"EBeam_pg35.gds" Final Report

---Mach Zehnder Interferometer Design Report

Peng Gao

Abstract:

This report will present simulated performances and fabricated for the Mach Zehnder Interferometer designs at ~1550 nm. The results show that the Mach Zehnder design can achieve ~0.8 nm free spectral range and provide a possibility to separate 0.8nm channels. The strip waveguide has a group index of 4.19 at 1550nm, which is extracted from the interferometer characterization results.

1. Introduction:

The Mach Zehnder Interferometer (MZI) is one of basic components in the integrated Si photonic circuits. MZIs have a wide range of applications from high-speed communications to highly sensitive sensing. Their design, fabrication, and performance are essential to advancing silicon photonics technology.

In wavelength-division multiplexing (WDM) systems, the free spectral range (FSR) between consecutive peaks in a spectrum is a key parameter for the application, which requires a precise wavelength selection. For example, in a coarse interleaver with a central wavelength at 1550 nm, the FSR is ~ 0.8 nm and it is determined by the group index $\boldsymbol{n_g}$.

2. Basic Theory

2.1. Waveguide $\boldsymbol{n_g}$ and $\boldsymbol{n_{eff}}$[1]

In a waveguide, the electromagnetic field is propagating in the core or/and in the cladding depending on the EM wave modes. The group index $\boldsymbol{n_g}$ and the effective index $\boldsymbol{n_{eff}}$ are needed to describe the waveguide property, which are the wavelength and geometry dependent.

$$n_g = n - \lambda \frac{dn}{d\lambda} \qquad \text{(eq. 1)}$$

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

the effective index is in the Taylor expression format (eq.2). At λ_0,

$$n_{eff} = n_1 \qquad \text{(eq. 3)}$$

$$n_g = n_1 - n_2 * \lambda_0 \qquad \text{(eq.4)}$$

$$D = -2 * \lambda_0 * \frac{n_3}{c}, \qquad \text{(eq.5)}$$

D is the dispersion of the waveguide, in the unit [s/m^2].

2.2. Interferometer FSR

FSR, the spacing between adjacent peaks is defined as:

$$FSR = \Delta\lambda = \lambda_{m+1} - \lambda_m \qquad \text{(eq. 6)}$$

For an imbalanced silicon waveguide interferometer, FSR can be in the following format:

$$FSR = \frac{\lambda^2}{n_g * \Delta L} \qquad \text{(eq. 7)}$$

ΔL the difference of the waveguide arms,

n_g the group index corresponding to the wavelength λ.

2.3. n_g extraction:

At a certain wavelength λ_0, n_g is a function of ΔL

$$n_g = \frac{\lambda^2}{FSR * \Delta L} \qquad \text{(eq. 8)}$$

n_g is extractable when the transmission spectrum is available and ΔL is known.

2.4. MZI Transfer Function:

The Mach-Zehnder interferometer transfer function is:

$$T_{\mathrm{MZI}}(\lambda) = \frac{1}{4}\left[e^{-i\beta L_1} + e^{-i\beta L_2}\right]^2 \qquad \text{(eq. 9)}$$

$L1$ and $L2$ are the lengths of the two interferometer waveguide arms. β is the propagation constant of the waveguide:

$$\beta = \frac{2\pi * n_{eff}(\lambda)}{\lambda} + i\frac{\alpha}{2} \qquad \text{(eq. 10)}$$

α is the propagation loss of per length, units matching 1/λ, namely μm^{-1}:

$$\alpha_{m^{-1}} = \frac{\alpha_{dB/m}}{4.34} \text{ or equivalently } \alpha_{\mu m^{-1}} = \frac{\alpha_{dB/cm}}{4.34} \cdot 10^{-4} \quad \text{(eq.11)}$$

$\alpha_{dB/cm}$ is 1 to 10 dB/cm for a silicon photonic waveguide.

Assume *L1*=0*,* MZI transfer function (eq.9) becomes:

$$T_{\text{MZI}}(\lambda) = \frac{1}{4}\left[1 + e^{-i\beta\Delta L}\right]^2 \text{ or in decibel format}$$

$$T_{MZI-dB}(\lambda) = \log_{10}(T_{\text{MZI}}(\lambda)) \qquad \text{(eq.12)}$$

3. Proposed MZI and simulation results:

3.1. Proposed MZI

The proposed MZI layouts are drawn by KLayout with the tool kit Ebeam-V0.4.51 technology [2]. The interferometers are built with the strip waveguides, Y-couplers and the grating couplers. In the figure 1, left panel is showing the MZI layout.

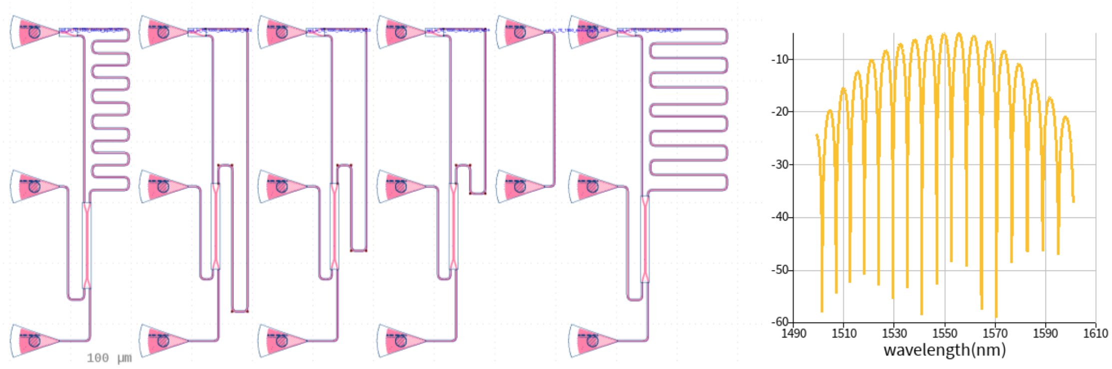


Figure 1. Interferometer Design and a typical simulation result. (left panel) Interferometer layout designs; (right panel)The simulated gain spectrum with $\Delta L =$ 98.7 um.

The Si strip waveguide has dimensions of a height of 220nm and a width of 500nm, which is cladded by SiO2 layer. The waveguide is working at 1550nm TE mode. The waveguide bending radius is a 5um and it is designed with the Beziner parameter 0.20. The 1550nm TE grating coupler and 1550nm Y-coupler are used for the interferometer. In figure 1, one spectrum with a FRS value of 6.06 nm is displayed in the right panel, which is simulated by Lumerical INTRRCONNECT. With different ΔL designs, n_g can be derived by the equation 8, which are listed in the table 1. According the simulation, when ΔL is ~ 730 nm, MZI can achieve a FSR ~ 0.8nm. On Average, the $\boldsymbol{n_g}$ at 1550 nm is ~4.16.

Table1. **Circuit Simulation n_g at 1550 nm**

Design ID	ΔL(um)	Simulated FSR (nm)	n_g
MZI 1	393.9	1.45	4.206
MZI2	292.7	1.96	4.187
MZI3	192.7	2.97	4.197
MZI4	98.7	6.06	4.016
MZI5	0	N.A.	
MZI6	736.3	0.78	4.183

A loopback waveguide is included in the design, which is the fifth devices. It will be used to acquire the grating coupler loss as the base line. All interferometer spectrum will subtract the baseline before the spectrum fitting.

Furthermore, n_1 *and* n_2 will be extracted according equations 3 and 4 in the following real device fabrication and characterization work are completed. n_3 can be determined by equation 2, when n_{eff}, n_1 and n_2 are found.

3.2. Corner Analysis

Using Si-On-Insulator Technology to make the waveguide illustrated in Figure 2, the top Silicon layer variation will dominate the component and the circuit performance variation. For example, the SOI wafer used for MZI in this report, which made by Soitec, Grenoble, France. The Si mean thickness is 219.2 nm with a 6-sigma thickness of 23.4 nm; SiO2 thickness 2994.5nm with a 6-sigma thickness of 6.3nm. The ratio of the thickness variation on the Si is much larger than it on the SiO2.

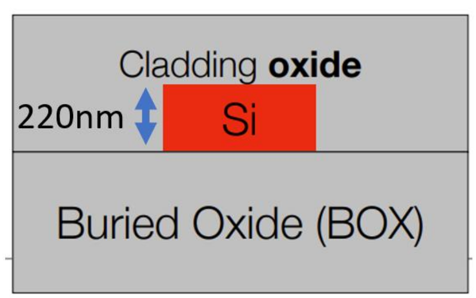


Fig2. Illustration of Strip Waveguide

Even with a stable fabrication process, there are existing systematic variation, process drift and random variation. After the lithography and etching steps, the feature size can vary. For a strip waveguide, its performance variations can be simulated and predicted by the simplified corner analysis on the height and width only. In this report, the corner analysis is done at the conditions, where Si waveguide width is at 215.3nm and 223.1nm, and the waveguide height is at 470nm and 510nm. The group index at 1550nm (Table 1.) are simulated by Ansys Lumerical MODE Finite Difference IDE- Eigenmode solver. The straight and 5um bending radius waveguide is considered too. With the simulated waveguide property .lsf files, the TE 1550nm transmission spectrum (Fig.3) can be simulated with the Mode waveguide and the library Y-splitter and GC-1550nm TE couplers.

Table 2. **Corner Simulation of n_g at 1550 nm**

	Straight Waveguide		Waveguide with 5um bending radius	
Corner Conditions (Waveguide Xsection)	n_g	FSR of MZI1	n_g	FSR of MZI1
470 x215	4.20	1.452	4.20	1.452
470x223	4.25	1.435	4.25	1.435
500x 220	4.26	1.432	4.26	1.432
510x215	4.18	1.459	4.18	1.459
510x223	4.18	1.459	4.19	1.456

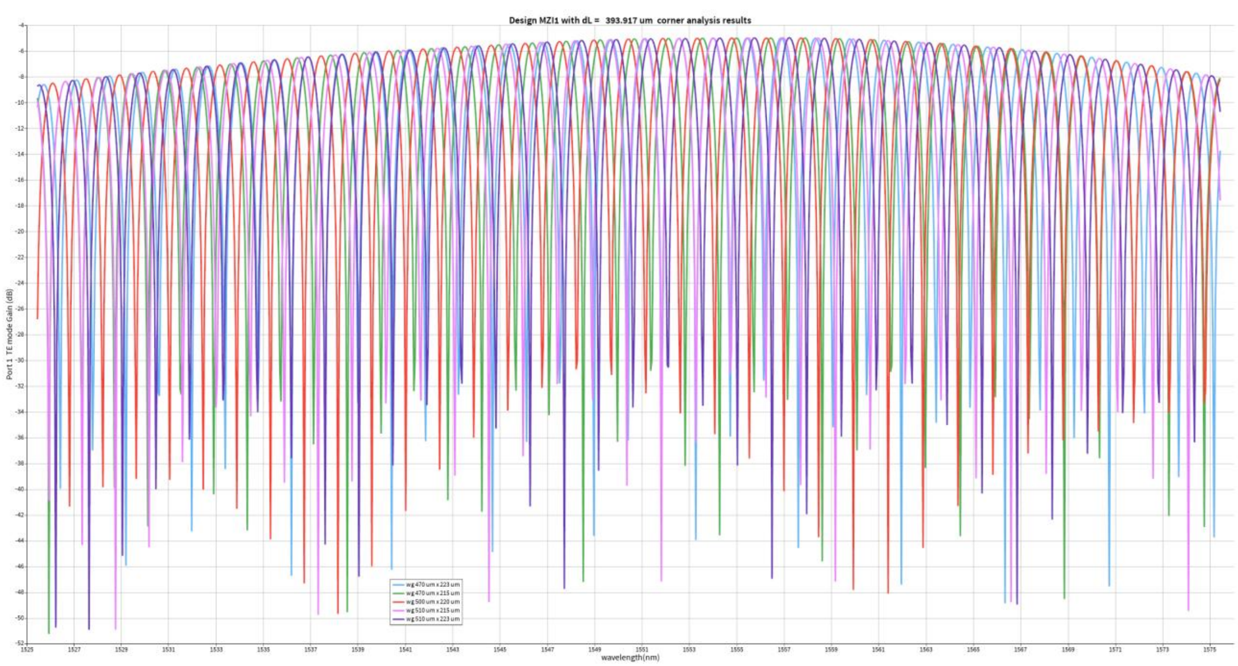


Fig3. Simuated Transmission Spectrum at Corner Conditions

4. Devices fabrication and characterization:

The photonic devices were fabricated using the Nano SOI MPW fabrication process of Applied Nanotools Inc. (http://www.appliednt.com/nanosoi; Edmonton, Canada), which is based on direct-write 100 keV electron beam lithography technology. 8” Silicon-on-insulator wafers, with the 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 25x25 mm square shapes, and lines were scribed into the substrate backsides to facilitate easy separation into smaller chips once fabrication was complete. After a thorough cleaning by using piranha solution (3:1 H2SO4:H2O2) for 15 minutes and water/IPA rinse, hydrogen silsesquioxane (HSQ) resist was spin-coated onto the substrate and heated to evaporate the solvent. The Ebeam lithography process was done on a JEOL JBX-8100FS electron beam instrument at The University of British Columbia. The exposure dosage 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” carrier wafer and underwent an anisotropic ICP-RIE etch process using chlorine after the etch rate qualification. The resist was stripped by using a 10:1 buffer oxide wet etch, and the devices were inspected again by using a scanning electron microscope (SEM) to verify patterning and etch quality. After inspection, a 2.2 µm oxide cladding layer was deposited by a plasma-enhanced chemical vapour deposition (PECVD) with the tetraethyl orthosilicate (TEOS) precursor at 300ºC. Reflectometry measurements were performed throughout the process to monitor SiO_2 thicknesses.

The devices are characterized on a custom-built automated test setup [6, 8] with automated control software written in Python was used [5] at University of British Columbia. 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) fiber was used to maintain the polarization state of the light, to couple the TE polarization into the grating couplers [6]. A polarization maintaining fiber array was used to couple light in/out of the chip [7].

5. Data Analysis:

In the design, the MZI5 is the on-chip loopback structure, which is a 140.277 um waveguide with two 1550nm grating couplers at both ends. Below is the spectrum of the loopback structure (Fig 4.) and it is the insertion loss baseline for other 5 devices.

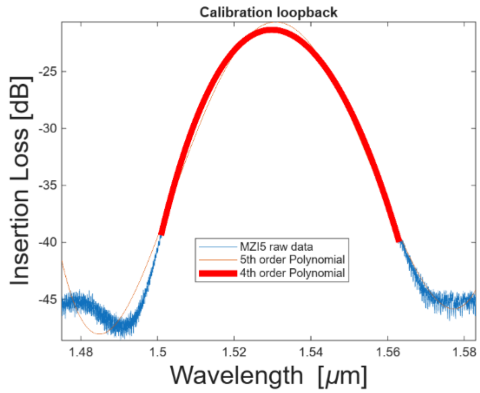


Fig 4. MZI5 Transmission Spectrum and the Polynomial fittings

The baseline fitting of the 4th order polynomial is:

$$IL\ (dB) = \ (-1588142.917752) * (\lambda - 1.5320)^4 + 69022.423911 * (\lambda - 1.5320)^3$$

$$-17394.788397 * (\lambda - 1.5320)^2 - 74.918654 * (\lambda - 1.5320)^1 - 21.413512 \qquad \text{(eq.13)}$$

, where the wavelength λ is in μm.

A typical interferometer of devices MZI1 raw spectrum and the calibrated spectrum are shown as below in Fig 4. The noisy edges are excluded. The data extraction work all are based on the calibrated spectrums.

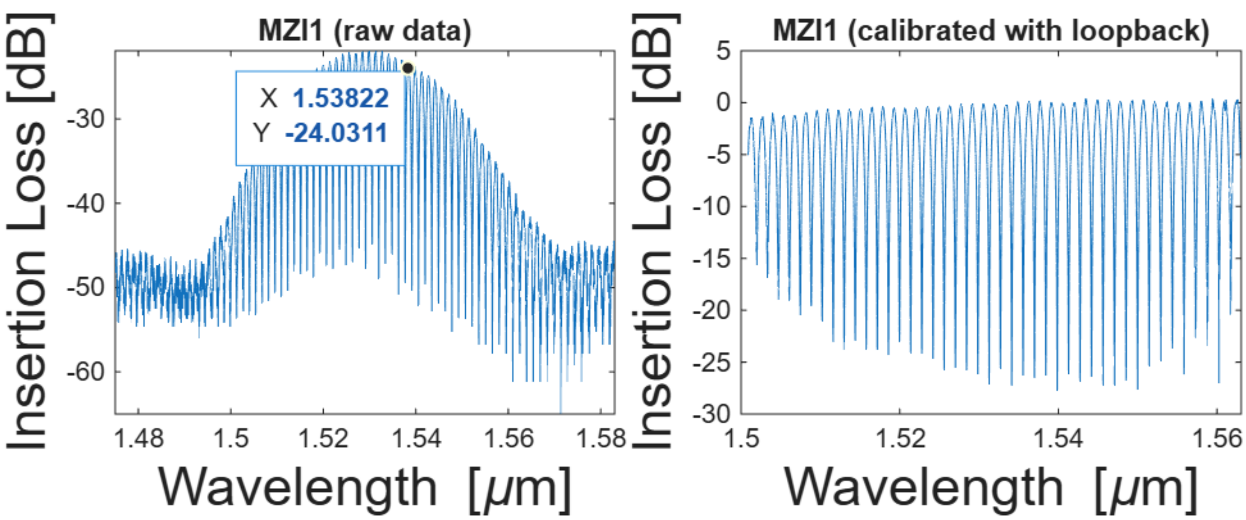


Fig 5. MZI1 Transmission raw spectrum (left panel) and the calibrated spectrum (right panel)

The waveguide properties are extracted by the Findpeak method and Autocorrelation Method. MZI1 and MZI2 are fitted with the Findpeak method. MZI3, MZI4 and MZI6 are evaluated by the Autocorrelation Method. MZI6 is using the Python code. The experimental $\boldsymbol{n_g}$

at 1550 nm are listed in the Table 2. The average $\boldsymbol{n_g}$ is 4.18, which is in the range 4.18~4.26 of the corner analysis. When the interferometer arm difference is less in MZI3 and MZI4, the $\boldsymbol{n_g}$ of 4.17 is near the low boundary. This indicates that the waveguide widths of MZI3 and MZI4 may be slight wider than 510nm. When the waveguide width increases, $\boldsymbol{n_g}$ decrease [9]. From the process aspect view, the low slab/area ratio may give the waveguide side wall a positive slope during etching and cause the waveguide wide. In future, this could be verified by the SEM.

Table 3. **Extract $\boldsymbol{n_g}$ at 1550 nm for 5 MZI designs**

Design	ΔL(um)	n_g @1550 nm	FSR (nm)
MZI1	393.917	4.19	1.409
MZI2	292.674	4.18	1.900
MZI3	192.674	4.17	2.894
MZI4	98.674	4.16	5.664
MZI6	736.264	4.19	0.754
	Average	4.18	

The $\boldsymbol{n_{eff}}$ related parameters are summarized in the Table 4. By the eq.2, the $n_{eff}(\lambda)$ is calculatable.

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

Table 4 **Extract $\boldsymbol{n_{eff}}$ parameters**

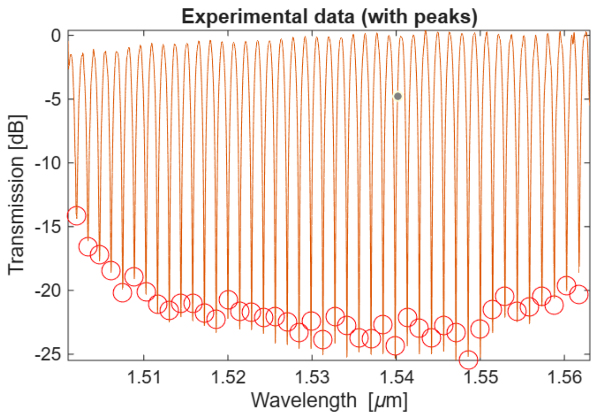
	n_1	n_2	n_3	λ_0 (µm)	alpha (1 /um)
MZI1	2.40	-1.17	-0.02	1.5299	7.00E-04
MZI2	2.40	-1.16	-0.01	1.5289	1.30E-03
MZI3	2.42	-1.14	0.00	1.5320	1.20E-03
MZI4	2.42	-1.14	0.05	1.5320	4.50E-03
MZI6	2.41	-1.16	-0.03	1.5350	6.02E-04

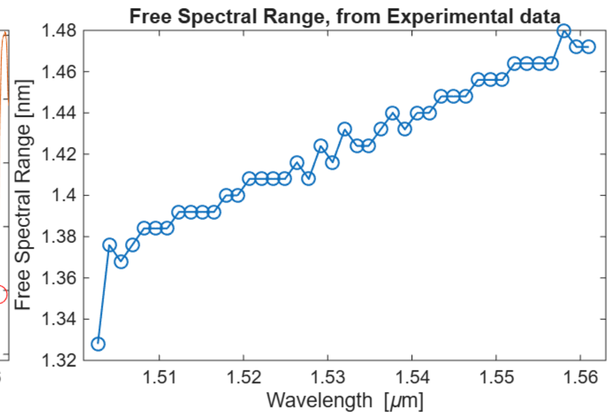
The fitting details and the fitting output are illustrating following.

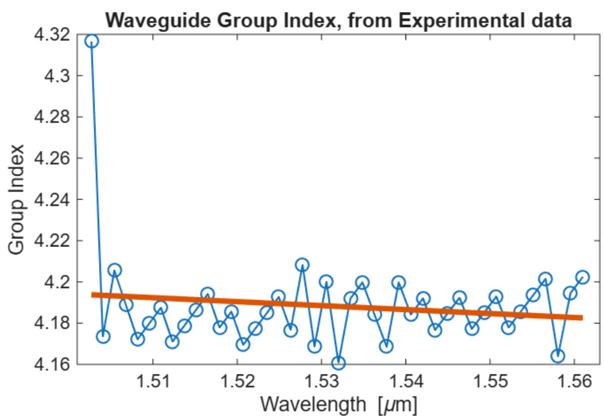
5.1. Fitting with Findpeak method:

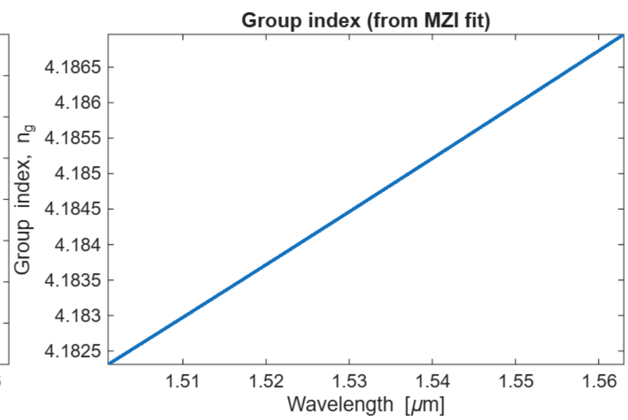
Devices MZI1 and MZI2 are using the findpeak method to extract $\boldsymbol{n_g}$, n_{eff}, n_1 and n_2.

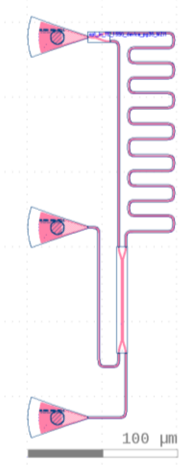
- **Device MZI1**:

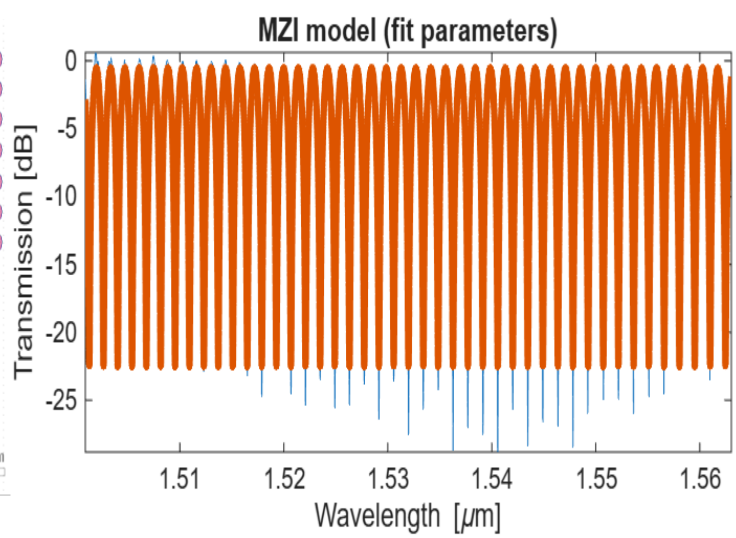












“>>finding peaks

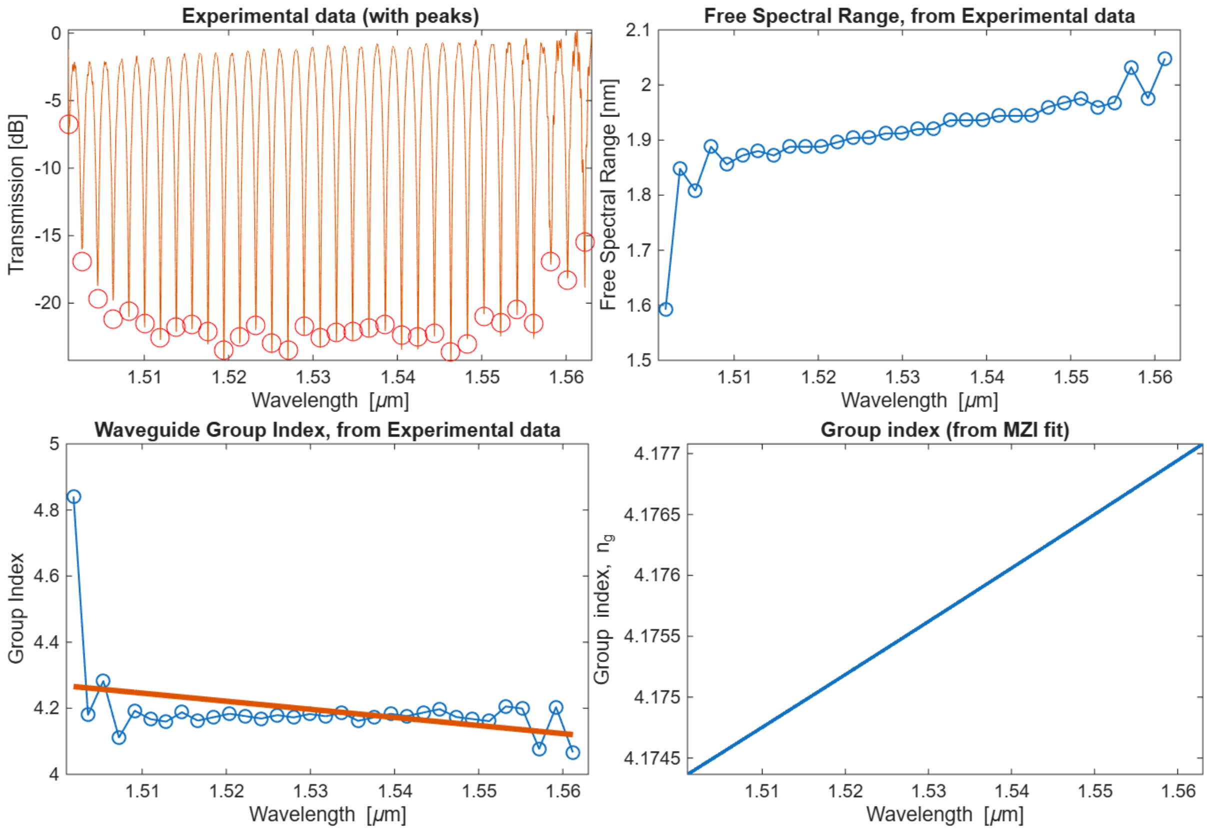
lambda_min =   1.5010e-06

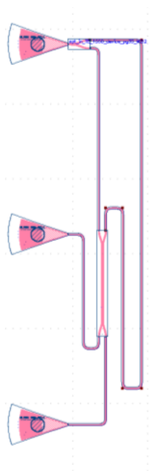
(estimate) Group index: 4.1882

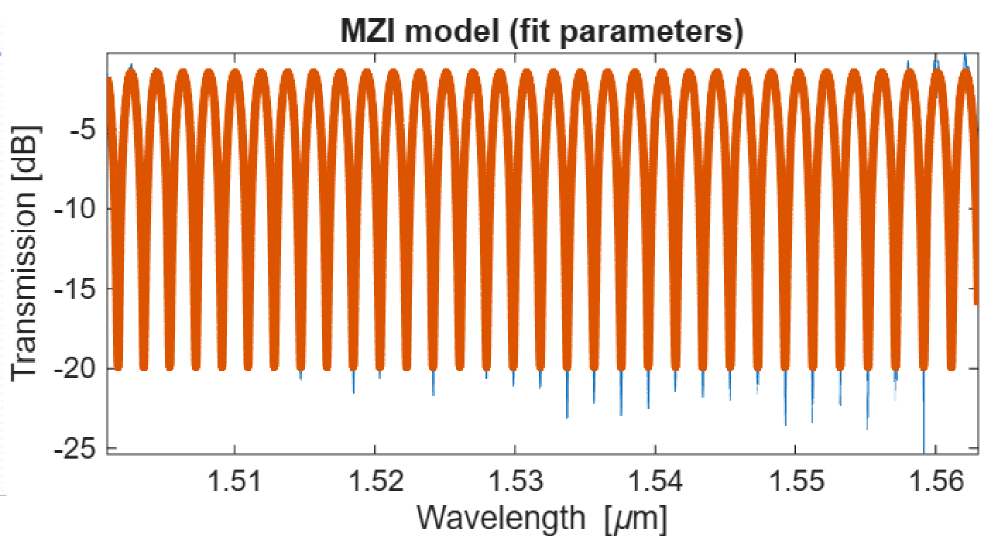
Local minimum found.
Optimization completed because the size of the gradient is less than the value of the optimality tolerance.
<stopping criteria details>
Goodness of fit, r^2 value: 0.02064
(estimate from ng slope) Dispersion [ps/nm/km]: -640.977
Local minimum possible.
lsqcurvefit stopped because the final change in the sum of squares relative to its initial value is less than the value of the function tolerance.
<stopping criteria details>
xfit = 2.3982   -1.1676   -0.0245   0.0007   0.3277
Goodness of fit, r^2 value: 0.98306

Waveguide parameters at wavelength [um]: 1.5299
Group index: 4.1845
Dispersion [ps/nm/km]: 249.776”

- **Device MZI2:**







“>>finding peaks

lambda_min = 1.5010e-06

(estimate) Group index: 4.1942

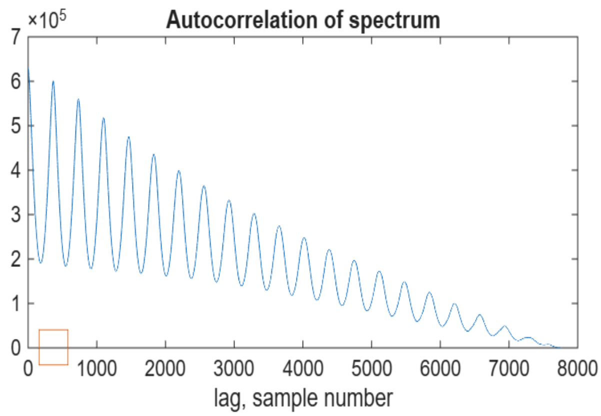
Local minimum found.
Optimization completed because the size of the gradient is less thanthe value of the optimality tolerance.
<stopping criteria details>
Goodness of fit, r^2 value: 0.12713
(estimate from ng slope) Dispersion [ps/nm/km]: -8171.3409
Local minimum possible.
lsqcurvefit stopped because the final change in the sum of squares relative to its initial value is less than the value of the function tolerance.
<stopping criteria details>
xfit = 2.3951   -1.1645   -0.0143   0.0013   -0.4361
Goodness of fit, r^2 value: 0.98091

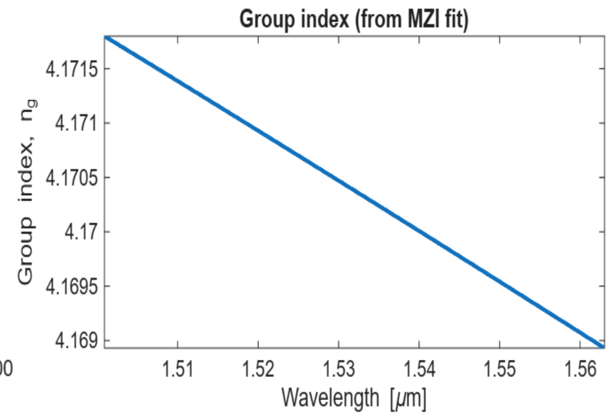
Waveguide parameters at wavelength [um]: 1.5289
Group index: 4.1756
Dispersion [ps/nm/km]: 145.6727”

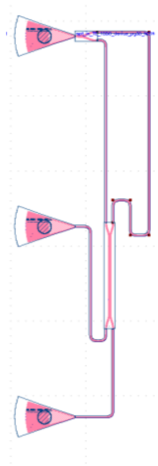
5.2. Fitting with Autocorrelation Method:

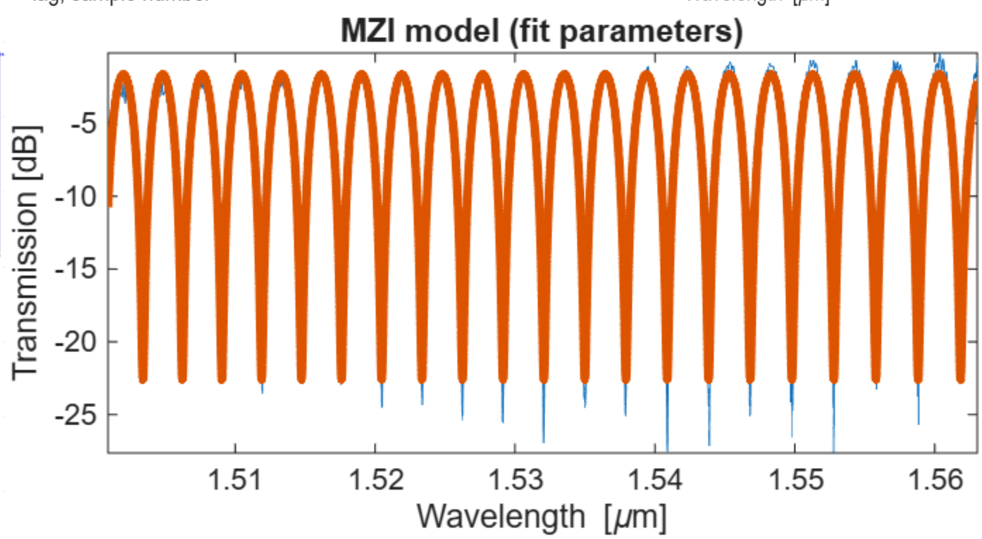
Devices MZI3 and MZI4 are using the Autocorrelation method to extract $\boldsymbol{n_g}$, n_{eff}, n_1 and n_2.

- **Device MZI3:**







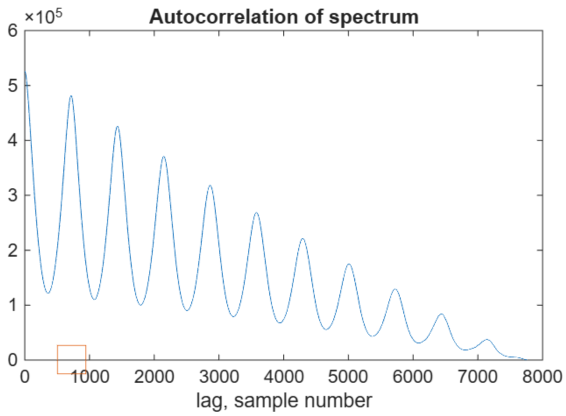


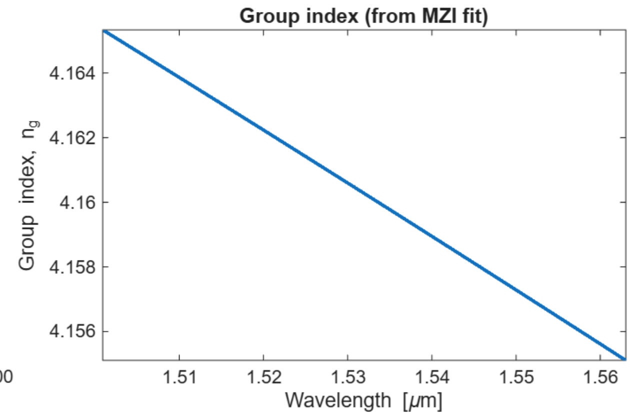
“>> FittingtheMZIwithAutocorrlation

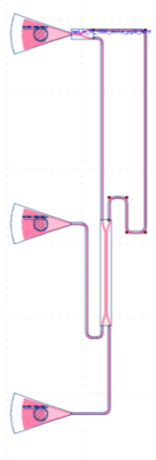
fsr = 2.9360e-09
ng_av =4.1488

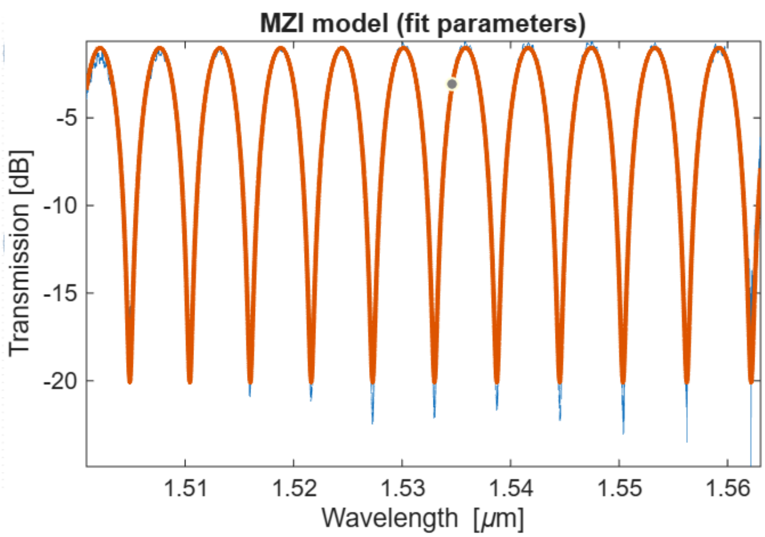
Local minimum possible.
lsqcurvefit stopped because the final change in the sum of squares relative to its initial value is less than the value of the function tolerance.
<stopping criteria details>
xfit = 2.4174 -1.1441 0.0040 0.0012 -0.8486
r2 = 0.9487
ng0 = 4.1701”

- **Device MIZ4:**









“>> FittingtheMZIwithAutocorrlation

fsr = 5.7440e-09

ng_av = 4.1408

Local minimum possible.

lsqcurvefit stopped because the final change in the sum of squares relative to its initial value is less than the value of the function tolerance.

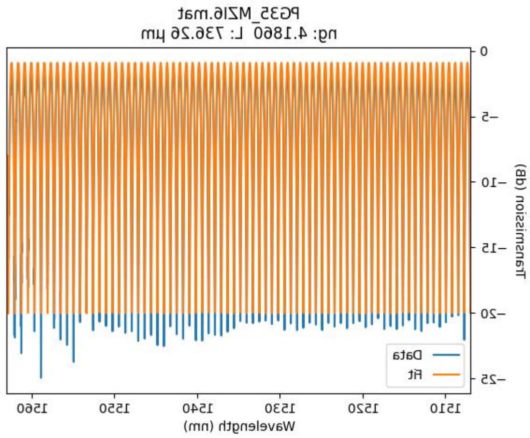
<stopping criteria details>

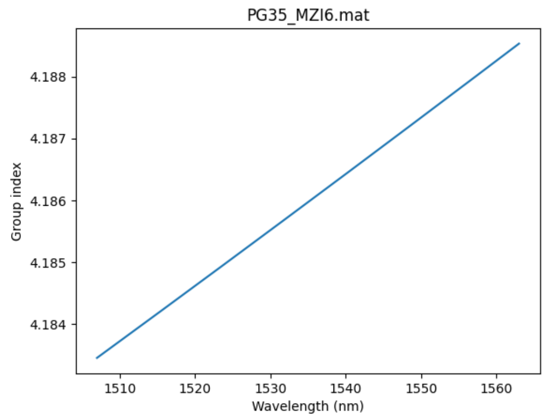
xfit = 2.4170 -1.1379 0.0537 0.0045 -0.0913

r2 = 0.9889

ng0 = 4.1603”

5.3. Fit MZI6 with Python Code





>“fsr = 7.7600e-10

ng_av = 4.1077

n1 = 2.410774

n2 = -1.156483

n3 = -0.029596

alpha = 602.212402

n_{EFF}= n1 + n2*(wavelength - w0)*1e6 + n3*(wavelength - w0)**2 * 1e12

w0= 1.534996e-06”

MZI6 is an 0.8 nm interleaver design. From the spectrum and the baseline corrected spectrum , The resolution of the interferometer is ~0.8nm and the peak noise ratio is high. Those show that the MZI6 can be used as a 1550nm interleaver.

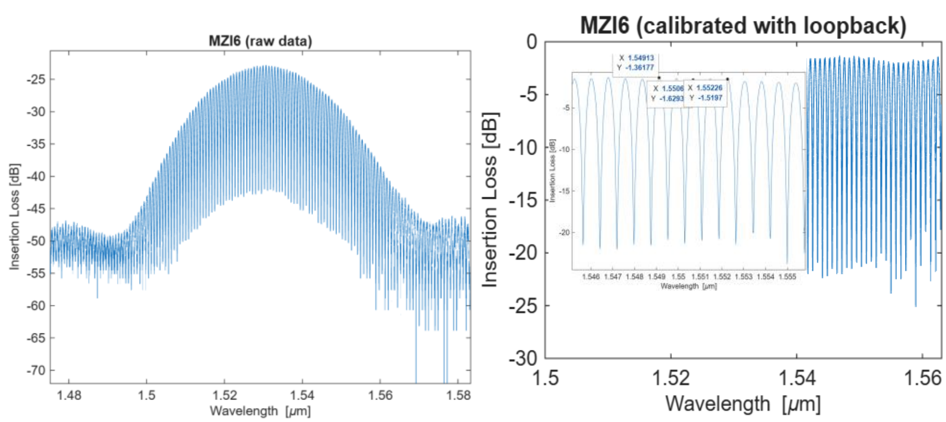


Fig 6. MZI6 Transmission raw spectrum (left panel) and the corrected spectrum (right panel)

6. Conclusion:

In this report, the experimental waveguide parameters are extracted from the MZI spectrum. The average n_g is 4.18, which is in the range 4.18~4.26 of the corner analysis results. The waveguide of MZI6 has n_g as 4.19 @1550nm and this is corresponding with a FSR value with 0.754 nm. The parameters of MZI6 can be used to design a coarse 0.8nm resolution interlever.

7. Acknowledgments:

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