

# Design Proposal

Wayne Lin

the date of receipt and acceptance should be inserted later

**Abstract** This report presents a design proposal that includes two Mach-Zehnder interferometer circuits and a ring resonator. The underlying theory for each circuit is described, and the estimated key parameters align with preliminary simulation results.

## 1 Introduction

Silicon photonics is growing as a practical way to build compact and low-cost optical circuits. In this project, I look at two basic building blocks: the Mach-Zehnder interferometer (MZI), used for modulation and filtering, and the ring resonator, useful for wavelength selection and sensing. [[1]] Both are simple but powerful examples of how integrated photonics can work in real systems.

## 2 Theory

### 2.1 Waveguide Compact Model

The effective index expansion:

$$n_{\text{eff}}(\lambda) \approx a_1 + a_2(\lambda - \lambda_0) + a_3(\lambda - \lambda_0)^2. \quad (1)$$

Group index:

$$n_g = n_{\text{eff}} - \lambda \frac{dn_{\text{eff}}}{d\lambda}. \quad (2)$$

### 2.2 Y-Branch

An ideal Y-branch splits power equally (-3 dB per port). Interference depends on phase:

$$P_{\text{out}} \propto |E_1 \pm E_2|^2. \quad (3)$$

### 2.3 Mach-Zehnder Interferometer

Normalized transfer function:

$$T_{\text{MZI}}(\lambda) = \frac{1}{2} [1 + \cos(\Delta\phi(\lambda))], \quad (4)$$

where

$$\Delta\phi(\lambda) = \frac{2\pi}{\lambda} n_g \Delta L. \quad (5)$$

Free spectral range:

$$\Delta\lambda_{\text{FSR}} = \frac{\lambda^2}{n_g \Delta L}. \quad (6)$$

### 2.4 Ring Resonator

All-pass transfer function:

$$T_{\text{ring}}(\lambda) = \left| \frac{t - Ae^{-i\phi}}{1 - tAe^{-i\phi}} \right|^2, \quad (7)$$

with  $t$  the amplitude transmission of the coupler,  $A = e^{-\alpha L/2}$  round-trip loss, and  $\phi = \beta L$ . Resonance condition:

$$m\lambda = n_{\text{eff}}L. \quad (8)$$

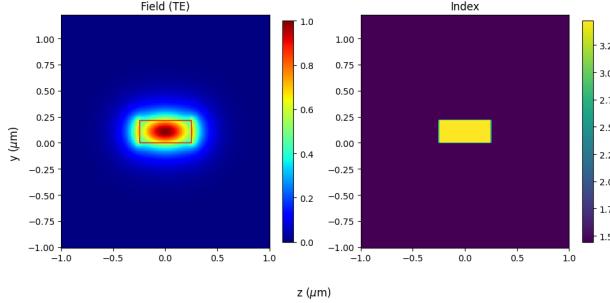
Free spectral range:

$$\Delta\lambda_{\text{FSR}} = \frac{\lambda^2}{n_g L}. \quad (9)$$

### 3 Chip Design and Simulation Results

#### 3.1 Waveguide Compact Model Simulation

A compact model simulation was conducted in Lumerical MODE module. The waveguide material is *Si* and the cladding material is *SiO<sub>2</sub>*. Lumerical's built-in dispersion data was used for the simulations.

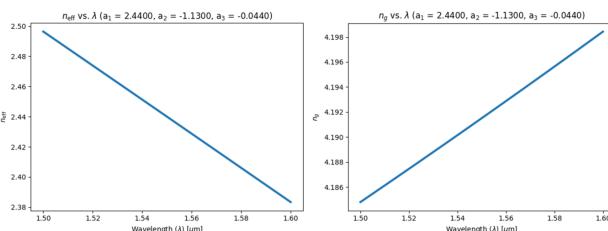


**Fig. 1** Waveguide Compact Model Simulation

#### 3.2 MZI & Ring Resonator Model Calculation

From the  $n_{eff}$  and  $n_g$  values obtained from the compact model simulation result. One can calculate the transmission spectrum of each component. The design values are listed in the table below.

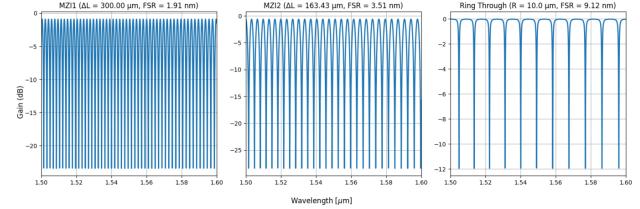
Component	Parameter	Value
MZI1	$\Delta L$	300 $\mu m$
MZI2	$\Delta L$	163.43 $\mu m$
Ring	R	10 $\mu m$



**Fig. 2** Effective Index and Group Index

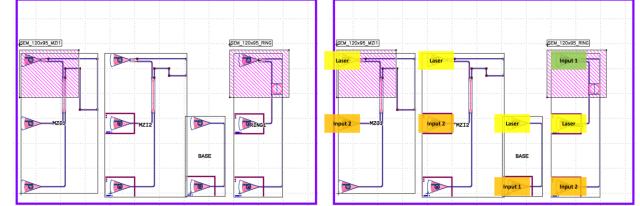
#### 3.3 Chip Design and Layout

The designs layout was created by klayout according to the specification of the foundry. A baseline circuit



**Fig. 3** MZI Transfer Functions and Ring Through Transmission

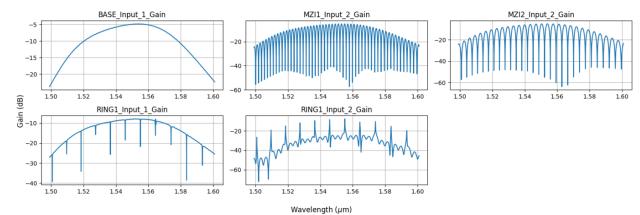
was included for filtering out the effect introduced by grating couplers.



**Fig. 4** Final layout for chip fabrication (left) and the corresponding layout annotated with port labels for circuit-simulation data collection (right).

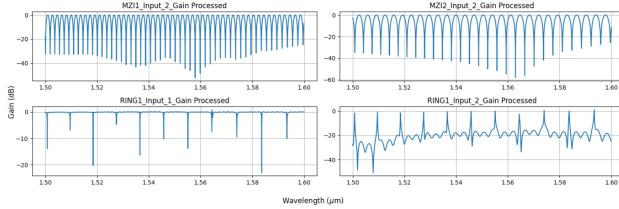
#### 3.4 Preliminary Simulation Results

The simulation result by Lumerical Interconnect module showed the baseline curves in all collected spectra, and it was removed by the subtraction of baseline spectrum.

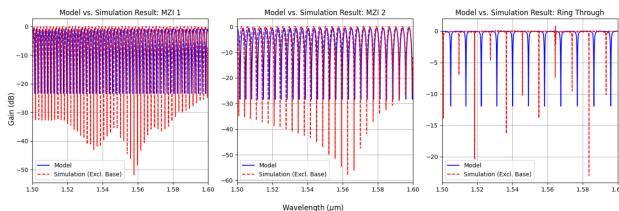


**Fig. 5** Simulation Results by Lumerical Interconnec

The comparison of simulated MZI spectrum with model calculation showed generally good agreement despite minor phase shift. For ring resonator the phase shift is more prominent, but the pitch is consistent to model calculation.



**Fig. 6** Simulation Result after Baseline Removal



**Fig. 7** Model Calculation vs. Simulation Results

## 4 Fabrication

Two chips were fabricated in this course. Either report on one dataset, or on both. Choose the text as appropriate.

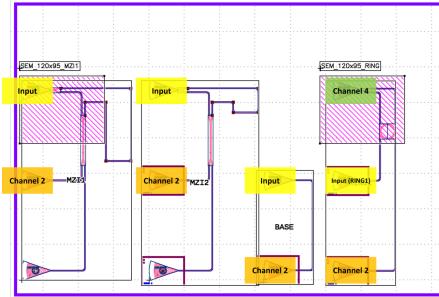
### 4.1 Washington Nanofabrication Facility (WNF) silicon photonics process:

The devices were fabricated using 100 keV Electron Beam Lithography [[2]]. The fabrication used silicon-on-insulator wafer with 220 nm thick silicon on 3  $\mu\text{m}$  thick silicon dioxide. The substrates were 25 mm squares diced from 150 mm wafers. After a solvent rinse and hot-plate dehydration bake, hydrogen silsesquioxane resist (HSQ, Dow-Corning XP-1541-006) was spin-coated at 4000 rpm, then hotplate baked at 80 °C for 4 minutes. Electron beam lithography was performed using a JEOL JBX-6300FS system operated at 100 keV energy, 8 nA beam current, and 500  $\mu\text{m}$  exposure field size. The machine grid used for shape placement was 1 nm, while the beam stepping grid, the spacing between dwell points during the shape writing, was 6 nm. An exposure dose of 2800  $\mu\text{C}/\text{cm}^2$  was used. The resist was developed by immersion in 25% tetramethylammonium hydroxide for 4 minutes, followed by a flowing deionized water rinse for 60 s, an isopropanol rinse for 10 s, and then blown dry with nitrogen. The silicon was removed from unexposed areas using inductively coupled plasma etching in an Oxford Plasmalab System 100, with a chlorine gas flow of 20 sccm, pressure of 12 mT, ICP power of 800 W, bias power of 40 W, and a platen temperature of 20 °C, resulting in a bias voltage of 185 V. During etching, chips were mounted on a 100 mm

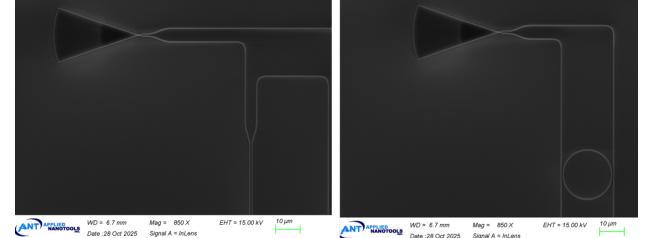
silicon carrier wafer using perfluoropolyether vacuum oil.

## 5 Experimental Data

### 5.1 Data Acquisition Locations & SEM Images



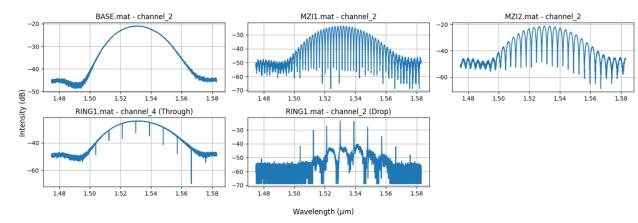
**Fig. 8** Layout with annotated data collection locations, including measurement port location and SEM image locations



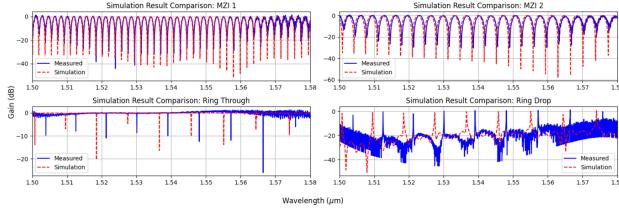
**Fig. 9** SEM images of the MZI1 device (left) and the ring resonator (right) in the fabricated photonic chip.

### 5.2 Measurement Results

The measurement result showed good agreement with simulation result. Phase shift still persists in the result of ring resonator.



**Fig. 10** Measured spectrum of fabricated photonic chip

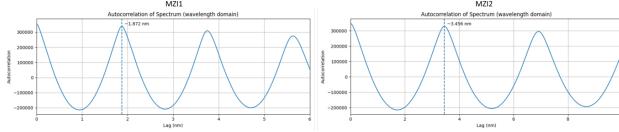


**Fig. 11** Measured and simulated spectral responses for MZI1, MZI2, the ring through port, and the ring drop port. The measured spectra are shown with the baseline excluded for clarity.

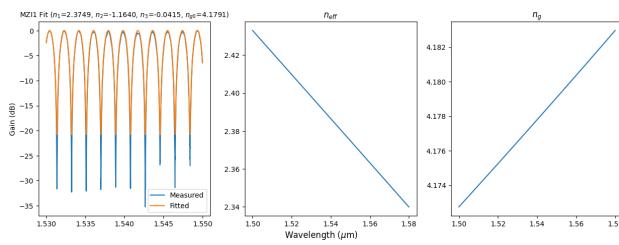
## 6 Analysis

### 6.1 MZI Transfer Function Fitting

With autocorrelation and MZI transfer function fitting on the measurement data. We can obtain the group index and effective index of the waveguide.



**Fig. 12** FSR calculation using spectrum autocorrelation on MZI1 and MZI2 spectrum



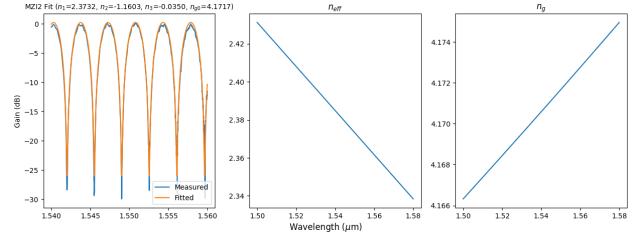
**Fig. 13** Fitted MZI1 transfer function and the extracted  $n_{eff}$  and  $n_g$  versus wavelength.

### 6.2 Ring FSR

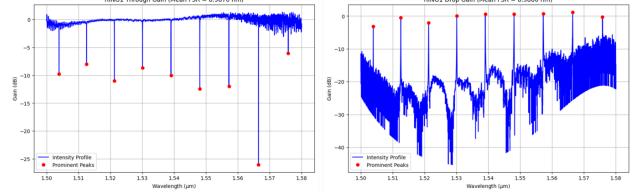
The FSR of ring resonator can be extracted by peak location, and the group index relation can be extracted via fitting.

### 6.3 Corner Analysis

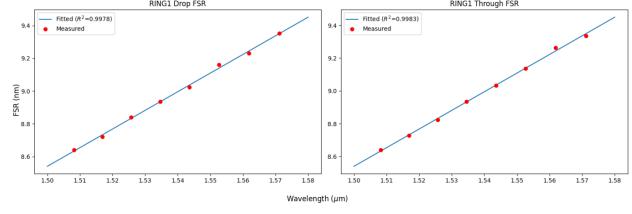
By varying different waveguide dimensions within the process window of the foundry, we can obtained a map



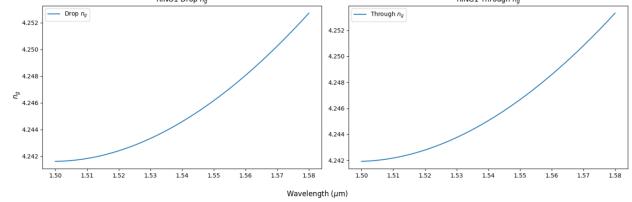
**Fig. 14** Fitted MZI2 transfer function and the extracted  $n_{eff}$  and  $n_g$  versus wavelength.



**Fig. 15** Mean FSR extracted from the through and drop spectra of the ring resonator.



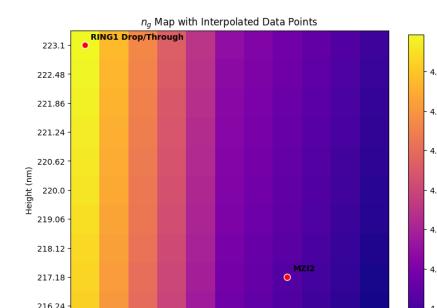
**Fig. 16** Fitted FSR-wavelength trends for the ring resonator (drop and through ports).



**Fig. 17** Fitted  $n_g$  for ring resonator (drop and through ports).

for the possible group index and use it to estimate the actual waveguide dimension in the fabrication.

Component	$n_g$
MZI1	4.1791
MZI2	4.1717
Ring (Drop)	4.2461
Ring (Through)	4.2467



**References**

1. Chrostowski L, Hochberg M (2015) Silicon Photonics Design. Cambridge University Press (CUP)
2. Bojko RJ, Li J, He L, et al. (2011) Electron beam lithography writing strategies for low loss high confinement silicon optical waveguides. Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures 29:06F309. <https://doi.org/10.1116/1.3653266>