Design proposal for a Mach-Zhender Interferometer using a Silicon Photonics Platform

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***Abstract*—This report summarizes the design of a Mach-Zhender interferometer using the SIEPIC silicon photonics platform. First the waveguide geometry is described, followed by some numerical simulations to validate the design. The circuit is built using the designed waveguide and Y-branches from the SIEPIC library as the splitter and combiner. Furthermore, multiple ring resonators are considered that have very high quality factors in simulation ($\approx 10^5$).**

I. Introduction

The Mach-Zhender interferometer (MZI) is a fundamental building block to photonic circuits. Through the simple mechanism of phase detuning between the 2 arms, which is possible via modulating the effective index or the length, the MZI finds uses in almost all areas of application, ranging from sensing to telecom, and even computing. This report summarizes the steps to design such an MZI. It is noteworthy to mention that the Y-branches shown later were not designed by us, but are a SIEPIC library component, oringinally published in [1]

II. Theory

A. Waveguide Design

We consider a 220 nm thick, 500 nm wide silicon core, surrounded by an oxide cladding on all 4 sides. We use Lumerical MODE solutions to calculate the effective index of the desired mode, namely the principal TE mode, as shown in fig. This is done after a material fitting step, to ensure that the material model is suitable in the desired wavelength range. The effective index is the refractive index a mode experiences due the boundaries imposed on it, arising from the waveguide geometry. This means that part of the mode will exist in the core (the majority in case of strong confinement), while the remainder will exist in the cladding. We plot this as a function of wavelength, followed by the group index, which describes the speed of a pulse of light (polychromatic), is also plotted as a function of the wavelength. Since we target a telecom application, and not for example a sensing application (which would benefit from TM operation), we consider the TE mode to make use of the tighter bends. A compact, behavioral model can describe approximately the waveguide behavior at a target wavelength; namely the phase evolution with length (including losses), the group index, and the dispersion. The effective index is thus calculated from the following equation through a Taylor expansion around the center wavelength:

$$n_{\text{eff}}(\lambda) = n_1 + n_2(\lambda - \lambda_0) + n_3(\lambda - \lambda_0)^2 \tag{1}$$

where λ is the desired wavelength, λ_0 is the wavelength at which n_{eff} and $\frac{dn_{\text{eff}}}{d\lambda}$ are evaluated. The coefficients are defined as follows

$$n_1 = n_{\text{eff}} \tag{2}$$

$$n_2 = \frac{n_1 - n_{\text{g}}}{\lambda_0} \tag{3}$$

$$n_3 = -\frac{Dc}{2\lambda_0} \tag{4}$$

$$D = \frac{-\lambda_0}{c}\frac{d^2 n_{\text{eff}}}{d\lambda^2} \tag{5}$$

where n_{g} is the group index, and D is the dispersion. It is worth noting that the compact model could not be used directly, until a few data points in the vicinity of λ_0 are gathered first. The compact model would essentially approximate the curves shown in section III-A.

B. MZI design

The MZI is created by splitting the light from one waveguide into two, propagating them along two separate waveguides with lengths L_1 and L_2, and then combining them again at the output waveguide. Splitters and combiners can be implemented in a variety of ways, for example multi-mode interferometers (MMIs) which use the self-imaging phenomena, directional couplers, or Y junctions which rely on adiabatically evolving the modes of the input waveguide to the modes in the output waveguide. In doing so evenly, a so-called 3-dB splitter/combiner is achieved. Let us assume the Y-junction as a component that couples the single-mode input to only a single output mode for each output waveguide. The input E-field oscillations can be assumed to be a plane wave traveling along the z-direction in the input waveguide;

$$E_i = E_0 e^{i(\omega t - \beta_{\text{in}} z) - \alpha L_{\text{in}}/2} \tag{6}$$

where ω is the angular frequency, α is the power loss coefficient (hence the half in the exponent), L_{in} is the distance propagated in the input waveguide before arriving at the Y-junction, and

$$\beta_{\text{in}} = 2\pi n_{\text{eff}}/\lambda \tag{7}$$

is the propagation constant of the field in the input waveguide. For our modeling purposes, which will take place on far slower timescales than the optical cycle, we can ignore the much faster $e^{i\omega t}$ oscillations, dropping them from the subsequent equations. At the output of the y branch, the fields in the two waveguides can be described by their propagation constants:

$$\beta_1 = 2\pi n_1/\lambda \tag{8}$$

$$\beta_2 = 2\pi n_2/\lambda \tag{9}$$

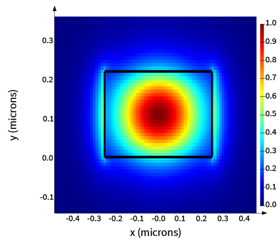

Fig. 1. TE mode of the designed waveguide at 1550 nm, $n_{\text{eff}} = 2.444$.

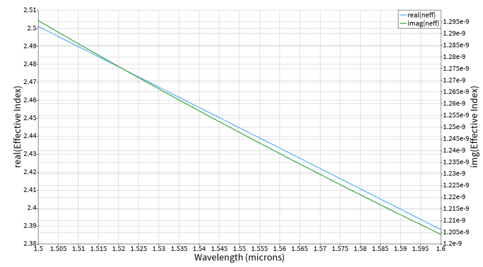

Fig. 2. Effective index (Re and Im) of the waveguide as a function of wavelength.

where the effective indices of the 2 output waveguides are assumed to be different (for the general case). The field after propagating a distance L_{wg} in each MZI arm becomes:

$$E_{\text{o1}} = \frac{E_i}{\sqrt{2}} e^{-i\beta_1 L_1 - \alpha_1 L_1/2} \tag{10}$$

$$E_{\text{o1}} = \frac{E_i}{\sqrt{2}} e^{-i\beta_2 L_2 - \alpha_2 L_2/2} \tag{11}$$

The combined output after the Y combiner is thus the linear sum of the two fields, yielding

$$E_{\text{out}} = \frac{E_{\text{i}}}{2} \left[e^{-i\beta L_1 - \alpha_1 L_1} + e^{-i\beta L_2 - \alpha_2 L_2} \right] \tag{12}$$

Since $I \propto |E|^2$, the MZI transfer function in terms of intensity can be written as

$$\frac{I_{\text{out}}}{I_{\text{in}}} = \frac{I_{\text{out}}}{4} \left[e^{-i\beta L_1 - \alpha_1 L_1} + e^{-i\beta L_2 - \alpha_2 L_2} \right] \tag{13}$$

This equation can easily be simplified further, under such assumptions as similar α, β, L. It can be seen that modulating the optical path length can be done through a change $\Delta\beta$ (through n_{eff}), or directly through a ΔL. Solving Eq. 13 for different λ, and under differing optical path lengths, yields a sinusoidal pattern with a distance between subsequent peaks, i.e. a free-spectral range (FSR). Under the assumption that β varies linearly with λ, meaning $\Delta\beta = \beta_m - \beta_{m+1} \approx \frac{-dB}{d\lambda}\Delta\lambda$, the FSR can be expressed as:

$$\Delta\lambda = \frac{\lambda^2}{\Delta L n_{\text{g}}} \tag{14}$$

From which we can extract the expression of the group index in terms of the FSR, which is useful in experimental measurements:

$$n_{\text{g}} = \frac{\lambda^2}{\Delta L \Delta\lambda} \tag{15}$$

III. Simulation Results

We now proceed to the simulation results for the waveguide, and subsequently the MZI circuit. The simulation parameters can be found in Table I.

A. Waveguide Results

The waveguide is modeled in Lumerical MODE. The TE mode profile at 1550 nm is shown in Fig. 1. Then a frequency sweep is performed to calculate the effective index variation (Fig. 2) and group index variation (Fig. 3) with wavelength.

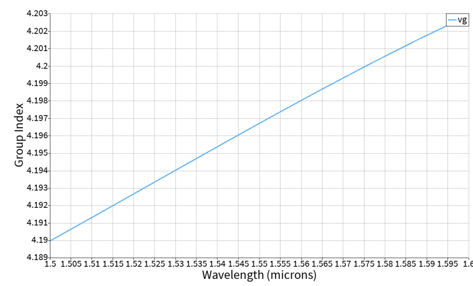

Fig. 3. Group index of the waveguide as a function of wavelength.

B. MZI Results

The waveguide modeled is then imported in Lumerical Interconnect, along with Y-branches and grating couplers, which were previously designed in the SIEPIC pdk. The circuit schematic is shown in Fig. 4, and the response for various ΔL is recorded and shown in Fig. 5.

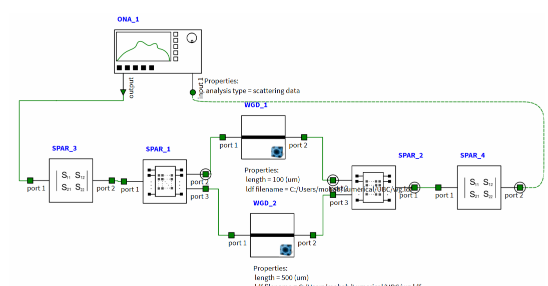

Fig. 4. MZI circuit schematic. The bottom arm was changed by the ΔL reported in Table I.

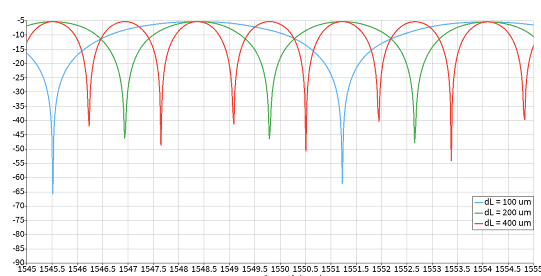

Fig. 5. The real part of TE gain for the various ΔL considered.

Parameter	Value
Waveguide width	500 nm
Waveguide thickness	220 nm
λ_0	1550 nm
ΔL	100 µm, 200 µm, 400 µm

TABLE I
SIMULATION PARAMETERS

C. Ring Resonator results

Here we design a ring resonator with multiple add/drop ports. We consider 4, 3, and 2 directional couplers, as shown in Fig. 6. In the case of 2 directional couplers, one can consider this to be a variation of a traditional add-drop resonator, where the through and add ports are connected (i.e. feedback). We aim to study the difference in FWHM, extinction ratio, and subsequently the Q-factor of these different instances. Furthermore, we add one additional copy of each design for redundancy (Similar to the MZI designs), which is especially important since fabrication variations can significantly affect the coupling regime in the ring. The behavior of this structure can be simulated with S-matrix while taking into account the temporal evolution of the signal. This can be modeled using a differential equation (with time) taking into account the leakage/loss and gain rates of the field in the resonator. For the sake of brevity, the theoretical discussion is not included here. The simulation results using Lumerical Interconnect show the possibility to achieve very high Q-factors, as shown in Fig. 7.

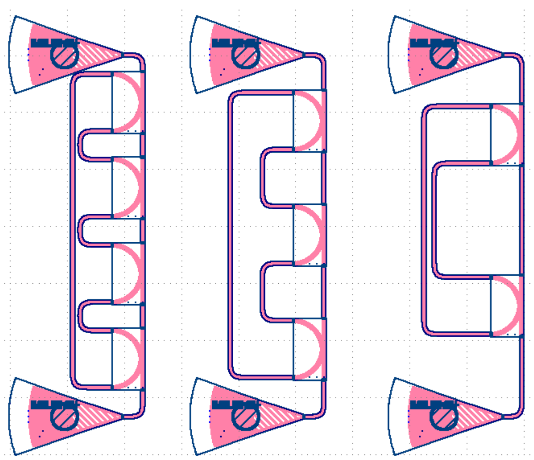

Fig. 6. Layout of 3 designs of ring resonators.

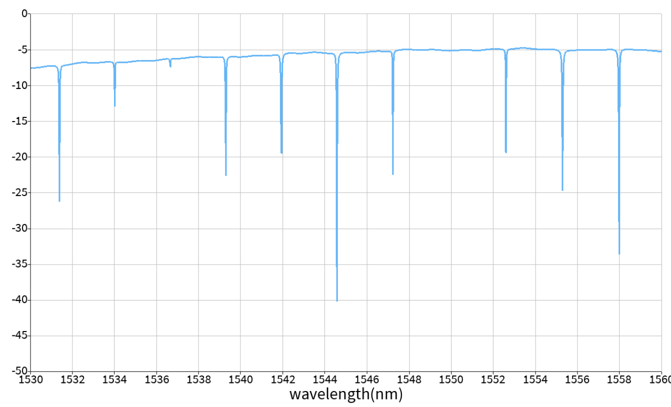

Fig. 7. Response of the designed ring resonator, showing a 35 dB extinction ratio and FWHM < 10 pm.

REFERENCES

[1] Y. Zhang, S. Yang, A. E.-J. Lim, G.-Q. Lo, C. Galland, T. Baehr-Jones, and M. Hochberg, "A compact and low loss y-junction for submicron silicon waveguide," *Opt. Express*, vol. 21, no. 1, pp. 1310–1316, Jan 2013. [Online]. Available: https://opg.optica.org/oe/abstract.cfm?URI=oe-21-1-1310