Report: Silicon Photonics Design, Fabrication and Data Analysis

Matthias Bittner (MatEdX51), *Course participant*

***Abstract*—The Mach-Zehnder interferometer or MZI is a measurement device to determine the relative phase shift between two light beams derived from a single light source. Further usecases for a Mach-Zehnder interferometer are high speed switching applications, electro-optical modulators, optical filters or as well as sensing applications.**

***Index Terms*—waveguide geometry, mode profile, effective and group index, compact model, transfer function, parameter variation, transmission spectra, free spectral range**

I. INTRODUCTION

THIS report gives insight into the theoretical background of silicon-on-insulator waveguides, the transmission spectra of Mach-Zehnder interferometers (MZI) and on how these theoretical assumptions match with self-designed and actual manufactured MZI. The data containing actual transmission spectra which can be used to determine the free spectral range (FSR) and the group index (n_g) of the waveguides. So, this course provides a complete design, manufacturing and analysis cycle of a photonic integrated circuit (PIC) on a silicon-on-insulator basis.

II. THEORY

In this report the software Ansys Lumerical Mode was used to determine the transmission spectra of the Mach-Zehnder interferometers as well as the effective index and group index estimations.

A. Compact model of the waveguide

From reasons of simplicity in this course a standard waveguide size is used. That means the height is set to 220 nm and the width is set to 500 nm. The used central wavelength in the models is 1550 nm of wavelength.

To get the compact model (polynomial expression) of the waveguide used in the MZI model it is needed to use a Finite Difference Eigenmode Solver (FDE). The equation (taylor expansion) of this model is stated below (see course material).

$$n_{eff}(\lambda) = n_1 + n_2(\lambda - \lambda_0) + n_3(\lambda - \lambda_0)^2 \quad (1)$$

In Fig. 1 one will find the energy density plot of the fundamental TE mode provided by the waveguide. A subsequent frequency analysis of the waveguide leads to a determination of the effective index (n_{eff}) and group index (n_g) versus wavelength (λ) as shown in Fig. 2.

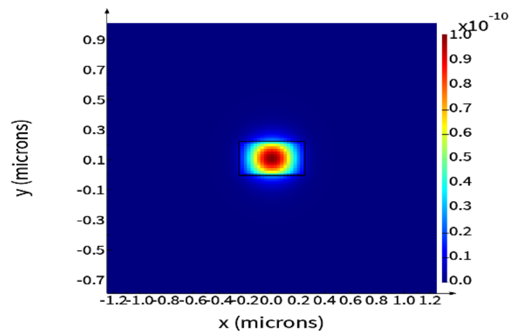

Fig. 1. Fundamental TE mode (energy density) provided by the stated waveguide in Section II

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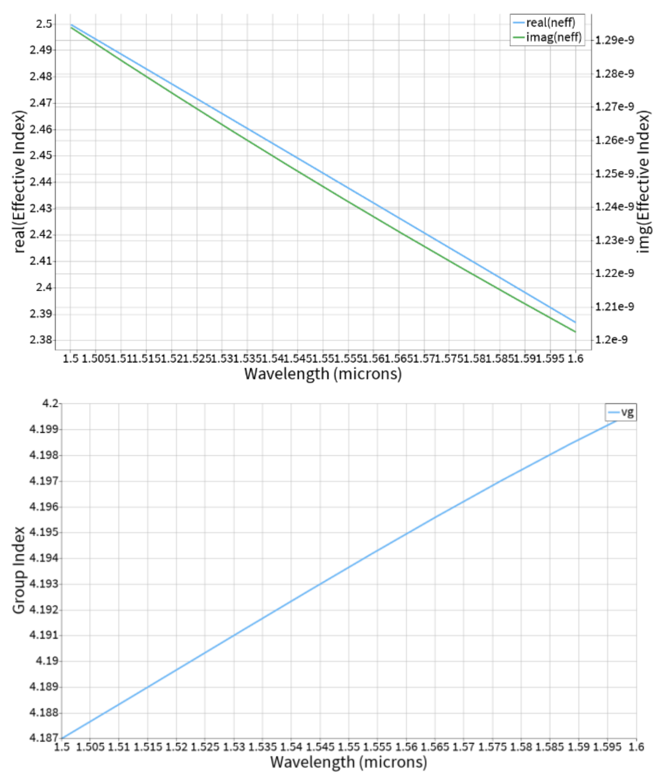

Fig. 2. Effective index versus wavelength (top) and group index versus wavelength (bottom)

LUMERICAL MODE provides a Script Prompt which is used to determine the polynomial coefficients of the compact model (see Table 1). The script for a polynomial model fit was provided by the lecture.

TABLE I
PARAMETERS OF THE COMPACT MODEL
(FUNDAMENTAL TE MODE)

Parameter	Value
λ_0	1550 nm
n_1	2.44
n_2	-1.13
n_3	-0.04

B. Transfer function of MZI and free spectral range (FSR)

For the simple case of an imbalanced Mach-Zehnder interferometer for identical waveguides the course lecture gives the following expression as optical transfer function (no propagation loss assumed, propagation constants β assumed to be constant for both waveguides in interferometer arms):

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

Hereby ΔL is the path length difference between the two arms of the Mach-Zehnder interferometer, I_i is the incident light power, I_o the output power and β is the waveguide propagation constant.
In the lecture the derivation of the free spectral range for the given interferometer type was shown. The conclusion is described in the formula below.

$$FSR = \Delta\lambda = \frac{\lambda^2}{\Delta L\left(n - \frac{\lambda dn}{d\lambda}\right)} = \frac{\lambda^2}{\Delta L(n_g)}(3)$$

C. Simulated gain (transmission) spectra for manufactured devices

In Table II the planned design variations are shown. In Fig. 3 the photonic circuit and the gain (transmission) spectra of design 1 and 7. SPAR_3 and SPAR_4 are the TE grating couplers (S parameters provided by lecture). SPAR_1 and SPAR_2 are the Y-branches. WGD_1 and WGD_2 are the waveguide models derived from previous LUMERICAL frequency analysis and ONA_1 the optical network analyzer.

TABLE II
DESIGN VARIATIONS

Design #	Polarization	ΔL /µm	Circuit type	Splitter type	WG width / nm
MZI 1	TE	50	Mach-Zehnder	Y-branch	500
MZI 2	TE	100	Mach-Zehnder	Y-branch	500
MZI 3	TE	100	Mach-Zehnder	Y-branch	500
MZI 4	TM	100	Mach-Zehnder	Y-branch	500
MZI 5	TE	150	Mach-Zehnder	Y-branch	500
MZI 6	TE	200	Mach-Zehnder	Y-branch	500
MZI 7	TE	250.104	Mach-Zehnder	Y-branch	500
MZI 8	TE	99.79	Mach-Zehnder	Broadband	500
MZI 9	TE	100	Michelson	Broadband	500
D 10	TE	----	Loss estimate (GC)	----	500
D 11	TE	----	Y-branch test	Y-branch	500

TABLE III
FSR SIMULATIONS FOR DIFFERENT DESIGN

Design #	Simulated FSR / nm
MZI 1	11.1
MZI 2	5.47
MZI 3	5.47
MZI 4	~6.4
MZI 5	~3.8
MZI 6	~2.8
MZI 7	~2.3
MZI 8	~5.9
MZI 9	~5.8
D 10	---
D 11	---

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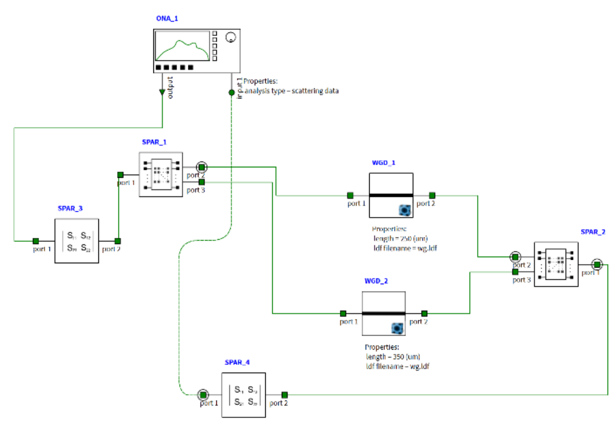

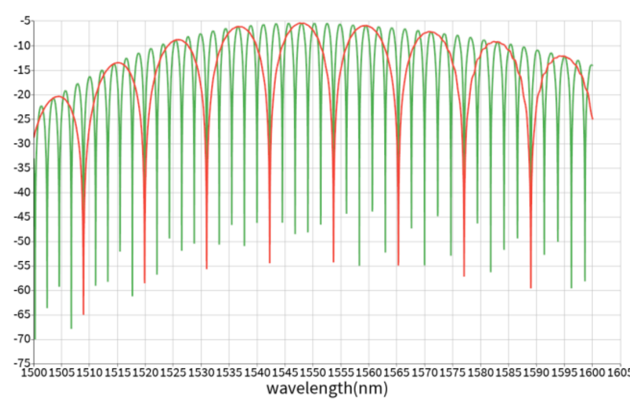

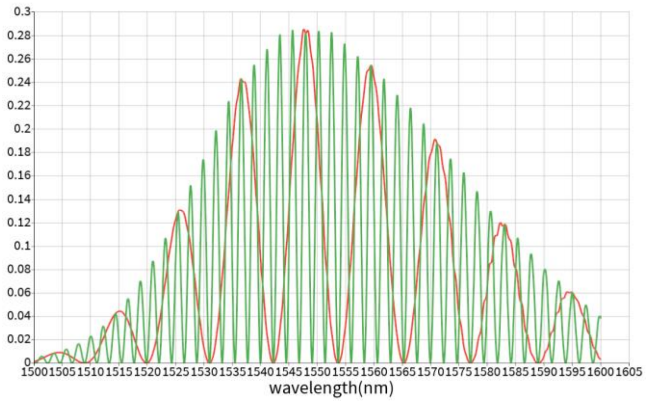

Fig. 3 Gain spectrum in dB (center) and transmission spectrum (bottom) of the MZI circuit (top) versus wavelength. The green curve is related to design 7 (MZI 7) and the red curve to design 1 (MZI 1) respectively.

The group index can be derived by rearrangement of the equation of the FSR for an unbalanced interferometer (see above). One could obtain from Fig. 3 that with increased path length difference ΔL the number of peaks in the spectrum will increase.

III. MANUFACTURING

A. Fabrication of waveguide structures at Applied Nanotools Inc.

The following text was copied from the course:
“The photonic devices were fabricated using the NanoSOI MPW fabrication process by Applied Nanotools Inc. (http://www.appliednt.com/nanosoi; Edmonton, Canada) which is based on direct-write 100 keV electron beam lithography technology. Silicon-on-insulator wafers of 200 mm diameter, 220 nm device thickness and 2 µm buffer oxide thickness are used as the base material for the fabrication. The wafer was pre-diced into square substrates with dimensions of 25x25 mm, and lines were scribed into the substrate backsides to facilitate easy separation into smaller chips once fabrication was complete. After an initial wafer clean using piranha solution (3:1 H_2SO_4:H_2O_2) for 15 minutes and water/IPA rinse, hydrogen silsesquioxane (HSQ) resist was spin-coated onto the substrate and heated to evaporate the solvent. The photonic devices were patterned using a JEOL JBX-8100FS electron beam instrument at The University of British Columbia. The exposure dosage of the design was corrected for proximity effects that result from the backscatter of electrons from exposure of nearby features. Shape writing order was optimized for efficient patterning and minimal beam drift. After the e-beam exposure and subsequent development with a tetramethylammonium sulfate (TMAH) solution, the devices were inspected optically for residues and/or defects. The chips were then mounted on a 4” handle wafer and underwent an anisotropic ICP-RIE etch process using chlorine after qualification of the etch rate. The resist was removed from the surface of the devices using a 10:1 buffer oxide wet etch, and the devices were inspected using a scanning electron microscope (SEM) to verify patterning and etch quality. A 2.2 µm oxide cladding was deposited using a plasma-enhanced chemical vapour deposition (PECVD) process based on tetraethyl orthosilicate (TEOS) at 300ºC. Reflectrometry measurements were performed throughout the process to verify the device layer, buffer oxide and cladding thicknesses before delivery.”

B. Manufacturing variability and corner analysis

Process variations in manufacturing can cause changes in waveguide thickness and width, and the waveguide shape may also deviate somewhat from an ideal square form. Also, these parameters in principle could change from chip to chip on the same wafer and from wafer to wafer as well. For the corner analysis in this report the following assumptions (see Fig. 4) were made:

corners (height / width):

223.1/470	223.1/500	223.1/510
	220/500	
215.3/470	215.3/500	215.3/510

group index (LUMERICAL Mode)

4.257218	4.198195	4.182782
	4.193659	
4.246376	4.189106	4.173782

Fig. 4 Top: corners identified based on deviations in height and width. Bottom: simulated group index for the fundamental TE mode, geometrically related to the defined corners. Considering these assumptions, the group index for the TE mode with a 220 nm x 500 nm waveguide should range from 4.174 to 4.257.

IV. ANALYSIS

A. Measurement of devices

The following text was copied from the course materials: “To characterize the devices, a custom-built automated test setup [2, 6] with automated control software written in Python was used [3]. An Agilent 81600B tunable laser was used as the input source and Agilent 81635A optical power sensors as the output detectors. The wavelength was swept from 1500 to 1600 nm in 10 pm steps. A polarization maintaining (PM) fibre was used to maintain the polarization state of the light, to couple the TE polarization into the grating couplers [4]. A 90º rotation was used to inject light into the TM grating couplers [4]. A polarization maintaining fibre array was used to couple light in/out of the chip [5].”

B. Experimental results and discussion

In this section the performance of the manufactured Mach-Zehnder interferometers (MZI1 to MZI7) is analyzed. This means in detail the determination of the free spectral range and the group index respectively. The evaluation of MZI2 ($\Delta L = 100.102\ \mu m$) is described in more detail (see Fig. 5).

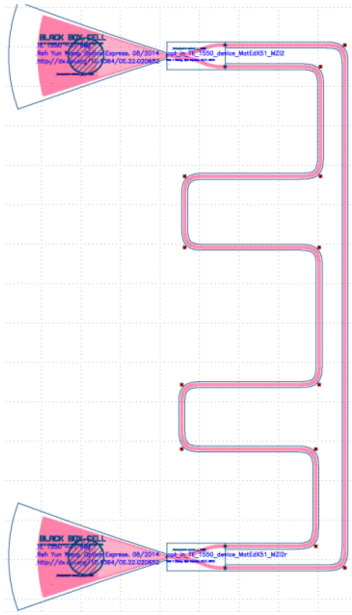

Fig. 5 MZI2 (geometrical appearance in KLayout)

The analysis contains at first the determination of the transmission spectra of the loop back calibration structure D10 (see Fig. 6).

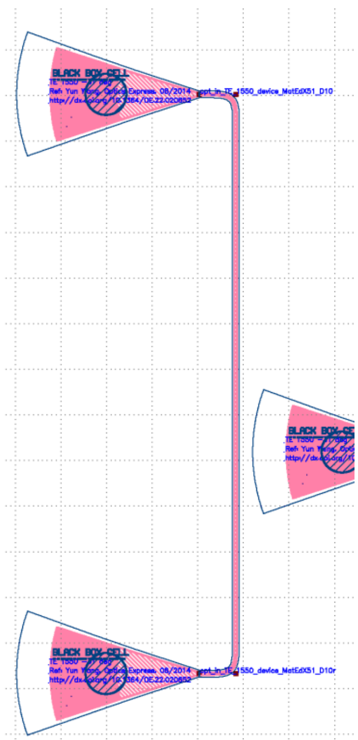

Fig. 6 calibration loopback D10 (geometrical appearance in KLayout)

The spectrum is fitted to a polynomial curve (refer to Fig. 7) within a wavelength range where the maximum permissible loss is approximately -10 dB, thereby excluding noisy regions of the spectrum. The calculated insertion loss is subsequently subtracted from the transmission spectrum obtained from MZI2 to produce a baseline-corrected spectrum (see Fig. 8). Thereafter, the MZI is fitted (see Fig. 9) to a more accurate model of the gain spectrum as specified below in Formula (4).

$$(4)\; F(\lambda) = 10 \cdot log_{10}\left(\frac{1}{4}\left|1 + exp\left[-i\frac{2\pi n_{eff}}{\lambda}\Delta L - \frac{\alpha\Delta L}{2}\right]\right|^2\right) + b$$

The parameter b is the excess insertion loss [dB], ΔL the waveguide length mismatch, α the waveguide loss and n_{eff} the effective index.

The measured group index for MZI2 is 4.189 (FSR = 5.72 nm), which closely matches the simulated group index of 4.193 corresponding to the nominal waveguide dimensions of 220 nm × 500 nm (see Fig. 4).

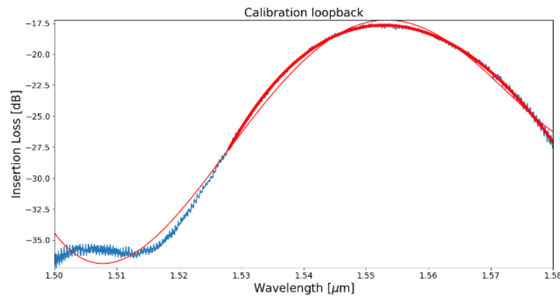

Fig. 7 Calibration loopback insertion loss: Use only the wavelength range (thick red line) where noise is negligible.

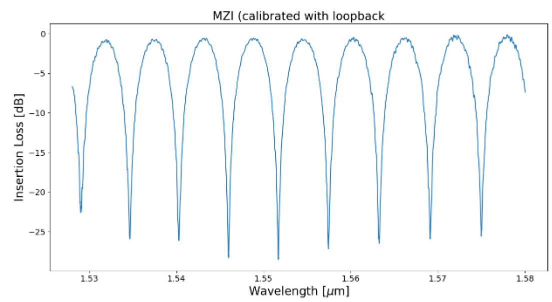

Fig. 8 Calibrated transmission spectrum of MZI 2

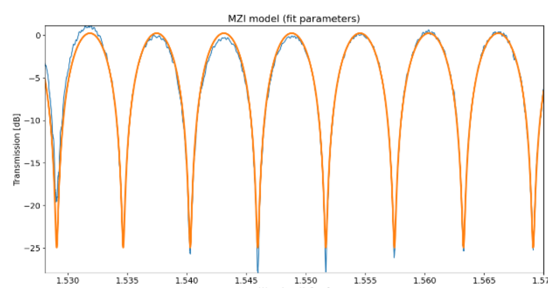

Fig. 9 MZI model fit and final extraction of FSR and group index n_g

For some further Mach-Zehnder interferometers (with different ΔL) Table 3 provides additional experimental estimations for the group index n_g and a comparison to the simulated values.

TABLE III
DESIGN VARIATIONS FOR MACH-ZEHNDER INTERFEROMETERS

Design #	Simulated FSR / nm	Simulated n_g	Measured FSR /nm	Measured n_g
1	11.1	4.194	11.45	4.179
2	5.47	4.194	5.72	4.189
3	5.47	4.194	5.71	4.188
4	~6.4	3.7205	6.43	3.73
5	~3.8	4.194	3.81	4.187
6	~2.8	4.194	2.86	4.183
7	~2.3	4.194	2.29	4.182

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