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Abstract In this work a Mach-Zehnder Interferometer concept is evaluated in terms of theory, simulation and production in a CMOS factory.

1 Introduction

Silicon is by far the most used material in 21st century due to huge demand on communication and data exchange. After 40 years of constant improvement in transistor gap size, microchip industry struggle with quantum effects at 1-5 nanometers scale. Exponential increase in demand forced scientific and business area to find new ways in order to supply in high speed, quality and volume.

In visible spectrum, silicon is opaque, so that it is not possible to transmit light inside, but adapting light wavelength as Infrared, silicon can be used as a transparent medium, and allows to use transmitting data in much more speed, to be exact, the speed of light, like fiberoptics. CMOS manufacturing is mature due to ICs experiences more than 40 years, and in that time area, silicon is mostly used in production. By adapting the same foundations, silicon photonics can be manufactured in high volume and low cost.

Interferometry has been used in so many diversed areas, from detection of the speed of light, to detection of gravitational waves. Main idea behind interferogram is the wave nature of light. If two waves are in phase, cumulative effect will be higher than alone, and it is called as constructive interference. On the contrary, if there is a 180 degree phase difference, they will cancel each other, and this is called as destructive interference.

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2 Theory

According to the logic of interferometry, phase shift should be build-up between two waves by using passive or active methods. Passive methods require no additional power, like changing pathlength of one waveguide, but don't allow to modify after production. Active methods, on the contrary, give oppurtunity to manipulate phase of the waves after production and do it in very high speed(GHZ range). There are two methods mostly in usage, thermal or electrical. Thermal phase shifters can be very compact, but they are relatively slow compared to electrical charge accumulation methods. In our design, we will use passive method.

In order to design a Mach-Zehnder interferometer production-ready, some of the parameters should considered as "constant", like height of waveguides, 220nm in our case, due to already defined silicon wafer thickness by CMOS foundry. Besides, according to mode theory, which solves Maxwell's EM Equations in 2D, after passing a value for width of a waveguide, additional modes are emerging, and it affects the efficiency negatively. Thus, we selected 500nm as waveguide width, which is very close to theoretical limit value. Slab waveguide geometry is selected, due to low bending loss and ease of production. (There is no active component on chip, so it is not needed to use rib waveguide at all)

Waveguide mode has been defined by using effective index method, which calculates 1D slab modes in 2 different orientations and combine the results. To get more realistic data and compare effective index method vs. vectorial analysis, fully vectorial eigen mode solution is also simulated in Lumerical Mode. Wavelength is selected as 1550nm, which is widely used in telecommunication.

3 Modelling and Simulation

As a first step, effective index method has been implemented to get effective index value and transverse field distribution inside and nearby of waveguide. Real part of the refractive index for designed waveguide is calculated as n_{eff} =2.4135(TE_0). It can be observed that transferse electric field is mostly trapped inside waveguide.

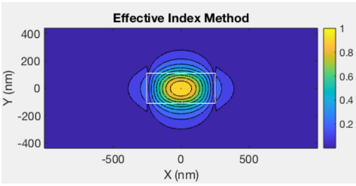

Fig. 1 Matlab solution for 2D Effective index, wavelength 1550nm, 500x220nm

To get more realistic solution, same geometrical waveguide has been simulated in Lumerical Mode fully vectorial eigen mode solver. Real part of the refractive index is calculated as n_{eff}=2.4452(TE_0). Difference between two methods is apprx. 1.3%. Group index also calculated as n_g=4.1976(TE_0). Loss is 4x10^{-4}dB/cm.

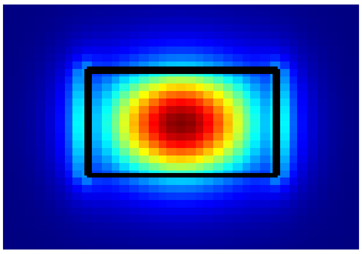

Fig. 2 Transverse electric field(TE_0) in waveguide, simulated by Lumerical Mode.

Transverse magnetic field of waveguide is also simulated in Lumerical Mode. Calculated values are n_{eff}=1.7691(TM_0) and n_g=3.7481(TM_0). Field profile is mostly in normal direction to the wafer, and considering the edge roughness of waveguide as the primary reason of scattering loss, in TM mode loss is much more lower compared to TE mode. Loss is 3x10^{-4}dB/cm.

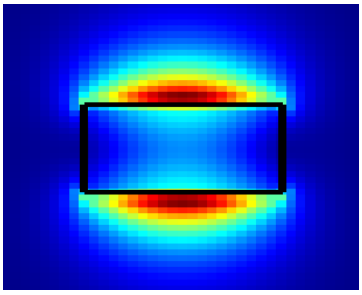

Fig. 3 Transverse magnetic field(TM_0) in waveguide, simulated by Lumerical Mode.

Bending radius is selected as $5\mu m$ throughout all photonic chip design. After fully vectorial analysis, shift of field lines due to bending can be seen. Overlap between with and without bent is 0.9986.

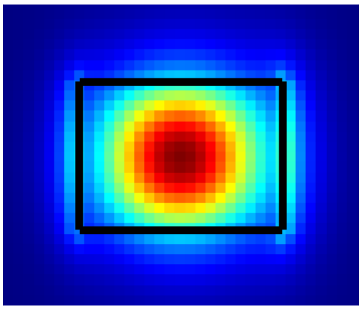

Fig. 4 Transverse electric field(TE_0) in waveguide with a 5 micron bend radius, simulated by Lumerical Mode.

Dependencies of both effective and group indexes to wavelength of light source can be seen from below given chart. Sellmeier's formula has been used. In Lumerical simulations, Lorenz method was preferred. Even though it is not preferred to use two different formula, it would be interesting to calculate effect of this difference on solutions. Here we can see material dispersion effect.

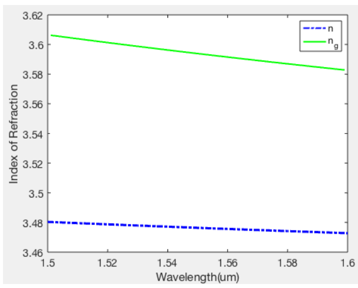

Fig. 5 Material dispersion effect, simulated in Matlab.

There is another dispersion effect, which is called as waveguide dispersion. It is dependent on both waveguide geometry and light source wavelength. Frequency sweep from $1.5\mu m$ to $1.6\mu m$ gives us below shown chart. Curve-fitting of n_{eff} values into a second order polynomial gives us the formula:

$$n_{eff} = 2.44 - 1.13\,(\lambda - 1.55) - 0.04\,(\lambda - 1.55)^2$$

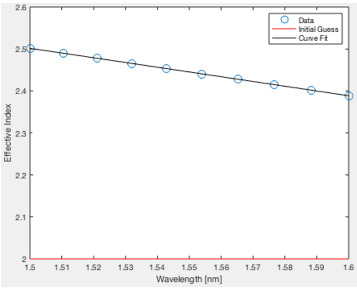

Fig. 6 Waveguide dispersion effect, simulated in Matlab.

Following base calculations about waveguide and working mode(TE/TM), Mach-Zehnder interferometer can be designed and simulated in Lumerical Interconnect via using n_{eff} and n_g values.

Basic Mach-Zehnder interferometer setup is given below. According to the phase properties of sample, constructive or destructive interference can be observed in outputs. In bulk optics, each beam splitter apply 90^o phase shift to reflected light.

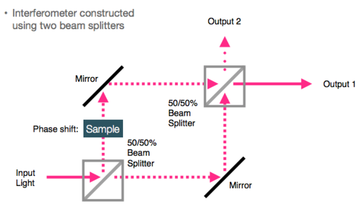

Fig. 7 Schematic of bulk-optic Mach-Zehnder Interferometer

Similar setup can be implemented in SOI chip by using Y-Branches as shown below. It is a multi-input multi-output component which divides light intensity. In splitting configuration, each branch on output side will get half of the light intensity. On the other hand, in collecting configuration, incoming light will be distributed between 1st, 2nd and radiation modes, so even in 1 input - 1 output configuration, only half of the intensity will be delivered to output. There is no phase shifting due to Y-Branches.

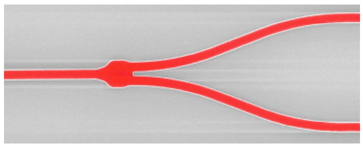

Fig. 8 SEM image of a Y-Branch

In simulations, S-Parameters from PDK has been used. S-Parameters mostly defined by 3D FDTD simulations and measured data from already produced components. Values in S-Parameter matrix are wavelength dependent and define insertion loss due to transmitted light, return loss due to reflected light and couplings in between.

Interferometer needs a kind of phase difference between transmitted and reflected lights, and in order to have this effect, there are 2 options according to theoretical calculations. α is imaginary side of complex refractive index, which is used to calculate losses due to scattering from sidewall imperfections created during E-Beam lithography process. Because of it's dependency on fabrication process, only some estimated values can be used. (Typically 3dB/cm for λ=1500nm, straight waveguide in TE mode) β is propagation constant of waveguide, and depends on wavelength and effective index.

$$\beta_1 = \frac{2\pi n_1}{\lambda},\ \beta_2 = \frac{2\pi n_2}{\lambda}$$

$$E_{output} = \frac{E_i}{2}\left(e^{-i\beta_1 L_1 - \alpha_1/2L_1}\right) + \left(e^{-i\beta_2 L_2 - \alpha_2/2L_2}\right)$$

$$I_{output} = \frac{I_{input}}{4}\,|\left(e^{-i\beta_1 L_1 - \alpha_1/2L_1}\right) + \left(e^{-i\beta_2 L_2 - \alpha_2/2L_2}\right)|^2$$

As can be seen from equations, output intensity can be adjusted by changing propagation constants of each branches, or creating a path length difference between them.

If propagation loss is ignored, equation can be simplifed as :

$$I_{output} = \frac{I_{input}}{2}[1 + cos(\beta_1 L_1 - \beta_2 L_2)]$$

Propagation constant can be changed by adjusting waveguide geometry(height is fixed, only width can be adjusted) or manipulating material properties via thermal or electrical disturbances. This configuration is called as "balanced" and "active" MZI.

As a second option, path length difference can be created during fabrication via adjusting waveguide lengths. This configuration is called as "imbalanced" and "passive" MZI. Output intensity formula can be organized as :

$$I_{output} = \frac{I_{input}}{2}[1 + cos(\beta\delta_L)]$$

δ_L is path length difference between two arms of interferometer. Output intensity change sinusoidally dependent on propagation constant, hence on wavelength of light source.

$$I_{output} = \frac{I_{input}}{2}[1 + cos(\frac{2\pi n_{eff}}{\lambda}\delta_L)]$$

Theoretical calculations can be validated in Lumerical Interconnect, which simulates designed concept in system level. Part of the configuration from GDS file(standardized CAD file format), which includes optical grating fiber in TE mode to be able to transfer light effectively from optical fiber into waveguide, Y-Branch and 2 waveguides is given below.

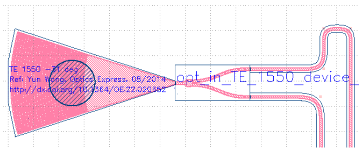

Fig. 9 Optical grating coupler in TE Mode, Y-Branch and waveguides, designed in K-Layout.

As can be seen from below given graph(y axis as dB), transmission spectrum is a sinusoidal function of wavelength. Path length difference is designed as $107.52\mu m$.

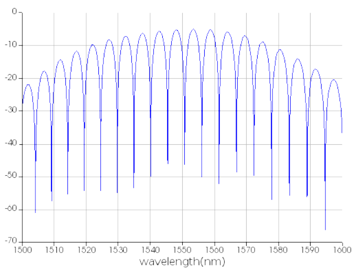

Fig. 10 Gain-Wavelength graph of imbalanced Mach-Zehnder interferometer with a path length difference 107 micron, simulated in Lumerical Interconnect

Distance on wavelengths between two consecutive peaks on graph called as "Free Spectral Range(FSR)" of interferometer and can be calculated mathematically using formula :

$$\text{FSR} = \delta\lambda = \frac{\lambda^2}{\delta L(n - \frac{dn}{d\lambda})} = \frac{\lambda^2}{\delta L n_g}$$

If FSR of interferometer can be obtained by optical analyser, than group index of waveguide can be derived from formula as :

$$n_g = \frac{\lambda^2}{\delta L * FSR}$$

In already defined simulation configuration, FSR has been calculated as 5.3nm+-0.5nm from software internal functionality. Now, group index can be calculated as :

$$n_g = \frac{1.55^2}{107.52^2 * 0.0053} \approx 3.92$$

After reducing of path length difference nearly by half as $50\mu m$, simulation result is :

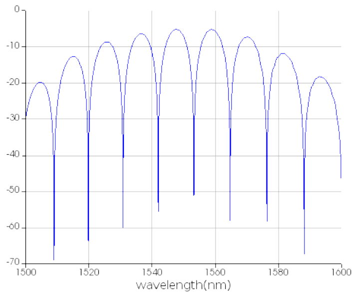

Fig. 11 Gain-Wavelength graph of imbalanced Mach-Zehnder interferometer with a path length difference 50 micron, simulated in Lumerical Interconnect

According to simulation results, FSR value is increased to 11nm+-1nm as expected.

Until now, only 1 output from Y-Branch has been evaluated. Much more realistic Mach-Zehnder interferometer can be build via using a 2-input, 2-output port device, like 50-50% Broadband Directional 3dB Coupler as shown below.

Because it is a 50-50% coupler, there will be destructive interface in one of the branches when there is a constructive one in the other, and simulation results prove it as given below :

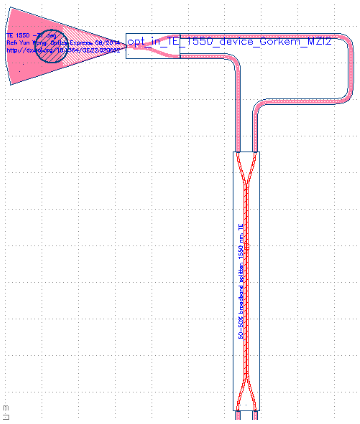

Fig. 12 50-50% broadband directional coupler, designed in K-Layout

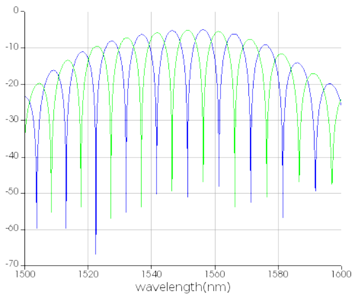

Fig. 13 Gain-Wavelength graph of imbalanced Mach-Zehnder interferometer with 2 outputs, simulated in Lumerical Interconnect

As mentioned before, there is no analytical method to calculate scattering loss due to fabrication imperfections, but it can be estimated in some boundaries using probabilistic approaches, like Monte-Carlo method.

4 Fabrication

4.1 Applied Nanotools, Inc. NanoSOI process:

The photonic devices were fabricated using the NanoSOI MPW fabrication process by Applied Nanotools Inc. (`http://www.appliednt.com/nanosoi`; Edmonton, Canada) which is based on direct-write 100 keV electron beam lithography technology. Silicon-on-insulator wafers of 200 mm diameter, 220 nm device thickness and 2 μm buffer oxide thickness are used as the base material for the fabrication. The wafer was pre-diced into square substrates with dimensions of 25x25 mm, and lines were scribed into the substrate backsides to facilitate easy separation into smaller chips once fabrication was complete. After an initial wafer clean using piranha solution (3:1 H_2SO_4:H_2O_2) for 15 minutes and water/IPA rinse, hydrogen silsesquioxane (HSQ) resist was spin-coated onto the substrate and heated to evaporate the solvent. The photonic devices were patterned using a Raith EBPG 5000+ electron beam instrument using a raster step size of 5 nm. The exposure dosage of the design was corrected for proximity effects that result from the backscatter of electrons from exposure of nearby features. Shape writing order was optimized for efficient patterning and minimal beam drift. After the e-beam exposure and subsequent development with a tetramethylammonium sulfate (TMAH) solution, the devices were inspected optically for residues and/or defects. The chips were then mounted on a 4" handle wafer and underwent an anisotropic ICP-RIE etch process using chlorine after qualification of the etch rate. The resist was removed from the surface of the devices using a 10:1 buffer oxide wet etch, and the devices were inspected using a scanning electron microscope (SEM) to verify patterning and etch quality. A 2.2 μm oxide cladding was deposited using a plasma-enhanced chemical vapour deposition (PECVD) process based on tetraethyl orthosilicate (TEOS) at 300ºC. Reflectrometry measurements were performed throughout the process to verify the device layer, buffer oxide and cladding thicknesses before delivery.

5 Experimental Data

To characterize the devices, a custom-built automated test setup [[1]] with automated control software written in Python was used (`http://siepic.ubc.ca/probestation`). An Agilent 81600B tunable laser was used as the input source and Agilent 81635A optical power sensors as the output detectors. The wavelength was swept from 1500 to 1600 nm in 10 pm steps. A polarization maintaining (PM) fibre was used to maintain the polarization state of the light, to couple the TE polarization into the grating couplers [[2]]. A 90º rotation was used to inject light into the TM grating couplers [4]. A polarization maintaining fibre array was used to couple light in/out of the chip [www.plcconnections.com].

6 7 Analysis

7 Conclusion

The conclusion goes here.

8 Acknowledgements

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2. Wang Y, Wang X, Flueckiger J, et al. (2014) Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits. Opt Express 22:20652. https://doi.org/10.1364/oe.22.020652