[DRAFT] Design of a 25 GHz Free Spectral Range Wavelength Division Multiplexer Using Silicon on Insulator Technology

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***Abstract*—This document presents the design, simulation, and testing of an optical wavelength division multiplexer with a free spectral range of 25 GHz implemented as a Mach Zehnder Interferometer. The design process covers background, modeling, simulations and layout.**

***Index Terms*—Mach Zehnder Interferometer (MZI), Silicon on Insulator (SOI), Wavelength Division Multiplexer (WDM)**

I. Introduction

This document provides the design process for a wavelength division multiplexer using a mach-zehnder interferometer at the O-Band wavelength of $\lambda = 1310$ nm.

The wavelength division multiplexer is realized using an unbalanced Mach Zehnder Interferometer topology, which consists of a beam splitter at the input port followed by waveguide arms with unmatched length ΔL then a combiner into the output ports.

The transfer function of the MZI, assuming lossless waveguides is given by:

$$\frac{I_o}{I_i} = \frac{1}{2}\left[1 + cos(\beta_1 L_1 - \beta 2 L_2)\right]$$

The designs in this document uses a MZI with equal effective index n_{eff} and a path length difference ΔL between the arms. In this case the MZI transfer function is given by:

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

The free spectral range ΔL of the equal waveguide is approximated by the following equation:

$$\Delta\lambda \approx \frac{\lambda^2}{n_g \Delta L}$$

The free spectral range can also be expressed in terms of frequency, in Hz using the following equation:

$$\Delta\nu \approx \frac{c}{n_g \Delta L}$$

Where c is the speed of light in vacuum. In the FSR equation given above, only the group index is unknown given the target FSR of 25 GHz in order to determine the required ΔL of the MZI. The next step of the design is to determine the group index n_g by first using the effective index method, then using *Ansys Lumerical MODE* eigenmode solver to determine the group index of the waveguide TE fundamental mode.

II. Waveguide Modeling

A. Effective Index Method

The effective index method is an efficient algorithm that can be used to get a first approximation of the effective index n_{eff} and group index n_g of a waveguide given its dimensions using the method of separation of variables to independently solve each dimension of the waveguide cross section to produce a full 2D profile of the field intensity in the waveguide.

The matlab script *wg_EIM_profile_main.m* provided in the course is used with the following input parameters below:

1) λ = 1310 nm
2) Waveguide height = 220 nm
3) Waveguide width = 350 nm
4) SiO_2 Cladding and Buried Oxide material
5) Si waveguide material

The effective index method yield the following effective index for the fundamental TE mode:

$$n_{eff} = 2.4594$$

The group index is determined by changing the wavelength input to the *wg_EIM_profile_main.m* script by $\Delta\lambda$, then approximating $\frac{dn_{eff}}{d\lambda}$ like so:

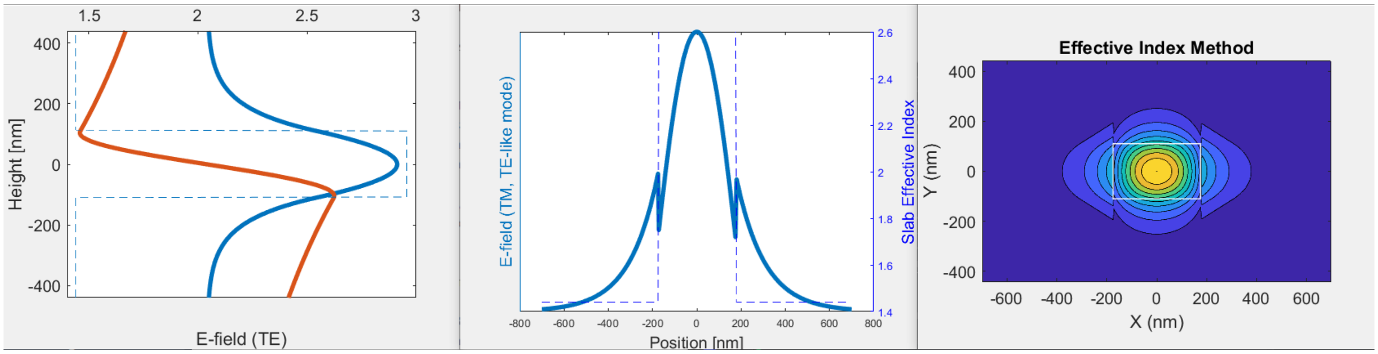

Fig. 1. (Left) Vertical field profile. (Middle) Horizontal field profile. (Right) Combined 2D waveguide field intensity profile.

$$\frac{dn_{\text{eff}}}{d\lambda} \approx \frac{n_{\text{eff}}(\lambda + \Delta\lambda) - n_{\text{eff}}(\lambda - \Delta\lambda)}{2\Delta\lambda}$$

$$n_g = n_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}$$

The group index approximation is found:

$$n_g = 4.0130$$

The field profile for the separate dimensions and the combined intensity profile is visualized in Fig. 1.

Finally, the path length difference using the effective index method is found:

$$\Delta\lambda = 2.988 \text{ mm}$$

B. Lumerical MODE Simulation

The next step is to approach a closer estimation of the group and effective indices using more computationally heavy numerical methods. The eigenmode solver provided by *Ansys Lumerical MODE* is used to find the effective and group indices of the supported modes in the waveguide structure using FEA techniques. The numbers generated by *Ansys Lumerical MODE* is more accurate than the effective index method as it considers material dispersion and field profiles are solved without fully decoupling the 2D cross section of the waveguide. It will be seen later that the modes are quasi-TE or quasi-TM, where the E and H fields are not fully in transverse in the transverse plane.

The setup for *Lumerical MODE* begins by defining the stackup and geometry of the waveguide. The stackup is taken from the fabrication plant website Applied Nanotools. The stackup is summarized below:

1) Cladding SiO_2: 2.2 μm
2) Waveguide Si: 220 nm
3) Buried Oxide SiO_2: 2 μm

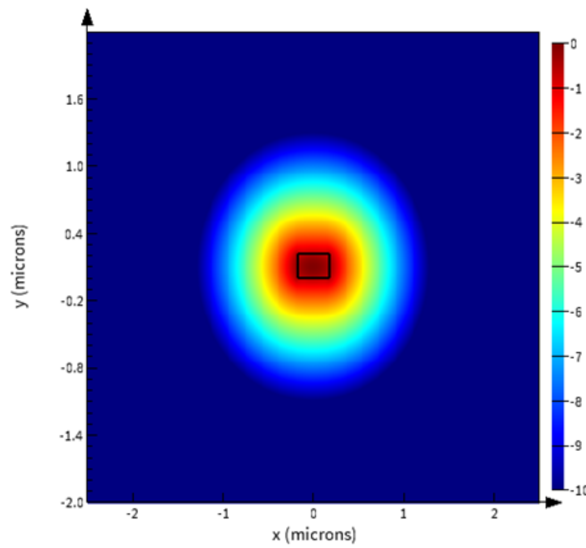

Fig. 2. Fundamental Mode Intensity Profile at 1310 nm, W = 350 nm, H = 220 nm.

After the stackup and geometry is defined, modal analysis is performed which comes up with a list of supported modes in the waveguide. Of course, only the fundamental mode is of interest in this design. The list of modes and their properties such as effective index, group index and TE/TM fraction is generated. Additionally, intensity of the fields can be visualized to determine spacing between waveguides to avoid coupling as shown in Fig 2. It can be seen that the field intensity is dissipated by -8 dB after 1 μm distance from the waveguide.

The fundamental TE mode is found to have the following group and effective index which yields the required path length difference for 25 GHz FSR in the MZI design.

$$\boxed{\begin{aligned} n_{\text{eff}} &= 2.432 \\ n_g &= 4.497 \\ \Delta\lambda &= 2.667 \text{ mm} \end{aligned}}$$

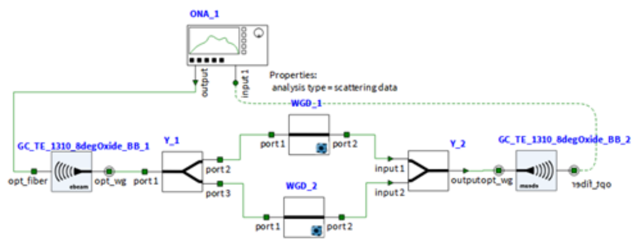

Fig. 3. Ansys Lumerical Interconnect Schematic Setup.

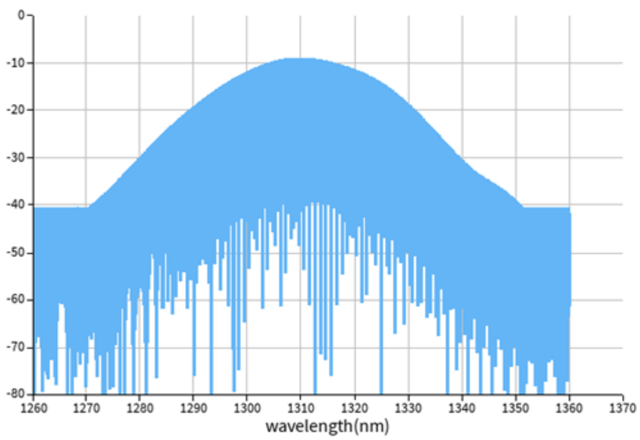

Fig. 4. Zoomed Out MZI Response.

Finally, a frequency sweep from 1260 to 1360 nm is performed and a model of the waveguide is exported for use in *Ansys Lumerical INTERCONNECT* in the next section.

III. Circuit Simulation

Ansys Lumerical INTERCONNECT is used to simulate a schematic formulation of the MZI design. The schematic layout consists of a 1310 nm TE grating coupler provided by the *SiEPIC EBeam* compact model library, the waveguide model generated from the previous section using *Lumerical MODE* and an ideal Y-Branch splitter taken from the default library that comes with *Lumerical INTERCONNECT* as shown in Fig 3.

An Optical Network Analyzer interfaces with the grating couplers to provide input and output to the MZI circuit. The simulation results show the logarithmic plot of the full MZI response enveloped by the grating coupler response as shown in Fig 4.

Zooming in around the target 1310 nm wavelength, the periodic nature of the MZI transfer function can be seen as shown in Fig 5.

The free spectral range is extracted from the design and yields a value close to the target 25 GHz FSR:

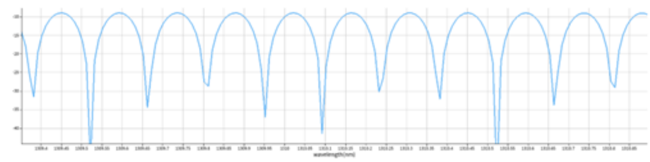

Fig. 5. Zoomed In MZI Response.

$$FSR = 24.49Ghz$$

The next step is to perform the layout of the design using *KLayout* and to directly simulate the netlist generated from *KLayout* in *Lumerical INTERCONNECT* using the provided *SiEPIC* tools in the course.

IV. Design Topology

Two different topologies are explored to realize the MZI with the target FSR of 25 GHz, both of which are discussed in this section.

A. Paperclip Design

The paperclip design uses the paperclip primitive provided in the *SiEPIC EBeam Beta* components library. The paperclip design provides a compact form factor of the MZI design. The layout is shown in Fig 6.

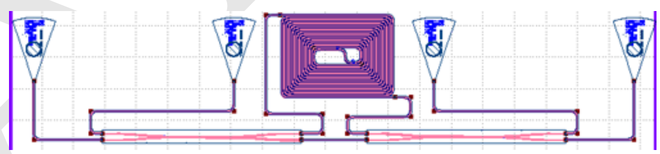

Fig. 6. Paperclip Design (Rotated 90^o CW).

B. Meander Line Design

The meander line design minimizes cross talk by increasing the distance between the waveguides compared to the paperclip design. The layout is shown in Fig 7.

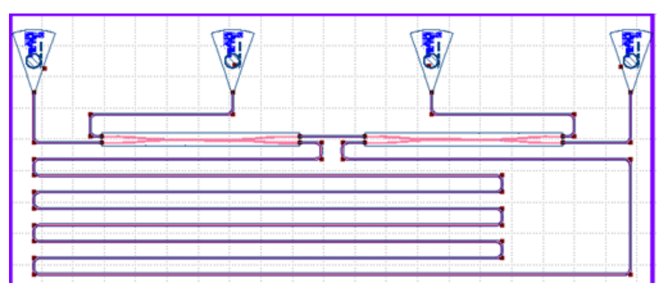

Fig. 7. Meander Line Design (Rotated 90^o CW).

C. Design for Manufacturing

Variations in terms of the path length difference ΔL of the two designs mentioned above are instantiated in the circuit design, filling the entire 605 $\times$ 410 mum space alloted for the design. The full layout is shown in **Appendix A.**

V. Simulation Results

KLayout is used to generate a netlist that is used for co-simulation using *Lumerical INTERCONNECT*. The co-simulation results for both designs are discussed in this section.

A. Meander Line Design

The meander line design is simulated with the FSR shown below. The response of the meander line design is also shown in Fig 8.

$$\boxed{FSR\text{ (Hz)} = 24.495\text{ GHz}}$$

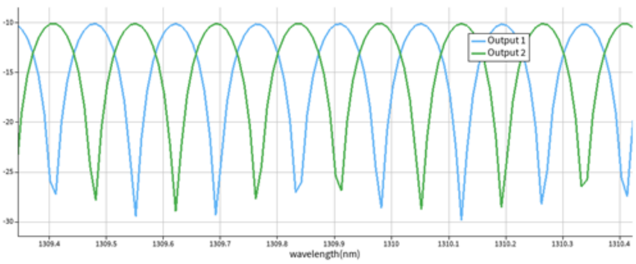

Fig. 8. Meander Line Design Response.

B. Paperclip Design

The paperclip design is simulated with the FSR shown below. The response of the paperclip design is also shown in Fig 9.

$$\boxed{FSR\text{ (Hz)} = 24.492\text{ GHz}}$$

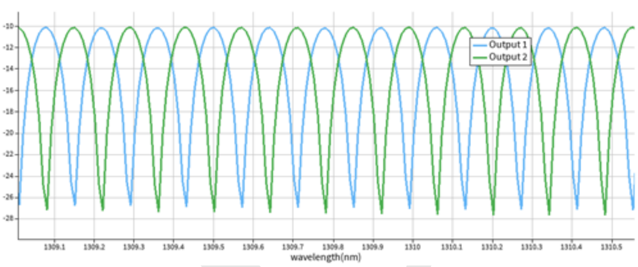

Fig. 9. Paperclip Design Response.

The two outputs are 90^o out of phase and provides the de-multiplexing capabilities of this MZI design.

NOTE: FULL LAYOUT PICTURE AND DESCRIPTION IN THE NEXT PAGE

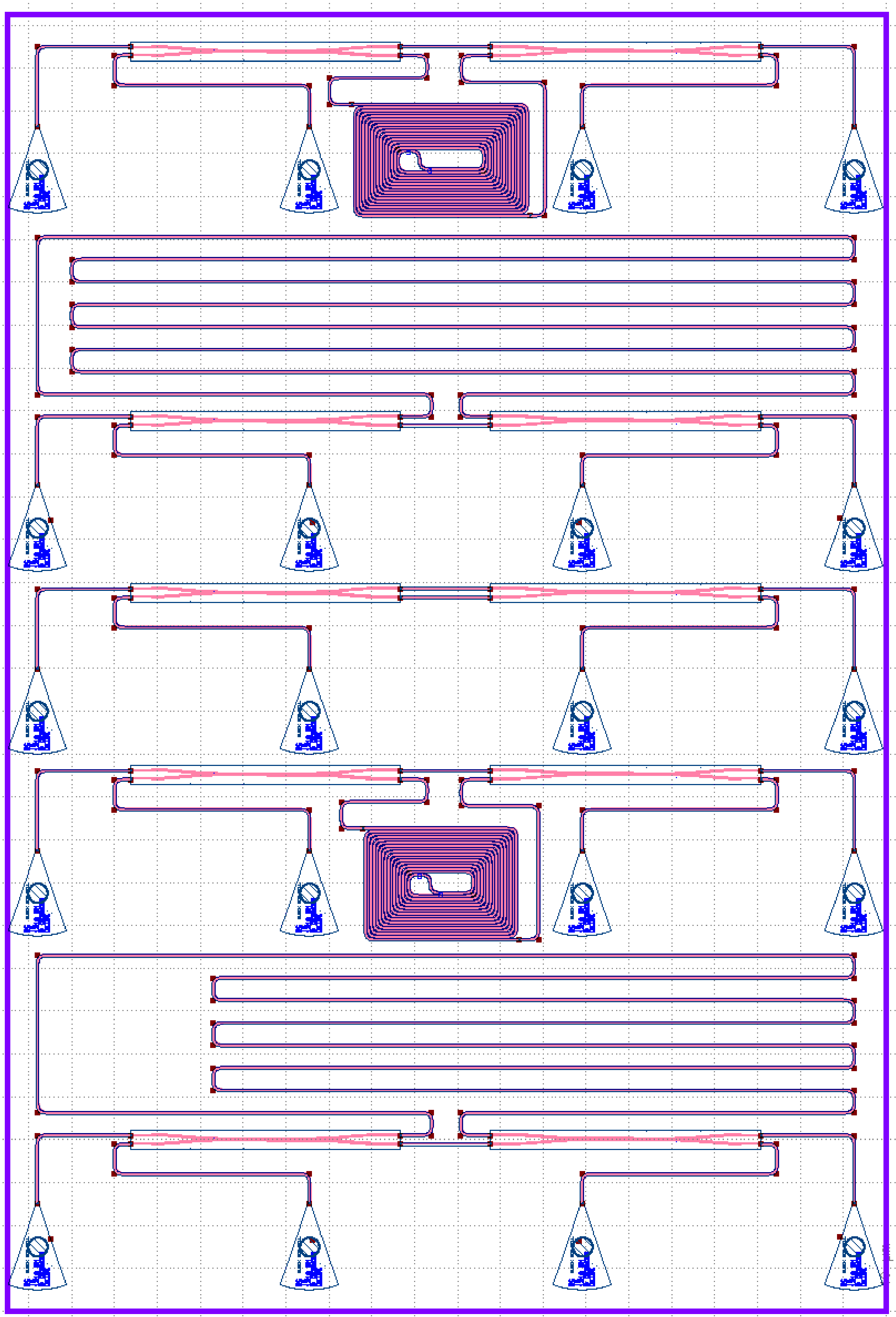

Fig. 10. **Appendix A**: Numbered from bottom(1) to top(5): (1) Meandered line topology designed to minimize crosstalk by incorporating larger spacing between adjacent waveguides; (2) Paperclip topology featuring a compact design, though with a reduced spacing of 1 µm between waveguides; (3) Balanced Mach-Zehnder Interferometer (MZI), which can serve as a calibration reference; (4) A second variation of the meandered line topology with modifications to the path length difference; and (5) A second variation of the paperclip topology, also introducing variations in the path length difference.