Unbalanced Mach-Zehnder Electro-Optic Modulator and Waveguide Components

Konstantin Yurchenko
Department of Microelectronic Engineering, 82 Lomb Memorial Dr., Rochester, NY 14623. Email: kjy0892@rit.edu

Abstract— **Design and fabrication of waveguide structures on silicon-on-insulator (SOI) such as couplers and S-bends as components of Mach-Zehnder modulator (MZI) are presented here. These basic devices are important for processing light signals using silicon. Beam propagation method (BPM) was used to obtain dimensions of discussed structures for future manufacturing. During the design of the interferometer it was found that parameters of only either of branches could be altered to induce desired interference effect at the output of MZI. Hence, the device was dubbed unbalanced MZI. Since coupling separation was a factor that determines coupling length, it was chosen to be 1um in order to decrease overall length of the final structure and ensure that photolithography could be contained within the field size of the available steppers. The width for all waveguide components was chosen to be 1um to accommodate photolithographic constraints as well. It was discovered that MEBES mask-writing tool produces field stitching. Features written across the boundary of two fields gaps produced notches that were expected to severely decrease the transmission of the 1.55um light through the waveguides. New mask was sought and some devices were still built with the old mask to determine the viability of the proposed process.**

Index Terms—**Mach-Zehnder, waveguide, photonics, coupler, y-junction, interferometer**

I. Introduction

MACH-ZEHNDER modulator employs interference produced between phase coherent light waves that have traveled over different path lengths. A beam splitter is used to divide the light into two equal beams that are set to travel through parallel waveguides. The injection of carriers (electrons or holes) into these silicon guides can cause band shrinkage and band filling that change the refraction index of the material thus effective optical path length.

Optical path length is defined to be the product of the geometric length of the path light follows through the system, and the index of refraction of the medium through which it propagates.

Ideally, the path lengths and waveguide characteristics are identical, so that without the carrier injection the split beams recombine in the output waveguide to produce the lowest-order mode similar to the input. If an electric field is applied to produce a phase change of π radians between the two arms the modulator can be switched off from a transmitting to non-transmitting state.

Free-carrier plasma dispersion effect is used to convert the phase-shift to an amplitude modulation. This phenomenon is employed to alter the properties of silicon of one of the branches of MZI to produce a phase-shift at the output side of the device.

Confinement of light in a material is dependent on condition called total internal reflection. Total internal reflection is an optical phenomenon that occurs when a ray of light strikes a medium boundary at an angle larger than the critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary no light can pass through, so effectively all of the light is reflected.

However, an electromagnetic wave cannot propagate at any angle less then the critical angle but rather only discreet allowed angles. These discrete solutions are called modes of propagation.

To ensure that the majority of optical power is delivered and the resulting field distribution is most confined the structures are condition to operate in the single mode region. At multi-mode operation the optical power is split equally between the modes.

Mach-Zehnder interferometers can be used to fulfill two functions: modulation and switching. Optical modulators are devices that are able to control the amount of light passing through them. Optical switches are devices that change spatial position of light (on/off).

Device description: The source beam with wavelength of 1.55μm is split into two waves using a coupler and guided along varying path lengths. The split beams are then recombined to produce phase change. The electro-optic effect states that the change in index of refraction in a material is produced by the application of the electric field. Refractive index of silicon without the electric field is 3.48, however it varies as function of bias under varying electric field. [2]

Silicon optical modulators are relatively low speed compared to those made from III-V semiconductor compounds or other electro-optic materials such as lithium niobate. The fastest silicon waveguide modulator was demonstrated to have frequency of only 20MHz although devices of gigahertz range frequencies were theoretically described. [4]

II. Project Objective

A. Goal

The main objective of this undertaking was to manufacture and characterize silicon waveguides, beam splitters, and Mach-Zehnder interferometers at RIT semiconductor and Microsystems fabrication laboratory (SMFL).

B. Components

1) Waveguides

An optical waveguide is a fundamental element that interconnects the various devices of an optical integrated circuit. Optical waves travel in these structures similar to electric current in a metal wire. Light however propagates in modes inside the material, which once again means that the optical energy of the traveling waves is spatially distributed in one or more dimensions. Ridge waveguide has been chosen for classification due to its ability to support single mode propagation over larger range of dimensions eliminating fabrication constrains that are present in more planar models.

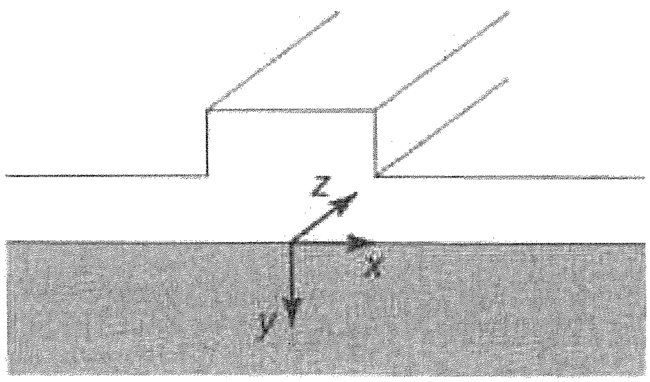


Fig. 1. 3D profile of an optical ridge waveguide

Figure 1.0 shows the cross-sectional view of a silicon waveguide, the shaded area bellow the structure is the buried oxide layer located in bulk material. To minimize losses from sidewall scattering the waveguide is most desired to be of dimensions that guarantee the confinement of fundamental mode. [3] These dimensions include a specific height and width of the structure that can be determined using theoretical calculations and software simulation.

2) Splitters

Splitter is a device that allows branching of optical power. There is a number of alternatives that can be used to accomplish this: couplers and multi-mode interference waveguides (MMI). 1x2 power splitter can be used to split the optical power entering the Mach-Zehnder and to merge it after the phase shift is introduced.

3) Carrier drivers

Forward biasing the p-i-n diode across the intrinsic region of the waveguide accomplishes carrier injection or depletion of electrons and holes into the silicon and changes its refractive index. Using an MOS capacitor produces the same results, however instead of direct injection of carriers accumulation conditions are applied and the majority carriers modify the silicon properties.

C. Mach-Zehnder Device

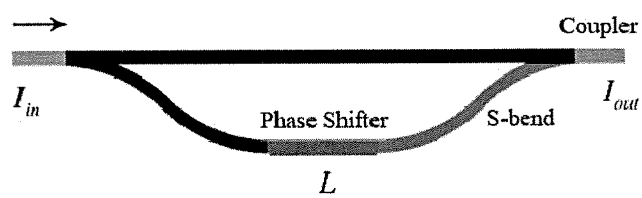
Modulation of the refractive index of silicon can be achieved via the free carrier plasma dispersion effect. The phase change can be determined using the following relationship:

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta n_{eff} L,$$

where L is the active length of the phase shifter, λ is the wavelength of light in free space, and Δn_{eff} is the effective index change in the waveguide, that is the difference of the refractive index of the waveguide with and without electric bias. The output light intensity is related to the phase difference and can be expressed as:

$$I_{out} \propto I_{in} \cos^2(\Delta\phi/2),$$

where I_{in} is the intensity of light at the input of Mach-Zehnder.



$$\Delta\phi = \frac{2\pi}{\lambda}\Delta n_{eff} L \qquad I_{out} \propto I_{in} \cos^2(\Delta\phi/2)$$

Fig. 2. Mach-Zehnder interferometer with input/output y-junction couplers

Figure 2.0 demonstrates the schematic for the interferometer.

III. Plan of Work

The following section details accomplished and future project's steps.

A. Simulations

1) Waveguide dimensions

Using BeamProp software a number of ridge waveguides was simulated, this assisted at studying the dependence between the structures sizes and propagation of the modes of light through the device and its components. Parameters suitable for such investigation were waveguide height and width. It was determined that for single mode propagation necessary waveguide ridge height was found to be 0.7 um.

2) Splitter dimensions

The dimensions of the coupler also a splitter were found using alike method. These parameters included length,

width of the coupler and the distance between the output waveguides that is a property dependent on the location where the multi-mode operation occurs inside the coupler. The minimal coupling length for equal optical power splitting was found to be dependent of the slab height of the silicon in which this waveguide structure was fabricated. The smallest coupling length allowed was found to be around 200 um.

Figure 3.0 shows one of the numerous simulation runs that allowed determining coupler size for future mask design.

3) S-bends

S-bend is a curved waveguide that allows spatial shifting of light in respect to plane within which light propagates.

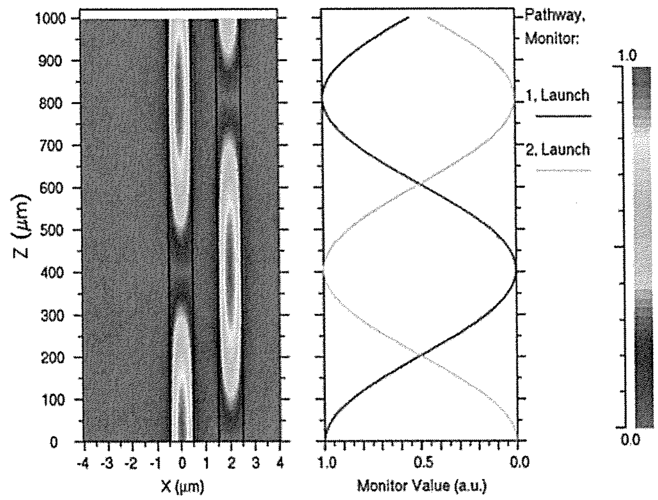


Fig. 3. Coupler beam propagation method simulation

Optimal S-bend radius was determined for slab thickness range of 1.2 um to 1.4 um of silicon layer on top of silicon dioxide film. It was determined that 300 um bending radius was minimal for manufacturing of nearly ideal Mach-Zehnder interferometer (MZI) using this thickness range. Figure 4.0 shows power loss inside one of simulated silicon S-bends.

4) Diode

In order to obtain electric properties for the carrier driver p-, n-well implant doses and junction could be simulated

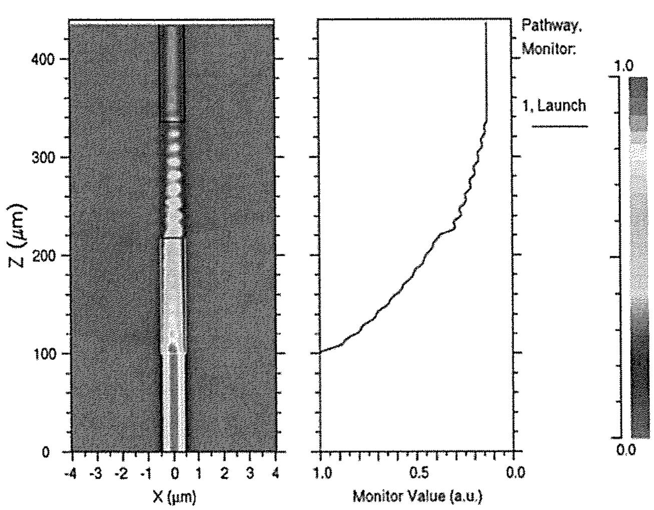


Fig. 4. S-bend beam propagation method simulation

using Deckbuild Athena. Using this information active length of this device could be found and targeted at manufacturing. Also placement of the diode wells in relation to the waveguide would be extracted from this study.

B. Preliminary steps

Since this was a planned five level lithography process, alignment marks test features, and overlay verniers were needed. These are generally standard features available in the CAD library for GCA type steppers and can selected when the layout for the masks is proposed.

C. Fabrication

First level photolithographic was designed to define physical structures on the wafers. These included definitions of waveguides, beam splitters, s-bends and Mach-Zehnder modulators of varying dimension. GCA resolution of 1um and field size of 2cm by 2cm were considered when these structures were mapped in the L-Edit layout environment. Aligned second and third level lithography were to be devised to define p- and n- wells, fourth level to provide contact cuts and fifth exposure to pattern metal. Only first level lithography was performed and future processing was required to be carried out to produce electrically active devices. Some passive testing was to be done after the first level lithography to observe whether the waveguides and couplers were transmitting optical power. This stage would allow determination whether the entire process flow could be carried out on or the processed wafers would have needed rework.

D. Characterization

IV characteristics and threshold voltage of the diode were to be measured at SMFL device testing area. The intensity measurements of the light would be completed in the photonics laboratory. Devices would be considered functioning if the power at the output of the interferometer would be minimal when the voltage was applied to the driving diode. Plots of the diode bias to the normalized output intensity would be generated to make conclusion about device performance.

IV. Resources, Equipment and Materials

SOI 4 inch wafers were used as fabrication substrates. GCA g-line (436nm) stepper was used for photolithographic steps. For exposure wafers would be coated with Shipley 1813 and developed in CD-25 aqueous developer. PE5000 tool was used for depositing and etching LTO layer to produce mask for silicon etching, which was later patterned using Drytech Quad plasma etcher. Boron and phosphorous would be the dopant species used to define wells using Varian 350D implanter. Implant energies and dose would be obtained using the software simulations.

V. Preliminary Investigation

A. Y-Junction Vs. MMI

When deciding which of the coupler is more suitable fabrication tolerance was considered. Since MMI is a relatively large structure, edge roughness does not influence it performance significantly. Also, relative dimensions of an MMI coupler is smaller compare to that of a y-splitter because it device has a short coupling region comparing to single-mode waveguide couplers. Performance of y-junctions is also heavily dependent on the capabilities of the lithographic equipment unlike MMI's. However, MMI splitters are difficult to design, hence the coupler was chosen as the power splitters for this design.

B. Diode Vs. Capacitor

Capacitor MZI requires extra process steps. p-i-n diode MZI is slower than capacitor driven device. [1] P-i-n diodes enable the use of plasma dispersion if it is forward bias and use of thermo-optic effect if it is reverse bias. [5]

Injection of excess of free carriers leads to recombination, and heating in the waveguide core. Small changes in temperature can produce a large thermo-optic shift in the refractive index, leading to a device dominated by thermal rather than electrical effects. [6]

In order to minimize the volume over which recombination occurs, and prevent carriers from diffusing, isolation trenches are usually etched to the buried oxide layer. This method ensures increase in injection efficiency.

VI. Results

Manufactured devices included interferometers consisting of 300 um and 500 um S-bends, coupling regions of lengths of

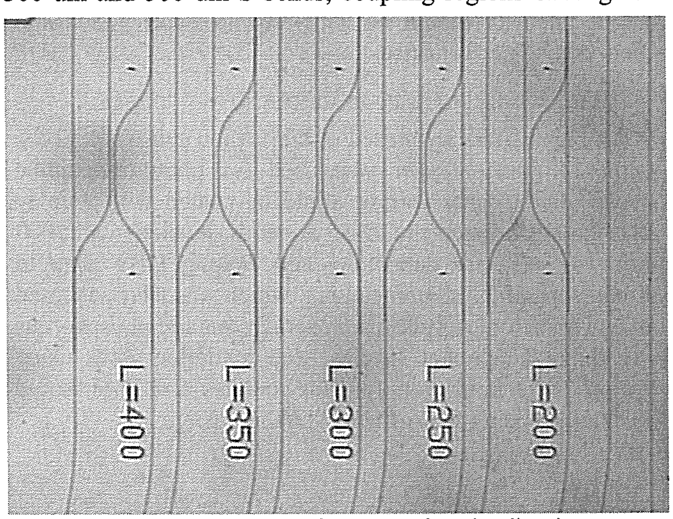


Fig. 5. Manufactured interferometers of varying dimesions

200um, 250um, 300um, 350um, and 400um as well as waveguide structures. Photolithography yielded desired critical dimension on SOI substrates. Figure 5.0 shows successfully manufactured devices.

It was determined that to produce a nearly ideal oxide mask for silicon etching using SMFL tools and to accommodate this design, the thermal conductivity of the substrate had to be increased. Using photoresist to improve conductivity showed positive results. However, etching in Drytech Quad

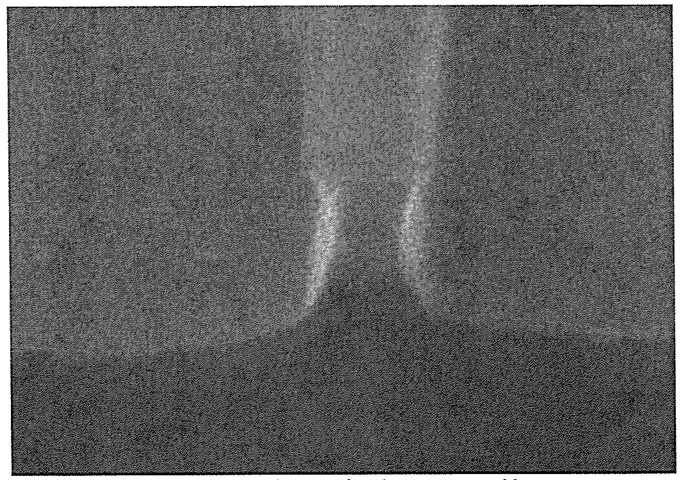


Fig. 6. SEM image of undercut waveguide

did not produce ideal silicon structures. Undercutting was observed and the coupler separation was increased. Further optimization of the etching of silicon was required to be carried out however the time and budget constraints did not allow for further processing. Figure 6.0 shows undercutting of the waveguide ridge during dry etching of silicon.

If this stage was successful and passive characterization of the devices was completed, it was expected from coupler to split the optical power into beams of equal intensity, and also merge such beams into one even if the input and output of this device were reversed. It was expected for light wave to experience attenuation, as it would travel through the waveguide structures. Attenuation in return would reduce the total transmitted power. Some losses that are encountered in literature associated with waveguide components are presented below.

A. Scattering Loss

1) Volume Scattering

Caused by imperfections such as contaminants and crystalline defects. This type of scattering is negligible when the volume imperfections are small comparing to wavelength.

2) Surface Scattering

Surface roughness causes optical loss when propagating waves interact with the waveguide. Surface roughness arises due to non-ideality of wet and dry etch of the material.

B. Absorption Loss

Absorption loss is negligibly small compared to scattering loss. Photons with energies greater than the bandgap energy of silicon are absorbed in the waveguide structure to raise electrons from the valence to conduction band.

C. *Radiation Loss*

Radiation loss occurs when optical energy is lost from the waveguide if photons emitted into the media surrounding the waveguide instead of being guided within the structure. Attenuation that happens due to this usually occurs in curved and angled structures like splitters and s-bends.

VII. Conclusion

Fundamental characteristics of Mach-Zehnder device and other optical structures were described. The Mach-Zehnder interferometer (MZI) is the basis of a wide variety of optical devices e.g. modulators, sensors and optical switches. Beam Prop simulations were used to make decisions about the selecting appropriate feature size for mask design. Using this information unbalanced Mach-Zehnder interferometers and other waveguide components were fabricated. Thinning of waveguides was discovered upon inspection using scanning electron microscopy. High transmission loss for features with such defect was expected. An alternative etching technique was suggested to produce devices with minimal undercutting. Silicon etch resistant masks were successfully manufactured. However, more dry etching process experiments were suggested to adapt this design of 1um wide silicon waveguide components and MZI to SMFL.

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