Design proposal: Unbalanced Mach-Zehnder Interferometer

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I. Introduction

Integrated silicon photonics has emerged as a key platform for high-speed, low-power optical signal processing in modern communication and computing systems. Among various on-chip photonic components, the Mach–Zehnder interferometer (MZI) implemented on a silicon-on-insulator (SOI) platform plays a central role in realizing linear operations such as modulation, switching, and filtering due to its compatibility with CMOS fabrication and its flexible interferometric transfer function [1,2].

The SOI technology provides a high refractive index contrast between the silicon core and the silica cladding, enabling sub-micrometer waveguides with tight light confinement and compact device footprints. This strong confinement enhances phase sensitivity to effective index changes, which can be exploited via carrier-depletion, carrier-injection, or thermo-optic mechanisms integrated into the arms of the MZI. As a result, SOI-based MZI modulators have demonstrated high modulation speeds and energy-efficient operation suitable for chip-scale interconnects and wavelength-division multiplexed (WDM) links [3]

At the same time, the performance of SOI MZI devices strongly depends on waveguide geometry, imbalance between the interferometer arms, and fabrication tolerances, which affect insertion loss, extinction ratio, and phase response. Careful design and characterization of the MZI—covering waveguide dimensions, directional couplers, and phase-shifter sections—are therefore essential to ensure robust operation under realistic process variations. This design proposal focuses on the investigation of an SOI-based Mach–Zehnder interferometer, including analysis of its principle of operation, numerical modeling of its transfer characteristics, and evaluation of key performance metrics relevant for integrated optical communication systems [4]

II. MZI theory

A silicon Mach–Zehnder interferometer (MZI) is a two-path interferometric device that splits an input optical field into two waveguide arms, introduces a relative phase shift, and then recombines the fields to generate constructive or destructive interference at the outputs. The device is typically implemented on a silicon-on-insulator (SOI) platform, where a high-index silicon core is surrounded by a lower-index SiO_2 cladding, enabling strong confinement and compact waveguide bends. A typical layout of such an interferometer is presented in Fig.1.

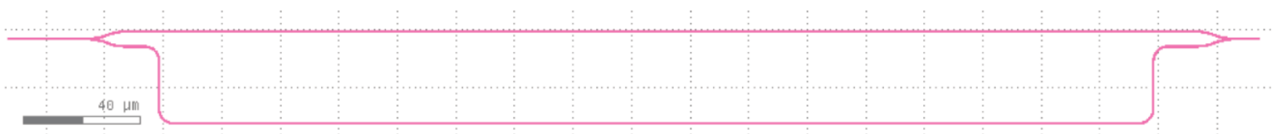


Fig. 1 Schematic represantation of a silicon MZI [1].

Y-splitter divides input light intensity into two arms with 50/50 amplitude ratio. Two arms have different length L1 and L2. After propagating with effective indices n_{eff} the fields accumulate phases:

$$\phi_{1,2}=\beta_{1,2}L_{1,2}=2\pi\lambda n_{eff\,1,2}L_{1,2}$$

After propagation into these two arms light interfere in the second Y-splitter. The output transmission is then:

$$T=\frac{I_{out}}{I_{inp}}=\cos^2\left(\frac{\phi_1-\phi_2}{2}\right)$$

For an unbalanced SOI MZI with arm length difference $\Delta L=L_1-L_2$, the phase difference depends on wavelength as

$$\Delta\phi(\lambda)=2\pi\lambda n_g(\lambda)\Delta L$$

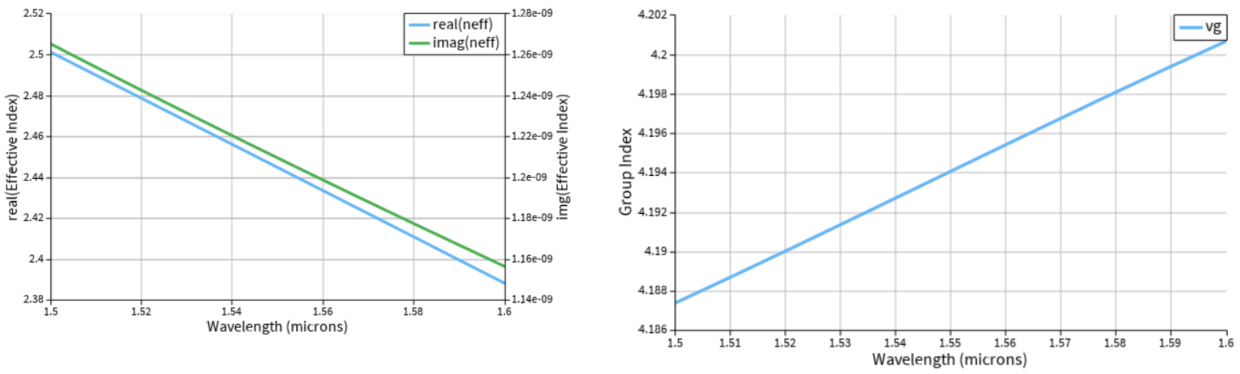
Here $n_g(\lambda)=n_{eff}(\lambda)-\lambda\frac{d\,n_{eff}}{\lambda}$. The transmission spectrum is periodic in wavelength, with the free spectral range (FSR) given by

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

By designing ΔL and the SOI waveguide geometry (which sets n_{eff} and n_g), one can tailor the spectral period and use the silicon MZI as a wavelength-selective filter or sensor.

III. MZI simulation

MZI was simulated using Lumerical INTERCONNECT. Effective refractive index simulaiton of a waveguide was simulated using Lumerical MODE. The simulated structure consists of a silicon strip waveguide with a core thickness of 220 nm and a width of 500 nm, surrounded by a silicon dioxide cladding. During sumilation I focused on the fundamental transverse-electric (TE). Fig. 2 shows effective and group refractive indices of the waveguide.



a b

Fig. 2 Effective (a) and group (b) refractive indices of the waveguide as a function of a wavelength

Fig. 3 shows distribution of ligth intensity inside the waveguide.

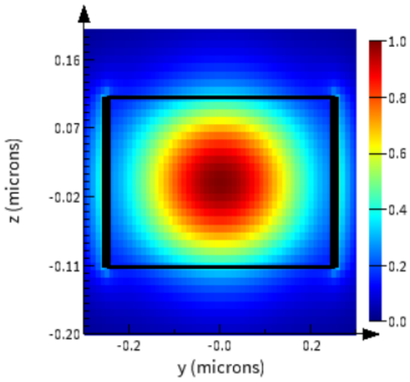


Fig. 3 Light intesity profile incide the waveguide.

Fig. 4 depictes design of the unbalanced MZIs. The MZIs constist of 2 grating couplers, 2 Y-splitters and 2 arms each.

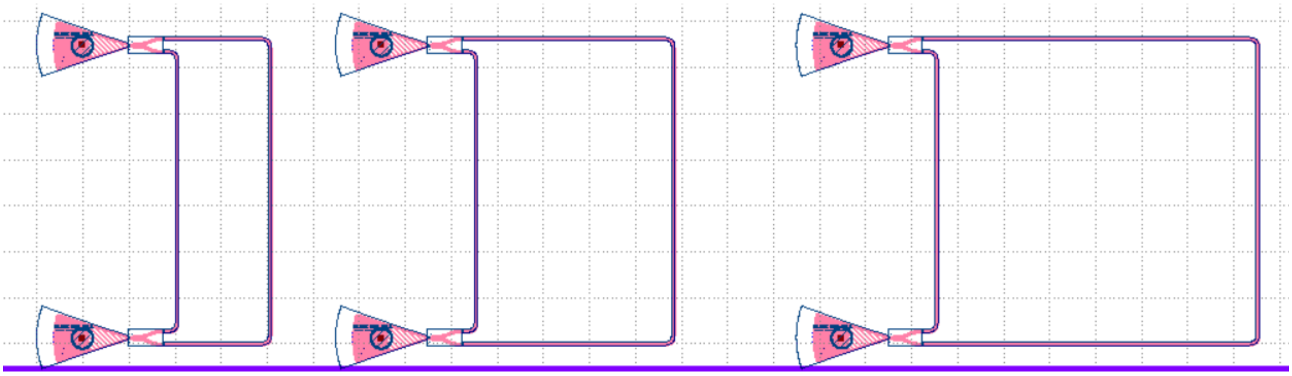
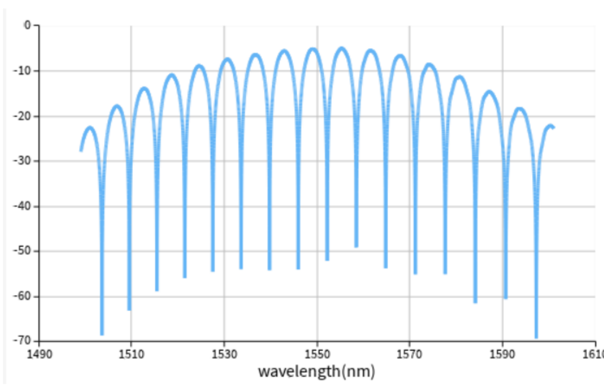


Fig. 3 Proposed unbalanced MZIs.

Length difference of these 3 MZIs are $\Delta L_1 = 92\,um$, $\Delta L_2 = 183\,um$, and $\Delta L_2 = 290\,um$ which result in FSR ~ 4.14, 2.08, 1.3 nm.

Fig. 4 show transmission spectra of the proposed MZIs.



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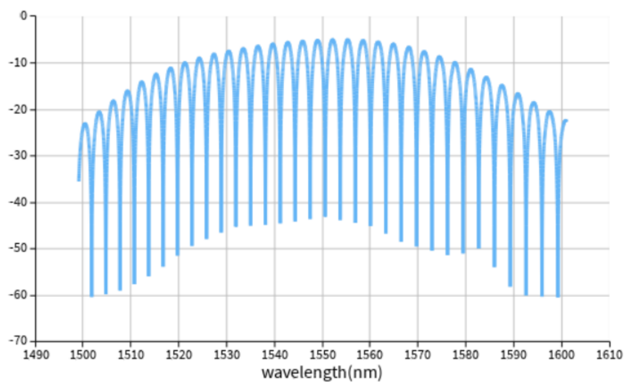

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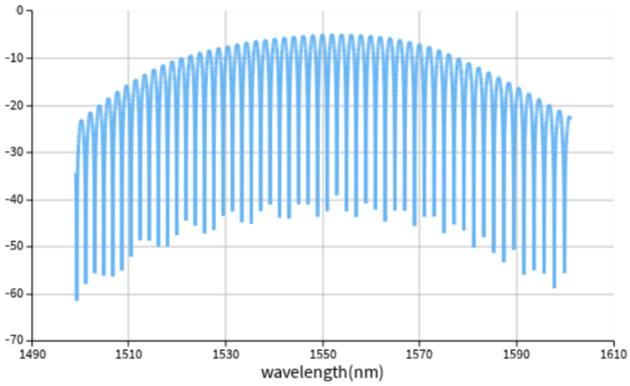

c

Fig. 4 Transmission of the MZIs with $\Delta L_1 = 92\,um$ (a), $\Delta L_2 = 183\,um$ (b), and $\Delta L_2 = 290\,um$ (c).

References:

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

[2] Moralis-Pegios, M., Giamougiannis, G., Tsakyridis, A., Lazovsky, D., & Pleros, N. (2024). Perfect linear optics using silicon photonics. *Nature Communications*, *15*(1), 5468.

[3] Yuan, Y., Peng, Y., Cheung, S., Xiao, X., Sorin, W. V., Huang, Z., ... & Beausoleil, R. G. (2025). The perspective of all-silicon photonics and systems. *APL Photonics*, *10*(6).

[4] Demkov, A. A., Bajaj, C., Ekerdt, J. G., Palmstrøm, C. J., & Ben Yoo, S. J. (2021). Materials for emergent silicon-integrated optical computing. *Journal of Applied Physics*, *130*(7).