Design proposal for Silicon Photonics, Fabrication and Data Analysis – Mach-Zehnder Interferometer

Dinka Milovančev, dinka.milovancev@ait.ac.at

I. Introduction

The Mach-Zehnder Interferometer (MZI) is an optical device in which input optical signal is split into two optical paths, after paths recombine the two optical waves interact at the output. The light intensity at the output is a measure of the relative phase shift among two optical paths. The common use cases of MZI are as an optical switch or high-speed modulator. The basic building blocks of an integrated MZI are input and output grating couplers for optical fiber coupling i.e. interfaces toward outside system, an optical splitter and combiner (usually Y-branches, but directional couplers or adiabatic couplers can also be used) and waveguides for guiding two split optical beams. In this work I am designing an MZI with two grating couplers, two Y-branches and two strip waveguides with varying lengths and same cross-section (220 nm x 500 nm).

II. Theory

In Fig. 1. we can see a simplified block schematic of MZI with light intensities I and optical fields E at points of interest. The depicted MZI is unbalanced i.e. there is optical path difference $\Delta L = L_1\text{-}L_2$.

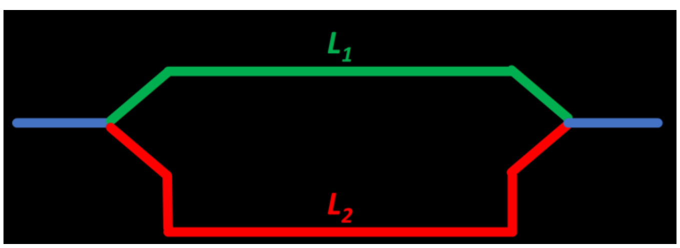

Fig. 1. Block diagram of Mach-Zehnder Interferometer.

The light split into two MZI arms, with lengths L_1 and L_2, is traveling with propagation constants:

$$\beta_{1/2} = \frac{2\pi n_{1/2}}{\lambda} \tag{1}$$

Where $n_{1/2}$ is effective index of refraction in each waveguide and λ is the operating wavelength. In this work we have the same geometry (width and heights) of the waveguides and the same material, so the effective index is same in both waveguides.

At the combiner Y-branch at the MZI output, the two electrical fields are:

$$E_{o1} = E_1 e^{-i\beta_1 L_1 - \frac{\alpha_1}{2}L_1} = \frac{E_i}{\sqrt{2}}\, e^{-i\beta_1 L_1 - \frac{\alpha_1}{2}L_1} \tag{2}$$

$$E_{o2} = E_2 e^{-i\beta_2 L_2 - \frac{\alpha_2}{2}L_2} = \frac{E_i}{\sqrt{2}}\, e^{-i\beta_2 L_2 - \frac{\alpha_2}{2}L_2} \tag{3}$$

Where $\alpha_{1/2}$ is propagation loss constant usually bellow 10 dB/cm. In further discussion we will consider an ideal lossless case for simplicity. The output of the MZI, in a lossless case, is:

$$E_o = \frac{1}{\sqrt{2}}(E_{o1} + E_{o2}) = \frac{E_i}{2}\,(e^{-i\beta_1 L_1} + e^{-i\beta_2 L_2}) \tag{4}$$

And output light intensity is:

$$I_o = \frac{I_i}{4}\left|e^{-i\beta_1 L_1} + e^{-i\beta_2 L_2}\right|^2 = \frac{I_i}{2}[1 + \cos(\beta_1 L_1 - \beta_2 L_2)] \tag{5}$$

In this work the waveguides are the same, so $\beta_1 = \beta_2 = \beta$ and path difference is $\Delta L = L_1\text{-}L_2$, so the expression (5) can be rewritten as:

$$I_o = \frac{I_i}{2}[1 + \cos(\beta \Delta L)] \tag{6}$$

Therefore, the unbalanced MZI transfer function T_{MZI} is:

$$T_{MZI} = \frac{1}{2}[1 + \cos(\beta \Delta L)] \tag{7}$$

Another important property od MZI is its free spectral range (FSR) which is the spacing between its maximum points in its T_{MZI}.

$$FSR = \frac{\lambda^2}{\Delta L n_g} \tag{8}$$

Where n_g is defined as group index which is a value larger than effective index, it determines the group velocity which ultimately limits the propagation speed of optical pulses. The group index is defined as:

$$n_g(\lambda) = n(\lambda) - \lambda \frac{dn}{d\lambda} \tag{9}$$

III. Modeling and Simulation

First simulations are done in Lumerical MODE using Eigenmodel Solver Analysis to investigate the quasi-TE mode confinement of 220 nm x 500 nm Si waveguide at 1550 nm wavelength. The waveguide effective index and group index dependence on wavelength were also simulated. Based on the simulated data compact waveguide model is obtained.

A. Lumerical MODE

From Figure 2. we can see that the TE-mode field is well confined and that there is no significant optical filed in TM mode inside waveguide (Fig. 3).

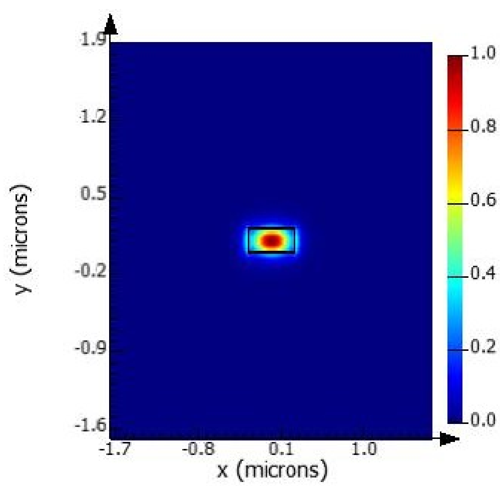

Fig. 2. TE-mode optical field intensity in Si waveguide.

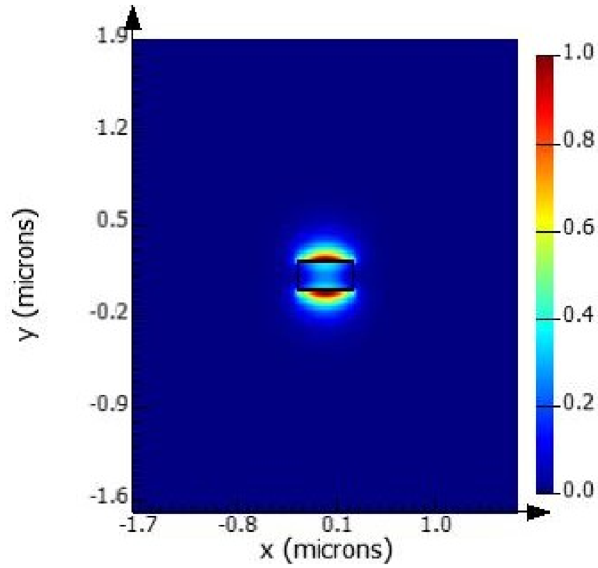

Fig. 3. . TE-mode optical field intensity in Si waveguide.

The effective index is decreasing with increasing wavelength (Fig. 4) while the group index is decreasing with wavelength, see Fig 5.

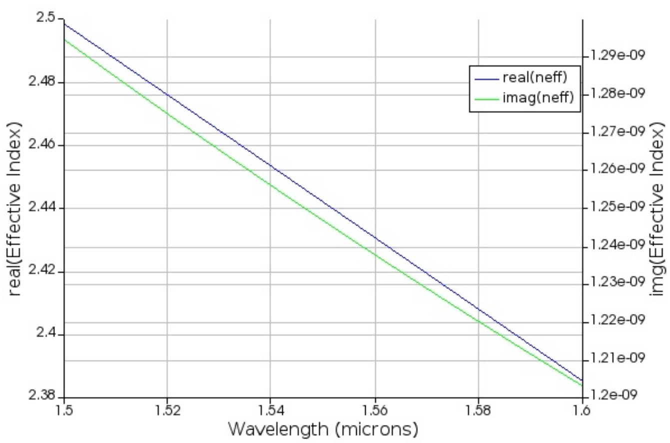

Fig. 4. . Effective index vs. wavelength.

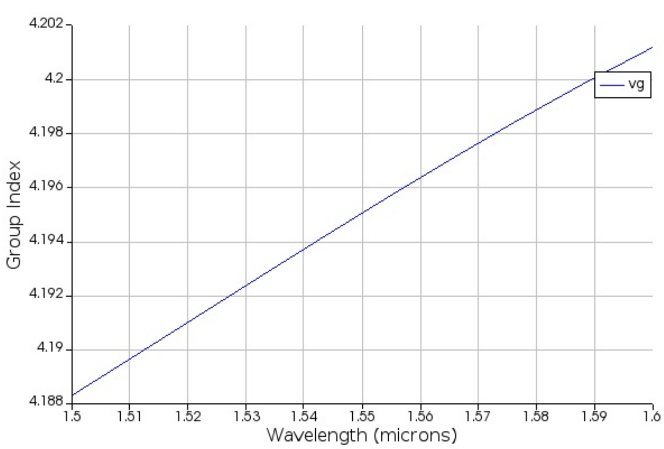

Fig. 5. . Group index vs. wavelength.

Based on the simulated parameters the compact model of a waveguide i.e. its effective index n_{eff} dependence on wavelength can be found as second order polynomial:

$$n_{eff}(\lambda) = 2.44 - 1.13(\lambda - 1.55) - 0.04(\lambda - 1.55)^2 \quad (9)$$

where 1.55 μm is the operating wavelength.

B. *Lumerical INTERCONNECT*

The simulations of MZI were performed with Lumerical INTERCONNECT, where the EBeam libraries were used with models of grating couplers, Y-branches and strip waveguides. The insertion loss of the grating couplers is shown in Fig. 6 with waveguide length between them of 127 μm which is the pitch needed for automated measurements. This insertion loss shapes the transmission of the MZI. The path difference ΔL in MZI arms was varied from 30 μm up to 120 μm with steps of 30 μm. Table 1 shows the dependence of FSR on ΔL, as ΔL becomes larger FSR is smaller. Figure 7. shows the transmission of MZI for ΔL=30 μm, and Fig. 8 shows the gain.

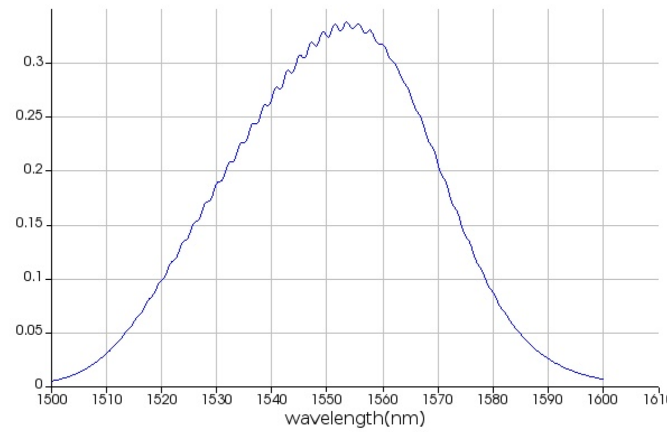

Fig. 6. . Grating coupler transmission.

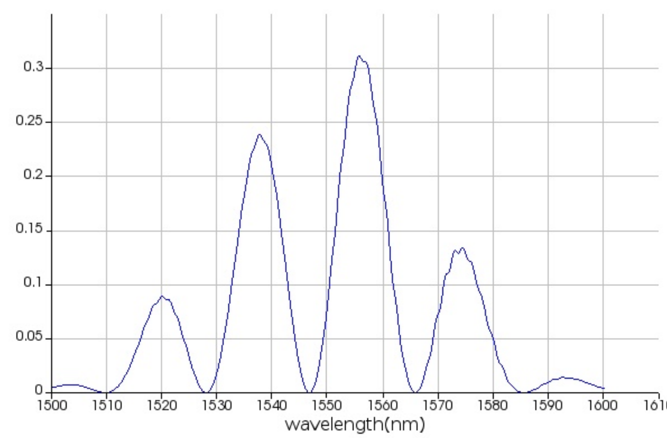

Fig. 7. . MZI transmission for ΔL=30 μm.

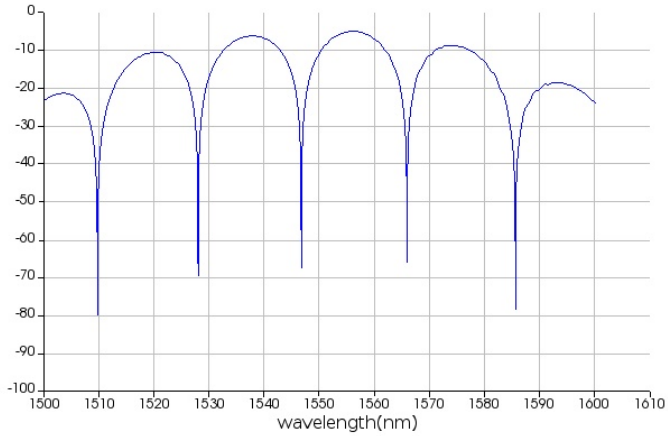

Fig. 8. . MZI gain for ΔL=30 µm.

TABLE I
FSR VS. PATH DIFFERENCE ΔL

ΔL [µm]	Free Spectral Range FSR [nm]
30	18
60	9.2
90	6.4
120	4.8

C. KLAYOUT design

The submitted layout is show in Fig. 9, for each ΔL two MZI circuit are made to see the process variability and two grating couplers are also added to see their insertion loss for different waveguide lengths.

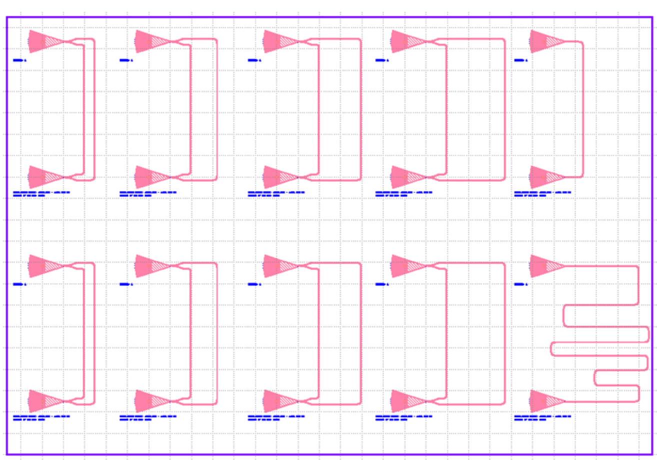

Fig. 9. . Layout of different MZI structures and test structures of grating couplers