWG, \( \Delta L \) is the intentional path difference between the adjacent waveguides and \( \Delta l \) is the path length error.
In general, the design of the AWG usually takes into account the mask resolution. In this particular case, where the mask is designed using Ledit with a 0.01μm resolution, hence this resolution need to be considered to minimise the phase error. However, ΔL is dependent on several parameters; (1) the grating order, m. (2) the effective index of the arrayed waveguide, neff. (3) the operating wavelength, λo. It is not possible to precisely generate ΔL without any deviation. The best possible way is to estimate ΔL to the nearest possible resolution point, therefore, minimising the phase errors and reducing the deterioration of the transmission characteristic of the AWG.

Considering the optical path length difference, ΔL, this can be calculated by:

\[ ΔL = \frac{m \cdot λ_o}{neff} \]  

This will yield a path length difference, ΔL, value of 23.6178603μm. If the mask resolution is 0.01μm, then only 23.62μm of ΔL is taken into consideration. Thus, this will inevitably introduce some degree of phase error (discussed overleaf).

To clarify the behaviour of the transmission spectrum due to the path length difference deviation, a plot of phase error against the resolution is shown in figure 7.51. It is noted that the phase error increases tremendously when the optical path deviation decreases to a resolution of 0.1μm. Hence, from the plot, we can deduce the phase error caused by Ledit limitation.

In order to calculate this phase error, ΔL is taken as 23.62μm, which gives rise to a phase error of 0.10874 (rad). If a uniform distribution phase error is implemented across the arrayed waveguides, obviously a shift in wavelength is observed as in figure 7.52.
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Figure 7.51 Phase errors due to Ledit resolution

Figure 7.52 Transmission spectrum of AWG due to Ledit resolution
If a random phase error is generated across the arrayed waveguides, in the range of ±0.10874 (rad), is implemented across the arrayed waveguides as in figure 7.53. The transmission spectrum for AWGs with both ideal and random phase error is plotted in figure 7.54. It can be seen that both the transmission appeared to be similar; hence we can conclude that the deviation of Ledit resolution can be considered to be negligible. However, it has been shown by Taksahi et al [7.10] that phase error is also introduced due to the fluctuation of waveguide length error, which is determined primarily by photolithography. Two kinds of length errors are generally considered:

1. A short μm order period, such as the etched side wall roughness of the rib.
2. A long period of more than 10mm, such as a photomask digitising error.

Currently, with photomask resolution ranging from 25nm to 250nm, considerable path length deviation can result from the photomask itself. If we consider an uncertainty of ±10% in terms of its resolution which is due to equipment capability, we can estimate the amount of phase error introduced as shown in figure 7.55.
This phase error can be translated to the amount of crosstalk introduced to the transmission spectrum of the AWG, which has previously demonstrated by C. D. Lee et al [7,9]. The crosstalk performance due to path length deviation is shown in figure 7.56.
The plot in figure 7.56 can be obtained by performing a numerical simulation of the transmission coefficient of the AWG and subsequently calculate the crosstalk level for difference path length deviation. The graph for 101 arrayed waveguides is of particular interest because the fabricated devices in this work implemented 100 AW, thus, yielding an approximately equal power profile. This concludes that a phase error of 100nm can increase the crosstalk by 25dB.

![Figure 7.56 Crosstalk performance due to path length deviation for different number of grating arms](image)

**Figure 7.56** Crosstalk performance due to path length deviation for different number of grating arms [7.9]

### 7.5 Phase Error Analysis on Fabricated AWG

The SEM photographs in figures 7.57(a) – 7.57(d) and figures 7.58(a) -7.58(c) show the rib waveguides from the grating arms of our fabricated devices for the first fabrication and the second fabrication runs respectively. Each of the photographs clearly indicates a variation of rib width and etch depth from the design value. According to the analysis in section 7.4.1, this will introduce a certain degree of phase error to the AWGs, and this phase error will cause an increase in the sidelobe level of the devices.
SEM photographs for first fabrication runs

Figure 7.57(a) SEM photograph taken at the leftmost arm of the arrayed waveguides. This rib waveguide has variation of 0.392μm on the rib width and 0.105μm on the etch depth.

Figure 7.57(b) SEM photograph taken at approximately 25th arm of the arrayed waveguides. This rib waveguide has variation of 0.214μm on the rib width and 0.113μm on the etch depth.
Figure 7.57(c) SEM photograph taken at approximately 75th arm of the arrayed waveguides. This rib waveguide has variation of 0.117\(\mu\)m on the rib width and 0.105\(\mu\)m on the etch depth.

Figure 7.57(d) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide has variation of 0.038\(\mu\)m on the rib width and 0.059\(\mu\)m on the etch depth.
SEM photographs for second fabrication run

Figure 7.58(a) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide has a rib width of 0.419μm and etch depth of 0.362μm.

Figure 7.58(b) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide rib width of 0.443μm and etch depth of 0.359μm.
Figure 7.58(c) SEM photograph taken at the rightmost arm of the arrayed waveguides. This rib waveguide rib width of 0.644μm and etch depth of 0.368μm.

It can be observed that the waveguide geometries in the second fabrication run suffer from a high degree of variation and as compared to the first fabrication run. This difference in the waveguide geometries results in a change of effective index from the design value, thus causing a mismatch in the phase condition. Therefore, we expect higher sidelobes from the devices in the second fabrication run as compared to the first. This effect of waveguide variation is clearly visible in the experimental results.

A phase error analysis is carried out based on the SEM photographs in the first fabrication run. From figures 7.57(a) -7.57(d), we can conclude the possibility of a random error due to the etching process. If we perform a BPM simulation based on the above waveguides dimension, we could obtain the effective index variation, $\Delta n_{\text{eff(i)}}$, for the $i^{th}$-arrayed waveguides and consequently calculate the phase error due to such variation for each arrayed waveguides respectively.
If the worst-case for the photomask resolution (100nm ± 10%) based on the photolithography equipment in Southampton University, according to section 7.5.2, figure 7.53, a phase error of approximately 1.5rad is introduced to the devices. This 1.5rad of phase error will result in a crosstalk of -16dB [7.9] as shown in figure 7.56.

Figure 7.59 shows the accumulated phase errors imposed on the AWG as a result of rib geometry variation and path length deviation. If we implement these phase errors upon each arrayed waveguide and perform a numerical simulation based on the transmission coefficient of the AWG, we can then compare the simulated result to the measured result.

Figure 7.59 Cumulative phase error due to waveguide geometry and path length deviation

Figure 7.60 shows good agreement between the theoretical simulation and fabricated devices. Two main contributors are present in our devices; (1) the systematic error due to waveguides geometry and (2) the random error due to path length deviation. The systematic error compared to the random error is relatively small; however, this
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systematic error causes a shift in wavelength of approximately 0.5nm. The high crosstalk level as shown in figure 7.60 is primarily the result of the random path length deviation.

Figure 7.60 Simulated and measured transmission spectrum of the AWG with high sidetone due to phase error
7.6 Analysis for Flat-Spectral Width

The transmission characteristic of the flat-top AWG shows a flat spectral region of approximately 0.5 nm. This value differs from our design value in section 4.4.2 by a factor of 2. If we considered the equation which governed the flat-spectral region in equation (4.28) given as:

\[ \text{Spectral Width, } F_w = \text{FSR} \times \frac{q}{M} \]  (7.7)

The spectral width is clearly dependent on the FSR of the AWG. The FSR, according to equation (4.18) is given by:

\[ \text{FSR} = \frac{\lambda_0}{m} \]  (7.8)

and the grating order, \( m \), again based on the design rule in section 4.4.1 is given by:

\[ m = \frac{n_{av} \cdot \Delta L}{\lambda_0} \]  (7.9)

From equation (7.8), we know that the grating order \( m \) is dependent on two parameters which are controlled by the fabrication process; (1) the effective index of the waveguide and (2) the path length difference. Thus, equation (7.9) can be rewritten, to include the fabrication errors based on the SEM photographs of the fabricated waveguides and also the photomask resolution which will result in a random variation of the path length difference. This yields:

\[ m = \left[ n_{av} + \left( \left( \Delta n_{av} \right) + \Delta n_{uncertainty} \right) \cdot M \right] \left[ \frac{\Delta L + \left( \left( \Delta L + \Delta L_{uncertainty} \right) \cdot M \right)}{\lambda_0} \right] \]  (7.10)
where $\Delta n_{aw}$ is the systematic variation of effective index caused by waveguides geometry fluctuation, $\Delta n_{uncertainty}$ is the certainty due to the etching process, $\Delta l$ is the random variation of path length caused by photomask resolution, $\Delta l_{uncertainty}$ is the uncertainty specified by the photolithography equipment and $M$ is the number of arrayed waveguides. $\Delta n_{aw}$ can be obtained in a similar way as section 7.41 by performing a BPM simulation based on the waveguides geometries photographed in figures 7.57(a) – 7.57(d). $\Delta n_{uncertainty}$ in this instance, is assumed to be 10% of its true value based on the equipment uncertainty. $\Delta l$, again is based on equipment specification, which is specified as 100nm with an uncertainty, $\Delta l_{uncertainty}$ of 10%. Thus this yields a worst case value of $m$ which is approximately 84.

Using equation (7.8), we can calculate the worst case value of FSR which is approximately 18.5nm. Hence the new spectral width, based on equation (7.7), is approximately 0.58nm. This value shows good agreement with our experimentally measured flat spectral width. The above calculation is based on the assumption that a systematic error occurs across the array waveguides, since it is not possible to examine each of the waveguide geometries across the grating arms by SEM.
7.7 Summary

In summary, we have demonstrated experimentally the flat spectral response of the SOI AWG via ion implantation. We first characterised a SOI rib waveguide using the Fabry-Perot resonance method. This waveguide structure shows a loss of 1.1dB/cm. The origin of such losses on the SOI waveguide is mainly due to the prominent sidewall roughness caused by the etching process.

The measured results of the gaussian-like transmission peak and the flat-spectral response have shown a relatively good agreement in terms of their channels spacing with our designed value. However, these results suggested a high crosstalk level (-3dB). This crosstalk is the result of phase errors arising within the grating arms of the AWG. The main contributions to the phase error are investigated which are primarily due to the systematic error of the rib width and etched depth of the waveguides and the random path length deviation. The match between the value taken from SEM photographs for variation in the waveguides geometry across the grating arms and the photomask resolution confirms the dominant factor that affects the AWG crosstalk performance.

By improving the photomask resolution, we believe that the AWG crosstalk performance can be improved tremendously.
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References:


CHAPTER 8  
Summary, Conclusion and Future Work

The secret of success is consistency of purpose.

Benjamin Disraeli

8.1 Introduction

This thesis has aimed to provide a thorough description of the research on silicon-on-insulator (SOI) based Arrayed Waveguides Grating (AWG) carried out by the author. The thesis is grouped into three key chapters which describe the design, the fabrication and the measurement of the devices. While this ordering may seem logical, it does not necessarily describe the actual or optimal sequence of events. The most successful device development projects involve several cycles of iteration and prototyping.

This chapter presents the conclusions of the work. In addition, it also prompted ideas which are suitable for future research.

8.2 Summary and Conclusion

In this work, we have demonstrated a Unibond SOI based AWG operating at a centre wavelength of 1550nm. The AWG is configured as a 1x8 demultiplexer using a 1.5μm Si-overlayer. The rib width, 1.1μm, and etch depth, 0.88μm, are designed to operate in singlemode and zero birefringence condition. The channel spacing Δλ is 1.6nm with a free spectral range of 30nm.

The AWG works on the principle of light interference. It consists of five optical sub-components, (1) the input waveguide, (2) the input slab waveguide (free space region), (3) the array waveguides, (4) the output slab waveguide (free space region) and (5) the output waveguides. The array waveguides have a constant optical path length difference ΔL, equal to 2mπ, between the adjacent waveguides in order to excite a constructive interference of the optical field at the output slab waveguides.
This resultant optical field will focus at a position along the output slab/waveguide interface and depends on the wavelength of interest, and the focal beam will be coupled to the output waveguide.

Such devices will exhibit a typical response of a Gaussian, with a narrow 'peak'. This will impose a deficiency in WDM networking systems for the following reasons; Firstly, small fluctuations in the wavelength of a laser source can cause a large loss. Secondly, the narrow peak will place tight restrictions on the wavelength tolerance of laser diodes and requires accurate temperature control for both the AWG and the laser diode. Thirdly, due to the multiple uses of filters in a WDM ring/bus network, the cumulative passband width of each channel becomes much narrower than that of a single stage AWG filter. Hence, a flat spectral passband within each channel becomes one of the most desirable characteristics of the AWG.

Therefore, we proposed and demonstrated a novel method of achieving a flat-top transmission characteristic via ion implantation. It is well known that the focused beam profile at the output waveguides is the spatial Fourier transform of the optical field profile at the output array-slab interface. Hence in order to achieve a flat spectral response, theoretically, a rectangular function, a $\sin(x)/x$ field distribution is required across the output of the array waveguides (AWs). The introduction of free carriers will cause absorption to the optical field of the AWs and at the same time, change the refractive index of the material. The phase of the optical field in the AWs is dependent upon the propagation constant, $\beta$, hence, a change in refractive index will cause a change in phase. However, it is crucial to maintain the $2m\pi$ phase difference between adjacent waveguides to enable constructive interference at the output slab. Thus, an additional optical path length is needed to compensate for such a difference. This will lead to a change in the conventional geometry of the AWG. In order to achieve a near uniform doping concentration throughout the guiding region to avoid any phase errors resulting from the implantation, multiple ion implantations steps were used.

We conducted two fabrication runs; each fabrication run consists of two AWG designs. The first run fabricated the design for the AWG with Gaussian-like and flat-
top response with $9 \times 10^{17} \text{cm}^{-3}$ phosphorus net doping concentration. The second run fabricated the design for both flat-top response with $1 \times 10^{18} \text{cm}^{-3}$ and $2 \times 10^{18} \text{cm}^{-3}$ phosphorus net doping concentrations respectively.

The measured results of the conventional AWG show good agreement in terms of the centre wavelength of each channel. However, the sidelobe components of each channel are relatively high—approximately 3dB. This is due to (1) the systematic phase error caused by variation of waveguides geometries across the arrayed waveguides and (2) the random phase error due to photomask resolution as described in section 7.5.

The measured results of the flat-top validated our methodology; the transmission characteristics of the devices clearly exhibited a flat spectral response with a spectral width of 0.5nm. Although, such spectral width appears to be narrower than our proposed spectral width, we have verified the cause, which is due to the imperfection of the fabrication. This imperfection clearly caused a variation in the waveguides geometries across the grating arms and imposed a random variation of approximately 100nm to the optical path length due to photolithography resolution as described in section 7.6.

In this work, we fabricated our example in Silicon-on-Insulator (SOI) because this material is of great interest in the field of optical communications. However, our design can be applied to any other semiconductor. We can also include materials that are insulators such as silica (glass), or Lithium Niobate (LiNbO$_3$) in which we can introduce absorption either through doping or crystal damage. In either case the doping can be performed by ion implantation, or some other doping mechanism and the principles of the design procedures still hold.

AWGs have been proposed and/or demonstrated in different technologies and one can argue that an alternative technology, that of silica based integrated optic, is of lower cost but it exhibits passive properties with little prospect of active devices such as sources, detectors or optical modulators.

The careful choice of a particular dopant can result in the elimination of polarisation dependence. Since refractive index is changed by the introduction of free-carriers, this
also results an effective index change of the TE and TM modes. Hence by careful consideration of the change in effective index for each polarisation, we can achieve a polarisation independent device.

Another important point to note is, by introducing absorption loss to each array waveguide, we can ultimately shape any kind of spectral response in taking the Inverse Fourier Transform of the targeted response and subtract it from the conventional, “gaussian-like” response.

In conclusion, we have successfully demonstrated the principle of achieving a flat-top transmission characteristic AWG in SOI based on ion implantation. Although, the sidelobe components measured are relatively high and the flat spectral width measured differ by approximately twice the theoretical value, we have demonstrated that, these inconsistencies are due to fabrication error and tolerance. This method gives the robustness of tailoring the optical field distribution across the array waveguides by the appropriate choice of net doping concentration, and hence gives room for design flexibility without increasing the physical dimension of the AWG significantly. This potentially creates the opportunity of achieving a smaller SOI AWG device with the use of higher net dosage and the realisation of achieving a uniformity doping concentration through multiple implantations.

This experiment has shown the validity of the methodology which could be useful for future development for a low cost, small scale flat-top AWG in SOI.

8.3 Future Work

The immediate part of the future work is to characterise and optimise the device transmission characteristics. This includes, using fabrication equipment with higher resolution, hence provides a better devices. Also, phase error compensation techniques can be employed. One of the accurate methods for characterisation and phase-error compensation of the AWGs is to employ the experimental technique proposed by Takada et al [8.1]. In this method, both the phase error $\varepsilon_p(\sigma)$ and the
power-splitting ratios $P_m(\sigma)$ can be measured. Figure 9.1 shows the proposed experimental setups for measuring both $\varepsilon_m(\sigma)$ and $P_m(\sigma)$.

The experimental setup in figure 8.1 has a Mach-Zehnder interferometer with a variable optical delay in one arm and an AWG in the other arm. The light source is a 1.5μm band LED and the output is split into two by the first coupler. One half of the optical light is used as a local oscillator (LO) and is optically delayed with a moving stage. The other is launched into the AWG under test. The outputs from both the LO and the AWG are then combined by the second coupler. Since the optical lengths of the arrayed waveguides are designed to increase in order by a constant $AL > L_c$ (coherence length of the LED) an isolated fringe $I_m(x)$ is produced by the interference between the LO light and the light that has passed through the $m^{th}$ waveguide, where $x$ is the optical path change induced by the stage translation. The Fourier transform of $I_m(x)$ provides the accumulated phase $\phi_m(\sigma)$ and the amplitude $A_m(\sigma)$ of the light for $m^{th}$ waveguide. Thus, the phase error $\varepsilon_m(\sigma)$ is given as $\phi_m(\sigma) - 2\pi n(\sigma) mAL$ with $n(\sigma)$ being the effective refractive index of the waveguides and the power-splitting ratios $P_m(\sigma)$ is $\propto /A_m(\sigma)^2$.

Another possible suggestion for future work is to incorporate various components that will help characterising the AWG. For example; (1) by placing a straight waveguide next to every AWG device, we could improve the loss characterisation of the waveguides, at the same time, we could also determine the propagation loss instead of the on-chip insertion loss of the AWG, by normalising the AWG output power to the
waveguide output power. (2) By including an isolation trench between each output waveguides, we can minimise the experimental error. This is possible because optical power that leaked into the slab will not be coupled to the adjacent waveguides, hence the detector fibre will not pick up additional crosstalk due to the stray signal. (3) Different bend radius should be included in the waveguide design, since the bend is one of the most fundamental elements in the AWG. By doing so, we can optimise the bent waveguides and minimise the total propagation loss within the AWG.

To include the wider field of silicon photonics, the following recommendation are advised.

Multimode and polarisation issue should be considered. We have seen in earlier chapter that different modes propagating within the slab waveguides will result in different phase shift. This will cause 'ghosting' in the output slab of the AWG, as each mode is corresponded to different focal point in the output slab. The degree of crosstalk will depend on both the phase relative to each mode and their optical power. Hence, a possible suggestion is to perform an overlap integral, to estimate the relative coupling, between each mode presents in the slab and the rib waveguide.

Polarisation sensitivity of the AWG arises from two sources; (1) the polarisation dependence of the array waveguides and (2) the polarisation dependence of the slab regions. If both waveguides are carefully designed, the AWG should exhibit zero birefringence condition. However, in practice these designs may be compromised somewhat by unwanted strain. Hence a polarisation compensation technique should be considered.

These suggestions for future work aim to exploit the SOI based AWG to its full capability. If these areas are fully realised, we can indeed demonstrate our methodology fully.
Reference

Appendix A

Boundary Conditions of Electromagnetic Fields

The reflection and transmission of an arbitrary TEM wave at a boundary is determined through the application of boundary conditions for electric and magnetic fields. For an electric field, the tangential (parallel to the interface) component of $E$ must be continuous across the boundary and the normal component (perpendicular to the interface) of the flux density, $D = \varepsilon_0 E$, must be continuous. The latter is only true in the absence of any surface charges, which is usually the case for our considerations. For an interface between two materials 1 and 2, we thus have:

$$E_{1T} = E_{2T} \quad (A1)$$

and

$$D_{1N} = \varepsilon_1 E_{1N} = \varepsilon_2 E_{2N} = D_{2N} \quad (A2)$$

where the subscripts {1,2} correspond to either side of the boundary and the {T,N} correspond to the tangential and normal components, respectively.

For magnetic fields, the tangential components of $H$ must be continuous across the boundary, as must the normal components of the flux density, $B = \mu_0 H$. This implies

$$B_{1N} = \mu_1 m' H_{1N} = \mu_2 m' H_{2N} = B_{2N} \quad (A3)$$

Application of these boundary conditions to a wave incident from one material onto another will then permit the calculation of how much will be transmitted and reflected.
Appendix B
Numerical Calculation for Array Waveguides Geometry

In this section, numerical calculation is presented for the formation of the AWG geometry. The following values are assigned to some of the parameters as described in section 4.3.5.

\[ x(0) = 5\text{mm} \]
\[ r(0) = 1\text{mm} \]
\[ a(0) = 37.08^\circ \]
\[ L_{slab/2} = 5.7889\text{mm} \]

Based on these values, we can calculate each of the array waveguide geometry as shown in table B1. Table B1 shows the value for AWG geometry for 9e17\text{cm}^{-3} \text{net concentration.}

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Table B2 shows the calculated value for arrayed waveguides geometry with $1\times 10^{18}\text{cm}^{-3}$ concentrations.

Table B2: Calculated values for arrayed waveguides parameter for $1\times 10^{18}\text{cm}^{-3}$ net concentrations
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Table B3 shows the calculated values for $2e18\text{cm}^3$ net concentration.

Table B3: Calculated values for array waveguides geometry for $2e18\text{cm}^3$ net concentrations.
<p>|    | 26   | 27   | 28   | 29   | 30   | 31   | 32   | 33   | 34   | 35   | 36   | 37   | 38   | 39   | 40   | 41   | 42   | 43   | 44   | 45   | 46   | 47   | 48   | 49   | 50   | 51   | 52   | 53   | 54   | 55   | 56   | 57   | 58   | 59   | 60   | 61   | 62   | 63   | 64   | 65   | 66   | 67   | 68   | 69   | 70   |
|----|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|    | 41.24| 41.4 | 41.56| 41.72| 41.88| 42.04| 42.2  | 42.36| 42.52| 42.68| 42.84| 43   | 43.16| 43.32| 43.48| 43.64| 43.8  | 43.96| 44.12| 44.28| 44.44| 44.6  | 44.76| 44.92| 45.08| 45.24| 45.4  | 45.56| 45.72| 45.88| 46.04| 46.2  | 46.36| 46.52| 46.68| 46.84| 47   | 47.16| 47.32| 47.48| 47.64| 47.8  | 47.96| 48.12| 48.28|
|    | 1.47E-06 | 1.97E-06 | 2.79E-06 | 1.85E-06 | 1.29E-06 | 1.09E-06 | 9.63E-07 | 8.97E-07 | 8.79E-07 | 9.1E-07 | 1E-06 | 1.19E-06 | 1.61E-06 | 2.88E-06 | 1.37E-06 | 9.28E-07 | 6.59E-07 | 4.7E-07 | 3.27E-07 | 2.18E-07 | 1.36E-07 | 7.47E-08 | 3.28E-08 | 8.1E-09 | 6.2E-08 | 3.28E-08 | 7.47E-08 | 1.36E-07 | 2.18E-07 | 3.27E-07 | 6.27E-07 | 4.7E-07 | 6.59E-07 | 9.28E-07 | 1.37E-06 | 2.88E-06 | 1.09E-06 |
|    | 0.005945 | 0.005956 | 0.005998 | 0.005979 | 0.005991 | 0.006002 | 0.006014 | 0.006025 | 0.006037 | 0.006048 | 0.00606 | 0.006071 | 0.006082 | 0.006094 | 0.006105 | 0.006117 | 0.006128 | 0.00614 | 0.006151 | 0.006163 | 0.006174 | 0.006186 | 0.006197 | 0.006208 | 0.006222 | 0.006231 | 0.006243 | 0.006254 | 0.006266 | 0.006277 | 0.006289 | 0.006312 | 0.006323 | 0.006334 | 0.006346 | 0.006357 | 0.006369 | 0.00638 |
|    | 0.004662 | 0.004674 | 0.004664 | 0.004668 | 0.004671 | 0.00468 | 0.00467 | 0.00468 | 0.004683 | 0.004685 | 0.004688 | 0.004691 | 0.004694 | 0.004695 | 0.004699 | 0.004703 | 0.004706 | 0.004709 | 0.004712 | 0.004715 | 0.004718 | 0.004721 | 0.004724 | 0.004727 | 0.00473 | 0.004733 | 0.004736 | 0.004739 | 0.004741 | 0.004744 | 0.004747 | 0.00475 | 0.004753 | 0.004756 | 0.00476 | 0.004762 | 0.004765 | 0.004768 | 0.00477 |
|    | 0.001606 | 0.001734 | 0.001628 | 0.001648 | 0.00168 | 0.001708 | 0.00168 | 0.001786 | 0.00168 | 0.001698 | 0.001861 | 0.001885 | 0.001908 | 0.001926 | 0.001959 | 0.001987 | 0.002013 | 0.002039 | 0.002085 | 0.00209 | 0.002115 | 0.002124 | 0.002165 | 0.00219 | 0.002214 | 0.002243 | 0.002263 | 0.002287 | 0.00231 | 0.002334 | 0.00238 | 0.002398 | 0.002423 | 0.002443 | 0.002472 | 0.002498 | 0.002522 | 0.002548 | 0.002599 | 0.00263 | 0.002648 | 0.002682 |
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