Silicon Photonics Design, Fabrication and Data Analysis edX Course Report

Fedor Goncharov

edX name: feddd0r

Abstract: This is not my final report. Lot's of content still not here. I will provide it later. I was mostly focused on the layout submission for fabrication.

1. Introduction

Photonic integrated circuits (PICs) are the promising approach for many applications including optical communications, computation, sensing, and so on. PICs allow to design scalable, stable, small and ready to mass production solutions. Silicon photonics is one of the technologies commonly used for PICs implementations. It benefits from CMOS capability, which means that it is possible to fabricate such photonic chips using the same equipment as for electronics.

The project objective is to go through all design steps from idea to fabrication, including experimental data analysis. Namely, the focus of the project is Mach Zehnder interferometer (MZI). MZI is a basic block for a lot of applications, such as optical switchers, filters, optical processors for neuromorphic neural networks, and many others.

In the project the standard waveguide cross section for Silicon on Insulator (SOI) of 500x220 nm and quasi-TE mode is chosen for work.

2. Theory

2.1. Waveguides

Waveguide is an optical pipe which guides light. The refractive index contrast is required for light guide: the core refractive index has to be higher than the cladding's index. Light propagates through the waveguide as modes. A mode is a stationary field profile of a traveling wave and it is obtained as a wave equation solution for a particular waveguide geometry. Waveguides may be single- or multi-mode. The plane wave in a waveguide is given as follows:

$$E = E_0 e^{i(\omega t - \beta z)}$$

with propagation constant β:

$$\beta = \frac{2\pi n_{\text{eff}}}{\lambda},$$

where n_{eff} is an effective index and λ is a wavelength. Besides effective index describing the phase velocity $v_p = c/n_{\text{eff}}$, the group index is needed for describing a group velocity ($v_g = c/n_g$):

$$n_g = n_{\text{eff}} - \lambda \frac{dn}{d\lambda}$$

Group velocity describes the propagation of the whole pulse consisting of multiple wavelengths.

Polarization also plays a role in a waveguide. Two polarization modes are distinguished in a waveguide:

- The transverse electrical (TE) mode with electrical field transverse to the direction of propagation and parallel to to the waver surface;

- The transverse magnetic (TM) polarization with magnetic field being parallel to the wafer surface.

A waveguide cross-section geometry is very important since it determines an effective and group index. Usually, it is preferred to work with a single mode. In a slab waveguide, the effective index dependence on thickness is provided in Figure 1(a). The 220 nm thickness is a standard for many fabrications. Then the width is chosen for maximizing an effective index while holding the single-mode regime. Higher effective index means that more field is focused in the middle of a waveguide. Thus, for TE-mode the 500 nm is a common width (Figure 1(b)).

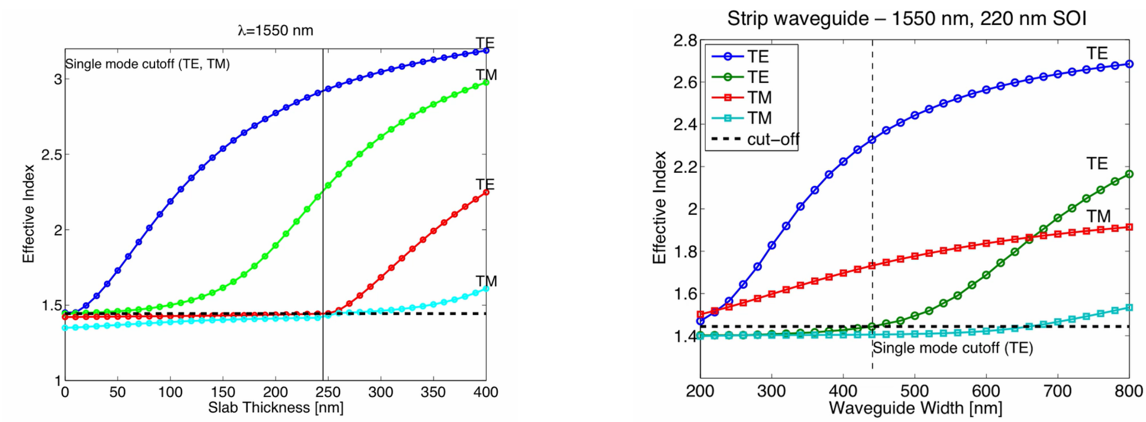

Fig. 1. Effective index dependence on (a) thickness, (b) width

Since core and cladding materials are dispersive media, the effective index is wavelength-dependent. Basically, the effective index can be described in the compact model as a Taylor expansion around the central wavelength, λ_0:

$$n_{eff} = n_1 + n_2(\lambda - \lambda_0) + n_3(\lambda - \lambda_0)^2,$$

where n_1, n_2, n_3, λ_0 are the parameters for the waveguide compact model.

The propagation constant with losses is given as

$$\beta(\lambda) = \frac{2\pi n_{eff}(\lambda)}{\lambda[\mu m]} + i\frac{\alpha_{\mu m^{-1}}}{2},$$

where $\alpha_{\mu m^{-1}}$ is the propagation loss per one micrometer, and could be converted from a commonly used $\alpha_{dB/cm}$ as:

$$\alpha_{\mu m^{-1}} = \frac{\alpha_{dB/cm}}{4.34} \cdot 10^{-4}$$

2.2. Waveguide Y-branch

Y-Branch splits one waveguide into two waveguides (a splitter) or vise versa (a combiner). In the case of splitter, a light input field E_{in} splits equally for two outputs with the fields of $E_{out1} = E_{out2} = E_{in}/\sqrt{2}$. For the combiner case, the out power a sum of two inputs divided by square root of two:

$$E_{out} = \frac{E_{in1} + E_{in2}}{\sqrt{2}}$$

The $1/\sqrt{2}$ factor appears due to the existence of at least one more mode except mode in the output waveguide.

2.3. Waveguide bends

The light propagating through the bend is pushed out to the side. Thus, two additional loss mechanisms appear: mode-mismatch and radiational losses. The first one occurs after the bend, since some of the light goes to the higher-order modes. The second one is due to the shifting of light to the border of the waveguide and scattering on its roughness. For a SOI platform, a radius from 5 to 10 microns is sufficient for negligible losses.

2.4. Mach-Zehnder Interferometer

A Mach-Zehnder interferometer (MZI) consists of one splitter, two waveguides, and one combiner. If we consider Y-branch as splitter and combiner, the output intensity of the MZI (for the lossless case) will be:

$$I_{out} = \frac{I_{in}}{2}(1 + cos(\beta_1 L_1 - \beta_2 L_2)),$$

where I_{in} is an input intensity, β_1 and β_2 are propagation constants of both arms the waveguides, and L_1, L_2 are their lengths. If $L_1 = L_2$, the MZI is balanced; if $L_1 \neq L_2$, the MZI is unbalanced.

Generally, the MZI spectrum has a sinusoidal dependence on wavelength. The wavelength distance between two neighbor is given by free spectral range (FSR). If the arms waveguides are identical (i.e. $\beta_1 = \beta_2$), FSR is given by:

$$\text{FSR} = \frac{\lambda^2}{\Delta L n_g}[nm]$$

For an imbalanced MZI with identical waveguides, the transmission is given by

$$T_{\text{MZI}} = \frac{1}{4}|1 + e^{-i\beta(\lambda)\Delta L}|^2$$

3. Modeling

3.1. Waveguide cross-section modeling

First, we start with cross-section analysis. The geometry of the cross section is provided in Figure 2. Then, we need to ensure that the simulation area is enough and that the boundaries do not influence

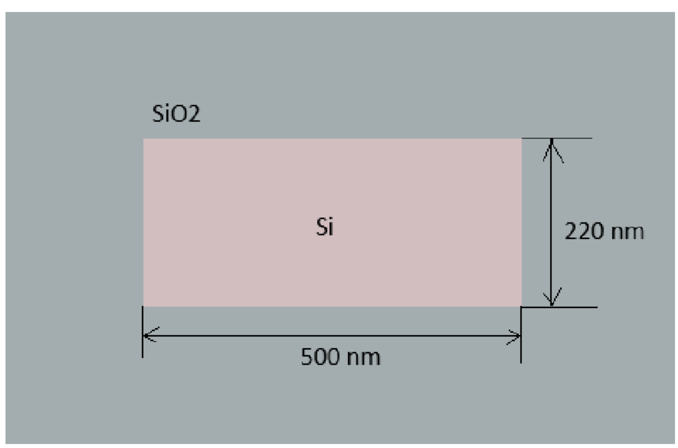

Fig. 2. Cross section geometry of the waveguide

the result. For this purpose, the E-field distribution is estimated on a logarithmic scale, as shown in Figure 3(a). It can be seen that the field is almost decayed in the boundaries. The mesh is small enough: 10 nm for both axes. Besides, it matches the boundaries of the waveguide. Finally, the fundamental TE-mode field distribution for a wavelength of 1550 nm is obtained and shown in Figure 3(b).

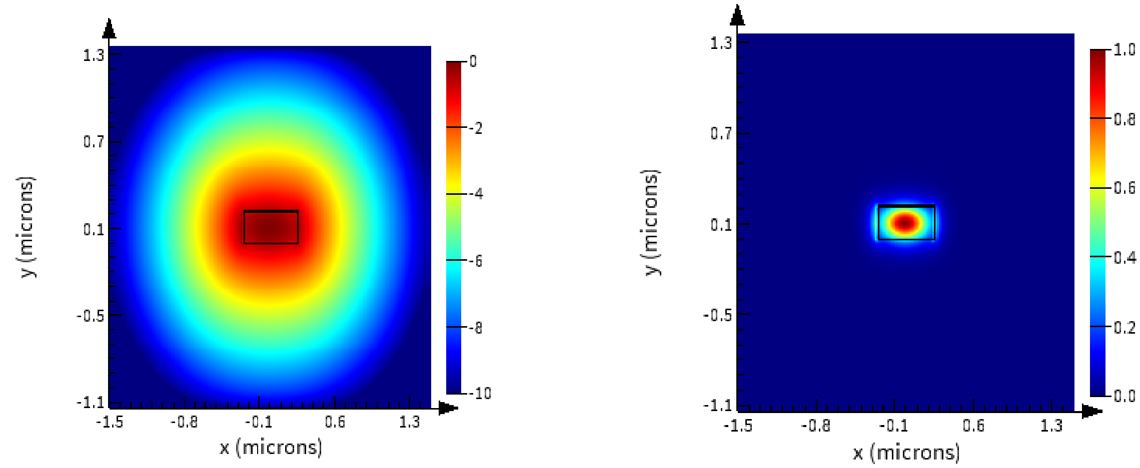

Fig. 3. (a) Field profile in the log scale for boundary influence analysis, (b) Fundamental TE-mode field distribution

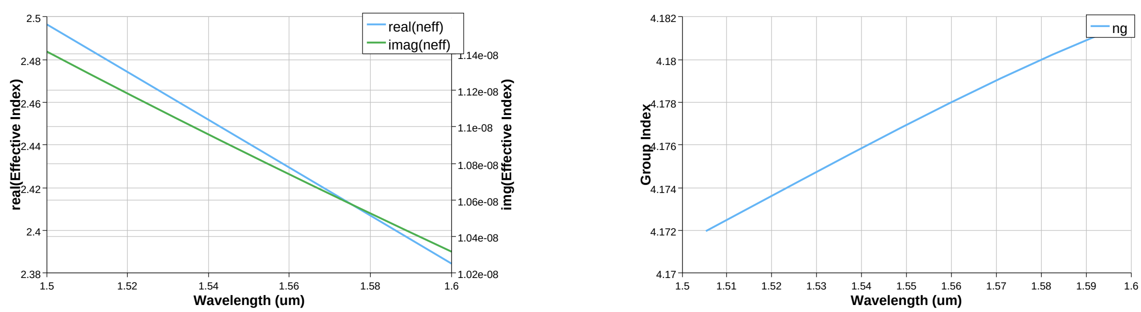

Fig. 4. Effective and group index wavelength dependence

Then, the effective and group indices are calculated (Figure 4).
Finally, the compact waveguide model was obtained.

$$n_{\text{eff}} = 2.44682 - 1.3339 * (\lambda - 1.55) - 0.0439366 * (\lambda - 1.55)^2$$

3.2. Y-branch and fibre grating coupler modeling

For the MZI design the y-branch splitter/combiner and fibre grating couplers are needed. In this course the SiEPIC-EBeam-PDK is used with already prepared element models. Thus, it is possible to simulate their behavior in the circuit level, in the Lumerical INTERCONNECT.

Firstly, it is desired to measure spectrum of fibre grating couplers for entering and escaping radiation into and out of the chip (Figure 5).

Secondly, the y-brach outputs are measured (Figure 6)

3.3. MZI modeling

For MZI design, the aim is to obtain values of ΔL in the way to transmit the central wavelength with almost no loss and investigate the FSR dependence on arm length difference ΔL. Consequently, we need to solve the equation:

$$T_{\text{MZI}}(1.55[\mu m]) = 1 = \frac{1}{4}|1 + e^{-i\beta(1.55[\mu m])\Delta L}|^2$$

This equation has multiple solutions. Some of them were chosen, and spectra were plotted for them. The circuit for measurement is based on basic y-branch models and does not take into account

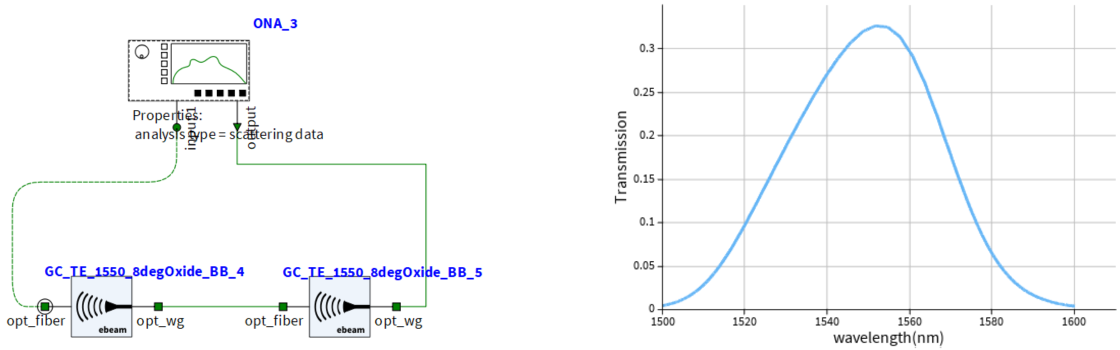

Fig. 5. (a) Scheme for measurement, (b) Transmission spectrum of two grating couplers

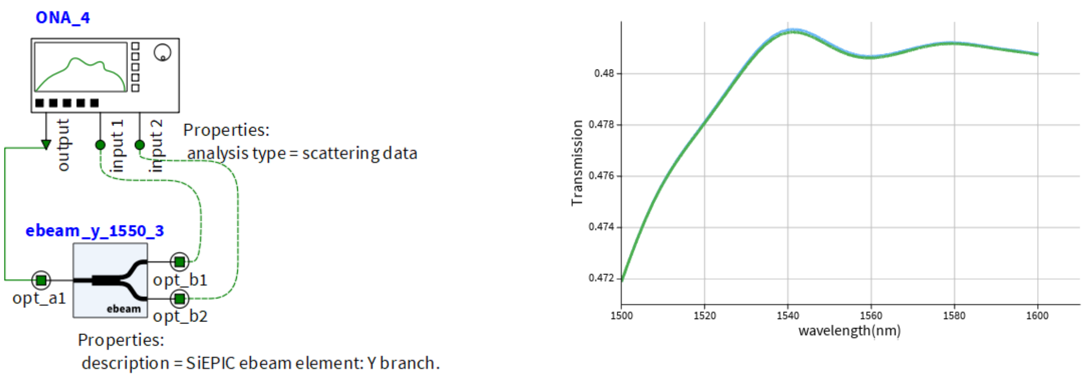

Fig. 6. (a) Scheme for measurement, (b) Transmission spectra of different outputs of Y-branch

grating couplers (Figure 7(a)). Waveguides parameters are calculated from waveguide compact model. The spectra are shown at Figure 7(b).

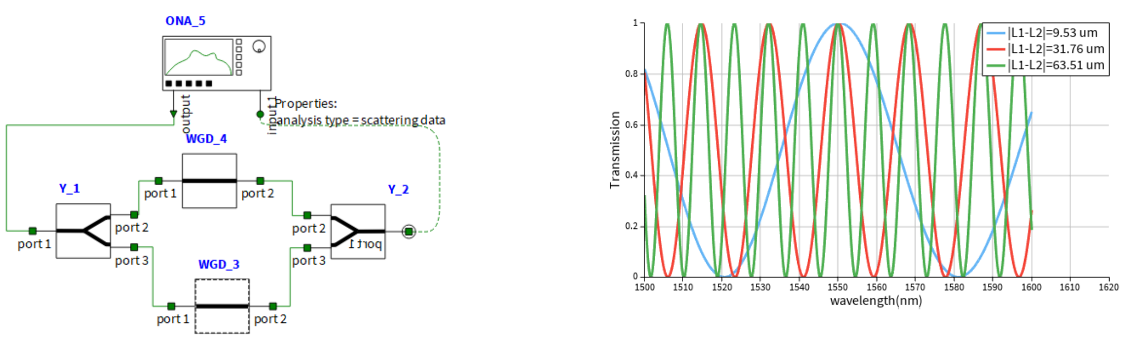

Fig. 7. (a) Scheme for measurement, (b) Transmission spectra of MZI model based on standard models

References