Design of a Mach-Zehnder Interferometer Using Silicon Photonic Waveguides

Ron Nelson

I. Introduction

In silicon photonics, Interferometers are important devices useful for transmitting light with an oscillatory dependence on wavelength. This property allows them to be used in multiplexers and demultiplexers for optical signaling purposes.

The objective of this project is to design a Mach-Zehnder Interferometer (MZI) with a 25 GHz Free Spectral Range (FSR) and high Extinction Ratio, operating near the 1310 nm wavelength. These terms, as well as other theory, design, manufacturing and testing will be described in this report. For the project, silicon photonic chips were manufactured and tested using two technologies: EBeam and SiEPICfab ZEP.

Commented [RN1]: Get better names later

II. The Mach-Zehnder Interferometer

The working concept of the MZI is splitting and recombining two light waves while applying a different phase shift to each path. When recombining, the relative phase of the waves determines whether they interfere constructively or destructively. In this project, the phase difference is generated by a difference in path length. Since the wavelength of the light depends on its frequency, the phase difference gained from a path length also depends on wavelength. This way, the device has an intensity transfer function that varies sinusoidally with input light frequency. The period of this sinusoidal transfer function is known as the Free Spectral Range and is given by the formula:

$$\Delta\nu = \frac{c}{\Delta L \cdot n_g}$$

Where $\Delta\nu$ is the FSR in units of frequency, ΔL is the path length difference, n_g is the group index of the waveguide mode, and c is the speed of light. After determining our waveguide's group index, we could calculate the path length difference required to generate the desired FSR. Another parameter of the MZI is the Extinction Ratio. This is the ratio between maximum and minimum output intensity for a given input intensity, usually expressed in decibels. With ideal, lossless components, the intensity transfer would vary from 1.0 when the two waves are in phase, to 0 when the waves are exactly out of phase. However, due to loss in the waveguides and other imperfections, the actual extinction ratio will be lower. In this project, one goal is to minimize the extinction ratio.

III. Modelling

The most critical parameter to design a well-tuned MZI is the waveguide's group index For this, the waveguides used were modeled in Lumerical MODE Solutions for each manufacturing technology. The waveguide's design width was fixed at 350 nm for compatibility with existing component designs, and the design height was fixed at 220 m by both manufacturing processes. In the EBeam process, the waveguides were cladded with silicon dioxide, and in the ZEP process, the substrate was also oxide, but the classing above and to the sides of the waveguides was air. The material indices used are shown below:

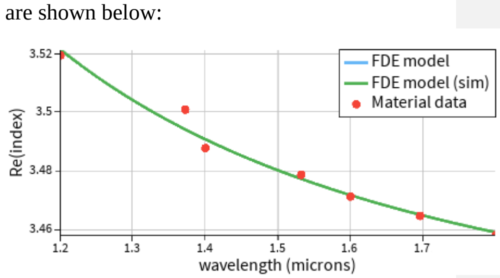

Figure 1: Material Index curve for Silicon

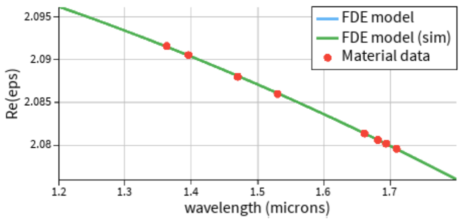

Figure 2: Material Index curve for SiO_2

To consider manufacturing variance and the -25 nm process bias of the EBeam technology, which makes all features 25 nm thinner than drawn, the following waveguide dimensions were simulated:

EBeam Technology				
w (nm)	h (nm)	λ (nm)	n_g	ΔL (mm)
335	220	1310	4.490943	2.670196
350	220	1310	4.443088	2.698956
345	230	1270	4.432688	2.705288
335	220	1270	4.467645	2.684121
335	220	1330	4.500646	2.664439

Table 1: Simulated waveguide dimensions for EBeam Technology

The calculated path length differences to achieve a 25 GHz FSR are also shown. Because parameter variations were not used in the ZEP process design, only one set of waveguide dimensions was simulated:

ZEP Technology				
w (nm)	h (nm)	λ (nm)	n_g	ΔL (mm)
350	220	1310	4.790139	2.503413

Table 2: Simulated waveguide dimensions for ZEP Technology

Simulation was also performed using Lumerical INTERCONNECT as a post-layout verification for the first variation of each manufactured design. As intended, the Free Spectral Range is simulated at approximately 25 GHz:

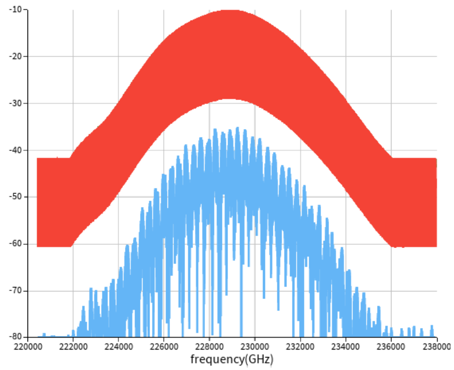

Figure 3: Transmission plot over wide frequency spectrum showing frequency response of grating coupler

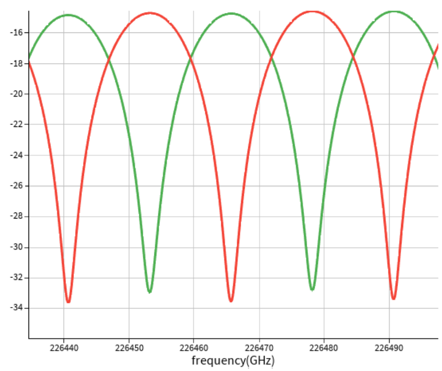

Figure 4: localized transmission plot showing 25 GHZ spacing on intensity transmission spectrum

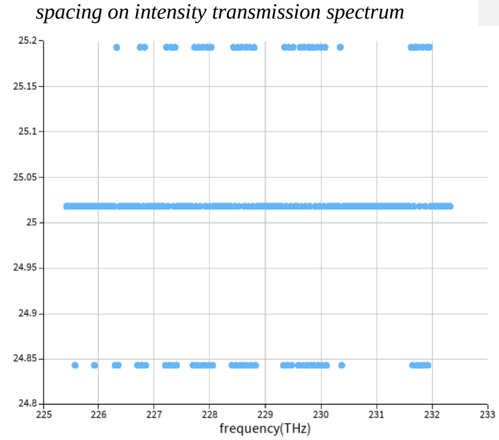

Figure 5: INTERCONNECT FSR plot showing calculated FSR near 25 GHz

IV. MASK LAYOUT

For the chip manufactured using the EBeam technology, a compact design was used, using the "spiral paperclip" component available in the SIEPIC EBeam Product Development Kit (PDK) to save space. In total, eight devices are on the chip with nearly identical designs: The path length difference is tuned by slightly varying the height of the spiral paperclip. Of the designs listed in Table 1, the first design, which designs for the "best guess" of the chip's properties, is repeated three times to assess the EBeam process' manufacturing variability. The other five designs represent a rough sweep over the predicted uncertainty in device performance. We hypothesize that this will increase the chance that at least one interferometer device will closely match the target 25 GHz FSR.

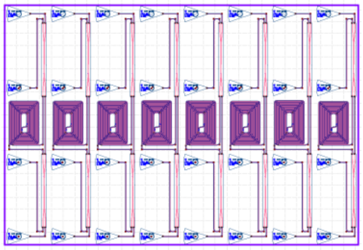

Figure 6: Mask layout of EBeam chip

For the chip manufactured using the ZEP process, fewer devices are included in the floorplan since only one device is able to use the on-chip laser, Still three copies of the device, without the input port for the on-chip laser, are included. Additionally, the ZEP design includes a "de-embedding structure" where a pair of grating couplers are directly connected together. This is to allow measuring the insertion loss, which can be subtracted from other measurements to isolate the performance of the other components.

Commented [RN2]: And opposite of insertion??

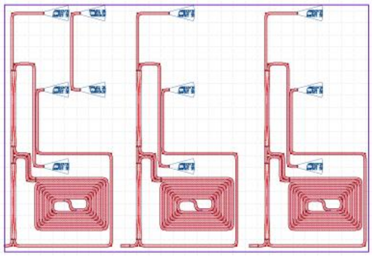

Figure 7: Mask layout of ZEP chip