Analysis of phase compensation method for the tunable coupler

Mi Wang,[1,2] Antonio Ribeiro,[1,2] Yufei Xing,[1,2] and Wim Bogearts[1,2]

[1] Ghent University -imec, Photonic Research Group,
Department of Information Technology, Ghent, Belgium.
[2] Center of Nano and Biophotonics, Ghent University, Belgium.

We present a phase compensation method for configuring a two stage MZI into a broadband tunable coupler, and compare the simulation result of broadband performance for different tunable coupler designs with ideal 3dB DCs in 100 nm wavelength range of central wavelength 1550 nm. We also analyzed the tolerance to fabrication variations for different tunable coupler designs with a Monte Carlo simulation.

1.Introduction

One of the essential building block for a photonic integrated circuits is the tunable coupler. Normally a tunable coupler is implemented by a balanced MZI in Fig 1a. However, the balanced MZI would achieve 0 - 100% coupling only when the directional couplers are ideal 3 dB couplers. Due to fabrication variation, the fabricated values will differ from the designed value. In order to solve this problem, Miller [1] proposed a three-stage MZI circuit in Fig 1c. This is simply a 2×2 MZI where the two directional couplers (splitter and combiner) have been replaced with a balanced MZI, thereby an accurate 50:50 coupling could be obtained in the splitter and combiner. Suzuki [2] also proposed a reduced two-stage design in Fig 1b (a 2×2×2 MZI).
For all three tunable coupler designs in Fig 1, wavelength dependence has never been addressed yet, and in this paper, we will explain the phase compensation method and how to configure the two-stage MZI circuit into a broadband tunable coupler [3]. Same phase compensation method could also be applied to three stage MZI circuit in order to make the device a broadband tunable coupler.
We will also compare the broadband performance of the three designs and analyze the tolerance to fabrication variation by Monte Carlo simulation.

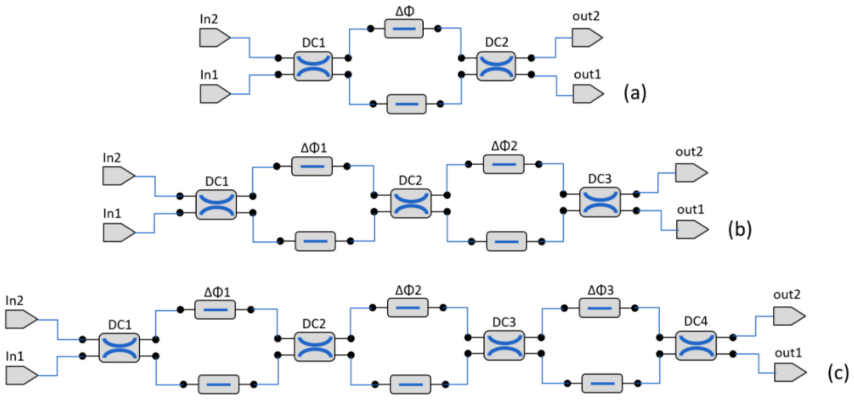

Figure 1 shows 3 designs for tunable coupler, Figure 1(a) is the one stage MZI composed by 2 ideal 3 dB couplers connected with 2 phase shifters. Figure 1(b) is the two stage MZI design and Figure 1(c) is the three stage MZI design proposed by Miller.

2. Theoretical analysis

An ideal 2×2 coupler should have broadband performance and with the spitting ratio tunable from 0-100% during operation. These couplers are essential for applications such as linear transformations, variable optical attenuators and switch fabrics.

In order to understand the working principle of a 2×2×2 MZI, the analytical model is built based on the transfer matrix method (TMM). The complex amplitudes of the input and output waves have the following relationship between each other:

$$\begin{bmatrix} E_3 \\ E_4 \end{bmatrix} = CPCPC \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} = CPCPC \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} \sqrt{1-k}\left(-k\left(e^{j\phi_1}+1\right)e^{j(\phi_1+\phi_2)} + \left(-ke^{j\phi_1}-k+1\right)e^{j\phi_1}\right)e^{-j(2\phi_1+\phi_2)} \\ j\sqrt{k}\left((k-1)\left(e^{j\phi_1}+1\right)e^{j\phi_1} + \left(k+(k-1)e^{j\phi_1}\right)e^{j(\phi_1+\phi_2)}\right)e^{-j(2\phi_1+\phi_2)} \end{bmatrix} \quad (1)$$

Where $E_1$and E_2 are the complex amplitudes of the light at the input, and E_3 and E_4 are the same quantities at the outputs for the device. Matrix C is the transfer matrix for the directional coupler and Matrix P is the transfer matrix of the phase delay section. k is the cross coupling value of the directional coupler, for simplicity of the simulation, we choose k to be the same for all the DCs used in the circuit. ϕ_1 and ϕ_2 are phase changes induced by the two phase shifters, which is also indicated in Fig 1b.

In the following section, we will perform numerical simulation based on equation (1) to analyze the two stage MZI tunable coupler design.

3. Tuning For Broadband Operation

A broadband 2×2 coupler would have the desired response that the coupling ratio remains the same in larger bandwidth. The basic working principle of configuring two stage MZI to a broadband coupler has been explained in Fig 2b.

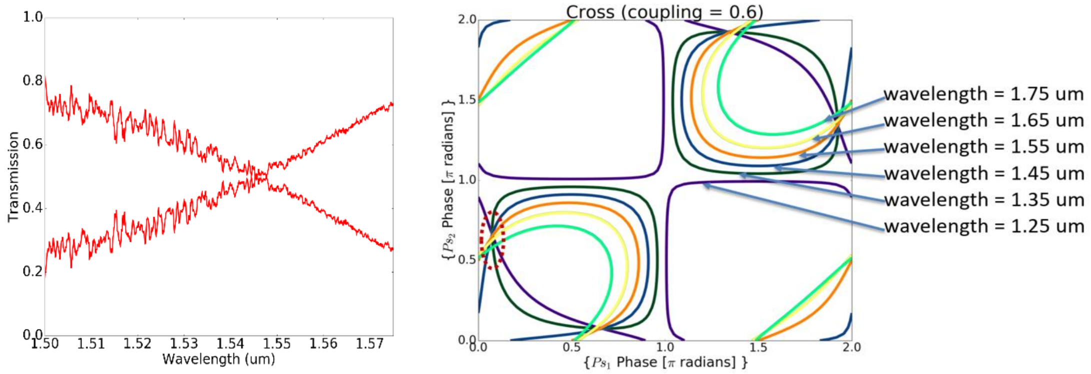

Fig. 2. (a) The spectrum response of a 50:50 DC. The DC is wavelength dependent, and the measured coupling values for different wavelengths are used in the simulation of (b).(b) In order to get a desired cross coupling of 0.6 for the two-stage MZI circuit, the phase shifters ϕ_1 and ϕ_2 can be configured in a wide range of combinations, which corresponds to a set of contour lines in the 2D phase space (ϕ_1, ϕ_2). At wavelength 1550 nm, the contour line for configuring the device into a 2×2 coupler with 0.6 cross coupling value is plotted in red in (b). Due to the dispersive nature of the directional coupler, the coupling value for different wavelengths also varies, which is shown in (a). Correspondingly, the contour lines for different wavelengths are distorted compared with the contour line for wavelength 1550 nm. However, different contour lines corresponding to different wavelengths within 50~nm wavelength range for central wavelength 1550 nm intersect with each other at the red dotted region in the 2D phase space. Thus, by operating the phase shifters in the red dotted region, the device would perform as a broadband coupler over a wavelength range of 50~nm.

Different combination of (ϕ_1, ϕ_2) would give a certain cross coupling value at certain wavelength for the 2×2 coupler. The simulation result for cross coupling of 0.6 for different wavelengths has been plotted in Fig 2b by the contours lines based on Equation (1). However due to the dispersion of the directional coupler, the contour lines corresponding to different wavelengths would be distorted compared with that for wavelength 1550 nm. The change in coupling strength would be compensated by constructive/destructive interference introduced by the two phase shifters. Essentially, the configuration of (ϕ_1, ϕ_2) results in a point where the contours of different wavelengths overlap.

Fig 3 is the simulation result of a two-stage tunable coupler with directional couplers with a perfect 50:50 splitting ratio at 1550 nm. The dark blue region surrounded by the yellow lines are the region in the 2D phase space where the broadband response has less than 3% deviation from the center wavelength of 1550 nm in 50 nm wavelength range. Thus, in order to configure the two stage tunable coupler into a broadband coupler, we need to work in the dark blue region. The white contour lines are cross couplings η (0-100 %) at 1550 nm. All white contour lines intersect with dark blue region, which indicates that the two stage MZI would be configured as a broadband tunable coupler with full tuning range from 0 – 100%.

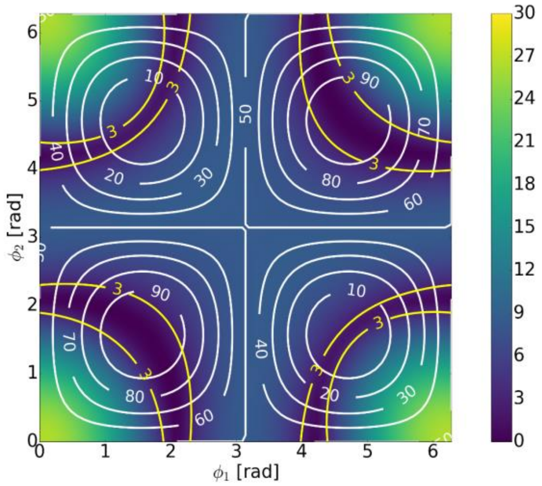

Figure 3. Cross couplings η at 1550 nm for the two stage MZI are plotted in white contour lines, dark region surrounded with yellow lines in the graph indicate the region of 3% deviation from the desired coupling within a 50 nm wavelength range of 1550 nm. The dark region covers all the coupling values, thus, we are able to configure the two stage MZI tunable coupler for all coupling values with 3% deviation.

4. Dispersion analysis for different tunable couplers

In this section, we will analyze the broadband performance in 100 nm wavelength range for these three tunable coupler designs in Figure 1. Figure 4(a), 4(b) and 4(c) are deviation simulation result for one stage, two stage and three stage MZI designs within 100 nm wavelength range for central wavelength 1550 nm. The x-axis is the cross coupling value and the y-axis is the minimum deviation of the broadband response for such cross coupling value. The minimum deviation of the broadband response was calculated through optimizing the phase shifters $(\boldsymbol{\phi_1}, \boldsymbol{\phi_2})$ with the Least Square method.

As shown in Figure 4(a), the single stage MZI is quite dispersive when working as a broadband coupler, however for higher cross coupling values, the device suffers from less dispersion. The two stage MZI has less than 3% deviation for coupling values near 0.5. However the three stage MZI has less than 2% deviation for all the coupling values. In conclusion, the two stage MZI design has the best performance as a 50/50 coupler however the three stage MZI has better performance when working as a switch.

In order to analyze the tolerance to fabrication variations of these three designs, Monte -Carlo analysis is applied to the coupling ratio of directional coupler in the circuit. If the coupling ratio of the directional coupler suffers from 5 % variation and the phase shifters

$(\boldsymbol{\phi_1}, \boldsymbol{\phi_2})$ are kept the same, the deviation plot could be regenerated based on the Monte-Carlo simulation. The maximum and minimum value of deviation after 100 Monte-Carlo samples are plotted as upper bound and lower bound for certain coupling value in Fig. 4.

The performance of the three tunable coupler designs are all degraded by the variation in fabrication; the three-stage MZI design would be the most tolerant design and with less than 3 % deviation even in the worst-case scenario. The two-stage design is the only tolerant design for higher coupler ratios. Currently the phase shifter is fixed in simulation and variation is only applied to the coupling ratio of the directional coupler, but in principle we could again adjust the phase shifter to compensate for the small coupling variation induced by fabrication variation.

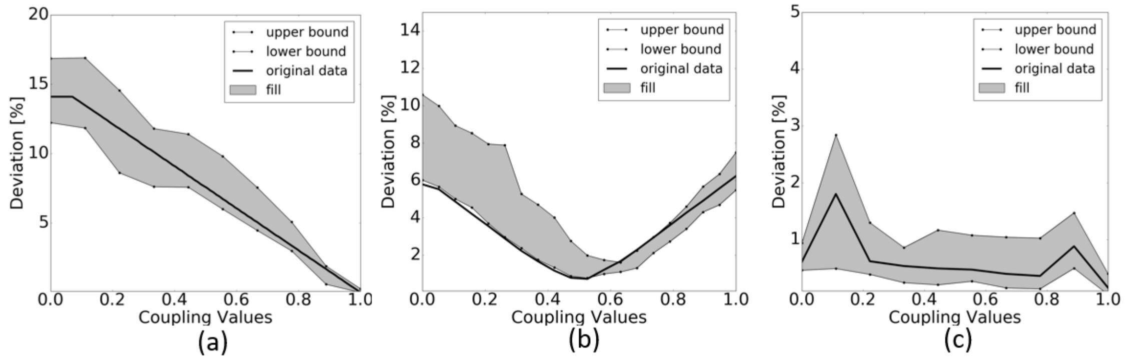

Figure 4(a), 4(b) and 4(c) are deviation simulation result for one stage, two stage and three stage MZI designs within 100 nm wavelength range for central wavelength 1550nm, the deviation is plotted as the original data. Later Monte-Carlo simulation is performed to mimic the fabrication variation in the DC. 5% variation of the coupling ratio is chosen and the 100 times Monte-Carlo simulation is applied. For a certain coupling value, the maximum deviation calculated by the Monte-Carlo simulation corresponds to the upper bound and the minimum deviation corresponds to the lower bound in Figure 4, between the upper bound and lower bound is the fill region indicated as grey color.

5. Conclusion

The wavelength independence of a single-stage, two-stage and three-stage MZI has been addressed. The principle of configuring the phase shifters in order to work in the broadband regime of the two stage MZI has been explained. The performance as a broadband coupler for these three tunable coupler designs have been compared and the tolerance to fabrication variation has been analyzed based on the Monte-Carlo simulation. The three-stage MZI circuit has the best broadband performance and is also tolerant to fabrication variations in 100 nm wavelength range, however the two-stage MZI circuit would require less control electronics and works as a broadband tunable coupler with full tuning range in 50~nm wavelength range with less than 3% variation.

[1] Mi Wang, Antonio Ribeiro, Yufei Xing and Wim Bogaerts, "Tolerant, Broadband Tunable 2×2 Coupler Circuit" in Proceedings of 2019 IEEE Photonics Society Summer Topical Meeting Series, 2019.

[2] David A. B. Miller. Perfect optics with imperfect components. Optica, 2(8):747-750, Aug 2015.

[3] Keijiro Suzuki, Guangwei Cong, Ken Tanizawa, Sang-Hun Kim, Kazuhiro Ikeda, Shu Namiki, and Hitoshi Kawashima, "Ultra-high-extinction-ratio 2 2 silicon optical switch with variable splitter," Opt. Express 23, 9086-9092 (2015).