Report on Design, Fabrication and Analysis of Mach-Zehnder Interferometers in SOI Photonics

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Abstract

This work presents the design and simulation of a silicon-on-insulator (SOI) Mach-Zehnder Interferometer (MZI), targeting fabrication compatibility. Transmission spectra were simulated for MZIs with varying path length differences, and key parameters such as Free Spectral Range (FSR) and group index were extracted. These results were compared with analytical measurements from fabricated devices to validate the design. Group index estimation errors were found to be less than 0.001% and 1% for TE modes at 1550 nm.

Introduction

The silicon-based Mach-Zehnder Interferometer (MZI) is a fundamental building block in silicon photonic integrated circuits, widely used in applications such as optical switching, routing, and modulation. This research investigates MZI of various configurations to evaluate their performance and suitability for practical implementation [2] [3]. The fundamental quasi-TE mode is analyzed for different arm lengths using a standard silicon waveguide with a cross-sectional dimension of 500×220 nm^2. The simulations are then extended to include variations in waveguide geometry, along with a corner analysis to assess fabrication-related impacts. By examining the influence of path length differences and design variations, this study aims to identify the most efficient MZI structure for the intended application.

Modelling & Simulation

The waveguide designed here is the buried channel waveguide consists of silicon dioxide as the BOX and upper cladding and Si, as the waveguide material on the SOI wafer. The waveguide has rectangular geometry 220 nm x 500 nm (HxW).A waveguide width of 500 nm was chosen based on two key considerations: first, this width-height combination allows the waveguide to operate near the single-mode cutoff region; second, experimental S-matrix data for the grating coupler and Y-branch components is readily available for this specific width as part of the course resources.
A modal analysis was carried out using Lumerical MODE for the specified waveguide geometry at a wavelength of 1550 nm. The supported guided modes and their corresponding effective indices for this specific geometry in the waveguide is summarized in table 1 Simulations were performed for both the fundamental TE and TM modes, with their respective mode profiles illustrated in the accompanying figures 1. The waveguide boundaries are indicated by a solid black outline in each profile. Following this, a wavelength sweep was conducted over the range of 1500 nm to 1600 nm.

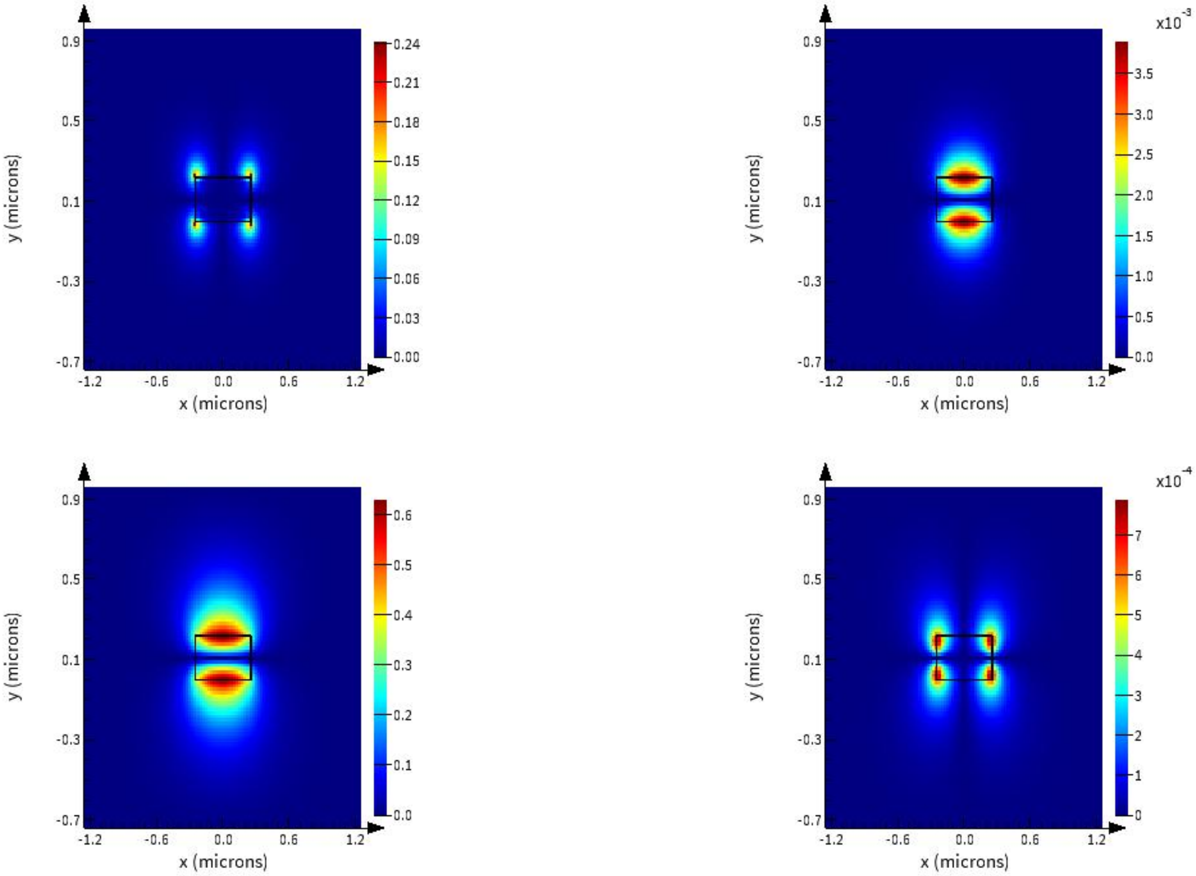


Figure 1: Effective index of waveguide simulated using FDE Solver for different modes is listed in Table 1

Mode	Effective Index
TE Fundamental	2.503
TM Fundamental	1.84
TE1	1.53

MZI Modeling and Analysis

The Mach-Zehnder Interferometer (MZI) model was developed using Lumerical INTERCONNECTM and the schematics of the steup is shown in the figure 2. Grating couplers were placed at the input and output ports to facilitate light coupling. The unbalanced MZI comprises two Y-branches (serving as a splitter and combiner) connected by two waveguide arms—an upper and a lower branch. In this study, interference at the output is achieved solely through the length difference between these two branches. Consequently, both waveguides share identical cross-sectional geometry and material properties. Figure 10 illustrates the schematic used for modeling. The waveguide components ("Upper-Path" and "Lower-Path") were defined using data obtained from the earlier modal analysis, while the grating couplers ("Grating-Coupler-Input" and "Grating-Coupler-Output") and Y-branches ("Y-

Branch-Splitter" and "Y-Branch-Combiner") were modeled using S-parameter data available from the course's device library.

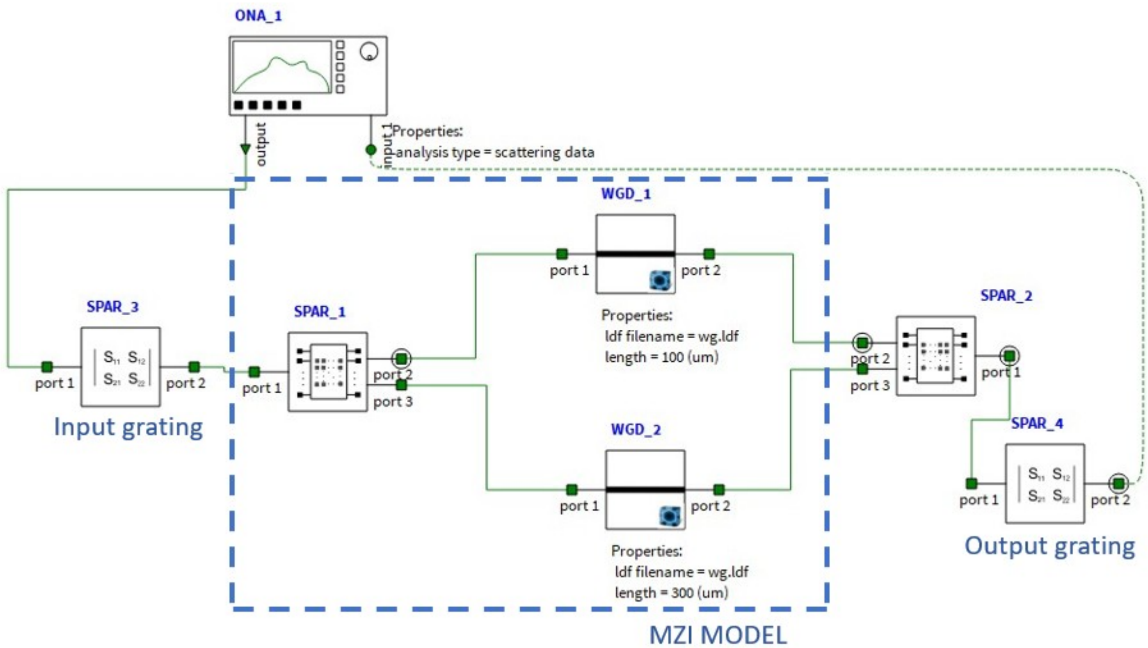


Figure 2: MZI model implemented in the INTERCONNECT software. ONA: optical network analyzer

The transfer function of the MZI of different path length difference was simulated in the Lumerical Interconnect software and is shown in the figure 3.

Layout

The next step is to fabricate these MZI devices. The MZI design proposal with different path length differences was developed in the KLayout software. The final layout for six different MZIs is shown in figure 4. The path length of MZIs varies from 0µm to 200µm.

Fabrication

At the Washington Nanofabrication Facility at the University of Washington, electron beam lithography (EBL) was used to build passive silicon photonics prototypes. The following are the fabrication steps:

- Spin coating a negative photo-resistive material on SOI wafer
- The wafer is exposed for the EBL
- Development process using TMAH, followed by rinsing

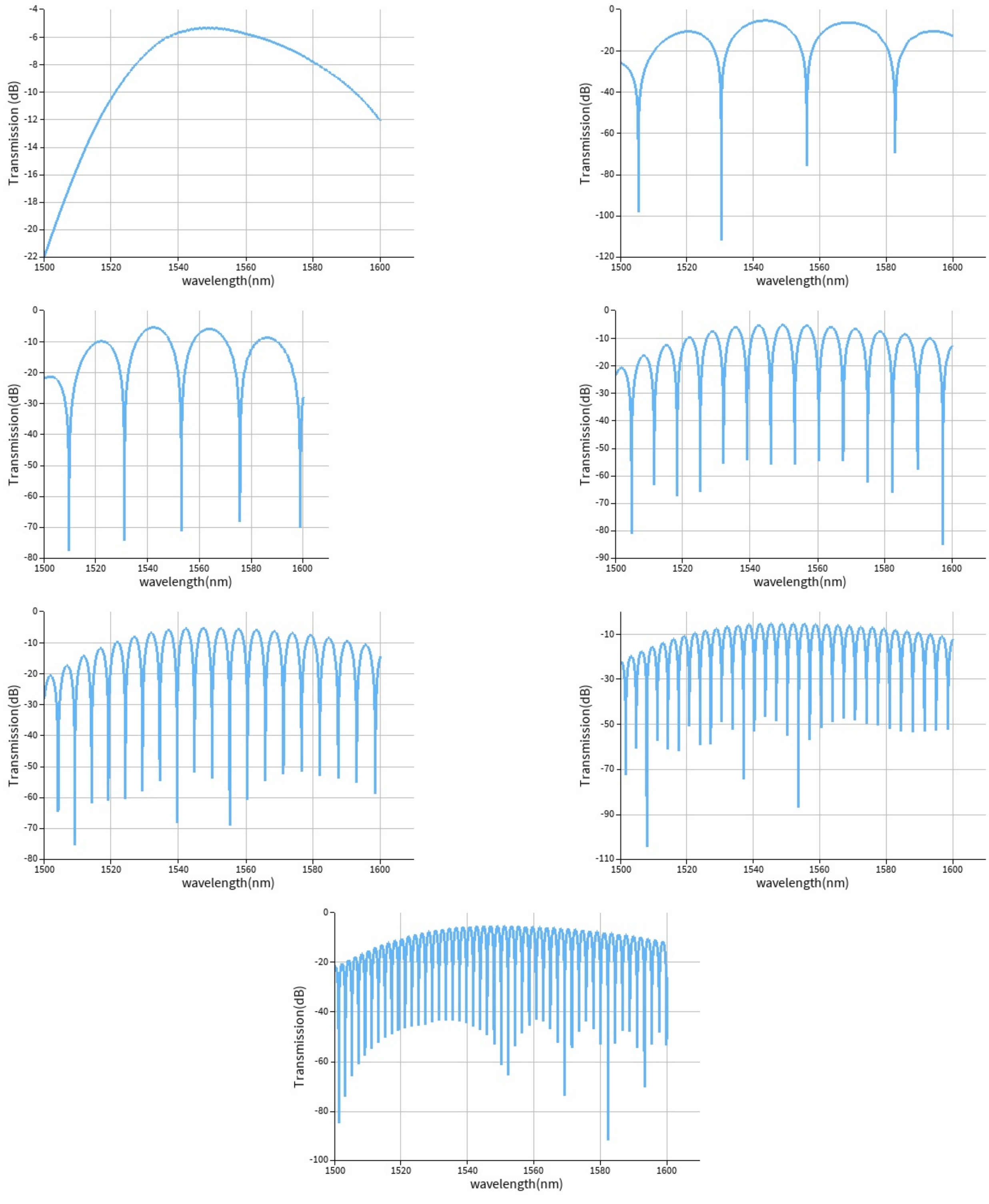


Figure 3: Transfer function of several MZIs, with length mismatches equal to a)0µm, b)22µm, c)25µm, d)50µm, e)100µm, f)150µm and g) 200µm.

- The unexposed areas on the wafer is removed by plasma etching

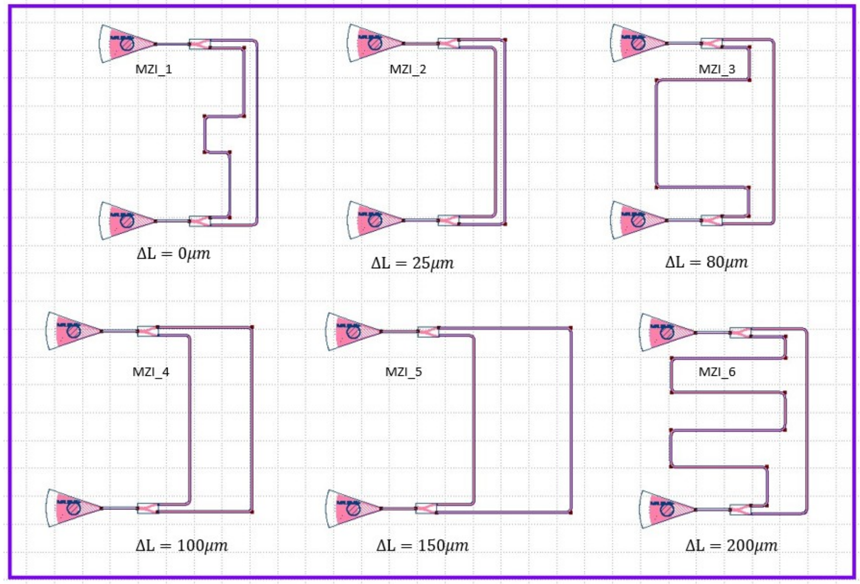


Figure 4: Final layout of the MZIs designed in KLayout Software

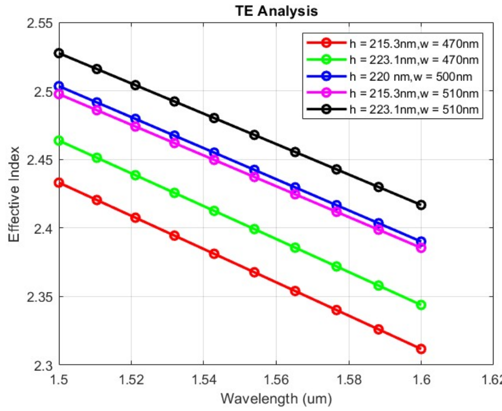
- Deposition of oxide on the wafer
- Dicing of chip

Manufacturing Challenges

Mismatches between intended and manufactured devices are one of the aspects caused by manufacturing difficulties. These manufacturing flaws result mostly in variations in the waveguide width and thickness. This variability is typically approximated using a Gaussian distribution, where the standard deviation represents the fabrication error and the nominal value corresponds to the distribution mean. The thickness variation is associated with the SOI wafer provided by the supplier. In this work, the provided wafers have an average thickness of 219.2nm, with a standard deviation deviation of 3.9 nm. The width variation of the waveguide is caused by several factors including:

- resist imperfections: thickness, sensitivity, and age;
- Exposure change;
- Development: development time and age of the chemical;
- Etching.

Considering these, it is expected that the width of 500nm have a variation within the +10/-30nm range. Figures **??** show the results of the corner analysis, which accounts for the width and thickness variability. [1]



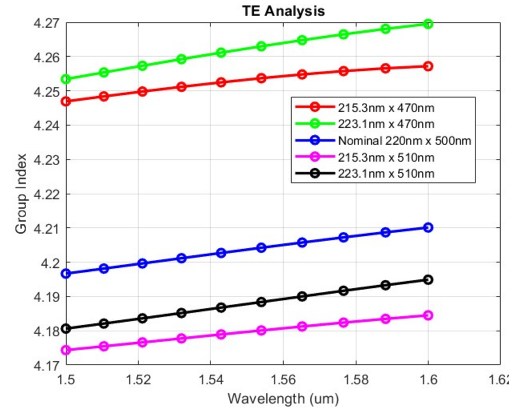


Figure 5: Corner analysis of the a) effective index and b) group index, in the TE mode. Graphs show the results for nominal design, 220nm-height x 500nm-width, and for the combinations, 219.2±3.9nm x 500 +10/-30nm..

Experimental Data

The waveguide characteristics were retrieved from experimental findings to assess the devices' performance. An advanced curve fitting technique, autocorrelation fitting, was used to assess the Free Spectral Range (FSR) and group index of MZIs. Before the improved curve fitting method, the impacts of grating couplers were removed from the MZI transmission spectrum using baseline correction and loop back structures[4].

In this report, to avoid using noisy parts of the transmission spectrum, a wavelength range with 10 dB variation in loss is used. This loss is subtracted from the transmission spectrum of the MZIs, and the calibrated transmission spectrum is used in curve fitting to find waveguide parameters. The entire process of analysis of the measurment data of a waveguide with path lenght difference of 200µm is shown in figure6. The extracted group index for this MZI is plotted in the last graph within figure 6. As can be seen, the extracted data lies within the obtained range in corner analysis very well.

The results from simulations and experiments for different waveguide structures with different waveguide path length difference and cross sections are summarized in table **??** . The value of group indices and FSRs at 1.55 µm are listed. The results from simulations and experiments agree very well FSR and group index (ng) with a slight mismatch when the path difference is 200nm.

Cross section	$\delta L(\mu m)$	FSR(nm) Simulated	ng Simulated	FSR (nm) exp	ng exp
500 x 220	0	-	4.2	-	-
500 x 220	25	22.88	4.2	22.86	4.20
500 x 220	80	7.15	4.2	7.14	4.20
500 x 220	100	5.72	4.2	5.73	4.19
500 x 220	150	3.81	4.2	3.82	4.19
500 x 220	200	2.86	4.2	2.33	5.16

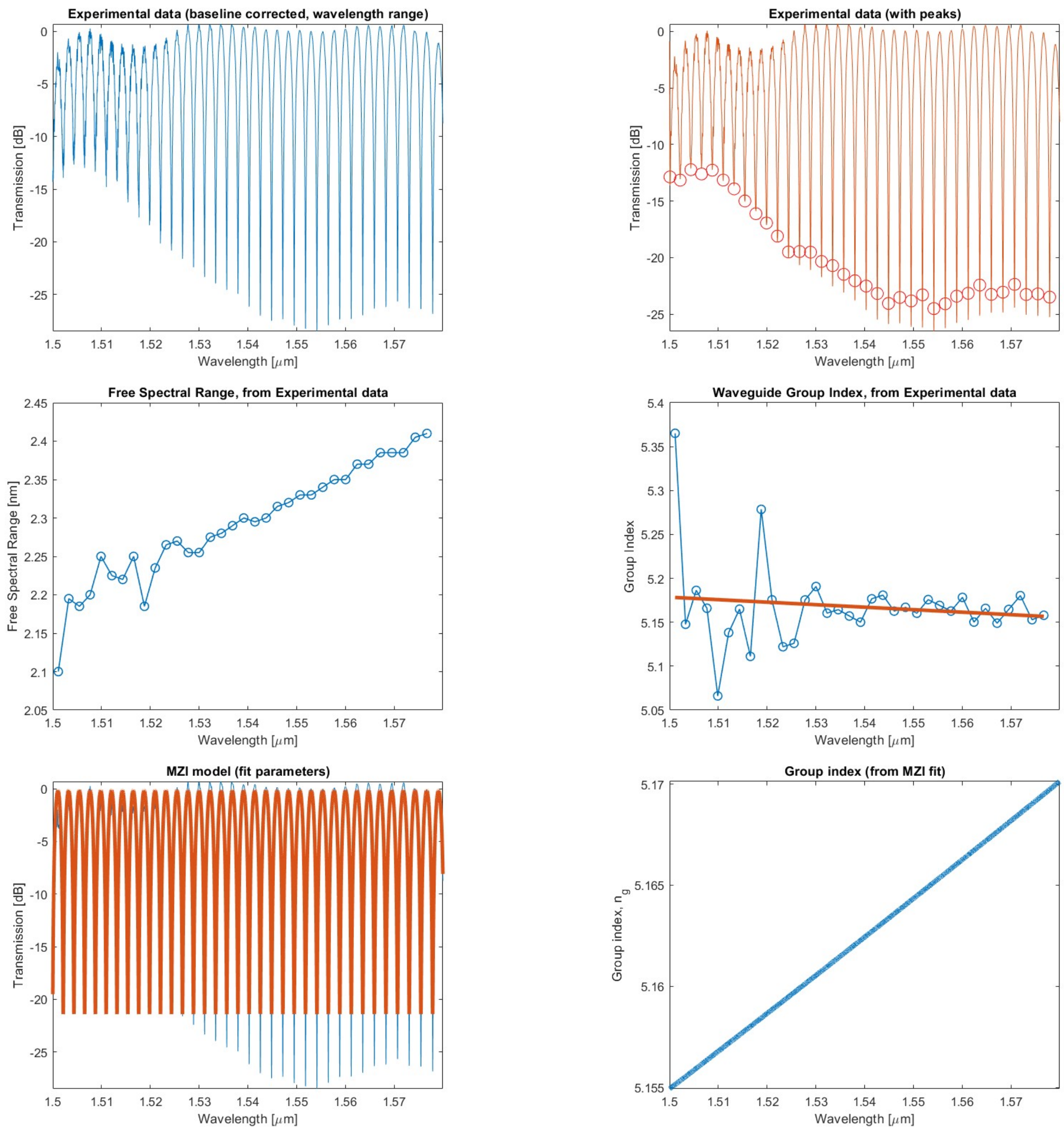


Figure 6: The sequential order of experimental analysis of the waveguide with $200\mu m$ path difference

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