Fabrication of Silicon Photonic devices using i-line Lithography

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Fabrication of Silicon Photonic devices using i-line Lithography

Sanjna Lakshminarayanamurthy
Fabrication of Silicon Photonic devices using i-line Lithography
SANJNA LAKSHMINARAYANAMURTHY
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in Partial Fulfillment
of the Requirements for the Degree of
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in
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KATE GLEASON
College of ENGINEERING

Department of Electrical and Microelectronic Engineering
Fabrication of Silicon Photonic devices using i-line Lithography
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Committee Approval:
We the undersigned committee members certify that the student has completed the requirements.

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Acknowledgments

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Dedicated to my family, Hope you’re proud of where I am today.
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Abstract

Silicon Photonics is a promising new technology for realizing efficient, high performance interconnects. There is a growing need for educating future engineers on how to design, fabricate, package and test silicon photonic circuits. Silicon photonic processing for an educational institution with i-line lithography capabilities is demonstrated and the thesis elaborates on the fabrication process used for realizing passive photonic devices and circuits (i.e. waveguides, interferometric structures and fiber-chip grating couplers). The process is realized in a CMOS compatible environment which has been in use since 1986 to teach microelectronic engineering. And is now also being used to support the AIM Photonics Academy education mission. Specifically, TM-polarized grating coupler with a ring resonator, y-branch, bidirectional coupler and three way couplers were fabricated with a lithographic resolution of less than 400 nm on an SOI wafer. The setup time and run time required was 3 days in comparison to the long wait time in the industry. Optimization of the resolution using ARC i-CON7, diluted OiR 620 and the etch selectivity of the silicon to the 1:1 OiR 620: PGMEA is key to the student run fabrication process. Alternatives for the hard mask used for etch and other plasma etch tool alternatives were explored and is supported by the Optical microscope and SEM results. The pattern fidelity of the Y splitter was simulated using PROLITH and the design was imported into Lumerical FDTD. The test results of the photonic circuits fabricated were analyzed and compared with the Lumerical FDTD and Lumerical INTERCONNECT simulations.
Chapter 1
Introduction and Motivation

The historical progress of technology associated with moore’s law is slowing to a point where new technologies must be considered to overcome the challenges of heat and power dissipation. Specifically, the flow of electrons in electronic interconnects generate heat and have challenges with signal integrity. This could be solved by replacing electronic interconnects with optical waveguides that use photons to transmit information. Photonic circuits and optical waveguides are known to exhibit superior quality and have recently been studied in an extensive manner.

Silicon photonics could potentially meet the demands of chip level interconnects with optical transmission that has high spectral efficiency, high channel data rates with low production costs because of the usable CMOS infrastructure. Silicon Photonics provides a unique platform for the integration of complex electronic and photonic functionality in the same chip. It could be expected that the integration of silicon photonics and electronics will result in an increase in high speed communication systems, this is mainly expected for applications within the computer, within data centers, sensor systems and also in bio-medical applications. The use of light as an alternative signal carrier has always been an attractive option and is expected to be in reach with silicon photonics expanding into the potential production qualified market.

Silicon is transparent at telecommunication wavelengths and its higher refractive
index(3.45) enables us to accommodate a significantly higher number of devices while maintaining the overall interconnect dimensions which will be elaborated on in further chapters. Grating couplers, waveguides with sharp bends, ring resonators, other interferometric structures exhibiting ultra-fast speed and low power consumption have been stepping stones in the evolution of integrated photonic circuits over time.

The success of the Complementary Metal Oxide Semiconductor (CMOS) industry has been based on accessibility to research facilities and the education of the working population. The electronics industry is now beginning to adopt silicon photonics technology for board-to-board and board level interconnections and in the near future will begin using the technology even within chips. Consequently, there is a growing demand for skilled photonic engineers and designers. In this thesis, the design and fabrication of silicon photonic circuits are made using i-line photolithography, which is generally available at many universities. These designs and processes have been implemented within a course (MCSE 889.02 Photonics Integrated Course) and laboratory environment at the Semiconductor and Microsystems Fabrication Laboratory (SMFL), Rochester Institute of Technology where students go through an entire design-build-test cycle.

This thesis elaborates on the opportunity to educate the future workforce of silicon photonics, the objective of the thesis is to prove the advantages of silicon photonic’s manufacturability in large scale (wafer level). All the circuits are fabricated in a CMOS compatible environment, which proves the usability of the silicon when compared to other III-V materials. It should also be noted that the process at RIT is performed using i-line lithography and can be further enhanced at industry with e-beam lithography or immersion lithography which can enable more complex designs and smaller gaps.

Silicon proves to be a very good material for telecommunication because it is transparent at 1550 nm which is the normal fiber optic telecommunication wavelength and
the material is abundant on earth. Silicon can perform almost all the potential electronic functions of the III-V material except behaving like a laser source, but research towards monolithic integration has proven to be very promising [5]. As for optical detectors the positive results of quantum dots and monolithic integration of germanium with silicon has been a breakthrough in the motion for silicon photonics. Silicon is the most researched material in the microelectronic industry and the information already available for use proves to be a strong point for the development of the silicon photonics industry.

The critical angle for the silicon waveguides is very small $(24.85^\circ)$ (elaborated in the first chapter) has allowed dense photonic circuits (see Figure 1.1) to be present in the chip leading to higher yield per die and would be a tempting alternative for business in comparison to III-V materials which are expensive and will need separate set of tools for being processed.

The Photonic Integrated Circuits (PIC) fundamentally use the photonic components and light wave propagates through the waveguide. Signal modulation is one important aspect in data communication. Ring resonators act as the perfect component that can be used to implement photonic multiplexing or demultiplexing circuits.
CHAPTER 1. INTRODUCTION AND MOTIVATION

When comparing conventional signal filters based on electric circuits, to photonics, photonics has a huge bandwidth, lower losses and longer propagation distances. Ring resonators exhibit superior performance with filtering selective bandwidth[6].

Complex silicon photonic systems are currently being researched for data communications for high bandwidth requirements, there are various other applications previously mentioned. Photonics is emerging as a popular choice for optomechanics and condensed matter physics [7] and one other currently available product is a biosensor, it runs 128 tests in less than 15 minutes[8]. Photonics is a good alternative for applications like LIDAR systems[9], optical receivers[10], gas sensors[11], signal processors[12] and many more.

Chapter 2 consists of detailed theory and working principle of the photonic components used for in this thesis. These photonic components circuits will then be cascaded and connected to be used as photonic circuits.

Chapter 3 elaborates on examples of circuits that could be fabricated and tested, this chapter details the expected results from testing the fabricated photonic circuit.

Chapter 4 is the essence of the thesis, it details the steps that were performed during the fabrication cycles. The factors that were taken into consideration include tool selection, material selection and processing, and the resulting choices are explained. This chapter is supported with SEM and optical microscope images that shows the circuits fabricated on the wafer.

Chapter 5 details the validation of the fabricated circuits on the wafer. The photonic circuits are tested and few key results are compared with the simulated results from chapter 3. This chapter also contains information about the custom built test setup implemented at RIT as part of the Photonic Integrated Circuits lab testing module.
Photonic components: Theory and Working principle

Photonic components are the building blocks of any photonic circuit. In the next few sections, the working principles of the components used in the layout that will be fabricated are explained in detail. It includes passive components i.e. waveguides, grating couplers, ring resonators, Y splitters and bidirectional couplers. These component’s functions include but not limited to couplers, interferometers, input and output ports, and filters.

2.1 Waveguide

The waveguide acts like an optical wire. Light propagates through the waveguide through a concept of total internal reflection (figure 2.1) i.e. when the incident angle of light is greater than or equal to the critical angle, light completely reflects into the waveguide. When solving Snell’s Law (Eq. 2.1), the critical angle($\theta_c$) is 24.85° (i.e. when the incident angle is greater than $\theta_c$) light is total internally reflected and propagates through the silicon waveguide.

$$\theta_c \geq \sin^{-1}\left(\frac{n1}{n2}\right)$$

(2.1)

$\theta_c$ is the Critical angle

n1 is the refractive index of silicon waveguide(n1=3.45)
CHAPTER 2. PHOTONIC COMPONENTS: THEORY AND WORKING PRINCIPLE

Figure 2.1: Total Internal Reflection[1]

n2 is the refractive index of SiO2 (n2=1.45)

The refractive index of a material is defined as the ratio of velocity of light in vacuum (c) (Eq. 2.3) to the velocity of light in the material (γ) (Eq. 2.4) as seen in Equation 2.2.

\[ n = \frac{c}{\gamma} \]  \hspace{1cm} (2.2)

\[ c = f\lambda_0 \]  \hspace{1cm} (2.3)

\[ \gamma = f\lambda \]  \hspace{1cm} (2.4)

Where f is the frequency of the light wave

λ is the wavelength of light in the medium and

λ₀ is the wavelength of light in vacuum

Because of the dual nature of light, it exhibits the properties of both a wave and a particle. When light (inside the waveguide) is considered as a wave, it interferes at certain angles. These interferences could be either constructive or destructive, when it is constructive interference (where two maxima line up), it is known as a mode.
\[ \vec{E} = E_0 \cos(kz - \omega t) \hat{x} = \text{Real}[E_0 e^{i(kz - \omega t)}] \hat{x} \quad (2.5) \]

\[ \vec{H} = H_0 \cos(kz - \omega t) \hat{y} = \text{Real}[H_0 e^{i(kz - \omega t)}] \hat{y} \quad (2.6) \]

**Figure 2.2:** Light as an electromagnetic wave[1]

\[ k = \frac{2\pi}{\lambda_0} n \quad (2.7) \]

\[ \omega = 2\pi f \quad (2.8) \]

\[ \text{Phase velocity} = \frac{c}{n} \quad (2.9) \]

The electric and magnetic field are transverse (orthogonal) to each other (as seen on the x and y axis of figure 2.2) and z is the direction of propagation, k is the wavenumber (Eq.2.7), it is the spatial frequency of the wave and \( \omega \) (Eq.2.8) is the radial frequency of the wave, \( \omega t \) includes the changes in time and \( k z \) gives the wavelength relationship with the electric field as seen in Eq. 2.16 and Eq. 2.6. The length of the vector (as denoted by arrows in Fig. 2.2) oscillates because of the vectors that are oscillating over time and the wavelength scales by n. The light wave moves at a phase velocity i.e. velocity of light in the medium(Equation. 2.9), when moving inside a medium, velocity is slower than the speed of light in vacuum (c) and it is scaled by...
CHAPTER 2. PHOTONIC COMPONENTS: THEORY AND WORKING PRINCIPLE

Figure 2.3: Graph representing a phase shift of the total internally reflected wave[1]

the refractive index (n).

From Maxwells equations (Eq. 2.16 and Eq. 2.6), it could be understood that there are two possibilities of polarization (light orientation) that is of interest, namely Transverse Electric (TE) and Transverse Magnetic (TM) Polarization. In TM mode polarization, the electric field is in the same plane as the waveguide and in TE mode polarization, electric field is perpendicular to the waveguide. Polarization is one of the factors that controls phase shift. When the angle is greater than the critical angle, total internal reflection occurs and there is a phase shift that occurs at the interface, this phase shift is controlled by the incident angle. At the critical angle, it follows the same shift without a phase shift. Fig. 2.3 represents the change in phase shift with angle greater than the critical angle which is derived from Eq. 2.10 and Eq. 2.11

\[ \theta_{(r,TE)} = -2\tan^{-1}\frac{\sqrt{\sin^2(\theta_1) - \left(\frac{n_2}{n_1}\right)^2}}{\cos(\theta_1)} \]  

\[ \theta_{(r,TM)} = -2\tan^{-1}\frac{\sqrt{\left(\frac{n_2}{n_1}\right)^2\sin^2(\theta_1) - 1}}{\left(\frac{n_2}{n_1}\right)^2\cos(\theta_1)} \]  

This dictates where the constructive interference (mode) occurs the kx component is the one that interferes and kz does not interfere with itself. It occurs when the overall phase is 2kxT for round trip of the wave. Therefore the condition for
constructive interference is given by Eq. 2.12.

\[ m2\pi = \left( \frac{2\pi}{\lambda_0} n_1 \cos(\theta_1) \right) x 2T + 2\theta_r \]  

Equation 2.12 proves that there are four factors that influence modal interference namely wavelength of the light, thickness of the waveguide, refractive index of the materials and polarization which is supported by light’s electromagnetic properties.

\[ k_z = \frac{2\pi}{\lambda_0} n_1 \sin(\theta_1) \]  

The quantity, \(k_z\) from Eq. 2.13 could now be known as \(\beta\) which is the propagation component, \(n_1 \sin \theta_1\) acts like a refractive index of the materials that depends on the angle at which light propagates through the waveguide. The interference creates a net result of a fundamental mode that enables propagation of light.

### 2.2 Grating coupler

Grating couplers are used to couple light to and from the optical fiber on the wafer. Grating is a periodic pattern, based on the period, there is diffraction of light. The grating coupler can be input or output port. It is a component that diffracts light from free space to and from the waveguide. Assume the wavelength of input light matches the grating period (\(\lambda = A\)) (Fig. 2.4), from Fresnel Huygen principle we know that when light scatters from the individual periodic gratings, scattered light is in the form of spherical waves that propagates and interferes.

There are two types of couplers, namely edge coupler and surface coupler. Edge couplers can also be used to couple light at the edge of wafer, but the chip needs to diced and polished in comparison to a surface grating coupler which is simpler to couple light into because of the easier alignment (due to bigger size). All the input and outputs need to be aligned to the edge of the chip for edge coupling whereas
a grating coupler input and outputs can be present anywhere on the chip. Although edge couplers don’t require angular dependence and loss is lower than 3dB and is polarization independent. Because this project is used for a teaching experience, grating couplers were chosen to couple light because of the simple and reliable process. As light enters the grating coupler’s periodic pattern, Light scatters off and as light propagates more light scatters resembling a point source. Grating couplers operates based on the Huygen Fresnel Principle. The Huygens Fresnel Principle states that every unobstructed point on a wavefront acts, at a given instant, as a source of outgoing secondary spherical waves. The resulting net light amplitude at any position in the scattered light field is the vector sum of the amplitudes of all the individual waves. The original formulation was in terms of an artificial concept of a large number of point sources somehow re-radiating from a wavefront. In fact, it is fundamentally sound as was shown by Kirchoff who derived a slightly modified form from a wave equation for the radiation. It is valid for describing diffraction in the far field well away from the diffraction source and when the source is larger than the light wavelength [13].

![Figure 2.4: SEM image of the grating coupler and cross sectional view of the grating coupler](image)

**Figure 2.4:** SEM image of the grating coupler and cross sectional view of the grating coupler
This yields the resulting output wave which is in phase and that propagates vertically creating a first order diffraction. Back reflections are created because of the scattered light having different momentum, if the back reflections are higher than the 1st order diffraction, it will create a Fabry Perot cavity i.e. light reflecting off the periodic grating causing variation in transmission. This in turn leads to first order diffraction and back reflection (2nd order diffraction). This undesired effect was eliminated after using a period that is greater than the wavelength of light as seen in Eq. 2.14.

\[
\frac{\lambda}{n_{eff}} < A \tag{2.14}
\]

The overall interference of the spherical waves comes out in an angle if the condition above is fulfilled. This leads to a reduction in back reflections because the interference does not contribute to the second order reflections coupling and smoother input and output.

2.3 Directional coupler

![Bidirectional coupler in Klayout](image)

**Figure 2.5:** Bi directional coupler in Klayout

Directional couplers(Fig. 2.5) work on the principle for supermodes. Supermodes are the modes created because of interaction between the waveguides. When two
waveguides come closer to each other light couples from one to another, because of the evanescent field. The evanescent field is formed at the waveguide cladding interface because of the decay of the light energy at the edges after formation of a mode. Similar to quantum mechanical tunneling through potential barriers, the gap or barrier length between the waveguides resulting in similar tunneling behavior. A supermode has even and odd modes which can have different effective index. As the gap distance between the waveguides increases, the super modes from the even effective index decreases, while the odd effective index increases.

A Directional coupler simply is two waveguides placed close to each other. This can be used to split and combine light. When two waveguides comes close to each other, the evanescent field and relative phase plays an important role in splitting and combining light. The two waveguides now have a vital role in forming a supermode, modes that result from the interaction of the waveguides. This acts as the basic principle behind ring resonators and many more circuits.

2.4 Ring resonator

![Figure 2.6: Double bus ring resonator used in Layout[1]](image)

Ring resonators are photonic circuits, which are made up of two bidirectional couplers. The Ring resonator circuit works on the principle of optical tunneling,
it acts like a directional coupler at the coupling ports between the ring and the waveguide. The evanescent field enters into the ring when the loss around the ring is equal to the waveguide-ring power transfer. Light couples at a coupling coefficient $\kappa$ and power remaining is denoted by $t$, $1-\kappa^2$ (Eq. 2.15). From the figure 2.6, it can be seen that the input port is denoted as $a_1$ and $a_2$ refers to the port where light tunnels into the ring, $b_2$ refers to the port where light tunnels out of the ring and $b_1$ is the output port.

$$t = e^{-\frac{\alpha L}{2}} \quad (2.15)$$

$$E_{b_1} = tE_{a_1} + \kappa E_{a_2} \quad (2.16)$$

$$E_{b_2} = tE_{a_2} - \kappa E_{a_1} \quad (2.17)$$

$$A = e^{(-aL)} \quad (2.18)$$

$$E_{a_2} = (\sqrt{A}e^{i\beta L})E_{b_2} \quad (2.19)$$

$$E_{b_2} = \frac{-\kappa E_{a_1}}{1 - t(\sqrt{A})e^{i\beta L}} \quad (2.20)$$

$A$ is the power and $E$ field is the square root of power. $\beta$ is the propagation constant and $L$ is the circumference of the ring. The electric field equations can be seen in equation 2.16, $\alpha$ is the propagation loss. On substitution, the $E_{b_2}$ can be derived as 2.16.

$$E_{b_1} = \frac{t - e^{i\beta L}}{1 - te^{i\beta L}} \quad (2.21)$$

$$\frac{m\lambda}{n} = 2\pi R \quad (2.22)$$

The ring resonator transfer function is defined as $t$. According to the theory of the resonance condition Eq. 2.22, resonance could be observed when propagation constant
is an integer multiple of $2\pi$, the transmission is zero when there is critical coupling i.e. when the coupling loss is equal to the ring round trip loss. At critical coupling Fig. 2.8, the intensity of light in the ring is greater than the waveguide. When the high intensity light is in the ring, a portion of the light is propagated to the outside into the waveguide, this light destructively interferes with the light transmitting past the ring resonator causing evanescent field.

$$\left| \frac{Ea_2}{Ea_1} \right|^2 = \left| \frac{t}{\sqrt{1-t^2}} \right|^2$$

(2.23)

**Figure 2.7:** Example of a ring resonator circuit result showing free spectral range[1]

The Free Spectral Range (FSR) is obtained from the difference of wavelengths between resonances. The group index was then extracted from the FSR (Fig. 2.7). The efficiency of a ring is quantified using the q factor, the q factor gives us information about how long light can stay inside the ring. The ring resonator acts as a filter and

**Figure 2.8:** Ring resonator example showing conditions where light enters into the ring the light is filtered at specific frequencies. This can be tuned to necessity within the
CHAPTER 2. PHOTONIC COMPONENTS: THEORY AND WORKING PRINCIPLE

Figure 2.9: Y branch used in the layout as a splitter and combiner

The working range of the resonator to achieve specific frequencies. From Fig 2.8 it can be observed that when there is destructive interference, there is no optical tunneling and all of the light is guided into the waveguide, when there is constructive interference i.e. when the impedance is matched), the light enters into the ring.

2.5 Y Branch

The main function of a Y-branch (Fig. 2.9) in the layout is to split and combine light depending on the circuit. The Y-branch could be used as a splitter, with input on one side and get output on two sides and vice versa for a combiner. This can be used in circuits where the input light needs to be split or light needs to be combined with other waveguides. It could be used in circuits like Michelson interferometer, Mach Zehnder interferometer which are elaborated on the next chapter. The components discussed in this chapter will be designed and simulated. Based on favourable results, these components will be used in circuits which will then be fabricated and tested.
Chapter 3

Design and simulation

All of the photonic devices in this thesis are designed with Lumerical FDTD Solutions and implemented in photonic circuit simulations using Lumerical Interconnect. The layout was realized by using the SiEPIC Silicon Photonic Process Design Kit with KLayout[14], an open source layout editor[15]. The Finite Difference Eigenmode (FDE) solver calculates the spatial profile and frequency dependence of modes and solves Maxwell’s equations on a cross-sectional mesh of the waveguide. The solver calculates the mode field profiles, effective index, and loss. Integrated frequency sweep makes it easy to calculate group delay, dispersion, etc. The solver can also treat bent waveguides[15] and this is used in simulation of the components and the design (Fig. 3.4).

3.1 Waveguides

3.1.1 Matlab Simulation

The Silicon photonic circuits are designed for a Silicon-on-Insulator wafer with 0.25 \( \mu \)m Silicon and 3 \( \mu \)m buried oxide, which are available commercially from SOITEC.

\[
n_1^2 E_{x, \text{Silicon}} = n_2^2 E_{x, \text{Glass}} \tag{3.1}
\]
CHAPTER 3. DESIGN AND SIMULATION

Figure 3.1: TM mode profile a) E field intensity b) H-field intensity of a waveguide of 0.5 µm width and 0.25 µm thickness computed using MATLAB

Figure 3.2: Representation of Strip waveguide used in MATLAB in the project[1] and the stack cross-sectional view after fabrication

A simulation was performed to find out the slab waveguides mode, it is changed only over the thickness of the waveguide. A numerical and analytic approach was used. The Matlab programs are attached in the appendix for reference. The stack used for the simulation is shown in figure 3.2. The waveguide geometry used were 250 nm depth and 500 nm wide. TM has lower effective index, This phenomenon is because of the electric field is pointing at the direction of the interface, the slab being thin makes the effective index lower than the TE mode. The modes(Fig. 3.3) are discontinuous because of the boundary condition (continuity equation) of the Maxwell’s equation, normal component obeys the eq. 3.1.
3.1.2 Lumerical Mode simulation

To determine the thickness of the waveguide required for a single mode TE or TM polarization, the effective index was calculated with respect to the thickness. This was solved analytically and the results could be seen in figure ???. It is observed that a thickness of 200 nm to 250 nm has a single mode cut-off for both TE and TM mode. This condition is satisfied by the specifications the SOI wafer.

All simulations are performed through wavelengths 1500 nm to 1600 nm. From the effective index plot vs. wavelength (Figure 3.5) it could be observed that the effective index is increasing with increasing waveguide width but decreases with the increase in the wavelength. This is because of the increase in the amount of silicon in the waveguide. The effective index reduction is because the longer wavelengths when propagating through the lower amounts of silicon, thereby causing a decrease in the silicon thickness. Waveguide dispersion is the change in effective index as a change of function, for silicon, material dispersion can be seen in figure  3.5.
In the TE effective vs light is in the glass so the mode will be big and unguided at lower waveguide widths, a waveguide width of 500 nm is optimum for having a single mode TM polarization. At 500 nm it could be observed that the multimode polarization effective index are very low and bends could be very lossy at widths lower than 500 nm.

3.2 Lumerical with Prolith

A comparison of the Y splitter simulation is performed with simulation software like PROLITH, KLA Tencor, Klayout and FDTD solutions by Lumerical. The Y splitter is very sensitive to design variations and the simulation of photolithography. The changes in optical pattern is simulated in Prolith lithography software which can be used to predict the patterned image after exposure. The Prolith parameters were set to match the process parameters of the ASML stepper that would be used during fabrication. ASML is an i-line stepper and uses 365 nm. The film stack, exposure,
focus, NA were mainly simulated to get an accurate profile.

From figure 3.6 it can be observed that the sharp edges of the y splitter was not replicated and in turn it yielded curved edges. This behavior is expected in an i-line set up and in future, this could be adjusted with the layout. This establishes the fact that the design changes after it is being fabricated. The gap between split of the y gap is 200nm which is less than the resolution limit of the ASML stepper that is being used. This leads to the gap getting closed during fabrication and the light with higher modes being propagated which is undesired. The RIT designed Y splitter was put through a Lumerical FDTD simulation. On comparison with the images in Fig 3.6, it could be observed that the y splitter is consistent with the fabricated y split.

This design is now loaded on the LUMERICAL FDTD software and the ports and monitor are set up, the simulation is performed with the simulated image and this image shows that the the width is reduced between legs of the Y and hence the
width is increased and the gap is adjusted according to the device and the results were obtained (Fig. 3.7).

3.3 Loopback circuit

Figure 3.8: Grating coupler showing Pitch and duty ratio, it is a representation of 1µm pitch, with a 40% duty cycle

Loopback circuits can be used as test circuits which verifies the efficiency of the grating coupler, two grating couplers are connected through a waveguide and the output is analyzed. The grating coupler’s design needs to be refined. Hence the teeth or gratings of the grating coupler are defined in terms of pitch and duty cycle. In Fig. 3.8, the grating coupler is of pitch 1µm and a duty ratio of 40%. The pattern is repeated from pitch of 1.0µm to 1.7µm in increments of 0.1µm and the duty cycle is varied between 40%, 50% and 60%.

These grating couplers are connected to loopbacks and simulated in Lumerical Interconnect like the example in fig. 3.9 yielding result in fig. 3.9 b).

In the layout, various grating couplers with radius 50µm and various pitch and duty ratio are designed. A summary of the designed loopback circuit can be seen in table 3.1.
Figure 3.9: Loop back circuit in Lumerical INTERCONNECT

Table 3.1: Summary of the loopback circuits designed in the layout

<table>
<thead>
<tr>
<th>Diameter of the Grating coupler = 50 m</th>
<th>Pitch (µm)</th>
<th>Duty ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
<td>40 50 60</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>40 50 60</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>40 50 60</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>40 50 60</td>
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<tr>
<td></td>
<td>1.4</td>
<td>40 50 60</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>40 50 60</td>
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<td></td>
<td>1.6</td>
<td>40 50 60</td>
</tr>
<tr>
<td></td>
<td>1.7</td>
<td>40 50 60</td>
</tr>
</tbody>
</table>
3.4 Mach Zehnder Interferometer

A Mach Zehnder interferometer is the photonic circuit that operate on the principle of relative phase difference of light. The splitting and combining of light depends on the different length and it interferes differently, therefore it could be shown that the transmission is a function of the path length difference path. It is further supported by equation 3.3.

\[
\beta_1 = \frac{2\pi}{\lambda} n_1, \beta_2 = \frac{2\pi}{\lambda} n_2
\]

\[
T = \frac{1}{4}[e^{i\beta_1 L_1}e^{-\alpha_1 L_1/2} + e^{i\beta_2 L_2}e^{-\alpha_2 L_2/2}]^2
\]

where $\beta_1$ and $\beta_2$ is propagation constant

$L_1$ and $L_2$ are the path lengths of the waveguides

$\alpha_1$ and $\alpha_2$ are the loss coefficient

Light could be split using photonic components like y-splitters, three way coupler
or directional couplers. As seen in figure 3.10, light travels through the waveguide and is split into two paths, this light now goes through different lengths and the propagation loss is determined by Equation 3.2. This propagation loss when combined with the electric field of the light in the waveguide results in equation 3.3.

The circuit is simulated in Lumerical Interconnect and the output will now be compared with the tested result.

### 3.5 Ring Resonator circuit

Simulations are run in Lumerical INTERCONNECT software with the SiEPIC library extension. A ring resonator is ideally designed using one or two directional couplers. Various ring resonator circuits could be designed with varying waveguide lengths, ring resonator gaps, ring resonator sizes. These designs have been fabricated and tested in the RIT custom built setup. The variations in design includes variation in the gap between the ring and the waveguide which was set between 300 nm to 700 nm. The radius of the ring was adjusted from 10µm, 15µm and 205µm. The circuits are designed in Klayout and simulated with Lumerical INTERCONNECT for this. An example of the expected result can be seen in fig. 3.13.
Figure 3.12: Example ring resonator INTERCONNECT circuit

Figure 3.13: Ring resonator INTERCONNECT Simulation of a TM ring resonator a) with a 300 nm gap and a 10µm radius, b) with a 400 nm gap and a 10µm radius
### Table 3.2: Summary of ring resonator designs in the layout

<table>
<thead>
<tr>
<th>Pitch ($\mu$m)</th>
<th>1.7</th>
<th>1.6</th>
<th>1.5</th>
<th>1.4</th>
<th>1.3</th>
<th>1.2</th>
<th>1.1</th>
<th>1</th>
<th>Duty Ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap (nm)</td>
<td>1350</td>
<td>1200</td>
<td>1050</td>
<td>900</td>
<td>750</td>
<td>600</td>
<td>450</td>
<td>300</td>
<td>40</td>
</tr>
<tr>
<td>Gap (nm)</td>
<td>1400</td>
<td>1250</td>
<td>1100</td>
<td>950</td>
<td>800</td>
<td>650</td>
<td>500</td>
<td>350</td>
<td>50</td>
</tr>
<tr>
<td>Gap (nm)</td>
<td>1450</td>
<td>1300</td>
<td>1150</td>
<td>1000</td>
<td>850</td>
<td>700</td>
<td>550</td>
<td>400</td>
<td>60</td>
</tr>
<tr>
<td>Gap (nm)</td>
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<td>750</td>
<td>900</td>
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<td>1200</td>
<td>1350</td>
<td>40</td>
</tr>
<tr>
<td>Gap (nm)</td>
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<td>500</td>
<td>650</td>
<td>800</td>
<td>950</td>
<td>1100</td>
<td>1250</td>
<td>1400</td>
<td>50</td>
</tr>
<tr>
<td>Gap (nm)</td>
<td>400</td>
<td>550</td>
<td>700</td>
<td>850</td>
<td>1000</td>
<td>1150</td>
<td>1300</td>
<td>1450</td>
<td>60</td>
</tr>
<tr>
<td>Gap (nm)</td>
<td>750</td>
<td>600</td>
<td>450</td>
<td>300</td>
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<td>1200</td>
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<td>900</td>
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</tr>
<tr>
<td>Gap (nm)</td>
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<td>350</td>
<td>1400</td>
<td>1250</td>
<td>1100</td>
<td>950</td>
<td>50</td>
</tr>
<tr>
<td>Gap (nm)</td>
<td>850</td>
<td>700</td>
<td>550</td>
<td>400</td>
<td>1450</td>
<td>1300</td>
<td>1150</td>
<td>1000</td>
<td>60</td>
</tr>
</tbody>
</table>

### 3.6 Summary

The basic circuits were designed and are ready to be fabricated. These designs are only a few examples of the circuit. The scope of the thesis is the fabrication of the many possible circuits and are not discussed in detailed at this juncture. The key components like the grating couplers, y branch, directional coupler and ring resonators will be used in the circuit and will be fabricated and tested. SEM images and test results will be recorded at every juncture and the results will be further analyzed and the appropriate changes will be suggested.
Chapter 4

Fabrication

Fabrication is the main objective of this thesis, after the design and simulation of the components that were extensively discussed in the previous chapters yield desired results, the layout is design using the Klayout software. In the layout, the components are simulated using the Lumerical Interconnect and is transferred on to the mask. This chapter details about the complete fabrication process Fig. 4.1, it includes details about the materials used, the considerations taken into account before selection of Lithography and Plasma etch tools which were used. This chapter also includes optical microscope and Scanning Electron Microscope (SEM) images which were taken to assure the pattern fidelity and etch depths according to the preceding mask and fabrication process design.

4.1 Mask Making

Mask making plays a critical role in the field of photolithography. A mask is a quartz plate coated with chrome that contains the layout that needs to be patterned on to the wafer. The pattern fidelity in the target layer is directly proportional to the quality of the pattern in the photomask. Photomask dictates the factors like, alignment, critical dimension and defect control.

A photomask is ideally a chrome quartz plate with photoresist coated on top of the chrome plate. The photoresist on the wafer is exposed using a laser head writer
and the photoresist after develop, acts as a hard mask for etching or blocking ion implantation. The chrome is etched transferring the pattern from the resist to the chrome, and the resist is removed. Chromium is deposited for approximately 100 nm through evaporation sputtering onto glass or UVGSFS substrate. Photoresist is spin coat resist at a thickness of 500 nm. "Photoresist" may be positive or negative acting. The mask pattern is exposed by an electron beam or laser pattern generator with required beam size, address or pixel size, and beam current or dose Fig. 4.2 a). The quartz plate is developed in the appropriate developer and rinsed Fig. 4.2 b).

Chromium is etched in chrome etch (ceric ammonium nitrate) and loaded onto a spin rinse dry station Fig. 4.2 c) The Photoresist is removed either using an O2 plasma or solvent (e.g. acetone) or acid (e.g. sulfuric/peroxide) and then the mask is rinsed in DI water and dried using N2 Fig. 4.2 d) and inspected for defects. The features are measured for critical dimensions, CDs. Depending on the exposure system, the
patterns are enlarged 5x or 4x, the lens system on the exposure tool dictates the pattern size. The photomask for this project, contains a single level exposure and there are no alignment marks present on the wafer, the mask also contains bar code that is used in selecting the right mask from the SMIF pod in the stepper.

The mask also contains alignment marks which is used to align the reticle with the wafer stage Fig. 4.3. These alignment marks are diffraction gratings and are present in both x and y direction. These marks are illuminated by the HeNe Laser which operates at a wavelength of 632.8 nm. The mask contains fiducial marks that are used when there are no alignment marks on the wafer which are present at the edge of the mask.

4.2 SOI wafer

Wafer preparation is one of the key aspects of the project. A bare silicon wafer with $<100>$ orientation was RCA cleaned using the process as mentioned in figure 4.4 in

---

**Figure 4.2:** Steps elaborating the mask making process performed at RIT [2]
CHAPTER 4. FABRICATION

Figure 4.3: RIT ASML mask with alignment marks and barcode representation

Figure 4.4: RCA clean process

APM
H₂O – 5000ml
NH₄OH – 300ml
H₂O₂ – 300ml
75°C, 10 min.

DI water rinse, 5 min.

50:1 HF 30sec.

HPM
H₂O – 5000ml
HCl – 300ml
H₂O₂ – 300ml
75°C, 10 min.

DI water rinse, 5 min.

SPIN/RINSE DRY
the General RCA bench. The wafer was then transferred into the Bruce furnace and thermal oxide of thickness 2\(\mu\)m was grown. Using PECVD process in P5000, a-Si:H was deposited using PECVD with gases like SiH\(_4\) and H\(_2\) at 400 °C at 1Torr pressure and 30W RF power for the detailed recipe refer the appendix A[16]. This wafer will be further referenced as ”SOI wafer”.

4.3 Photolithography

4.3.1 Lithography Overview

Photolithography is the most critical part of the fabrication, the silicon photonic wafer fabrication process used the ASML i-line stepper PAS 500 (Fig. 4.5). It uses i-line lithography (365 nm) to expose the feature, the stepper uses fiducial marks on the edge of the reticle, numerical aperture(NA) can be altered from 0.48 to 0.6, coherence(\(\sigma\)) between 0.35-0.8.

The process is a one step exposure process. The mask is placed on the platen and the reticle pre-alignment marks aligns it to the correct location relative to the optical column. The wafer is loaded into the stepper through the input port and the robot arm picks up the wafer. The flat of the wafer to be processed is found and the wafer is transferred to the pre-alignment chuck (P-chuck). The wafer is now centered and aligned to the stage and transferred under the column to be exposed. The wafer is exposed at the E-Chuck where the wafer is received and the stage vacuum down the wafer for the alignment and exposure steps. After exposure the wafer moves to the D-chuck or the Discharge chuck where the wafer waits until the robot is ready to return the wafer to the receive cassette. The reticle is returned to the Standard Mechanical Interface pod and the mask is retrieved.

\[
k1 = \frac{1}{2(\sigma + 1)} \quad (4.1)
\]
where $\sigma$ is a ratio of numerical aperture of the condenser lens to the numerical aperture of the objective lens
\[
R = \frac{k_1 \lambda}{NA}
\]  
(4.2)

where $\lambda$ is the wavelength of the source 436 nm (g-line) and 365 nm (i-line)
NA is the Numerical Aperture
k1 is the process constant which is generally assumed to be 0.5 for coherent and 0.25 for incoherent illumination

The use of an i-line source yields a smallest possible feature from Eq. 4.2 of approximately 300 nm, when used at NA of 0.6 and assuming a coherent source. A Focus exposure matrix (FEM) is performed to determine the optimum exposure and the focus that is required to transfer the pattern. Exposure dose is the energy density
4.3.2 BARC, Photoresist and Spin on Carbon coating

Bottom Anti Reflective Coatings (BARC) are used to reduce the standing waves generated from the reflective substrate during exposure. These results cause defects
that causes problems in fidelity of the patterns. For this project, bottom anti reflective coating (BARC) was used, Brewer science ARC Icon7 was spun at a thickness of 70 nm, this is a 365nm anti-reflective coating. There are various ways of etching the BARC using O<sub>2</sub> plasma, O<sub>2</sub>, CHF<sub>3</sub>, Ar plasma, C<sub>2</sub>F<sub>6</sub> plasma, Cl<sub>2</sub> etch or HCl. ARC icon is recommended to achieve feature sizes of <0.25µm. A Spin curve of the anti reflective coating used is seen in fig. 4.8.

Figure 4.8: Spin speed of the diluted OiR 620:PGMEA (left) and the Spin speed of the ICON7 (right)

Photoresist selection is a parameter that plays a critical role in photolithography, the does, exposure, critical dimension is all controlled by the material and thickness of the photoresist. Based on Prolith simulations, it was concluded that the thickness of 300 nm is required to have the least substrate and stack reflection, hence the OiR 620 resist was diluted with RER 600 and was spun at a thickness of 3000 rpm in the SSI Track. The spin curve was recorded and could be referred to in fig. 4.8. The non uniformity of the photoresist is 1.56% and the average measured thickness on the Prometrix spectramap is 2700Å.

Spin on carbon is material that can be used as a hard mask to etch silicon. Spin on carbon is selective and acts as an very good mask against plasma etch. Fluorine acts to etch silicon whereas forms a polymer when reacting with spin on carbon. For this experiment, the Spin on Carbon was spun at a thickness of 636Å with a standard
deviation of 1.408%. The wafer was initially baked for 150°C for one minute. Spin on carbon was spun at 2500 rpm for 60 seconds. The spin on carbon is then baked at 300°C for 5 minutes. Diluted OIR 620 was then spun at 3000 rpm for 30 seconds and then baked at 100°C. The wafer is exposed with the appropriate dose and focus concluded from the focus exposure matrix. The wafer is baked at 110°C for 1 minute and is developed for 90 seconds. A post development bake is performed at 145°C for 1 minute. This wafer will be used in the Drytek for etching.

### 4.4 Plasma Etch

Etching can be generally defined as the process of removing material. In this project, Plasma etch was chosen to be the ideal option for removal of BARC, spin on carbon, silicon. Plasma etch is an important process that enables the transfer of patterns from the photolithography process on to the substrate. This process requires high degree of anisotropy (A) as seen in equation 4.3 and fig. 4.10, where z is vertical direction of the etch and x is the horizontal direction of the etch or the undercutting resulting from the etch.

\[
A = \frac{z - x}{x} \quad (4.3)
\]
Plasma is partially ionized gas with equal number of positive and negative particles which is created by placing a bias between two electrodes in vacuum. Free electrons are created and they begin to accelerate towards the anode and gain kinetic energy and this electron eventually collides with a gas molecule and electrons reach the anode, ionized gas molecules strike the cathode and creates secondary electrons that are required to sustain plasma.

Before any plasma etch, it is always recommended to do a oxygen clean. The chamber is loaded with a dummy wafer and oxygen is flown in the chamber and the RF is turned on and this is performed before every etch and this is performed before every etch step.
4.4.1 BARC etch

BARC is made up of materials like the photoresist and is insoluble in CD-26, the preferred method for removing BARC is a plasma etch using gases like O$_2$, O$_2$/CHF$_3$, C$_2$F$_6$, Cl$_2$ or HCl, it can also be stripped off using an oxidizing solvent strip process. Figure 4.11 shows the optical microscope images after BARC etch.
### 4.4.2 Spin on Carbon etch

The spin on carbon is etched using the DRYTEK Quad RIE etcher at oxygen gas flow at 25 sccm for 30 seconds. From fig. 4.12 it could be clearly seen that the SOC is etched away with the 30 second etch.

### 4.4.3 Silicon Etch

Silicon etch is a very important step in the fabrication process because the waveguides and other photonic circuits are formed in the silicon layer, hence, various plasma etch tools were explored for this process.
4.4.3.1 DRYTEK Quad RIE Etcher

The drytek quad RIE etcher (Fig. 4.13) is a reactive ion etching tool that is used to etch silicon, silicon dioxide, silicon nitride and other photoresist like materials. The drytek is supplied with the following gases CHF$_3$, CF$_4$, SF$_6$, O$_2$ and Argon. Fluorine, creates a free radical under plasma and interacts with Si and forms SiF$_4$. Carbon forms a C-F polymer film and protects the sidewall and yields an anisotropic etch.

Silicon can be etched using gases like fluorine and with gases like CHF$_3$, CF$_4$, SF$_6$. Dry reactive ion etch is preferred over the wet etch process because dry etching provides an anisotropic etch where the sidewall is straight and can help in pattern fidelity. In anisotropic etching, there might be a slight tapered etch leading to undercutting, this when severe leads to problems like resist peeling. The recipe used for this etch is in Table 4.3.
Table 4.3: DRYTEK Quad recipe for etching silicon

<table>
<thead>
<tr>
<th>Recipe name</th>
<th>ANISOPOL</th>
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<td>Tool</td>
<td>DRYTEK Quad RIE</td>
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<td>Chamber Number</td>
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<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
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<table>
<thead>
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<tbody>
<tr>
<td>Etch rate of Silicon</td>
</tr>
<tr>
<td>Etch rate of Photoresist</td>
</tr>
<tr>
<td>Etch rate of Spin on Carbon</td>
</tr>
</tbody>
</table>

Figure 4.14: Photograph of the STS deep silicon etcher

4.4.3.2 STS Deep Si Etcher

STS deep silicon etcher is a tool that uses an inductively coupled plasma to increase the degree of anisotropy. It uses a Bosch process which alternates between the plasma to achieve vertical sidewalls. The first induced plasma will deposit a passivation layer which protects the sidewall to control etch, the second plasma formed etches the silicon. The STS ASE tool (Fig. 4.14) is very sensitive; any contaminants on the wafers backside will affect the vacuum that holds the wafer. So the wafer’s backside needs to be cleaned with IPA before putting it inside the tool. The loading chamber
Figure 4.15: Tool display of the STS deep silicon etcher showing gas flow and plasma turning on

Table 4.4: STS deep silicon etcher recipe for silicon etch

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<tr>
<th>Recipe name</th>
<th>Shallow etch</th>
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<tr>
<td>Tool</td>
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</tr>
<tr>
<td>Chamber Number</td>
<td>1 chamber process</td>
</tr>
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<td>RF Power</td>
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<tr>
<td>Pressure</td>
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**Gas**

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</tr>
<tr>
<td>C4F8</td>
<td>60 sccm</td>
</tr>
<tr>
<td>O2</td>
<td>10 sccm</td>
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<tr>
<td>Ar</td>
<td>40 sccm</td>
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**Etch rate**

<table>
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</thead>
<tbody>
<tr>
<td>Etch rate of Photoresist</td>
<td>10 nm/min</td>
</tr>
</tbody>
</table>

is vented and the wafer is loaded on to the slots, the wafer needs to be loaded properly and the flat of the wafer is aligned with the scribing on the slot. After loading the wafer click pump and map option and the wafers will be mapped. The slot is selected and the wafer to be etched is loaded. The chamber is cleaned with Oxygen plasma for 15 minutes, and the chamber is seasoned C4F8, SF6, O2 and Ar at a ratio of 85:130:12:20 sccm. The standard seasoning recipe time of 17 minutes and 30 seconds was used for seasoning the chamber. The shallow etch recipe has a gas flow of C4F8, SF6, O2 and Ar at a ratio of 60:19:10:40 sccm which was run for 3 minutes. The etch profile is measured using the Tencor P2 profilometer which could be measured as seen in the figure 4.16.
4.4.3.3 LAM 4600

The LAM 4600 is a chlorine based etcher, it uses reactive ion etching which is generally used to etch aluminum films. Experimental results from [17] shows that silicon could be etched with the chlorine chemistry. The main concerns with the etching recipe was the photoresist to silicon selectivity. The photoresist was etched faster than the silicon present. Optical end point detection is used and etch will be stopped. The tool is plumbed with chlorine, boron trichloride, chloroform, oxygen and nitrogen. Chlorine, and boron trichloride are the main components that etch silicon, chloroform is used to passivate the sidewalls and prevent it from further etching. Oxygen is used
Table 4.5: LAM 4600 recipe for Si etch

<table>
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<td>130</td>
<td>130</td>
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<td>0</td>
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<td>0</td>
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<tr>
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<td>125</td>
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<td>0</td>
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<td>Stable</td>
<td>time</td>
<td>time</td>
<td>Oetch</td>
<td>Time</td>
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<td>Time (s)</td>
<td>15</td>
<td>8</td>
<td>100</td>
<td>10%</td>
<td>15</td>
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</table>

for controlling the formation of polymer that is used to passivate the sidewalls and nitrogen is used to purge the chamber.

A standard recipe in the LAM 4600 contains 5 steps. Step 1 is mainly used for gas and pressure stabilization, the second step includes etching the native oxide present which is not required in out recipe and would be reduced to 2 seconds from the original recipe. Step 3 is responsible for etching silicon and the etch is dependent on the flow of these gases, step 4 is used for the over etch and step 5 is used to nitrogen purge. Currently the tool has some chlorine leak and other maintenance to be performed, hence the experiment was removed from the scope of this thesis, but could be performed in future experiments.

4.4.3.4 SEM Images after silicon etch in STS deep silicon Etcher Tool and Drytek Quad RIE etcher

From the SEM images, it is evident that the silicon etch can be performed in both the STS and the drytek quad although the etch rate of the hard mask is higher in the drytek. The isolated features present on the mask experience a reduction in the width of the pattern(approximately 125nm) and could be corrected using a mask bias.
or in the layout in future projects. The uniformity of the etch and the sidewalls look smooth when etched with photoresist or etched with Spin on carbon as hard mask. This isolated feature problem has lead to discontinuous waveguide in the directional coupler thereby is unfit to be tested.

![Figure 4.18](image)

Figure 4.18: Zoomed in view of a TM grating coupler with a pitch of 1 \( \mu \text{m} \) with a duty ratio of a) 40% b) 50% and c) 60%

![Figure 4.19](image)

Figure 4.19: SEM image of photonic components (left) Bidirectional coupler, (center) \( y \)-branch, (right) ring resonator

### 4.5 Cladding

The etched silicon wafer is usually clad using TEOS oxide, because of the tool restrictions at the SMFL 1.5\( \mu \text{m} \) thick photoresist is used, the refractive index of the OiR
Figure 4.20: SEM images Figure represents SEM image a) Bidirectional coupler with a gap of 0.6µm b) ring resonator with a radius of 15µm, c) y-branch from the Mach Zehnder Interferometer with a width of 1.5µm and 250 nm gap that was fabricated using DRYTEK Quad RIE

Figure 4.21: SEM images Figure represents SEM image a) showing depth of the grating coupler at 55° tilt etched in the Drytek etch b) edge of the pattern after etching in the STS etcher

620 is 1.54, and the TEOS oxide is 1.45, because the indexes are closer, undiluted OiR 620 is spun at at a speed of 3300 rpm for 30 seconds and is baked at 145°C and then developed in the SSI track with CD 26 for 60 second develop.

4.6 Summary

Overall, it could be concluded that the fabrication of silicon photonic structures have been successful and with the above mentioned changes with the design layout and the etch, the process can be further refined. The use of STS deep silicon etcher enables a better uniform etch with only photoresist as hard mask, but the photoresist hard
mask was completely etched in the Drytek before the desired amount of silicon is etched thereby leaving no hard mask. Spin on carbon with photoresist acts as a perfect solution as a hard mask and stays on with an etch rate of only 150 nm/min in the drytek and 95 nm/min in the STS deep silicon etcher.
Any device fabricated needs to be validated for its quality and functionality. The photonic wafers fabricated are tested with a custom built test setup. In this chapter, the test setup will be described along with the test results from the circuits and components like grating coupler, waveguides, Y-splitters and directional couplers. Transmission Losses are expected from the use of a-Si:H instead of crystalline silicon and the cladding is photoresist instead of oxide that was used in simulation. The coupling efficiency is determined from the factor and ring resonator and Y splitters.
5.1 Testing Setup

The wafer was tested after cladding using a custom-built test setup. Light was coupled into the grating couplers on the chip using a fiber array consisting of four polarization maintaining fibers separated by 127 \( \mu \text{m} \) each (Fig. 5.1). The polarization maintaining fibers ensure that TM polarized light is launched into the chip.

The fiber array was held at a 30° angle in the fiber array glass setup using a custom-built fiber array holder made in ABS plastic (CAD can be provided upon request). The fiber array was finely positioned to the chip using a Thorlabs Nanomax stage. Laser light was provided by a Keysight Technologies 81607A tunable laser with
a power of 4.6dBm (see figure 5.2).

The light exiting the photonic circuit on the wafer is detected using a 4-port Agilent N7744A Optical Multiport Power Meter (only 3 of the ports were used simultaneously). The tunable laser was swept over a wavelength range of 1500 nm to 1635 nm in 1 pm steps and a sweep rate of 200nm/s.

The wafer is placed on the wafer stage as seen in figure, and the wafer movement is controlled using the coarse x and y axis, fiber array’s movement is controlled by a 3 axis probe holder. The circuit on the wafer is viewed through the microscope and when the fiber is aligned with the circuit looks like figure 5.3.

The laser and the microscope are first set up after the wafer is placed on the stage. The fiber array is lowered by adjusting the z axis, after making sure that the wafer and the fiber are aligned to the horizontal plane. The fiber array need to be scratch free and shouldn’t be scratched during the axis movements. It is recommended to have a small gap between the wafer and the fiber while determining the coupling location by moving the x and y axis, then move the z axis have the fibers to touch the wafer to have maximum coupling. Similarly when moving to a new location on the wafer, the fiber array needs to be moved up before changing the x and y position to avoid damage to the fiber array.

**Figure 5.4:** View of the fabricated wafer under the microscope in the test setup
5.2 Data Analysis

5.2.1 Loopbacks

The different grating coupler designs were tested by directly connecting two grating couplers (input/output) together by a single waveguide. The grating couplers had varying pitch and duty ratios as described earlier. Based on the analysis (Fig. 5.5), the optical transmission is observed to be lower for grating couplers with a pitch higher than $1.3 \, \mu\text{m}$ because the spectral response of the grating couplers is shifted to longer wavelengths beyond which our power detector can measure. The best coupler was found to have a pitch $1.2 \, \mu\text{m}$ and a duty ratio of $40\%$. We observed that the amount of silicon content in the grating coupler had a strong effect on the coupler performance.

For higher pitches and duty ratios, the relatively larger amount of Silicon yielded large oscillations in the transmission because of large amount of reflected power that result from the impedance mismatch between the small Silicon waveguide and the wide grating coupler region.

5.2.2 Ring resonator circuit

Add-drop ring resonators with a range of gaps ($0.35 \, \mu\text{m}$ to $1.45 \, \mu\text{m}$) between the waveguides and the ring were tested. The test structure consists of four TM polarized grating couplers, one of which is an input and the other three are used as outputs to the device. The raw data (Fig. 5.6) was baseline corrected by fitting to a low order polynomial curve.

The resonant wavelengths were identified using peak finding with a ring resonator transfer function fitting algorithm (Fig. 5.6). The Q-factors of a range of devices was obtained and was found to vary from 2200 to 7538 (refer appendix for extracted results).
Figure 5.5: Output data from the detectors varying across various duty ratio and the pitch. a) 40% duty cycle b) 50% duty cycle c) 60% duty cycle. The large oscillations are due to undesirable reflections from grating couplers with large Silicon fill (large duty ratio and pitch) that result in a significant reflected power due to the impedance mismatch between the waveguide and grating.
Figure 5.6: Raw data obtained from the detector (blue) with the polynomial fit (red) for correction of data, Baseline corrected data after fitting the ring fit and peak fitting algorithm.

Figure 5.7: Ring resonator results with (left) grating coupler 50 $\mu$m radius and a ring radius of 10 $\mu$m and 500nm gap (right) grating coupler 50 $\mu$m radius and a ring radius of 10 $\mu$m and 300nm gap.

It could be observed that the results of the ring resonator are a close match with the simulated results Fig. 5.8 (blue). The baseline corrected data shows good q factors with an average 6754.

In one of the designs, the same ring resonator circuit was repeated 10 times to investigate intra-die variability as shown 5.1. It was observed that the free spectral range was below 1 nm for almost every device.

When measuring the same die and the same circuit across the wafer it could be seen that the dies away from the center exhibit lower performance when compared to the center. These variations are believed to be mainly because of the oxide, a-Si:H deposition and photoresist non uniformity and etch non uniformity.
CHAPTER 5. TESTING

Figure 5.8: Ring resonator results with a) grating coupler 50µm radius and a ring radius of 20µm and 300nm gap, b) Simulated results of grating coupler 50µm radius and a ring radius of 10µm and 300nm gap

Table 5.1: Ring resonator statistics depicts the ring resonator statistical results. TM polarization was utilized and the group index was extracted at a wavelength of 1.55µm

<table>
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<tr>
<th>Gap (nm)</th>
<th>Radius (µm)</th>
<th>Mean FSR (nm)</th>
<th>Std deviation of FSR(nm)</th>
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<td>400</td>
<td>10</td>
<td>13.07</td>
<td>0.21</td>
</tr>
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<td>300</td>
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<td>400</td>
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<td>7.98</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Figure 5.9: Across die variation of devices with ring radius 50µm 1.4 µm, 40% duty cycle with 300 nm gap
All the other factors have a standard deviation of 2.5% but the etch rate exhibited an etch depth of 235 nm in the center and 340 nm in the edges. This difference is because of the mechanism of etch which etches from the outside to edge of the wafer from inside to center and could be controlled with varying voltage across the chuck to create stable etch plasma.

It could be observed that as we increase the size of the ring, more resonant frequencies are present fig. 5.8 and can be utilized in applications like signal filters. The noise on top of the filter is a result of photoresist as cladding and can be avoided with TEOS as cladding.

### 5.2.3 Mach Zehnder Interferometer (MZI)

The device splits the light into two and then recombines it. A pair of y-splitter were used to create a Mach Zehnder interferometer. Figure 5.11 is an example of the
CHAPTER 5. TESTING

Figure 5.11: Simulated MZI Data with 3-Way Directional Couplers(left), Raw data of the same MZI with a 3 Way Directional Coupler(right)

Figure 5.12: Raw data of the MZI circuit with y branch, Raw data of the MZI circuit with 50% duty cycle

MZI test results. It could be seen from figure that the results closely match with the simulated results fig. 5.12. The noise on the peaks could be a result of the use of photoresist as cladding and the a-Si:H wafer instead of the crystalline silicon.

MZI also tested different grating couplers for the RIT TM design. The 1.25 µm pitch seemed to yield the cleanest results, which is to be expected from the loopback circuit results, followed closely by the 1.5 µm. The 1.00µm pitch was extremely noisy. The 50% duty cycle grating couplers seemed to be somewhat noisy as well.
Chapter 6

Conclusions and Future work

Until recently it has been believed that lithography limitations of simple optical wafer steppers would prevent practical fabrication of working photonic devices in a typical university laboratory and that only labs with advanced e-beam processing capabilities could teach how these devices could be made. The Microelectronic Engineering program at the Rochester Institute of Technology has a long history of using simplified processing to teach and illustrate micro/nano fabrication of basic devices. RIT set out to demonstrate how a complete photonic design, build and test cycle could be accomplished in as little as one week in a condensed course or easily spread out over a few weeks in a standard course laboratory setting. This thesis provided the foundation for just such a course that was successfully offered to 20 undergraduate and graduate students at RIT in the spring semester of 2017. Their successful realization of numerous photonic device design can be directly attributed to this thesis work. RIT now has plans to expand this course as an on-line course with a virtual laboratory experience.

During process designs, the tool restrictions were the main consideration factor. The designs were restricted to features greater than 300 nm because of the i-line capabilities. Basic passive photonic components like grating couplers, double bus ring, bidirectional couplers and y branch were designed and some simple circuits like Mach Zehnder Interferometer, loopbacks and resonators were simulated. The designs
that worked best were replicated into the layout for the mask.

Uniform and repeatable results are the goal of any process development effort but when creating new processes and process flows uniformity can be elusive. Engineers often use designed experiments to intentionally investigate the effect of variability but often the inherent variation of a film thickness or etch result can provide insight during the testing of the final devices. In this thesis and subsequent use as a teaching experiment this was found to be the case. Areas of the wafer with different dimensions in thickness and width performed differently in ways that could be aligned with theory to guide future design and process choices. By designing layouts with different duty ratios and examining the test results it can be concluded that a target pitch of 1.25 microns with at 40% duty ratio should produce the best results under the current lithography and etch conditions. It was also observed that ring resonators with a gap between 300 nm to 800 nm yielded good results.

The variety of the results obtained from testing presents us the opportunity to enhance the understanding of variability during fabrication of the silicon photonic structures. Overall, we observe that there is a lot of variability in the output results based on the coupling data as well as the resonance data. The variability was present for varying gaps between the ring resonator and the waveguide, the pitch and the duty ratio of the grating coupler. One reason for the large variability is because the a-Si:H etching process was non uniform across the wafer. As a result, only dies at the very center of the wafer yielded both good grating couplers and ring resonators. Intra die variability was analyzed, by repeating the same device 12 times in the same die, the free spectral range was calculated and the standard deviation was less than 1 nm, and concluded to be negligible. STS deep silicon etcher has always given good results for wafers and the Drytek quad can be used for pieces but needs a hard mask like spin on carbon with photoresist for etch.

The process can now be further refined with the use of a mask bias and complex
circuits like active components including heaters and modulators can be added to the present layout. Packaging is one of the key aspects of manufacturing. The challenges of packaging includes the alignment of fiber array and using the right adhesive to attach these fibers with the chip. With more research and ideas from the academic community, packaging standards is expected to be established and is expected to go into large scale production and consumer market. Photonics being an emerging field provides an excellent platform for education, access to resources can play a major role in development of skilled workforce. Because the silicon photonics industry is still very much in development phase, innovations in design and processes will be the most important factor that will expand the silicon photonics community. One particular area of innovation is integration of photonic and electronic components and this thesis hopefully will encourage more designers and engineers to be interested in the field.
Bibliography


Appendices
### Appendix A: a-Si:H deposition recipe

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<th>Step</th>
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<td>By Time</td>
<td>150 sccm</td>
<td>25 sccm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>RAMP 4</td>
<td>By Time</td>
<td>250 sccm</td>
<td>25 sccm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>DEPOSIT</td>
<td>By Time</td>
<td>250 sccm</td>
<td>25 sccm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>PURGE</td>
<td>By Time</td>
<td>4000 sccm</td>
<td></td>
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<tr>
<td>15</td>
<td>PUMP</td>
<td>Pressure &lt;200.0 T</td>
<td>-1 PU</td>
<td>-1 PU</td>
<td>-1 PU</td>
<td>-1 PU</td>
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<tr>
<td>16</td>
<td>PURGE</td>
<td>By Time</td>
<td>4000 sccm</td>
<td></td>
<td></td>
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<tr>
<td>17</td>
<td>PUMP</td>
<td>Pressure &lt;200.0 T</td>
<td>-1 PU</td>
<td>-1 PU</td>
<td>-1 PU</td>
<td>-1 PU</td>
</tr>
</tbody>
</table>
Appendix B: Testing scripts

B.1 Ring resonator test result analysis

# script for analyzing the thru port data from a ring resonator

from numpy import *
import matplotlib.pyplot as plt
from peakutils import indexes as findpeaks
from scipy.optimize import curve_fit
from glob import glob
import csv
import os
import urllib
import urllib.request

wl_column = 0  # column in the data corresponding to wavelength
thru_column = 1  # column in the data corresponding to transmission
radius = 15000  # radius of the ring in nm
poly_order = 5  # order of the polynomial used to flatten the spectrum
wl_min = 1500  # minimum wavelength of the region of interest
wl_max = 1600  # maximum wavelength of the region of interest
yscale = 'log'  # minimum resonance depth
min_depth = 10  # minimum separation between resonances in nm
min_dist = 4
skip_lines = 24  # number of lines to skip at the start of the file

results = [];
#directory = 'C:\Users\steid\Dropbox (RIT Nanophotonics)\Current Projects\2017_ProcessOptimization\2017_Mar_WaveguideLoss\Data\’
url = "https://www.dropbox.com/s/4mhkt4a8qk9xuk/600%20single%20bus%20R50_1.25_0.5D.csv?dl=1"
FileName = os.path.splitext(os.path.splitext(url)[0]+’.csv’)[1]
print(FileName)
urllib.request.urlretrieve(url, FileName)
directory=os.path.dirname(os.path.abspath(’__file__’))
filenames=glob(directory + ’\’ + FileName)
print(directory)

# uncomment if you want to use a local directory
APPENDIX B. TESTING SCRIPTS

```python
#directory = 'C:\Users\Stefan\Dropbox (RIT Nanophotonics)\Courses\2165_PIC_Course\RIT_Wafer_April2017\Class wafer Apr14\Dr. Preble\'
#filenames = glob(directory + '600 single bus R50 1.25 0.5D.csv')

for file in range(0, len(filenames)):
    print(filenames[file])
    filename = filenames[file].split('.csv')[0]

# import the data from a csv file
# wavelength and transmission must be in different columns
data = genfromtxt(filenames[file], delimiter=' ', skip_header=skip_lines)

# extract the data from the csv file
# this will only extract data within the wavelength range of interest
wl = array([])
thru = array([])
for i in range(0, len(data)):
    if (data[i][wl_column] >= wl_min*1e-9) & (data[i][wl_column] <= wl_max*1e-9):
        wl = append(wl, data[i][wl_column]*1e9)
        thru = append(thru, -1*data[i][thru_column])

if y_scale == 'lin':
    thru_db = 10*log10(thru/0.1)
elif y_scale == 'log':
    thru_db = thru

# plot of the raw data
fig, ax = plt.subplots()
fig.set_figwidth(8)
fig.set_figheight(5)
fig.set_dpi(600)
plt.rc('font', weight='bold')
plt.plot(wl, thru_db, 'b-')
ax.set_xlabel('Wavelength [nm]', fontsize=16, fontweight='bold')
ax.set_ylabel('Transmission [dBm]', fontsize=16, fontweight='bold')
ax.set_title('Raw Data', fontsize=24, fontweight='bold')
ax.set_xlim([wl_min, wl_max])
# plt.savefig(filename + '_Raw.png', dpi=600)
plt.show()

# fit the data with a polynomial so that the data can be flattened
```
APPENDIX B. TESTING SCRIPTS

```python
baseline = poly1d(polyfit(wl, thru_dB, poly_order))

# plot of the raw data with the polynomial fit
plt.plot(wl, thru_dB, 'b-', wl, baseline(wl), 'r--')
plt.title('Raw Data with Polynomial Fit')
plt.ylabel('Transmission [dBm]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()

# subtract the fit from the data and move the max close to zero
thru_dB = thru_dB - baseline(wl) + max(baseline(wl)) - max(thru_dB)

# plot of the baseline corrected data
plt.plot(wl, thru_dB, 'b-')
plt.title('Baseline Corrected Data')
plt.ylabel('Transmission [dBm]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()

# find the locations of all of the resonances
peaks = findpeaks(-thru_dB, min_depth/(max(thru_dB)-min(thru_dB)),
                   min_dist*len(thru_dB)/(wl_max-wl_min))
if len(peaks) != 0:
    peak_wl = array([])
    peak_thru = array([])
    for i in range(0, len(peaks)):
        peak_wl = append(peak_wl, wl[peaks[i]])
        peak_thru = append(peak_thru, thru_dB[peaks[i]])

    plt.plot(wl, thru_dB, 'b-', peak_wl, peak_thru, 'ro')
    plt.title('Baseline Corrected Data (w/ Peaks)')
    plt.ylabel('Transmission [dBm]')
    plt.xlabel('Wavelength [nm]')
    plt.xlim([wl_min, wl_max])
    plt.show()

Lrt = 2*pi*radius

fsr = array([])
```
APPENDIX B. TESTING SCRIPTS

```python
wl_ng = array([])
g = array([])
for i in range(0, len(peak_wl)-1):
    if (4 < peak_wl[i+1]-peak_wl[i] < 9):
        fsr = append(fsr, peak_wl[i+1]-peak_wl[i])
        wl_ng = append(wl_ng, (peak_wl[i+1]+peak_wl[i])/2)
        ng = append(ng, pow(wl_ng[-1],2)/(L.rt*fsr[-1]))

plt.figure(figsize=(8, 5), dpi=600)
plt.plot(wl_ng, fsr, 'bo')
plt.title('Free Spectral Range', fontsize=24, fontweight='bold')
plt.ylabel('Free Spectral Range [nm]', fontsize=16, fontweight='bold')
plt.xlabel('Wavelength [nm]', fontsize=16, fontweight='bold')
plt.xlim([wl_min, wl_max])
#plt.savefig(filename + '_FSR.png', dpi=600)
plt.show()

ng.R2 = 0
if len(ng) >= 2:
    w0 = peak_wl[int(floor(len(peak_wl)/2))]
    n1_init = 1.84
    modeNumber = n1_init*L.rt/w0 - 0.5
    n1_init = (2*floor(modeNumber)+1)*w0/2/L.rt
    n2_init = (n1_init-mean(ng))/w0

def ngFitFunc(x, a, b):
    return a*x + b

par, cov = curve_fit(ngFitFunc, wl_ng, ng, None, None)

ng_fit = ngFitFunc(wl_ng, par[0], par[1])

ng.R2 = 1-sum((ng-ng_fit)**2)/sum((ng-mean(ng))**2)

plt.figure(figsize=(8, 5), dpi=600)
plt.plot(wl_ng, ng, 'bo', wl_ng, ng_fit, 'r-')
plt.title('Group Index with Fit', fontsize=24, fontweight='bold')
plt.ylabel('Group Index', fontsize=16, fontweight='bold')
plt.xlabel('Wavelength [nm]', fontsize=16, fontweight='bold')
plt.xlim([wl_min, wl_max])
#plt.savefig(filename + '_ng.png', dpi=600)
```
plt.show()

print("Goodness of Fit=\%3f" % ng_R2)

n3_init = 0
if ng_R2 >= 0:
    n3_init = -par[0]/(2*wl0)

k_init = 0.2
alpha_init_dB = 10 #dB/cm
alpha_init = 1e-5*10**(-alpha_init_dB/10) #1/μm
phi0_init = pi
Tmax_init = 0
x0 = array([n1_init, n2_init, n3_init, k_init, alpha_init, phi0_init, Tmax_init])

def neffFitFunc(wavelength, n1, n2, n3):
    return n1 + n2*(wavelength - wl0) + n3*(wavelength - wl0)**2

def ringFitFunc(wavelength, n1, n2, n3, k, alpha, phi0, Tmax):
    t = sqrt(1-k**2)
    A = exp(-alpha*L_rt)
    neff = neffFitFunc(wavelength, n1, n2, n3)
    phi_rt = (2*pi/wavelength)*neff*L_rt + phi0
    return 10*log10(abs((t-conj(t))*sqrt(A)*exp(1j*phi_rt)) / (1-sqrt(A)*conj(t)**2*exp(1j*phi_lt))**2) + Tmax

plt.plot(wl, thru_dB, 'b-', wl, ringFitFunc(wl, x0[0], x0[1], x0[2], x0[3], x0[4], x0[5], x0[6]), 'r--')
plt.title('Baseline Corrected Data with Initial Fit Params')
plt.ylabel('Transmission [a.u.]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()

par, cov = curve_fit(ringFitFunc, wl, thru_dB, p0=x0, maxfev=1000)

ring_fit = ringFitFunc(wl, par[0], par[1], par[2], par[3], par[4], par[5], par[6])
APPENDIX B. TESTING SCRIPTS

\[ \text{ring}\_\text{fit}\_R^2 = 1 - \frac{\text{sum}((\text{thru}\_\text{dB} - \text{ring}\_\text{fit})^2)}{\text{sum}(\text{thru}\_\text{dB} - \text{mean(\text{thru}\_\text{dB})})^2) \]

plt.plot(wl, thru_dB, 'b-', wl, ring_fit, 'r--')
plt.title('Baseline Corrected Data with Ring Fit')
plt.ylabel('Transmission [a.u.]')
plt.xlabel('Wavelength [nm]
plt.xlim([wl_min, wl_max])
plt.show()

print("Goodness of Fit = %.3f" % ring_fit_R2)

if ring_fit_R2 >= 0.1:
    neff = neffFitFunc(wl, par[0], par[1], par[2])
    dndwl = diff(neff)/diff(wl)
    dndwl = append(dndwl, dndwl[-1])
    ng2 = neff - wl*dndwl

    #plt.plot(wl, ng2, 'b-')
    #plt.title('Group Index (from Ring fit)')
    #plt.ylabel('Group Index')
    #plt.xlabel('Wavelength [nm]
    #plt.xlim([wl_min, wl_max])
    #plt.show()

thru_lin = pow(10, thru_dB/10)
ring_fit_lin = pow(10, ring_fit/10)

plt.plot(wl, thru_lin, 'b-', wl, ring_fit_lin, 'r--')
plt.title('Baseline Corrected Data with Ring Fit')
plt.ylabel('Transmission [a.u.]')
plt.xlabel('Wavelength [nm]
plt.xlim([wl_min, wl_max])
plt.show()

# find maxima
min_depth = 0.25  # minimum resonance depth
min_dist = 4     # minimum separation between resonances in nm
maxima_fit = findpeaks(ring_fit_lin, min_depth/(max(ring_fit_lin)-min(ring_fit_lin))

min_dist*len(ring_fit_lin)/(wl_max-wl_min))
APPENDIX B. TESTING SCRIPTS

maxima = array([])
maxima_index = array([])
maxima_wl = array([])

for i in range(0, len(maxima_fit)):
    thru_sum = 0
    j_start = max([-1000, -maxima_fit[i]])
    j_stop = min([1001, len(thru_lin) - maxima_fit[i]])
    for j in range(j_start, j_stop):
        thru_sum = thru_sum + thru_lin[maxima_fit[i] + j]
    maxima = append(maxima, thru_sum / (j_stop - j_start))
    maxima_index = append(maxima_index, maxima_fit[i])
    maxima_wl = append(maxima_wl, wl[maxima_fit[i]])

# find minima in the data
# this will also detect any resonance splitting
min_depth = 0.4  # minimum resonance depth
min_dist = 0  # minimum separation between resonances in nm
minima_fit = findpeaks(-thru_lin, min_depth / (max(thru_lin) - min(thru_lin)),
                        min_dist*len(thru_lin)/(wl_max-wl_min))

# find minima in the fit to the data
# this will be used to help determine when resonance splitting has occurred
min_depth = 0.25  # minimum resonance depth
min_dist = 4  # minimum separation between resonances in nm
minima_ring_fit = findpeaks(-ring_fit_lin, min_depth / (max(ring_fit_lin) - min(ring_fit_lin)),
                            min_dist*len(ring_fit_lin)/(wl_max-wl_min))

# determine where resonance splitting is occurring
splitting = []
minima_to_delete = []

for i in range(0, len(minima_ring_fit)):
    num_res = 0
    res_index = []
    split = False
    for j in range(0, len(minima_fit)):
        if abs(wl[minima_ring_fit[i]] - wl[minima_fit[j]]) <= 0.1:
            num_res+=1
            res_index.append(minima_fit[j])

    if num_res > 1:
        splitting.append(i)
        minima_to_delete += res_index
if num_res > 1:
    split = True
if num_res != 0:
    splitting.append([split, res_index])
else:
    minima_to_delete.append(i)

if len(minima_to_delete) != 0:
    minima_ring_fit = delete(minima_ring_fit, minima_to_delete)

# determine which resonances to analyze
maxima_to_delete = []
for i in range(1, len(maxima_index)):
    if maxima_index[i] < minima_ring_fit[0]:
        maxima_to_delete.append(i - 1)
    if maxima_index[i - 1] > minima_ring_fit[-1]:
        maxima_to_delete.append(i)

if len(maxima_to_delete) != 0:
    maxima = delete(maxima, maxima_to_delete)
    maxima_fit = delete(maxima_fit, maxima_to_delete)
    maxima_index = delete(maxima_index, maxima_to_delete)
    maxima_wl = delete(maxima_wl, maxima_to_delete)

maxima_start_index = 0
maxima_stop_index = 0

if minima_ring_fit[0] < maxima_index[0]:
    for i in range(0, len(minima_ring_fit)):
        if minima_ring_fit[-(i + 1)] > maxima_index[0]:
            minima_start_index = len(minima_ring_fit) - (i + 1)
    else:
        minima_start_index = 0

if minima_ring_fit[-1] > maxima_index[-1]:
    for i in range(0, len(minima_ring_fit)):
        if minima_ring_fit[i] < maxima_index[-1]:
            minima_stop_index = i
    else:
        minima_stop_index = len(minima_ring_fit) - 1
APPENDIX B. TESTING SCRIPTS

# add all resonance information to an array
res_info = []
for i in range(minima_start_index, minima_stop_index + 1):
    # check for splitting
    if splitting[i][0] == True:
        res_info.append([True,
                          int(maxima_index[maxima_start_index + (i -
                          minima_start_index)]),
                          min(splitting[i][1]),
                          max(splitting[i][1]),
                          int(maxima_index[maxima_start_index + (i -
                          minima_start_index) + 1])])
    else:
        res_info.append([False,
                          int(maxima_index[maxima_start_index + (i -
                          minima_start_index)]),
                          splitting[i][1][0],
                          int(maxima_index[maxima_start_index + (i -
                          minima_start_index) + 1])])

# plt.plot(wl, thru_lin, 'b-', wl, ring_fit_lin, 'r--', maxima_wl,
#           'ro', minima_wl, 'ro')
# plt.title('Baseline Corrected Data with Ring Fit and Peaks')
# plt.ylabel('Transmission [a.u.]')
# plt.xlabel('Wavelength [nm]')
# plt.xlim([wl_min, wl_max])
# plt.show()

# determine the bandwidth of each resonance
fwhm = array([])
q_factor_wl = array([])
q_factor = array([])
q_factor_split_wl = array([])
q_factor_split = array([])
for i in range(0, len(res_info)):
    fwhm_left_list = array([])
    fwhm_right_list = array([])
    for j in range(res_info[i][1], res_info[i][-1]):
        if (thru_lin[j-1] >= (thru_lin[res_info[i][1]] + thru_lin[
            res_info[i][2]]) / 2):
if (mean(thru_lin[j-5:j]) >= (thru_lin[res_info[i][1]] + thru_lin[res_info[i][2]])/2):
    if (thru_lin[j+1] <= (thru_lin[res_info[i][1]] + thru_lin[res_info[i][2]])/2):
        if (mean(thru_lin[j+1:j+6]) <= (thru_lin[res_info[i][1]] + thru_lin[res_info[i][2]])/2):
            if (wl[res_info[i][1]] < wl[j] < wl[res_info[i][2]]):
                fwhm_left_list = append(fwhm_left_list, j)

if (thru_lin[j-1] <= (thru_lin[res_info[i][-1]] + thru_lin[res_info[i][-2]])/2):
    if (mean(thru_lin[j-5:j]) <= (thru_lin[res_info[i][-1]] + thru_lin[res_info[i][-2]])/2):
        if (thru_lin[j+1] >= (thru_lin[res_info[i][-1]] + thru_lin[res_info[i][-2]])/2):
            if (mean(thru_lin[j+1:j+6]) >= (thru_lin[res_info[i][-1]] + thru_lin[res_info[i][-2]])/2):
                if (wl[res_info[i][-2]] < wl[j] < wl[res_info[i][-1]]):
                    fwhm_right_list = append(fwhm_right_list, j)

fwhm_left = int((fwhm_left_list[int(argmin((fwhm_left_list - res_info[i][2])**2))]))

fwhm_right = int((fwhm_right_list[int(argmin((fwhm_right_list - res_info[i][-2])**2))]))

fwhm = append(fwhm, wl[fwhm_right] - wl[fwhm_left])

q_factor_wl = append(q_factor_wl, wl[int((res_info[i][2] + res_info[i][-2])/2)])

q_factor = append(q_factor, wl[int((res_info[i][2] + res_info[i][-2])/2)])

if res_info[i][0] == True:
    q_factor_split_wl = append(q_factor_split_wl, wl[int(res_info[i][2])])

q_factor_split = append(q_factor_split, wl[int(res_info[i][2])]/(2*abs(wl[int(res_info[i][2])]-wl[fwhm_left])))

q_factor_split_wl = append(q_factor_split_wl, wl[int(res_info[i][-2])])

q_factor_split = append(q_factor_split, wl[int(res_info[i][-2])]/(2*abs(wl[int(res_info[i][-2])]-wl[fwhm_right])))

else:
APPENDIX B. TESTING SCRIPTS

```python
q_factor_split_wl = append(q_factor_split_wl, wli(int(res_info[i][2])))
q_factor_split = append(q_factor_split, wli(int(res_info[i][2]))/(wli[fwhm_right] - wli[fwhm_left]))

plt.figure(figsize=(8, 5), dpi=600)
plt.plot(q_factor_wl, q_factor, 'ro')
plt.title('Quality Factor', fontsize=24, fontweight='bold')
plt.ylabel('Quality Factor', fontsize=16, fontweight='bold')
plt.xlabel('Wavelength [nm]', fontsize=16, fontweight='bold')
plt.xlim([wl_min, wl_max])
#plt.savefig(filename + '.Q.png', dpi=600)
plt.show()

# plt.figure(figsize=(8, 5), dpi=600)
# plt.plot(q_factor_split_wl, q_factor_split, 'ro')
# plt.title('Quality Factor (Split Resonances Separate)', fontsize=24,
# fontweight='bold')
# plt.ylabel('Quality Factor', fontsize=16, fontweight='bold')
# plt.xlabel('Wavelength [nm]', fontsize=16, fontweight='bold')
# plt.xlim([wl_min, wl_max])
# plt.savefig(filename + '.Q.png', dpi=600)
# plt.show()

results.append([filenames[file]])
results.append('Free Spectral Range')
results.append(wl_ng)
results.append(fsr)
results.append('Group Index')
results.append(wl_ng)
results.append(ng)
results.append('Quality Factor')
results.append([q_factor_wl])
results.append([q_factor])
```

B.2 MZI test result analysis

# Script for analyzing data from a Mach–Zehnder interferometer

```python
from numpy import *
import matplotlib.pyplot as plt
```
from peakutils import indexes as findpeaks
from scipy.optimize import curve_fit

# import the data from a csv file
# requires the file to be a .csv
# the first column must be wavelength
# the second column must be transmission
data = genfromtxt('mzi_100um_data.csv', delimiter=',

wl_column = 0   # column in the data corresponding to wavelength
trans_column = 1 # column in the data corresponding to wavelength
dL = 100000     # path length difference of the MZI in nm
poly_order = 4   # order of the polynomial used to flatten the spectrum
wl_min = 1525    # minimum wavelength of the region of interest
wl_max = 1570    # maximum wavelength of the region of interest

wl = array([])
trans = array([])
for i in range(0, len(data)):
    if (data[i][wl_column] >= wl_min) & (data[i][wl_column] <= wl_max):
        wl = append(wl, data[i][wl_column])
        trans = append(trans, data[i][trans_column])

plt.plot(wl, trans)
plt.title('Raw Data')
plt.ylabel('Transmission [dBm]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()

baseline = poly1d(polyfit(wl, trans, poly_order))

plt.plot(wl, trans, '-', wl, baseline(wl), '--')
plt.title('Raw Data with Polynomial Fit')
plt.ylabel('Transmission [dBm]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()

trans = trans - baseline(wl) + max(baseline(wl)) - max(trans)
APPENDIX B. TESTING SCRIPTS

```python
plt.plot(wl, trans)
plt.title('Baseline Corrected Data')
plt.xlabel('Wavelength [nm]')
plt.ylabel('Transmission [dBm]')
plt.xlim([wl_min, wl_max])
plt.show()

# find the locations of all of the resonances
min_depth = 8  # minimum resonance depth
min_dist = 5    # minimum separation between resonances in nm
peaks = findpeaks(-trans, min_depth/(max(trans)-min(trans)),
                  min_dist*len(trans)/(wl_max-wl_min))

peak_wl = array([])
peak_trans = array([])
for i in range(0, len(peaks)):
    peak_wl = append(peak_wl, wl[peaks[i]])
    peak_trans = append(peak_trans, trans[peaks[i]])

plt.plot(wl, trans, '--', peak_wl, peak_trans, 'ro')
plt.title('Baseline Corrected Data (Wavelength Range w/Peaks)')
plt.xlabel('Wavelength [nm]')
plt.ylabel('Transmission [dBm]')
plt.xlim([wl_min, wl_max])
plt.show()

fsr = array([])
wl_ng = array([])
ng = array([])
for i in range(0, len(peak_wl)-1):
    fsr = append(fsr, peak_wl[i+1]-peak_wl[i])
    wl_ng = append(wl_ng, (peak_wl[i+1]+peak_wl[i])/2)
    ng = append(ng, pow(wl_ng[i], 2)/(dL*fsr[i]))

plt.plot(wl_ng, fsr, 'ro')
plt.title('Free Spectral Range (from Data)')
plt.xlabel('Wavelength [nm]')
plt.ylabel('Free Spectral Range [nm]')
plt.xlim([wl_min, wl_max])
plt.show()
```
APPENDIX B. TESTING SCRIPTS

\[
\text{wl0} = \text{peak}_\text{wl}[\text{int}(\text{floor}(\text{len}(\text{peak}_\text{wl})/2))] \\
n1._{\text{initial}} = 2.4 \\
\text{modeNumber} = n1._{\text{initial}}*dL/wl0 - 0.5 \\
n1._{\text{init}} = (2*\text{floor}(\text{modeNumber})+1)*wl0/2/dL \\
n2._{\text{init}} = (n1._{\text{init}}-\text{mean(ng)})/wl0
\]

def ngFitFunc(x, a, b):
    return a*x + b

par, cov = \text{curve.fit}(\text{ngFitFunc}, \text{wl}_\text{ng}, \text{ng}, \text{None}, \text{None})

\text{ng\_fit} = \text{ngFitFunc}(\text{wl}_\text{ng}, \text{par}[0], \text{par}[1])

\text{ng\_R2} = 1 - \sum((\text{ng} - \text{ng\_fit})^2)/\sum((\text{ng} - \text{mean(ng)})^2)

plt.plot(\text{wl}_\text{ng}, \text{ng}, 'ro', \text{wl}_\text{ng}, \text{ng\_fit}, '-')
plt.title('Group\_Index with Fit (from Data)')
plt.xlabel('Wavelength [nm]')
plt.ylabel('Group\_Index')
plt.xlim([wl_min, wl_max])
plt.show()

print("Goodness of Fit = %.3f" % ng\_R2)

n3._{\text{init}} = 0
if ng\_R2 >= 0.01:
    n3._{\text{init}} = -par[0]/2/wl0

alpha._{\text{init}} = 1e-6
x0 = array([n1._{\text{init}}, n2._{\text{init}}, n3._{\text{init}}, alpha._{\text{init}}])

def neffFitFunc(wavelength, n1, n2, n3):
    return n1 + n2*(wavelength - wl0) + n3*(wavelength - wl0)**2

def mziFitFunc(wavelength, n1, n2, n3, alpha):
    L1=0
    L2=dL
    \text{neff}=\text{neffFitFunc}(\text{wavelength}, \text{n1}, \text{n2}, \text{n3})
    beta = 2*pi*\text{neff}/\text{wavelength}
    return 10*log10(0.25*abs(exp(-1j*beta*L1-alpha/2*L1)+exp(-1j*beta*L2-alpha/2*L2))**2)
plt.plot(wl, trans, '-', wl, mziFitFunc(wl, x0[0], x0[1], x0[2], x0[3]), '--')
plt.title('Baseline Corrected Data with Initial Fit Params')
plt.ylabel('Transmission [dBm]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()

par, cov = curve_fit(mziFitFunc, wl, trans, p0=x0, maxfev=1000)

MZI_fit = mziFitFunc(wl, par[0], par[1], par[2], par[3])

MZI_fit_R2 = 1 - sum((trans-MZI_fit)**2)/sum((trans-mean(trans))**2)

plt.figure(figsize=(8, 5), dpi=600)
plt.plot(wl, trans, '-', wl, MZI_fit, '--')
plt.ylabel('Transmission [dBm]')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.savefig("MZIfit.png", dpi=600)
plt.show()

print("Goodness of Fit = %.3f" % MZI_fit_R2)

if MZI_fit_R2 >= 0.8:
    neff = neffFitFunc(wl, par[0], par[1], par[2])
dndwl = diff(neff)/diff(wl)
dndwl = append(dndwl, dndwl[-1])
ng = neff - wl*dndwl

plt.plot(wl, ng)
plt.title('Group Index (from MZI fit)')
plt.ylabel('Group Index')
plt.xlabel('Wavelength [nm]')
plt.xlim([wl_min, wl_max])
plt.show()