Design Proposal: Mach Zehnder Interferometer

Abstract:

This report presents the design analysis of a Mach-Zehnder Interferometer (MZI) with different arm lengths (delay lengths) to study their impact on free spectral range (FSR) and wavelength group index. The MZI transfer function was analyzed for different unbalanced interferometers. The results of the simulations are compared against the results from the experiment.

1. Introduction:

The Mach-Zehnder Interferometer (MZI) is an optical device commonly used to precisely measure and control phase differences between two light paths. It operates by splitting a coherent light beam into two separate paths using a beam splitter. Each path takes a different route, and when the beams are recombined, they interfere with each other. The resulting interference pattern depends on the phase difference between the paths, which can be affected by changes in path length, refractive index, or the presence of a material in one of the arms [Chrostowski, 2015]. In this study, three different waveguide widths—300 nm, 400nm ,500 nm, and 800 nm were tested under TE polarization, and their optical characteristics were analyzed.

2. Theory

The optical properties of a silicon photonic waveguide are characterized by its effective index (n_{eff}) and group index (n_g). The effective index describes the phase velocity of light in the waveguide and depends on the waveguide geometry, material, and operating wavelength. For a given geometry (e.g., 220 nm height and 500 nm width), n_{eff} as a function of wavelength (λ) can be obtained via numerical simulation and fitted using a wavelength compact model [Little 1997]:

$$n_{eff}(\lambda) = n_0 + n_1(\lambda - \lambda_0) + n_2(\lambda - \lambda_0)^2 \qquad (1)$$

where n_0, n_1, and n_2 are fitting coefficients, and λ_0 is a reference wavelength (e.g., 1.55 μm).

The group index n_g quantifies the propagation of optical pulses and is given by:

$$n_g(\lambda) = n_{eff}(\lambda) - \lambda\left(\frac{dn_{eff}}{d\lambda}\right) \qquad (2)$$

This parameter is crucial for determining the spectral response of interferometric devices.

A Mach-Zehnder Interferometer (MZI) consists of two arms of (possibly) different lengths, connected by input and output splitters. When a coherent optical signal enters the MZI, it is split into two paths, accumulates a relative phase shift, and then recombines, producing interference at the output.

For an unbalanced MZI (with a path length difference $\Delta L = L_2 - L_1$), the normalized output intensity as a function of wavelength is:

$$I_{out}(\lambda) = \frac{1}{2} I_{in}\left(1 + \cos\left(\frac{2\pi n_{eff} \Delta L}{\lambda}\right)\right) \qquad (3)$$

The free spectral range (FSR), which is the wavelength spacing between adjacent transmission maxima, is given by:

$$FSR(\lambda) = \frac{\lambda^2}{n_g(\lambda)\Delta L} \quad (4)$$

This relationship allows extraction of the group index from measured or simulated transmission spectra:

$$n_g(\lambda) = \frac{\lambda^2}{FSR(\lambda)\Delta L} \quad (5)$$

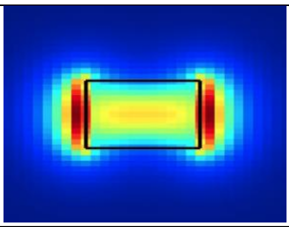
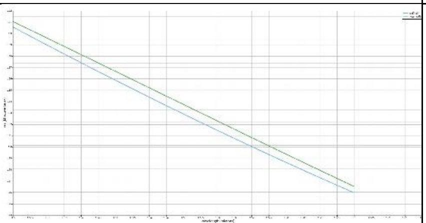
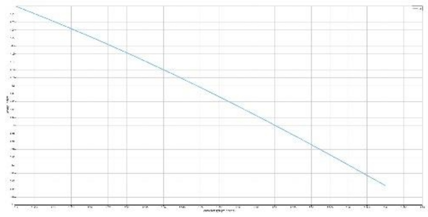
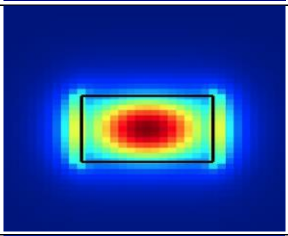
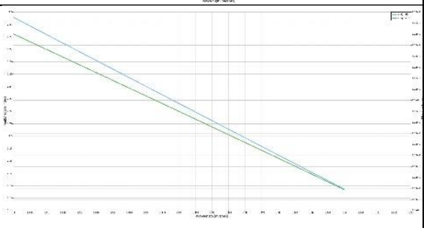
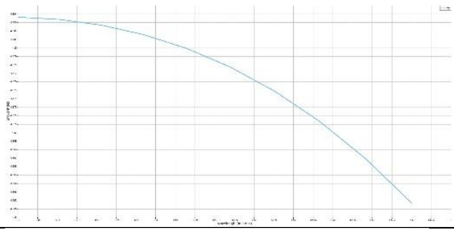
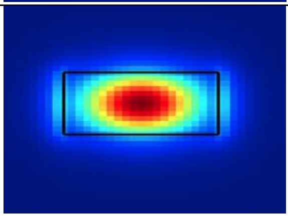
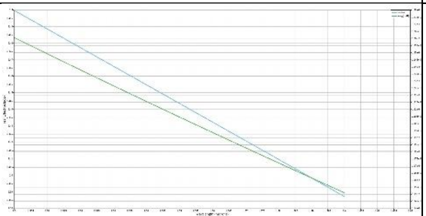
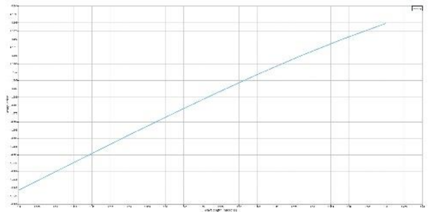
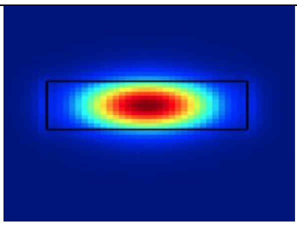
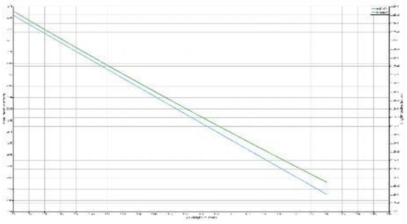
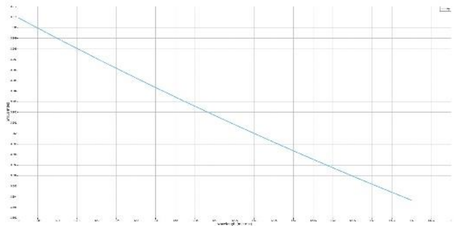
By designing MZIs with different arm length differences (ΔL), one can study how the FSR and group index depend on the waveguide and device parameters.

3. Modelling and Simulation

3.1 Waveguide Geometry and Mode Analysis

The chosen waveguide geometry is a silicon strip waveguide with a height of 220 nm. Waveguides with widths of 300 nm, 400 nm, 500 nm, and 800 nm were studied. The simulated mode profiles for the fundamental transverse electric (TE) mode were obtained using Lumerical MODE Solutions. A wavelength sweep from 1500 nm to 1600 nm was performed to extract the effective index (n_{eff}) and group index (n_g) of the fundamental TE mode. The results are shown in Figure 1.

Table 1: Simulated effective index (n_eff) and group index (n_g) versus wavelength for the fundamental TE mode.

Waveguide width (nm)	Te polarization	Effective index	Group index
300			
400			
500			
800			

3.2 Parameter Sweep and Results

A set of MZI designs with different path length imbalances (ΔL) was simulated. Table 2 summarizes the parameter variations and the corresponding simulated FSR values and group index values at 1550nm. The screenshot of all the MZI designs with varying delay length is shown in the figure below.

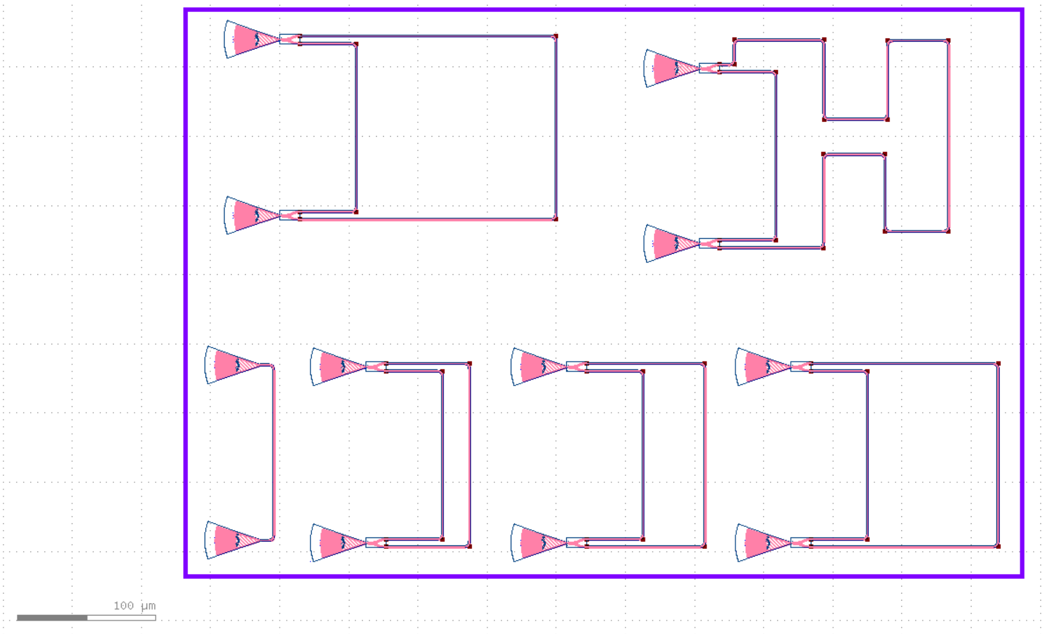


Figure 1: MZI design using KLayout

Table 2: FSR and group index for different delay length of MZI

ΔL(μm)	FSR	n_g
500	1.143E-9	4.150
300	1.903E-9	4.208
200	2.885E-9	4.164
100	5.674E-9	4.234
50	1.171E-8	4.103

In conclusion, the simulations of the Mach-Zehnder Interferometer (MZI) designs with varying decay length/ path length imbalances (ΔL) and the relationship between the free spectral range (FSR) and the group index (n_g) is studied. As observed from the results summarized in Table 2, the FSR decreases as the delay length increases, with corresponding variations in the group index values at 1550 nm.

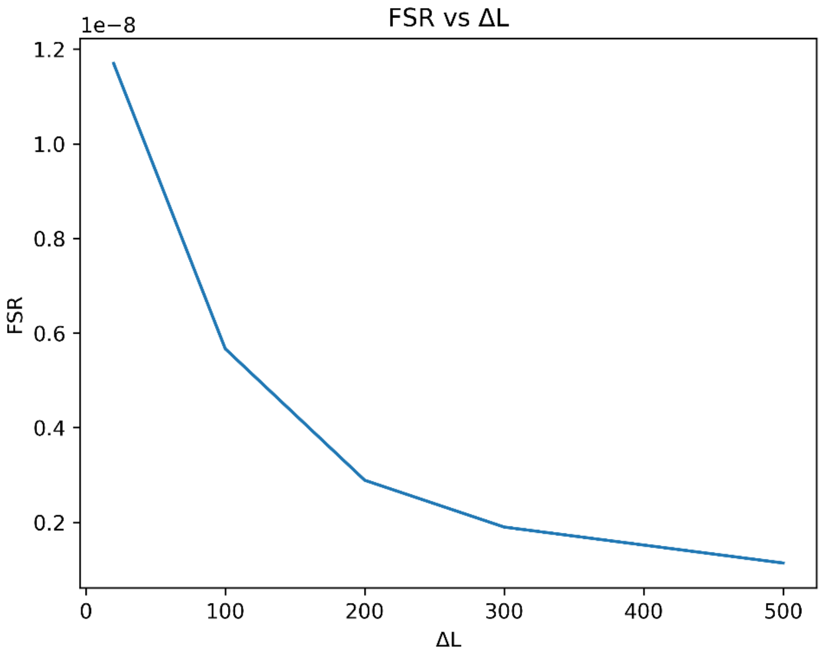


Figure 2: Free spectral range vs delay length

Reference:

1. Lukas Chrostowski, Michael Hochberg. Silicon Photonics Design. Cambridge University Press (CUP), 2015.
2. B. E Little, S. T Chu, H. A Haus, et al. Microring resonator channel dropping filters, IEEE Xplore, 1997.