Design and fabrication of Mach-Zehnder Interferometer on silicon on insulator platform

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I. Objective

To design, simulate and experimental validation of waveguide imbalance Mach-Zehnder Interferometer

II. Introduction

The Mach–Zehnder Interferometer (MZI) is an optical device in which an input light beam is split into two separate paths and later recombined to produce an interference pattern determined by the relative phase difference between the two waves. This phase difference can be controlled by introducing a path length imbalance between the interferometer arms. Owing to this phase-sensitive operation, MZIs are widely employed in a variety of photonic applications, including optical modulators and thermo-optic switches. In this work, an MZI is designed and fabricated on a silicon-on-insulator platform to investigate the influence of path length difference on the free spectral range (FSR). Both simulation and experimental results are presented and compared to validate the proposed design.

III. Theory

A Mach–Zehnder Interferometer (MZI) consists of a Y-branch splitter and a Y-branch combiner, which split an incoming optical signal into two separate paths and subsequently recombine them after propagation [1]. At the input of the Y-branch splitter, the optical intensity and electric field are denoted by I_i and E_i, respectively. Assuming an ideal 50:50 power split, the input light is equally divided between the two arms, resulting in output intensities $I_1 = I_2 = I_i/2$ and corresponding electric field amplitudes $E_1 = E_2 = E_i/\sqrt{2}$. Similarly, in the Y-branch combiner, the two input electric fields E_1 and E_2 are coherently combined to produce an output field given by

$$E_0 = \frac{E_1 + E_2}{\sqrt{2}}.$$

The propagation of light along the waveguide can be described by the plane-wave expression

$$E = E_0 e^{i(\omega t - \beta z)},$$

where β is the propagation constant of the guided mode, defined as

$$\beta = \frac{2\pi n}{\lambda}.$$

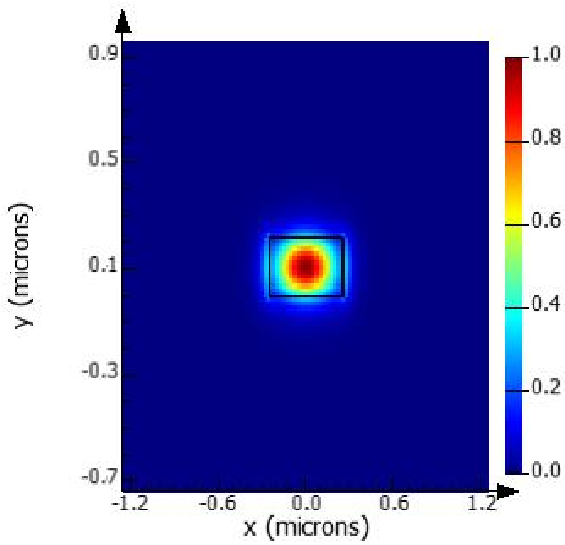

Fig. 1: Enter Caption

For the lossless case, with L_1 and L_2 denoting the lengths of the two waveguide arms, the electric fields at the outputs of the Y-branch splitter can be written as

$$E_{01} = E_1 e^{-i\beta_1 L_1} = \frac{E_i}{\sqrt{2}} e^{-i\beta_1 L_1}$$

$$E_{02} = E_2 e^{-i\beta_2 L_2} = \frac{E_i}{\sqrt{2}} e^{-i\beta_2 L_2}$$

For the Y-branch combiner, the resulting output electric field is given by

$$E_0 = \frac{1}{\sqrt{2}} (E_{01} + E_{02}) = \frac{E_i}{2} \left(e^{-i\beta_1 L_1} + e^{-i\beta_2 L_2} \right).$$

IV. MOdeling and simulation

A. Waveguide

In this design, a silicon strip waveguide with a height of 220 nm and a width of 500 nm is employed. The electric field intensity distribution of the fundamental transverse-electric (TE) mode is illustrated in Fig. 1. All simulations are carried out using the Lumerical MODE solver. A frequency sweep analysis

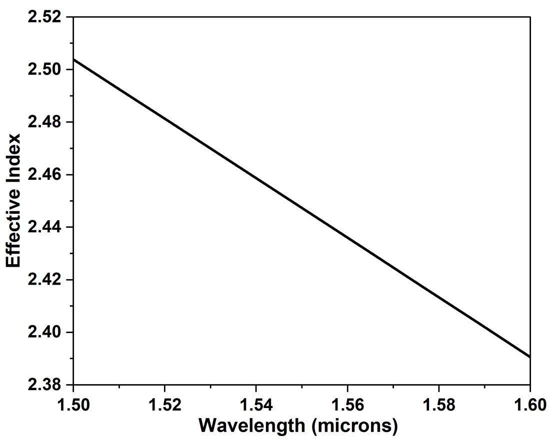

Fig. 2: Relation between the effective index and the wavelength

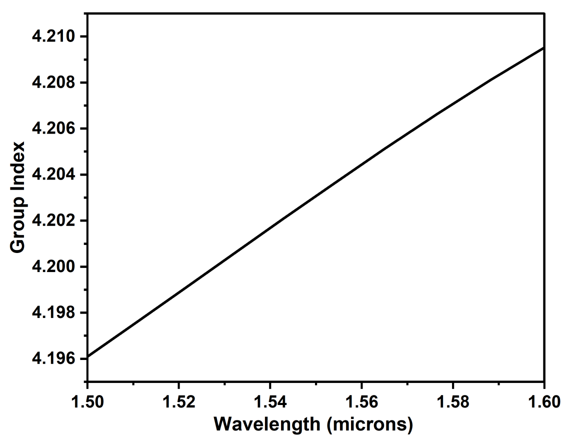

Fig. 3: Relation between the group index and the wavelength

is performed to investigate the wavelength dependence of the effective index and group index, and the corresponding results are presented in Figs. 2 and 3, respectively. It is observed that the effective index decreases with increasing wavelength, while the group index exhibits an increasing trend. Based on the simulation results, a compact model for the waveguide is extracted using the Lumerical MODE solver and can be expressed as:

$$n_{\mathrm{eff}}(\lambda) = 2.44733 - 1.13281(\lambda - 1.55) - 0.0441206(\lambda - 1.55)^2 \tag{1}$$

B. Mach–Zehnder Interferometer

From the above analysis, the normalized intensity transfer function of the Mach–Zehnder interferometer (MZI) can be

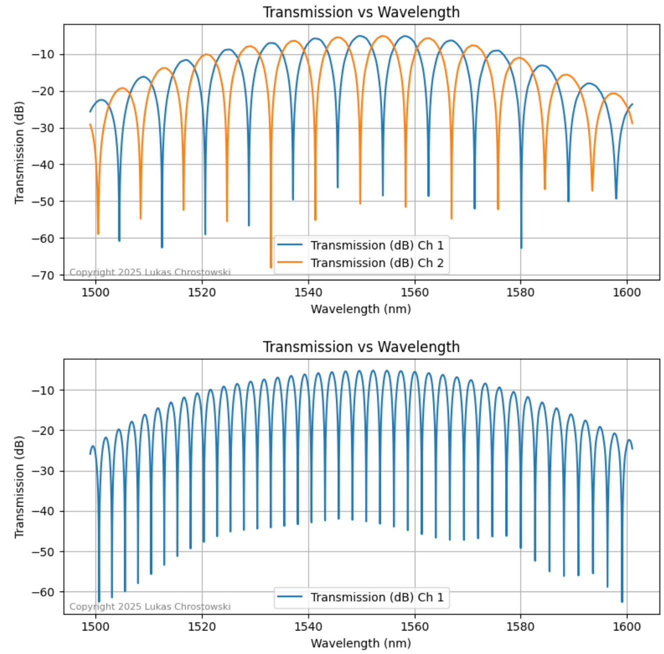

Fig. 4: The spectrum of two MZI1 and MZI2 is shown with different FSR values.

expressed as

$$\frac{I_0}{I_i} = \frac{1}{2}\left[1 + \cos(\beta \Delta L)\right], \tag{2}$$

where β is the propagation constant of the guided mode and $\Delta L = L_2 - L_1$ is the path length difference between the two arms of the interferometer. The free spectral range (FSR) is a key parameter of an interferometer and represents the wavelength spacing between two successive transmission maxima. The FSR can be theoretically expressed as

$$\mathrm{FSR} = \frac{\lambda^2}{n_g \Delta L}, \tag{3}$$

where λ is the operating wavelength and n_g denotes the group index of the waveguide. The schematic of the proposed MZI design, shown in Fig. 4, is simulated using Lumerical INTERCONNECT. In this work, the path length difference ΔL is systematically varied to investigate its impact on the FSR. The calculated FSR values corresponding to different ΔL are summarized in Table I. In addition, the gain and transmission spectra of the designed MZI for $\Delta L = 100\ \mu$m are presented in Figs. 5 and 6, respectively.

Figure 4 shows the transmission spectra of two Mach–Zehnder interferometers (MZI1 and MZI2) with different free spectral ranges (FSRs), arising from their unequal arm length differences. The variation in fringe spacing confirms the inverse dependence of FSR on the optical path length difference between the interferometer arms. path length of MZI1 is smaller than the MZ@ so the FSR of MZI1 is greater than the MZI2.

TABLE I: FSR for Different ΔL

ΔL (μm)	FSR (nm)
100	5.73
150	3.82
200	2.87
300	1.91

REFERENCES

[1] L. Chrostowski and M. Hochberg, *Silicon photonics design: from devices to systems*. Cambridge University Press, 2015.