Design Proposal : Mach-Zehnder Interferometer

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GDS File name : EBeam_archanas_v2.gds

I. Abstract

This report outlines details about the design of Mach-Zehnder Interferometer using Strip waveguide. The report presents simulated results and analytical expressions to corroborate the design choices. This design uses MZI using different components such as bidirectional coupler, directional coupler and adiabatic splitters in TE mode 1550nm. Simulation results shows difference in each of the approaches used and FSR is calculated for different in waveguide lengths.

II. Introduction

The Mach–Zehnder interferometer is a simple highly configurable device used to demonstrate interference by division of amplitude. The Mach–Zehnder interferometer can determine the relative phase shift variations between two collimated beams, derived by splitting light from a single source. A beamsplitter is used in order to split a light beam into two parts. The split beam is then recombined by a second beamsplitter. Based on the relative phase acquired by the beam along the two paths, the second beamsplitter will reflect the beam with an efficiency between 0 and 100%. The Mach–Zehnder interferometer also enables the determination of the wavelength of a laser beam, the ability to determine the refractive index of a transparent material and also to establish the refractive index of air.

III. Modelling and Simulation

A. WAVEGUIDE

In my design, I use Strip waveguide with 500nm width and 220nm height.

Here are the simulated waveguide profiles:

The MODE simulation results show us below that they are quasi-TE polarized with an effective index n of 2.442 for a wavelength of 1.55um for mode #1.

TE mode:

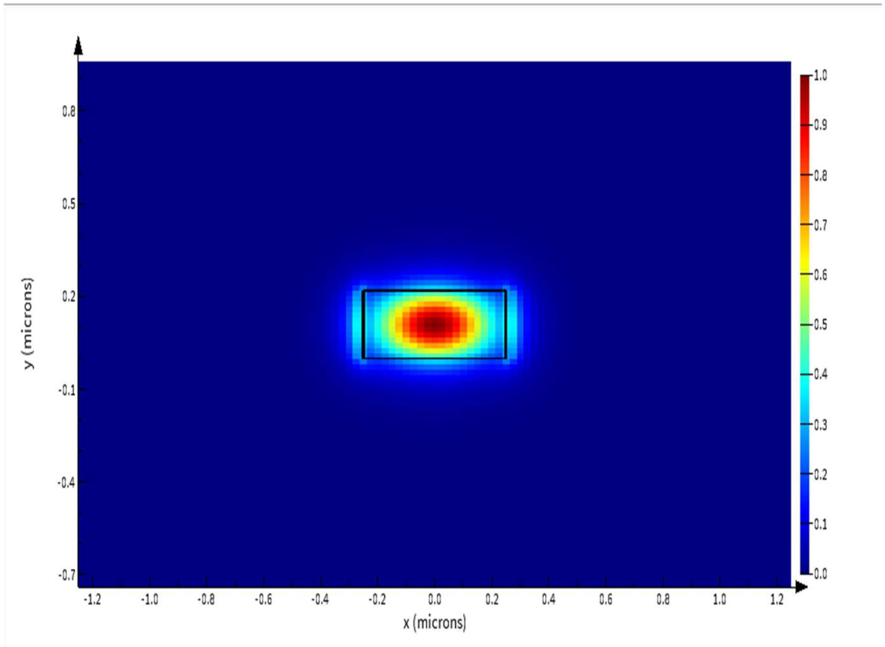

Figure1.Electric field intensity of TE mode in the waveguide

TM Mode:

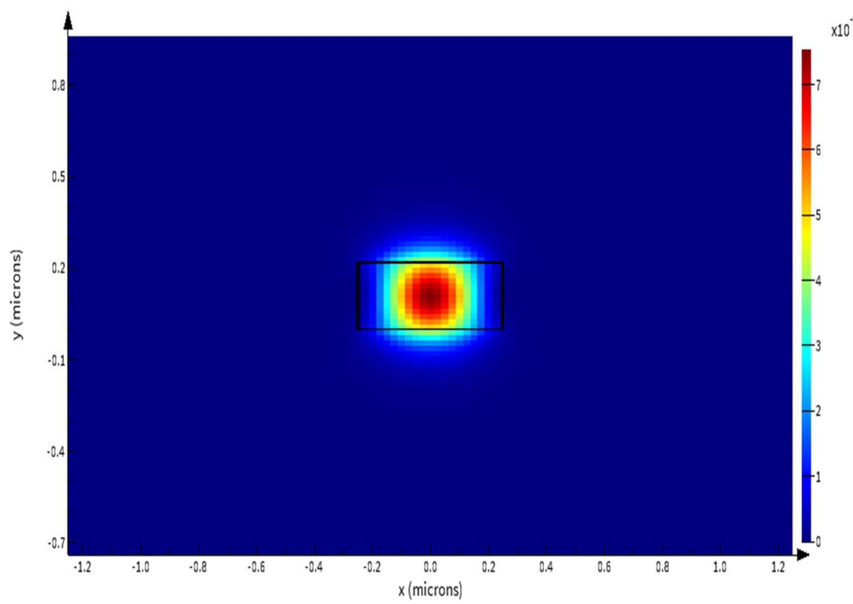

Figure2. Electric field intensity of TM mode in the waveguide

Variation of effective index n and group index ng with respect to wavelength.From the pictures we can infer that effective index decreases with wavelength and group index increases with respect to wavelength.

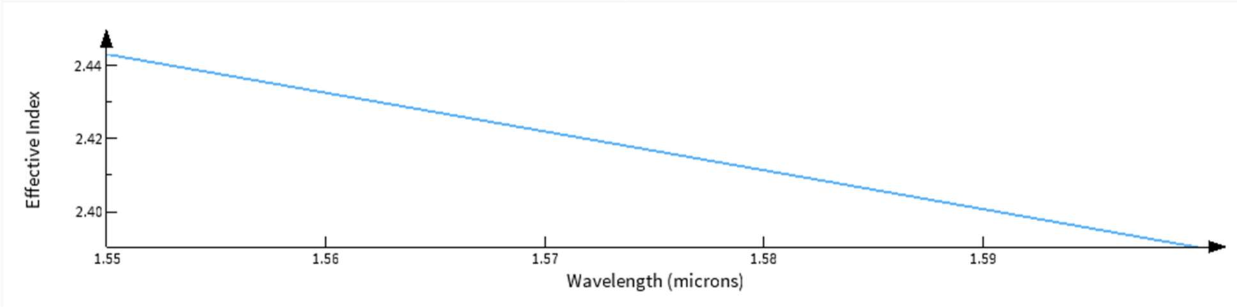

Figure 3. Wavelength vs. Effective Index from MODE simulations

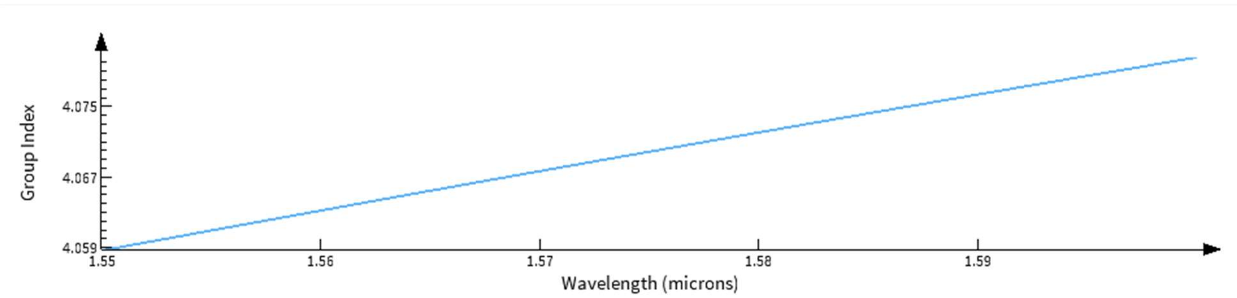

Figure 4. Wavelength vs. Group Index from MODE simulations

Using MATLAB, the compact model equation for the waveguide is obtained, which is a 2[nd] order polynomial.

***neff*(λ) = 2.44 - 1.1 *(lambda-1.55)-0.04*(lambda-1.55) ^2**

B. MACH-ZEHNDER INTERFEROMETER (MZI)

The transfer function of MZI is as follows:

T(MZI) = $I_i * 2[1 + \cos(\beta \Delta L)]$

where,

I_i = input intensity

β = Propagation constant of light

ΔL = Difference in waveguide length

Using Lumerical INTERCONNECT simulation and compact model waveguide generated from MODE simulation, here is how transfer function of MZI looks:

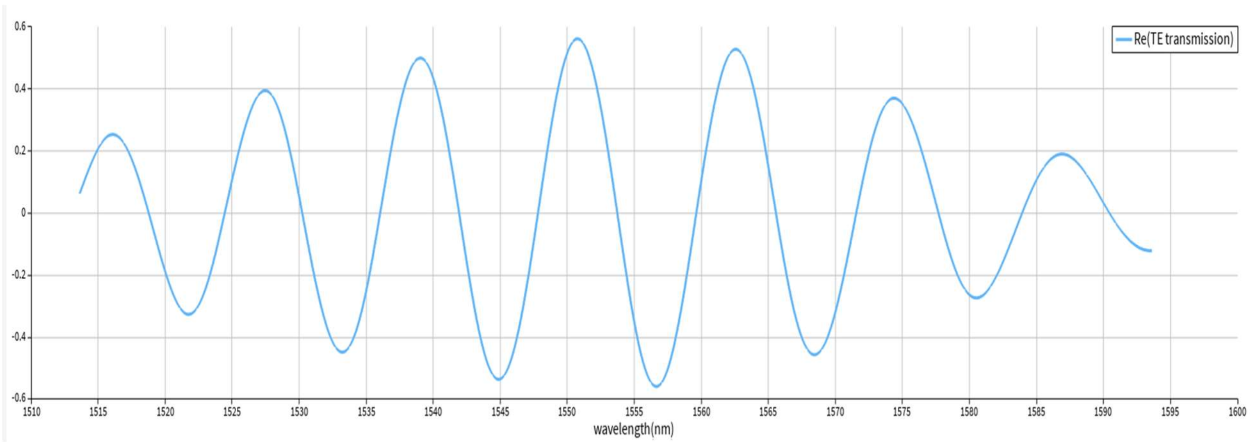

Figure 5. This is the Transfer function of an MZI using Y-branch and 2 waveguides of same length

C. FREE SPECTRAL RANGE

The Free Spectral Range of the Interferometer is calculated as

FSR = $\lambda^2 / (n_9 \lhd L)$

The Table below shows FSR simulated using Lumerical INTERCONNECT for different waveguide lengths done on the Klayout.

Width - 500

Delta L (um)	FSR (nm) mode 1, input1	FSR (nm) mode 1, input2
121.77	4.739	4.654
56.37	0.1035	9.974
46.32	0.1233	
126.36	4.545	

D.TRANSMISSION SPECTRUM

The picture below shows the TE spectrum of MZI with Delta L of 126.36um with both input1 and input2 in one graph based on Lumerical INTERCONNECT circuit simulations.

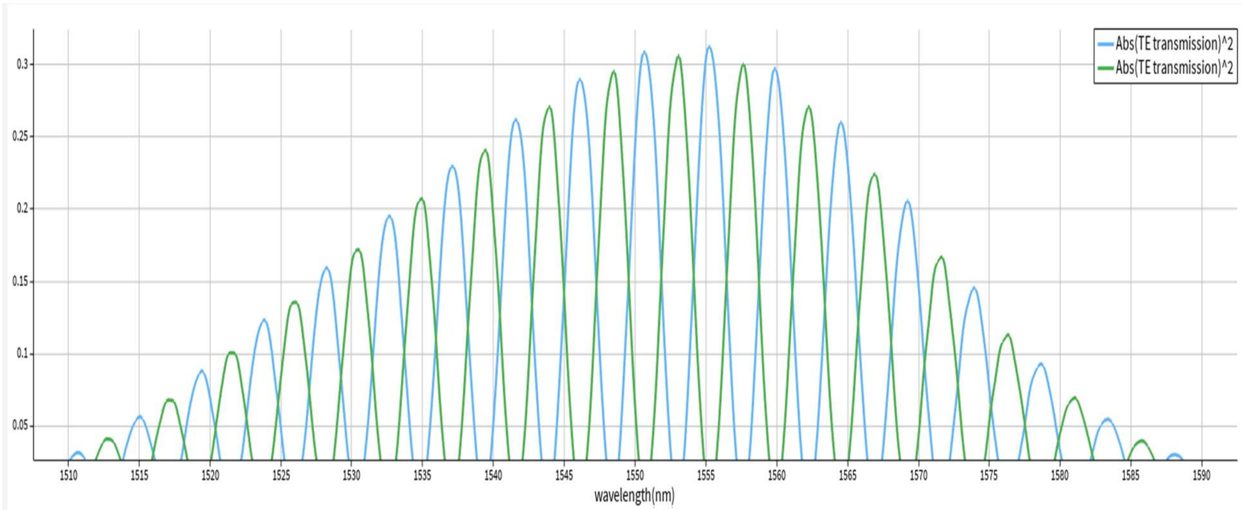

Figure6. MZI transmission spectrum using Y-branch for Mode 1, input 1 and input2

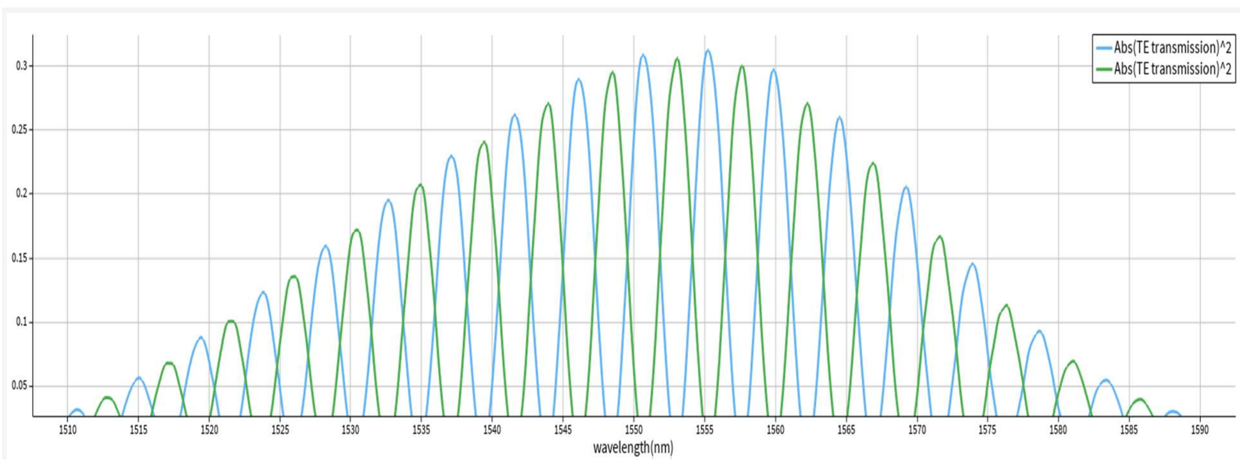

Fig 7. TE spectrum based on compact waveguide model from MODE and Optical 2-port s-parameter element with Y-Branch S-parameters populated. Waveguide length is 100 and 300um respectively.

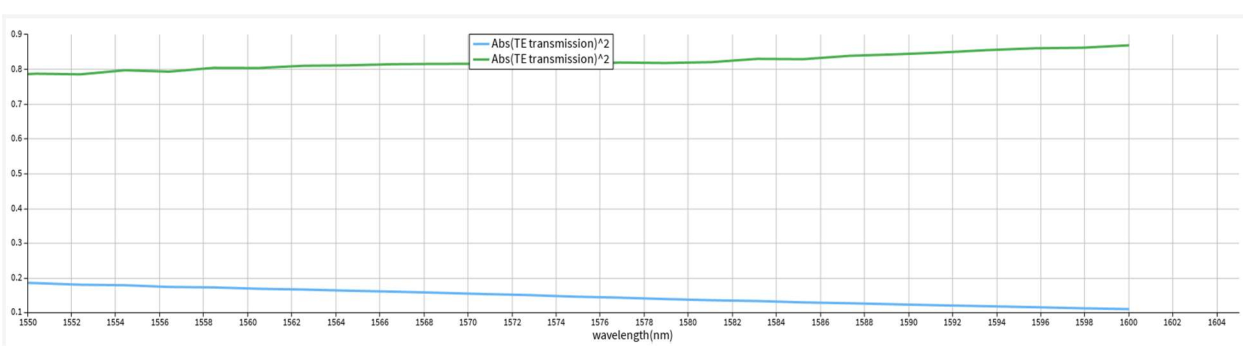

Fig8. 80-20 Adiabatic splitter transmission spectrum

E. IMBALANCED MZI INTERFEROMETER

For different levels of interference in MZI, an unequal length is introduced between the branches as indicated in Fig 9.

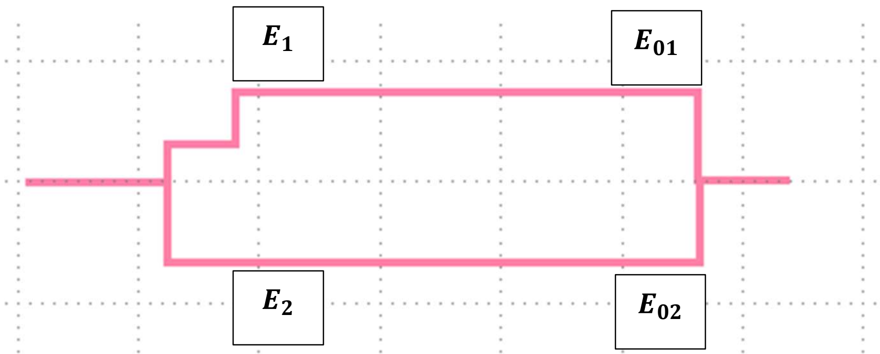

Fig 9. Imbalanced MZI

The upper and lower waveguides have different lengths, L1 and L2 with different effective indices n1 and n2. Hence the propagation constant for these two branches is defined as:

$\beta_1 = 2\pi n_1 \,/\, \lambda$

$\beta = 2\pi n_2 \,/\, \lambda$

The vectorial electrical field at the input of the MZI is represented by E*1 and* E2. At the output of the beam-splitter, the complex electrical fields at the upper and lower branches are given by,

$$E_1 = E_2 = \frac{1}{\sqrt{2}} E_i$$

The electrical fields at the input of the beam-combiner can be described by,

$$E_{01} = E_i e(-j\beta_1 L_1 - \alpha_1 L_1) \text{ -------------> (1)}$$

$$E_{02} = E_i e(-j\beta_2 L_2 - \alpha_2 L_2) \text{ --------------> (2)}$$

When light is combined in the y-branch at the output, output intensity is defined as follows,

$$E_0 = \frac{1}{\sqrt{2}} \cdot [E_{01} + E_{02}] \text{ ----------------} \rightarrow \text{(3)}$$

Combining eqns (1) and (2) in eqn (3),

$$E_0 = \frac{1}{2} \cdot [E_i e(-j\beta_1 L_1 - \alpha_1 L_1) + E_i e(-j\beta_2 L_2 - \alpha_2 L_2)] \text{ ------- > (4)}$$

Finally light intensity is squared power of intensity amplitude,

$$I_0 = \frac{1}{2} \cdot |[I_i e(-j\beta_1 L_1 - \alpha_1 L_1) + I_i e(-j\beta_2 L_2 - \alpha_2 L_2)]|\text{^}2 \text{ ------------- > (5)}$$

Solving for I_0,

$$I_0 = \frac{1}{2} \cdot I_i(1 + cos\, \beta \Delta L)$$

where ΔL = L1 -L2, and β1 = β2 = β

The spacing between the adjacent peaks is defines as free spectral range,

FSR = $\lambda^2 / \Delta L \cdot n_9(\lambda)$

F. MZI Design based on Layout and Circuit Simulation

The following table illustrates MZI using bdc_te couplers and corresponding FSR is calculated for different lengths of the waveguide

<table>
<tr><th>EBeam_bdc_te1550</th><th>L1</th><th>L2</th><th>Delta L (um)</th><th>FSR (nm) mode 1, input1</th><th>FSR (nm) mode 1, input2</th></tr>
<tr><td rowspan="2">Case i)</td><td>43.668</td><td>300</td><td>256.332</td><td rowspan="2">2.25</td><td rowspan="2">2.29</td></tr>
<tr><td>58.448</td><td>324.485</td><td>265.552</td></tr>
<tr><td rowspan="2">Case ii)</td><td>220</td><td>100.001</td><td>119.99</td><td rowspan="2">4.767</td><td rowspan="2">5.72</td></tr>
<tr><td>290</td><td>190.148</td><td>99.852</td></tr>
</table>

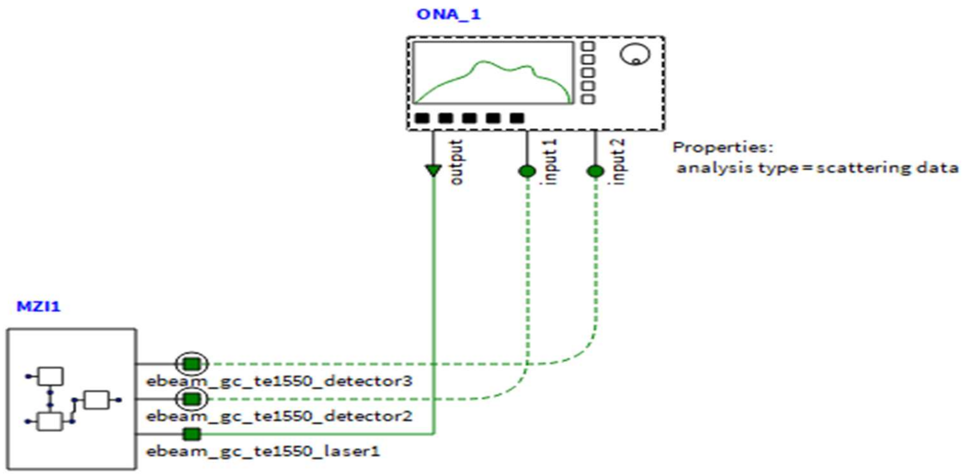

Figure10. Lumerical Interconnect simulations

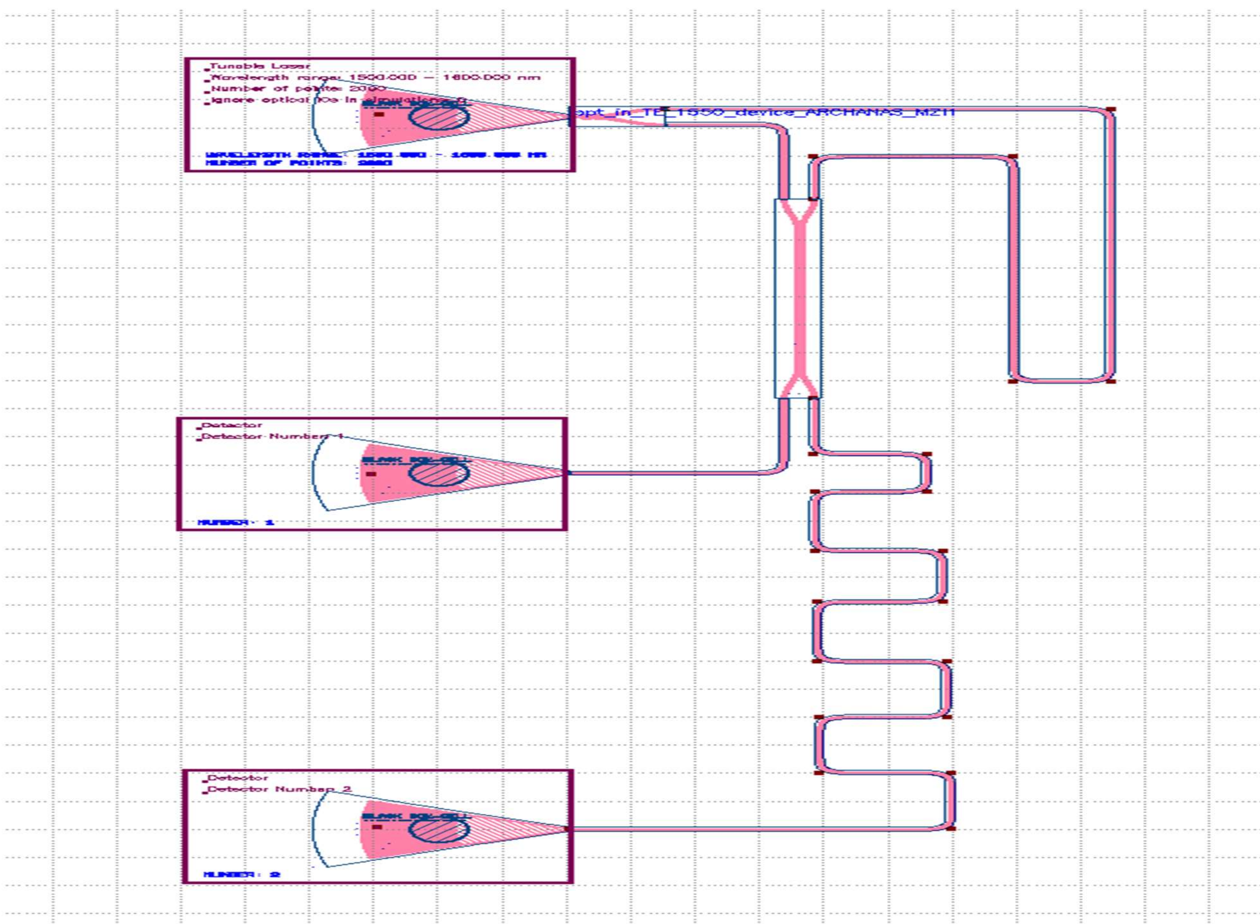

Figure 11. Layout of MZI using Bdc_te couplers

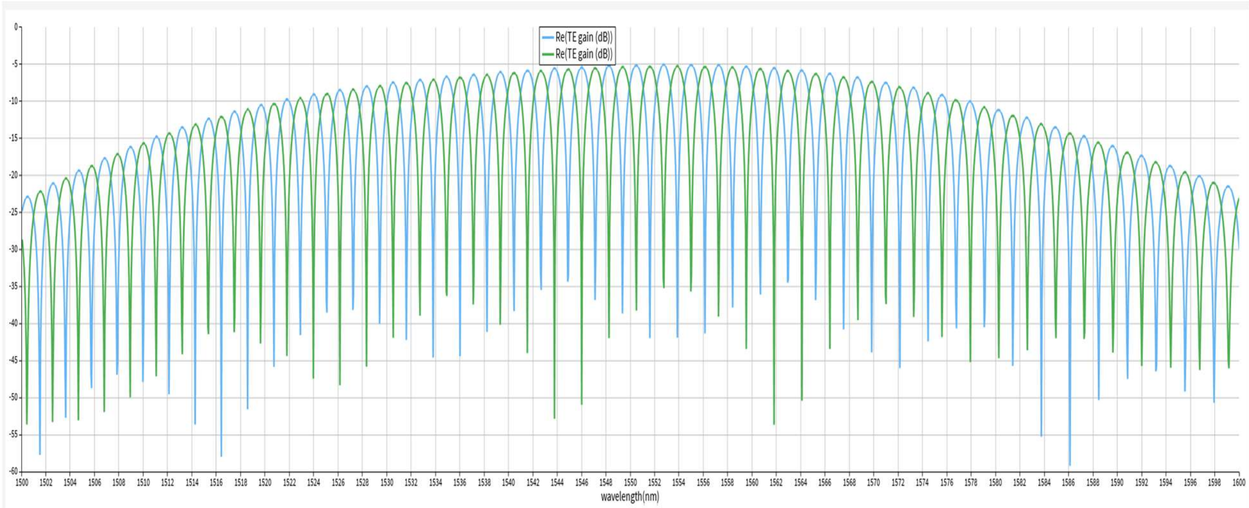

Figure 11.TE Gain a) Blue(input1) b) Green(input2)

The TE Gain observed at 1550nm wavelength for input1 is -5.98dB and for input2 is -12.712dB

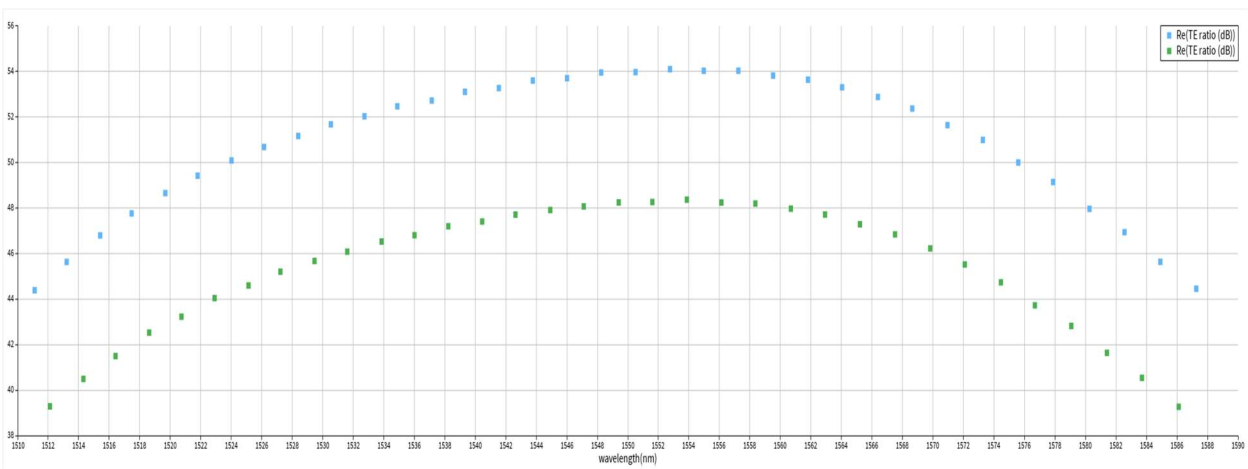

Figure 12.TE Ratio/Extinction Ratio a) Blue(input1) b)Green(input2)

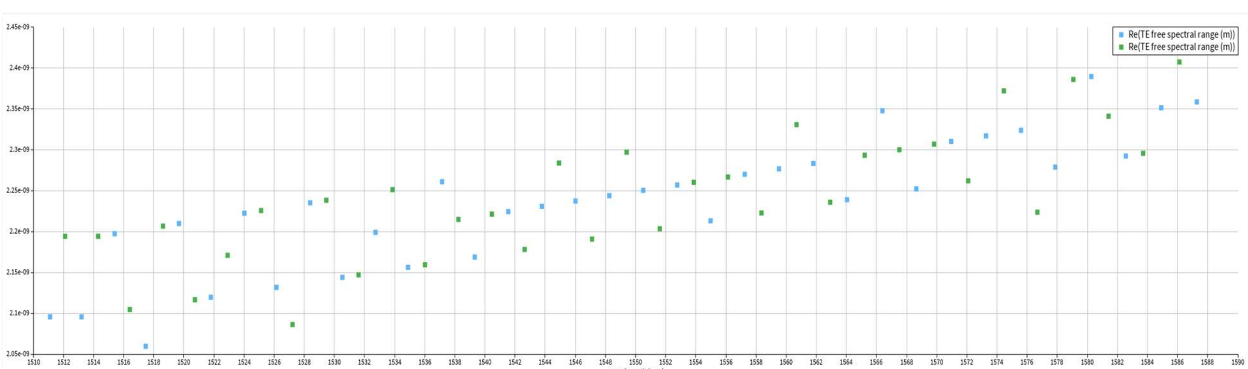

Figure 13. Free Spectral Range a) Blue(input1) b) Green(input2)

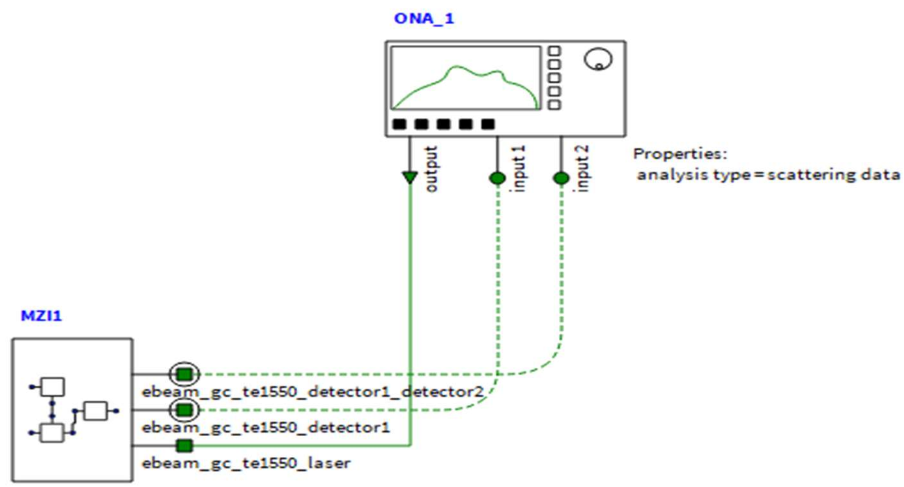

Figure 14. Simulation with Lumerical INTERCONNECT using bdc_te_1550

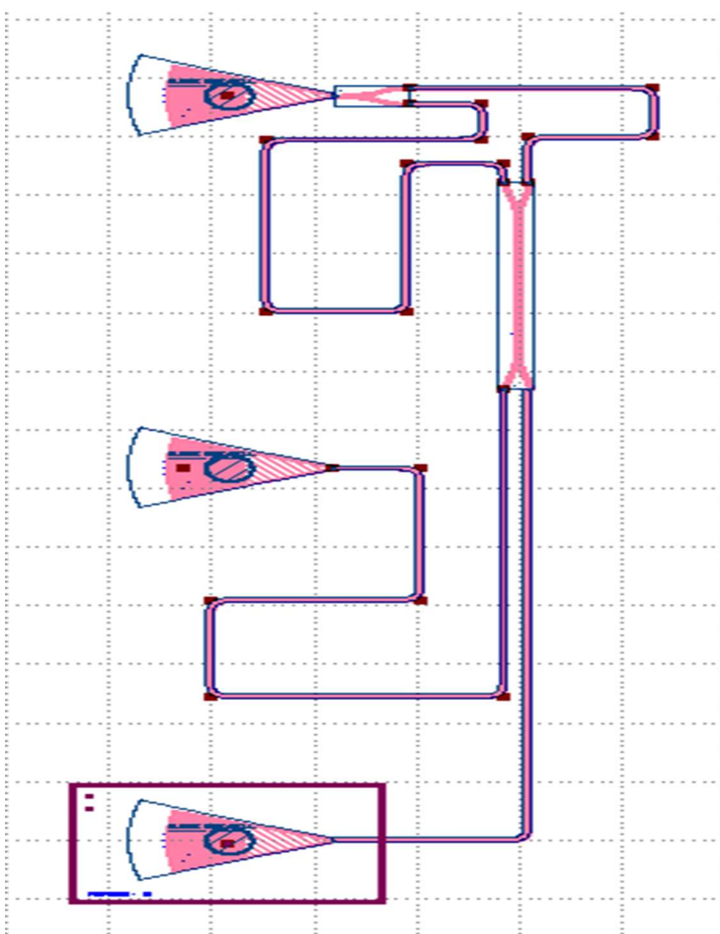

Figure 15. KLayout using bdc_te1550 for case ii)

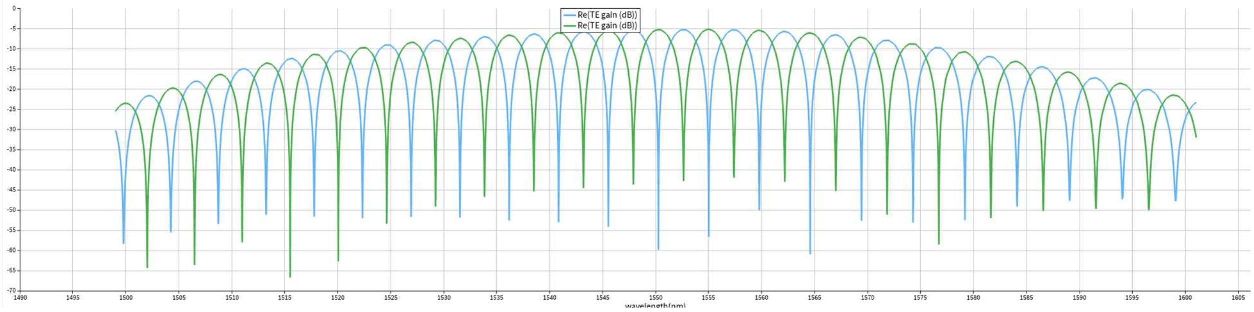

Figure 16.TE Gain a) Blue(input1) b) Green(input2)

The TE Gain observed at 1550nm wavelength for input1 is -21.145dB and for input2 is -5.438dB

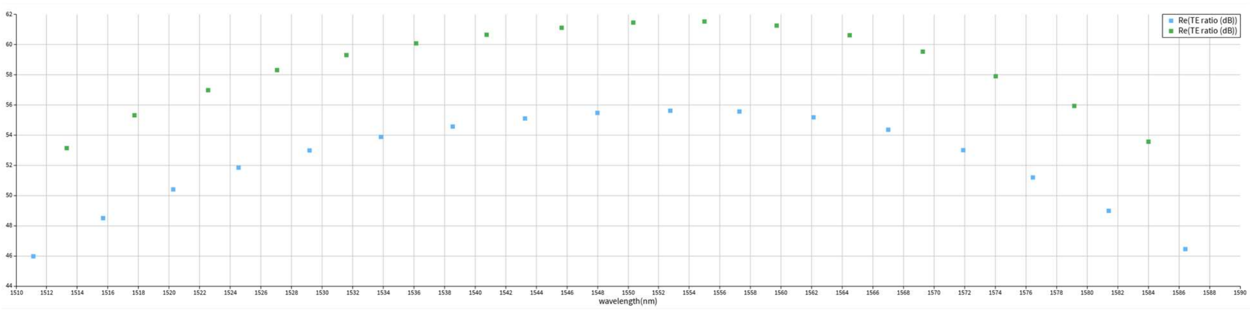

Figure 17.TE Ratio/Extinction Ratio a) Blue(input1) b)Green(input2)

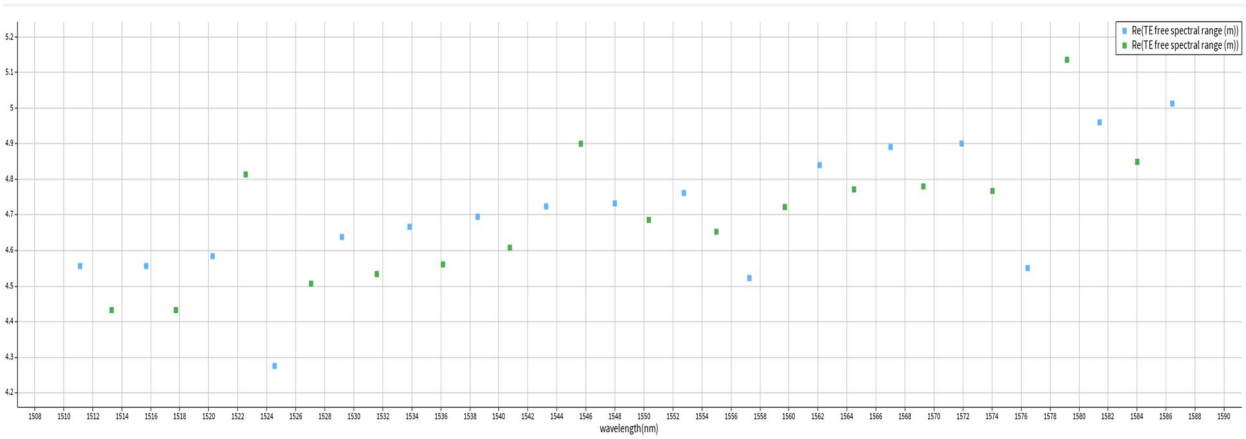

Figure 18. Free Spectral Range a) Blue(input1) b) Green(input2)

The following table illustrates MZI using dc_te couplers and corresponding FSR is calculated for different lengths of the waveguide

EBeam_dc_te1550	L1(um)	L2(um)	Delta L (um)	FSR (nm) mode 1, input1	FSR (nm) mode 1, input2
Case i)	61.558	320	258.442	2.213	1.917
	88.128	386.418	298.29		

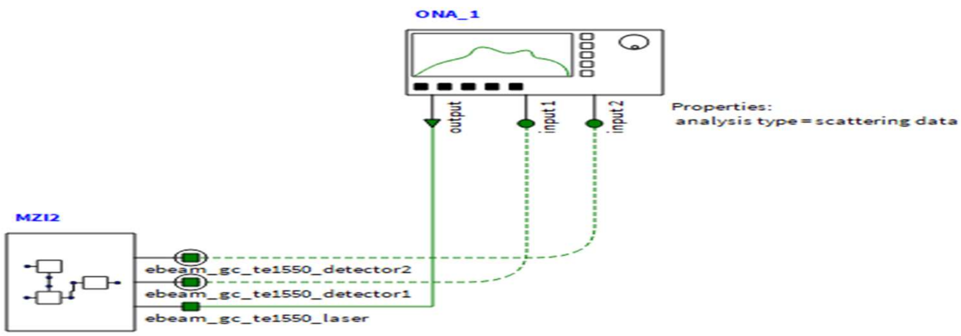

Figure 19. Simulation with Lumerical INTERCONNECT using dc_te_1550

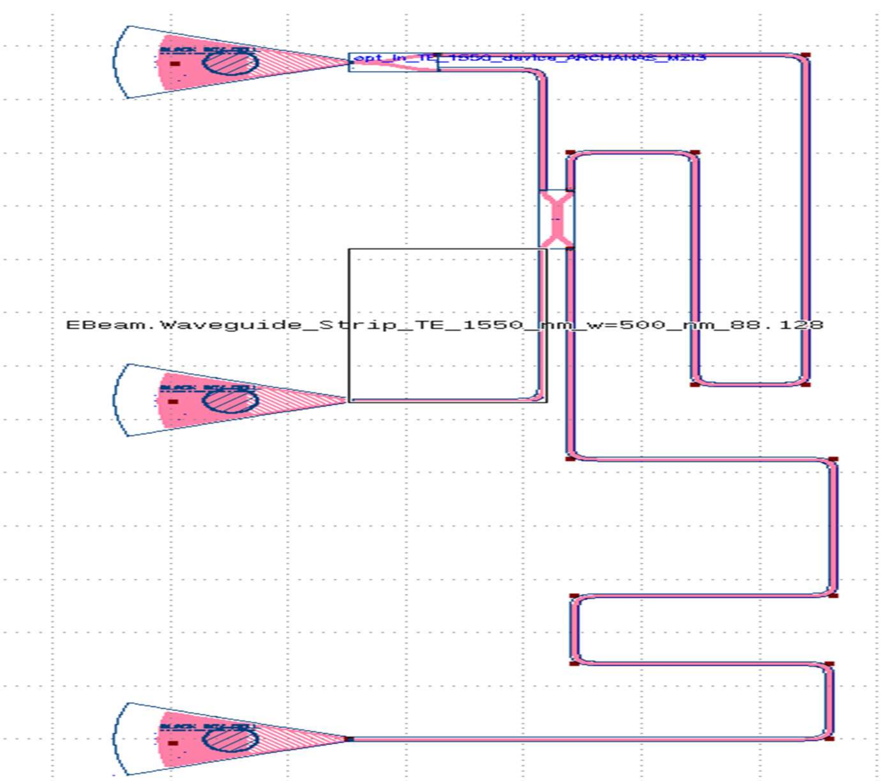

Figure 20. KLayout using dc_te1550 for case i) deltaL

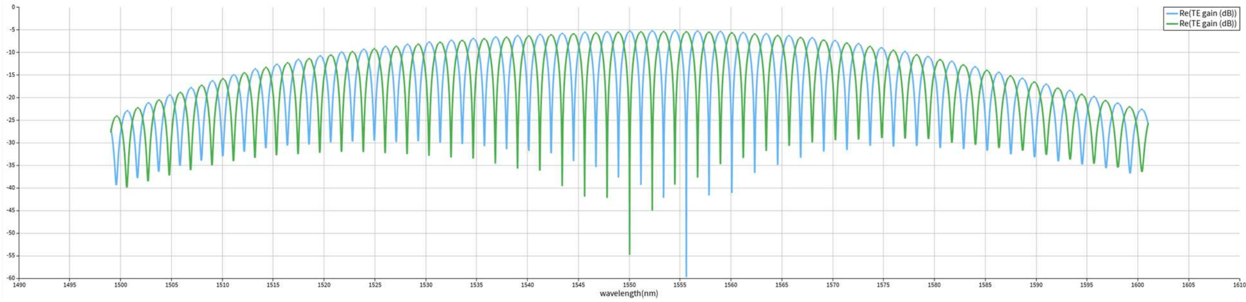

Figure 21.TE Gain a) Blue(input1) b) Green(input2)

The TE Gain observed at 1550nm wavelength for input1 is -5.29dB and for input2 is -29.78dB

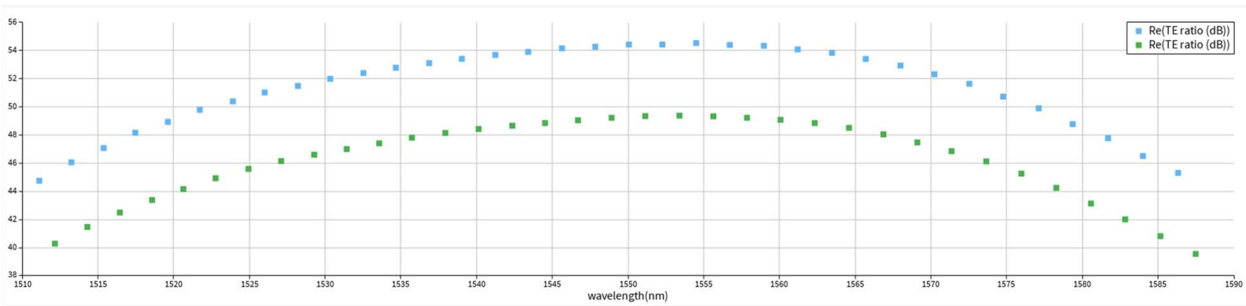

Figure 22. TE Ratio/Extinction Ratio a) Blue(input1) b) Green(input2)

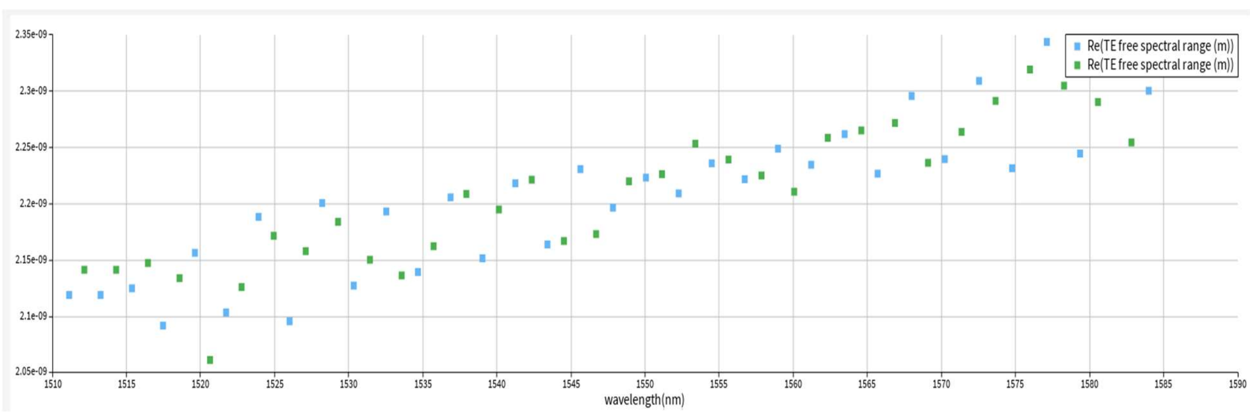

Figure 23. Free Spectral Range a) Blue(input1) b) Green(input2)

The following table illustrates MZI using adiabatic splitter and corresponding FSR is calculated for different lengths of the waveguide

EBeam_adiabatic_te1550	L1(um)	L2(um)	Delta L (um)	FSR (nm) mode 1, input1	FSR (nm) mode 1, input2
Case i)	38.298	222.012	183.714	3.09	9.48
	159.865	99.568	60.297		

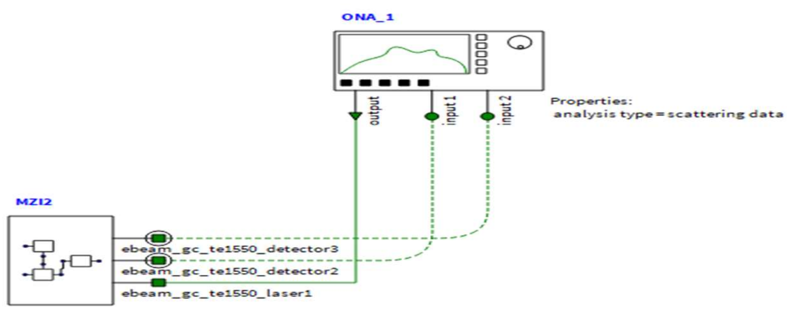

Figure 24. Figure 19. Simulation with Lumerical INTERCONNECT using dc_te_1550

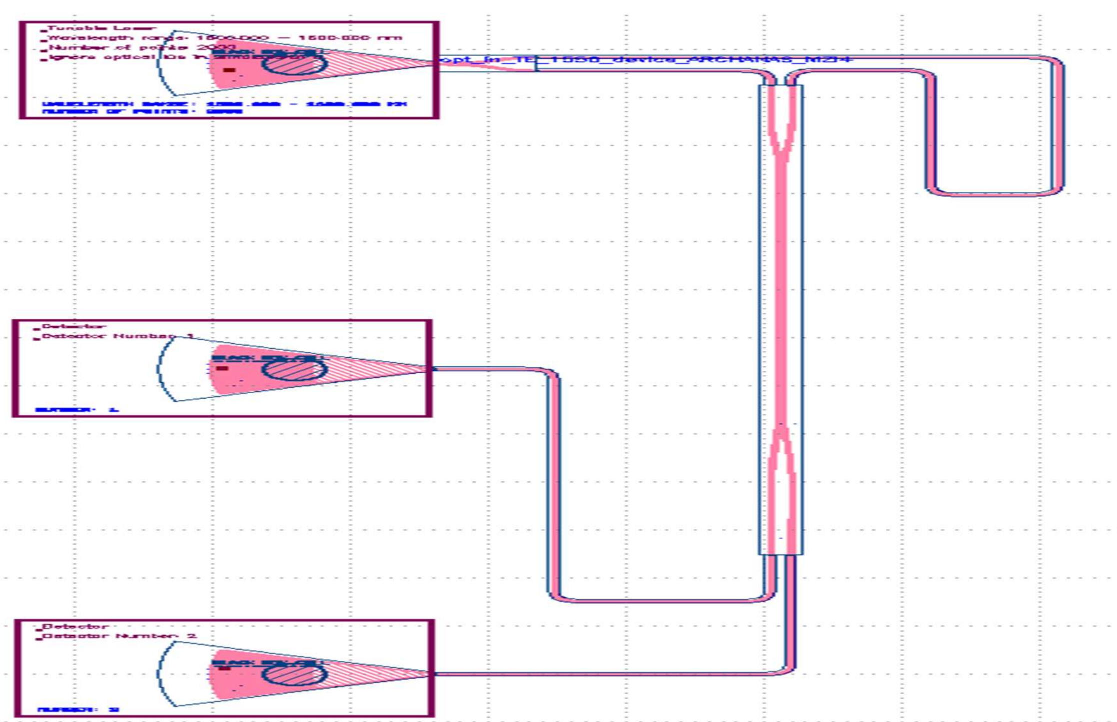

Figure 25. Figure 20. KLayout using adiabatic te1550

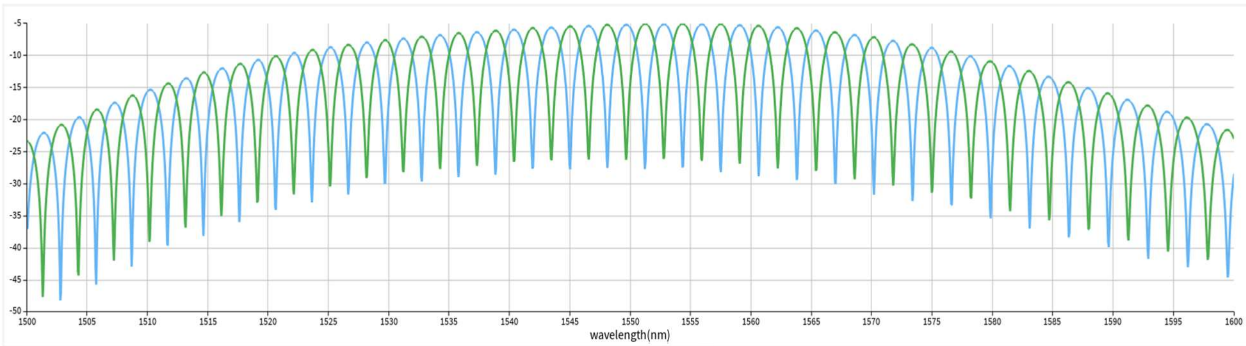

Figure 26. TE Gain a) Blue(input1) b) Green(input2)

The TE Gain observed at 1550nm wavelength for input1 is -5.38dB and for input2 is -13.177dB

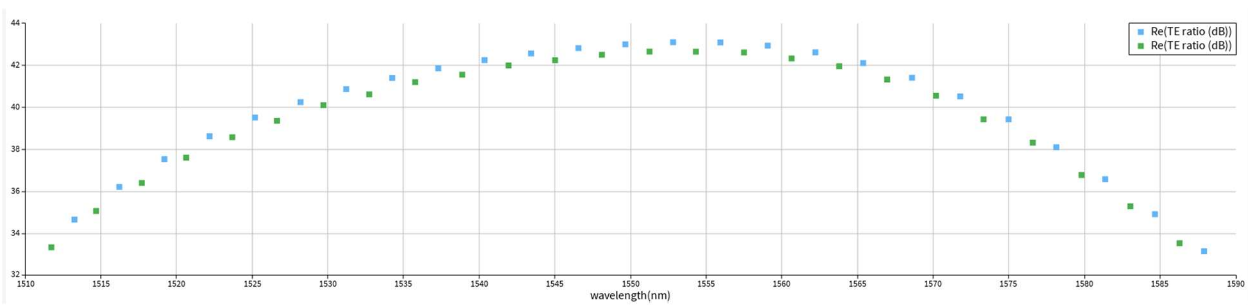

Figure 27.TE Ratio/Extinction Ratio a) Blue(input1) b) Green(input2)

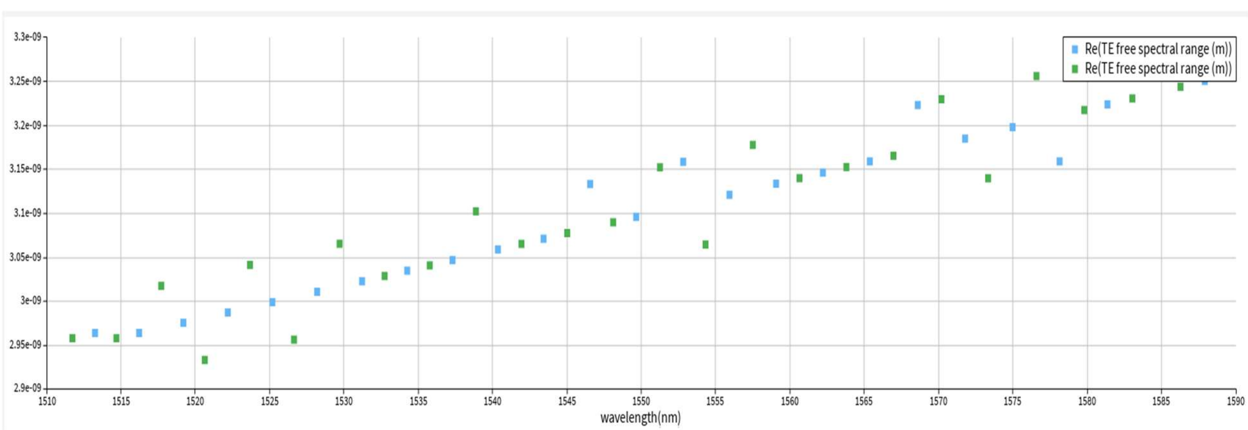

Figure 28.Free Spectral Range a) Blue(input1) b) Green(input2)