Github link: https://github.com/sish1ka/UBC-ELEC413-2025

ELEC 413 Project 1 Draft Design Report

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2.0 Table of Contents

3.0 Project Overview

3.1 Abstract

This project presents the design, simulation, and testing of a silicon photonic integrated circuit that connects a commercial swept tunable laser to a Mach-Zehnder Interferometer (MZI). The device is optimized for operation in the 1310 nm wavelength band with a Dense Wavelength Division Multiplexing (DWDM) channel spacing of 25 GHz. Emphasizing minimal optical loss, the design incorporates balanced 50/50 directional couplers and precisely controlled optical path lengths.

3.2 Design Objective and Specifications

The device is designed to operate at around 1310 nm with a DWDM channel spacing of 25 GHz. The MZI is engineered to have two outputs, allowing the measurement of transmission spectra with minimal insertion loss (targeting around 0.x dB). The waveguide dimensions and materials are selected according to the fabrication process, using silicon as the core and silicon dioxide (SiO_2) as the cladding. Key waveguide parameters such as the effective index (n_eff), group index (n_g), dispersion (D), and propagation loss are determined through simulation. In the MZI, the lengths of the two arms (L1 and L2) are designed to include a deliberate optical path difference (ΔL) of approximately 1 mm, which directly sets the free spectral range (FSR) via the relation $FSR = c/(n_g \times \Delta L)$.

3.3 Optical Modeling and Layout Design

Optical modeling was performed to determine the waveguide properties, ensuring that the selected dimensions support single-mode operation at 1310 nm. Mode solvers were used to extract parameters such as n_eff and n_g, which in turn informed the design of the MZI. The interferometer itself consists of a splitter and a combiner, both implemented as directional couplers engineered to provide a 50/50 power split with minimal loss. Finite-difference time-domain (FDTD) simulations were used to optimize the coupler's length and gap, ensuring robust performance over the operating wavelength range. Figure 3.1 describes the overall model of the optical modeling, Figure 3.2, 3.3, 3.4 describes the graph of effective index, loss, and group index of the model respectively. Figure 3.5 describes the E-intensity in the log scale.

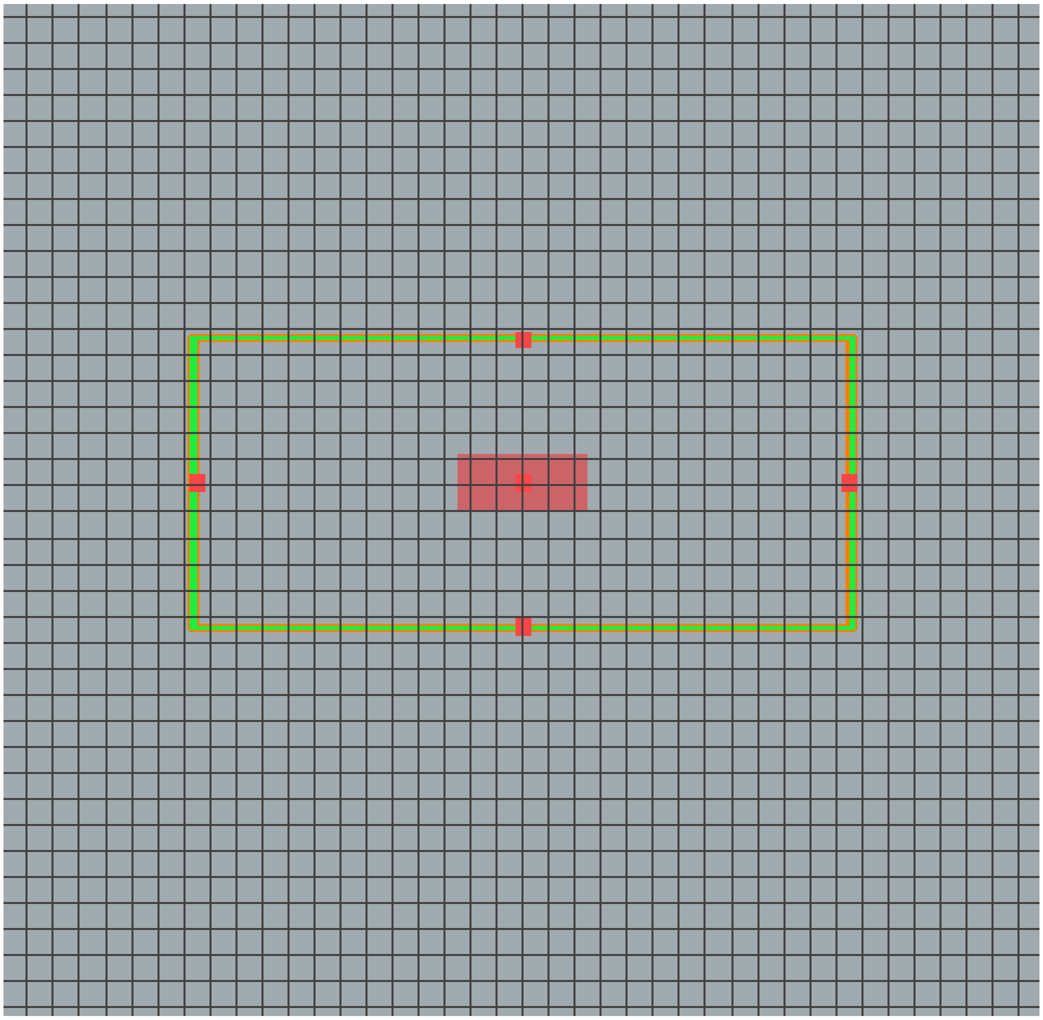


Figure 3.1

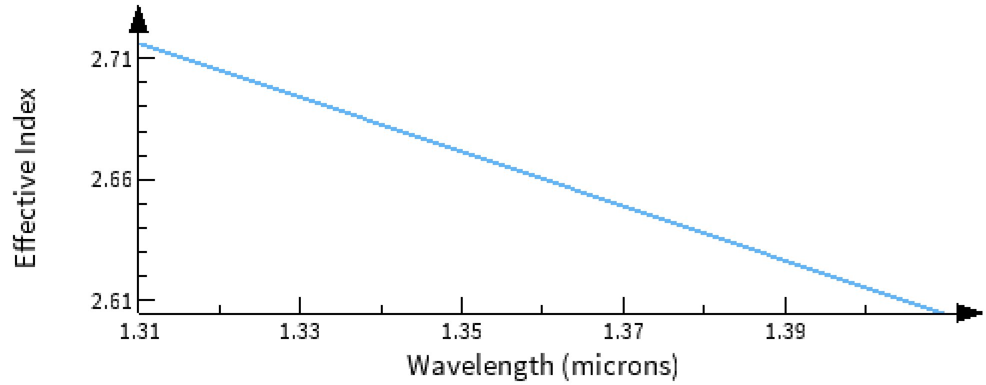


Figure 3.2

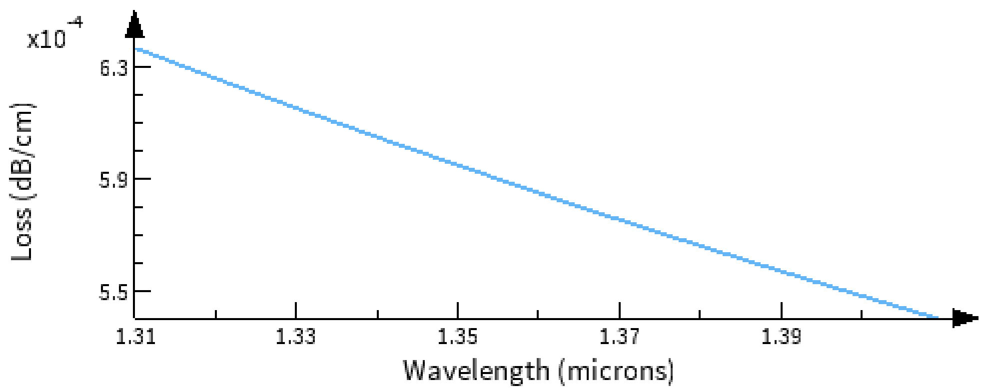


Figure 3.3

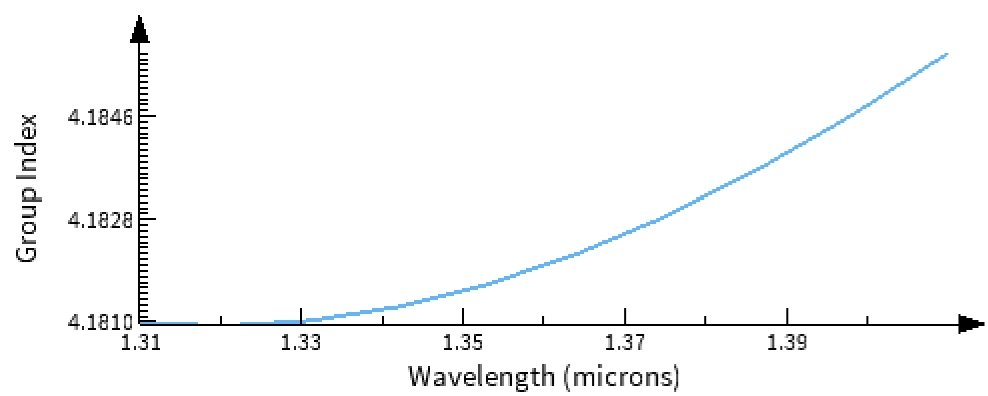


Figure 3.4

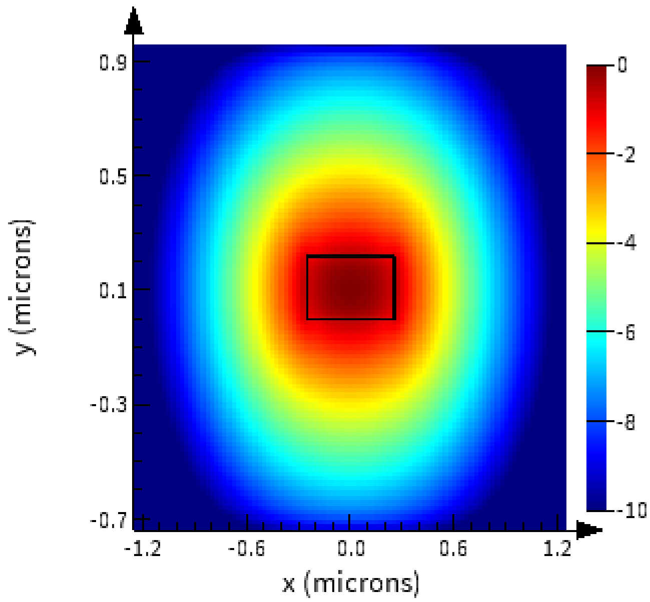


Figure 3.5

Eigensolver Analysis

Mode list

mode #	effective index	wavelength (µm)	loss (dB/cm)	group index	TE polarization fraction (Ex)	waveguide TE/TM fraction (%)	effective area (µm^2)
1	2.716522+1.529197e-09i	1.31	0.00063707	4.181021+3.462133e-09i	99	82.54 / 83.82	0.134173
2	2.164928+1.480281e-09i	1.31	0.00061669	4.695887+4.949953e-09i	4	60.18 / 91.08	0.230239
3	1.823261+1.507214e-09i	1.31	0.00062791	4.717190+7.920605e-09i	87	60.99 / 90.58	0.27606
4	1.581783+1.191964e-09i	1.31	0.00049658	4.172664+8.601641e-09i	28	86.8 / 55.01	0.425797
5	1.391524+1.715227e-10i	1.31	7.1457e-05	1.654335+3.357709e-10i	97	97.91 / 94.29	2.37998
6	1.383572+1.497787e-10i	1.31	6.2398e-05	1.633374+1.161993e-10i	3	95.01 / 94.46	2.22428
7	1.380990+1.628079e-10i	1.31	6.7826e-05	1.667692-2.873519e-10i	0	95.2 / 92.65	2.82478
8	1.358378+1.588678e-10i	1.31	6.6185e-05	1.673016-7.288471e-10i	99	92.61 / 94.03	1.8116

Figure 3.6

The simulation result gives $n_g = 4.181021$ as shown in figure 3.6. Since the specification for the project is $FSR = 2.5\,GHz$, we can now use the equation below.

$$\Delta L = \frac{c^2}{n_g * FSR} = \frac{3*10^8}{4.181021*2.5*10^9} = 2.87011 * 10^{-3} m = 2.87011mm$$

This indicate that total length of the waveguides that form the two arms of the MZI from the point of splitting to the point of recombination is approximately $2.87011mm$. After forming the spiral waveguide in Klayout, I adjusted the total length accordingly and the closest value I could get to was $2.87014mm$, which I assume to be appropriate since it has an error of less than 0.01%. Figure 3.7 indicates the total length estimate of the spiral.

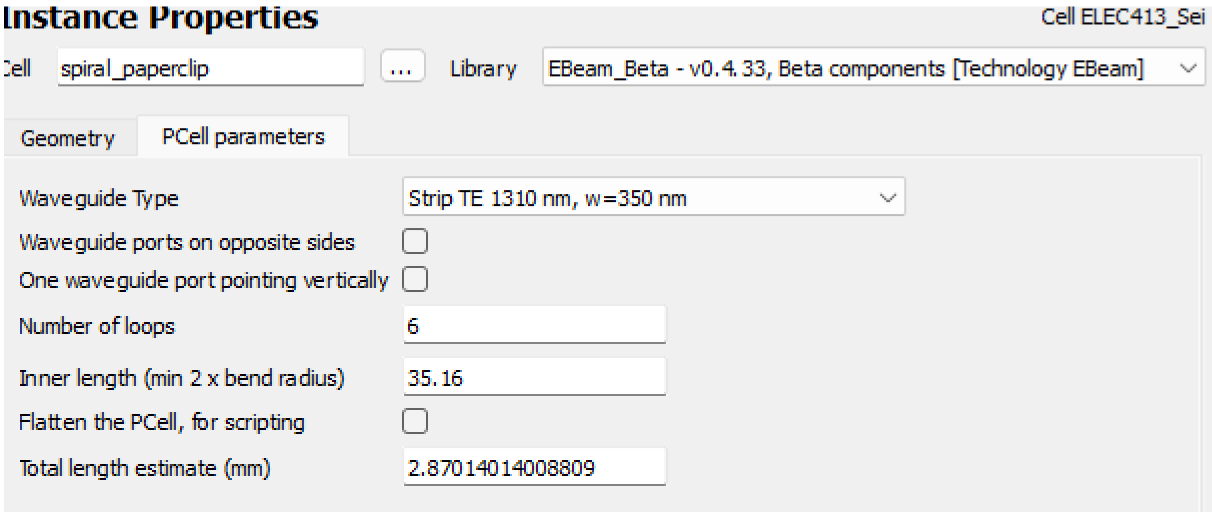
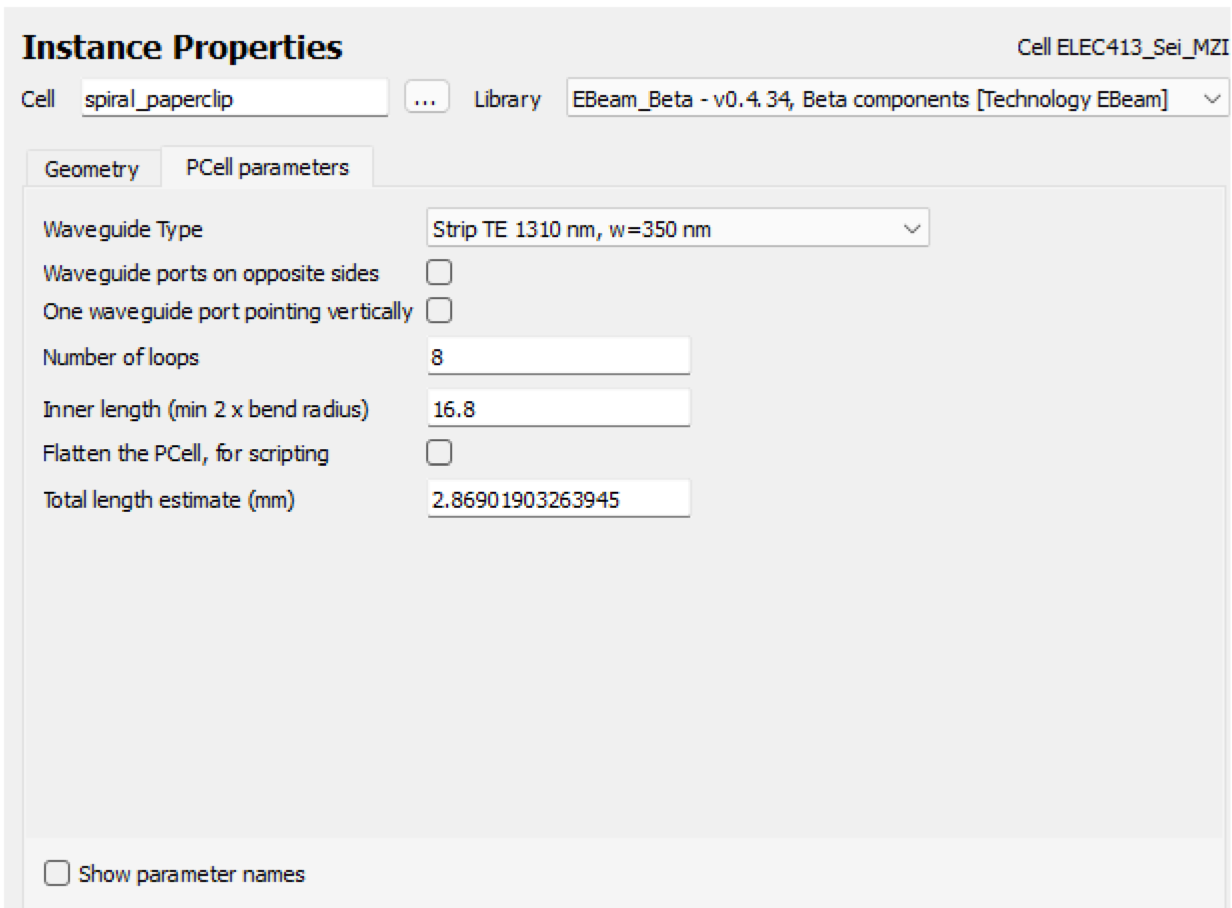


Figure 3.7



When designing the spiral, I made sure to increase the number of loops for maximum efficiency and less space coverage.

3.4 Fabrication and Testing

Before submitting the design for fabrication, the layout was rigorously checked using KLayout's Design Rule Check (DRC) tools to ensure full compliance with the fabrication process. Critical alignment markers, text labels, and layer assignments were added as required by the process guidelines. The layout is indicated as figure 3.8. As assigned in the project description, the MZI filter has 1 laser input and 2 outputs. After confirming that the verification had no errors, I then simulated on Ansys LUMERICAL to observe the TE gain and wavelength attribute.

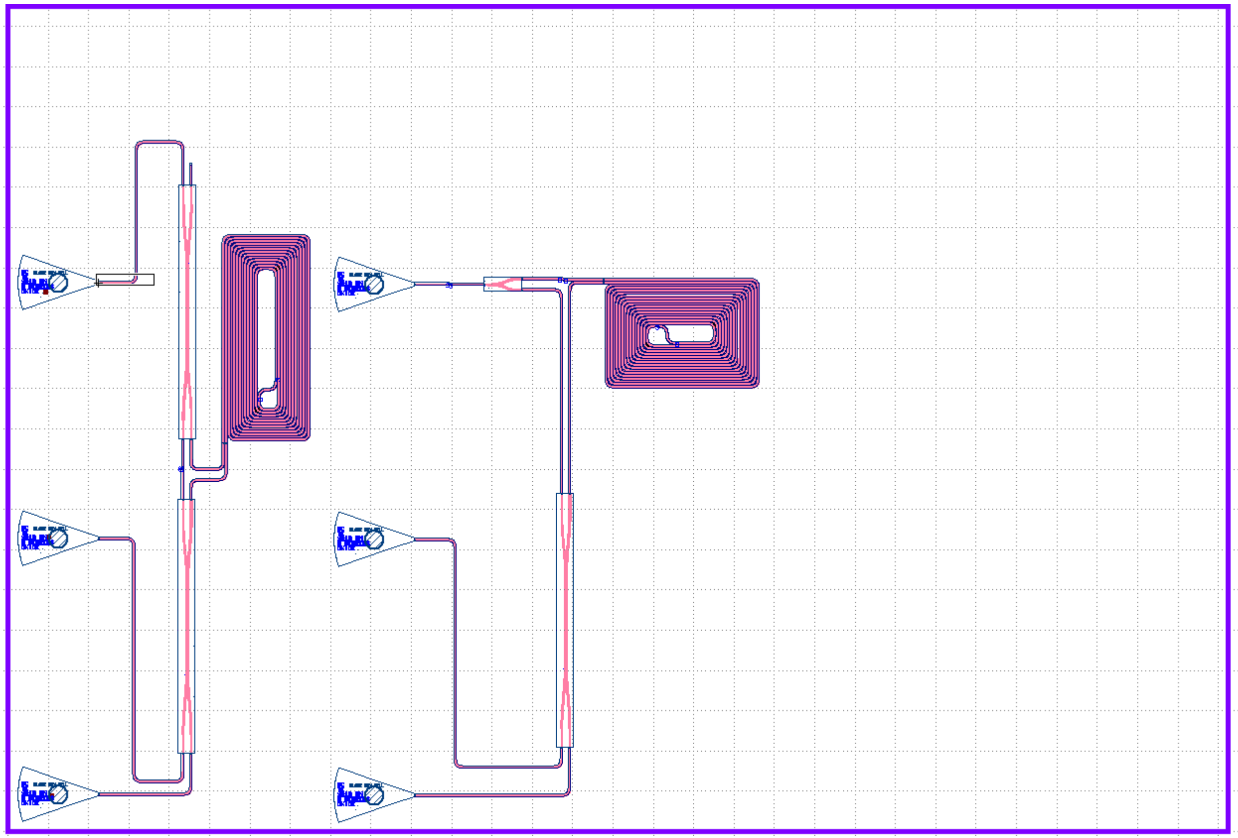
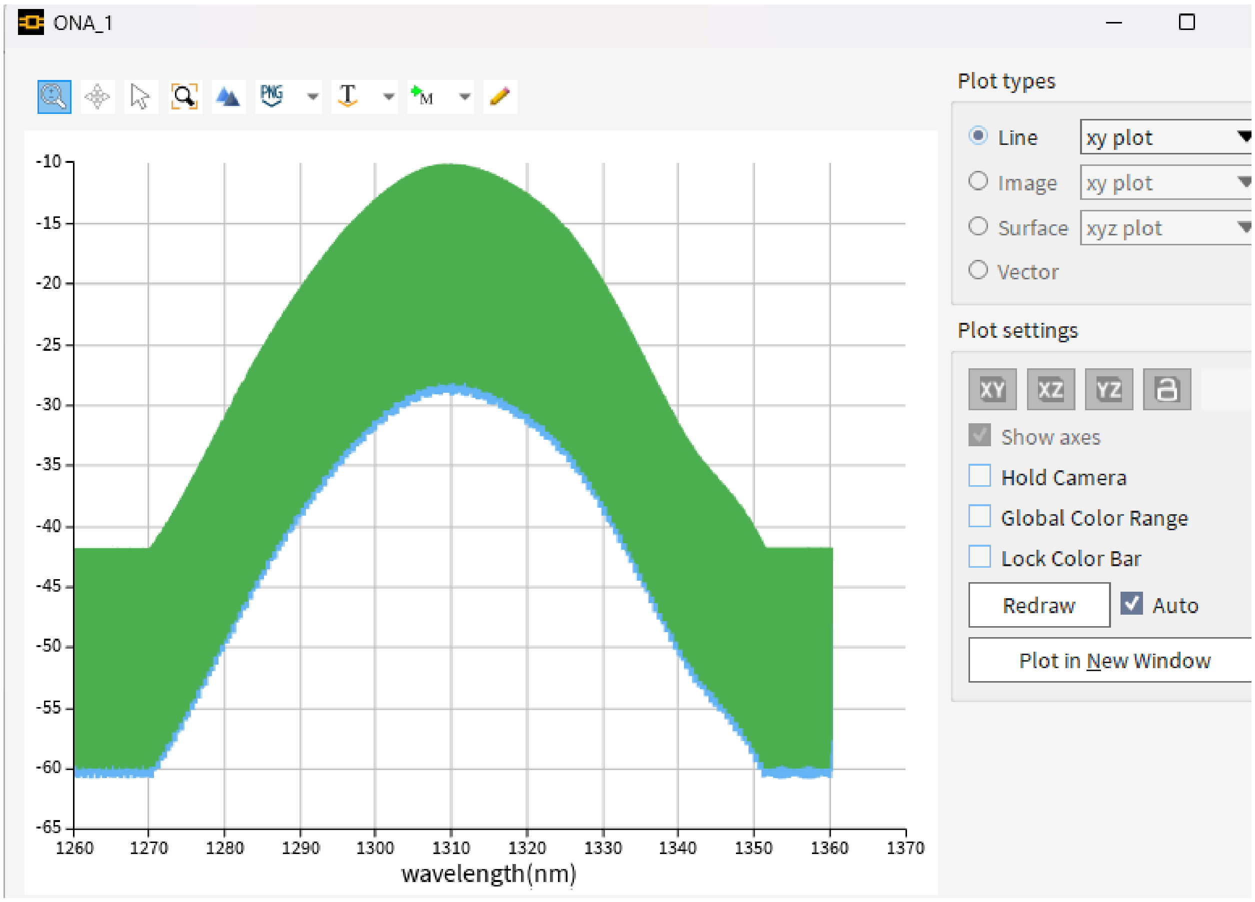


Figure 3.8

Figure 3.9 is the relationship between gain(dB) and wavelength as simulated in LUMERICAL.



ONA_1
Plot types
Line
xy plot
Image
xy plot
Surface
xyz plot
Vector
Plot settings
XY
XZ
YZ
Show axes
Hold Camera
Global Color Range
Lock Color Bar
Redraw
Auto
Plot in New Window
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
-60
-65
1260
1270
1280
1290
1300
1310
1320
1330
1340
1350
1360
1370
wavelength(nm)

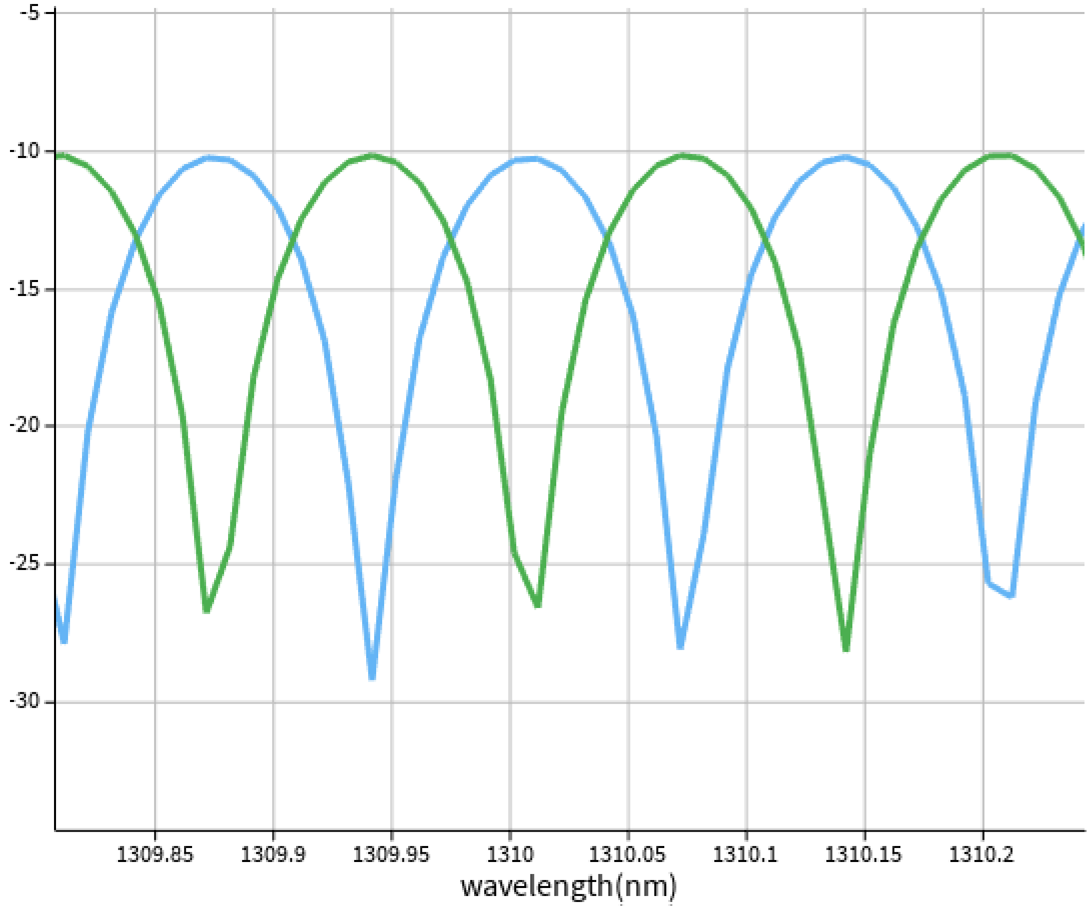


Figure 3.9

As can be seen from the graph, the transmission came out to be approximately -10dB for output 1 transmission and -27dB for output 2 transmission. Figure 3.10 is the MZI transmission graph with 25GHz FSR simulated through matlab.

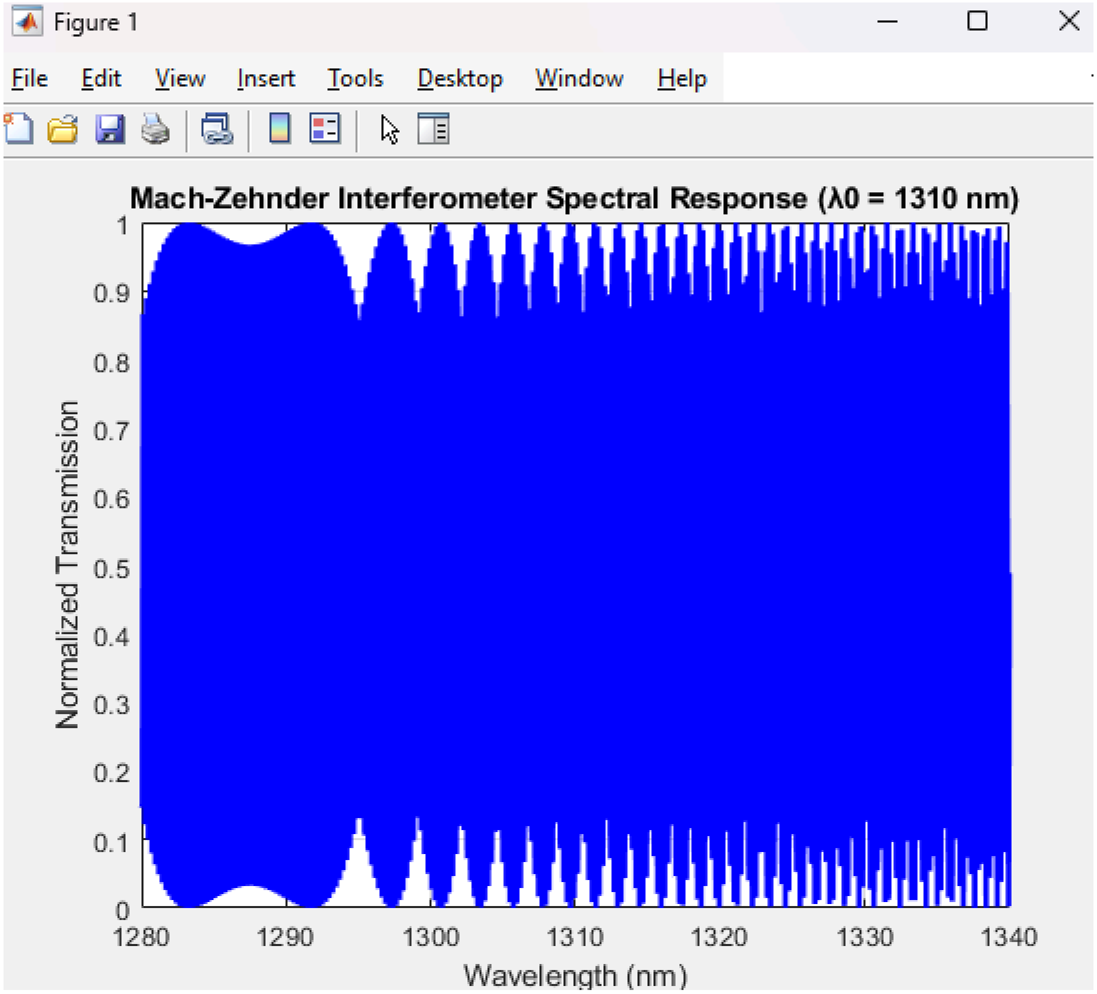


Figure 3.10

3.5 Discussion and Conclusion

The successful design of this Mach-Zehnder Interferometer demonstrates the importance of precision in waveguide routing, coupler design, and overall layout planning. Achieving a 25 GHz channel spacing at 1310 nm required meticulous control of the optical path length difference and the use of low-loss directional couplers. The project highlighted several challenges, including the need to maintain smooth waveguide transitions and to adhere to strict fabrication tolerances. Through careful simulation and verification, a design with minimal optical loss was achieved, laying the groundwork for future testing and characterization. In conclusion, the project effectively integrates the design, simulation, and layout processes required for developing a silicon photonic circuit that meets both performance and fabrication requirements for DWDM applications.

3.6 Codes and Calculations

delta_L calculation

```
%-------------------------------------------------------------
% MATLAB Code to Compute delta_L for a Mach-Zehnder Interferometer
% Using the formula: delta_L = c/(n_g * FSR)
%-------------------------------------------------------------
% Clear workspace and command window
clear;
clc;
% Define constants
c   = 3e8;      % Speed of light in vacuum (m/s)
FSR = 25e9;     % Free Spectral Range in Hz (25 GHz)
ng  = 4.181021;      % Group index (adjust as needed)
% Calculate the interferometer length delta_L
delta_L = c / (ng * FSR);
% Display the result
fprintf('Computed delta_L = %e meters\n', delta_L);
```

Table 3.1

```
clear; clc;
%% 1. Define Constants and Operating Parameters
c = 3e8;                  % Speed of light in vacuum (m/s)
lambda0 = 1310e-9;        % Operating wavelength (m) = 1310 nm
FSR = 25e9;               % Free Spectral Range in Hz
%% 2. Waveguide Simulation Parameters
% Fixed thickness and design parameter width (default 350 nm)
thickness = 220e-9;       % Waveguide thickness in meters (220 nm)
width_default = 350e-9; % Default waveguide width in meters (350 nm)
width = width_default;  % Use default width (modify as needed)
% --- Compact Model for Waveguide Mode ---
% For more accurate designs, use Lumerical MODE to extract these values.
% Here we assume typical values for a silicon waveguide:
n_eff = 2.3;  % Effective index (dimensionless)
n_g   = 4.0;  % Group index (dimensionless)
% --- Estimate Waveguide Loss ---
% Model the loss by assuming a small imaginary part (n_im) in the effective
index.
% The power attenuation coefficient is:
%    alpha = (4*pi*n_im) / lambda0   [in m^-1]
n_im = 1e-5;                   % Assumed imaginary part of n_eff
alpha = (4*pi*n_im) / lambda0; % Attenuation coefficient (m^-1)
% Convert the attenuation coefficient to dB/cm:
loss_dB_cm = 4.343 * alpha * 1e-2;
fprintf('--- Waveguide Simulation Results ---\n');
fprintf('Operating wavelength: %.0f nm\n', lambda0*1e9);
fprintf('Thickness: %.2f nm\n', thickness*1e9);
fprintf('Width: %.2f nm\n', width*1e9);
fprintf('Effective Index (n_eff): %.4f\n', n_eff);
fprintf('Group Index (n_g): %.4f\n', n_g);
fprintf('Estimated Loss: %.4f dB/cm\n\n', loss_dB_cm);
%% 3. Interferometer (MZI) Circuit Model
```

```
% For an MZI filter with a target FSR of 25 GHz, the required path-length
difference is:
%    Delta L = c / (n_g * FSR)
deltaL = c / (n_g * FSR);  % Path-length difference in meters
fprintf('--- Interferometer Design ---\n');
fprintf('Path-length Difference (Delta L): %.2f um\n\n', deltaL*1e6);
% --- MZI Spectral Response ---
% For a balanced Mach-Zehnder interferometer, the normalized transmission as a
function
% of wavelength is given by:
%    T(λ) = 0.5 * [1 + cos((2*pi*n_eff*Delta L)/λ)]
%
% Define a wavelength range for the simulation (for example, from 1280 nm to
1340 nm)
lambda_range = linspace(1280e-9, 1340e-9, 1000);  % Wavelength range in meters
% Calculate the phase difference for each wavelength:
phi = (2*pi*n_eff*deltaL) ./ lambda_range;
% Calculate the normalized transmission:
T = 0.5 * (1 + cos(phi));
%% 4. Plot the Spectral Response of the MZI
figure;
plot(lambda_range*1e9, T, 'b-', 'LineWidth', 2);
xlabel('Wavelength (nm)');
ylabel('Normalized Transmission');
title('Mach-Zehnder Interferometer Spectral Response (λ0 = 1310 nm)');
grid on;
```

Table 3.2

3.7 References

Snyder, A. W., & Love, J. D. (1983). *Optical Waveguide Theory*. Chapman and Hall.

Saleh, B. E. A., & Teich, M. C. (2007). *Fundamentals of Photonics* (2nd ed.). Wiley.

Yariv, A., & Yeh, P. (2007). *Photonics: Optical Electronics in Modern Communications* (6th ed.). Oxford University Press.

Table 3.3