Fabrication Tolerant Directional Coupler

(Student paper)

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We present the design of a fabrication-tolerant directional coupler in a passive photonic integrated chip fabricated on Imec's iSiPP50G silicon photonics platform. Based on Finite Difference Eigenmode, Finite-Difference Time-Domain simulations, and experimental measurements. We demonstrate that such a design is tolerant to waveguide width fabrication errors. The experimental results are in good agreement with the simulations.

Keywords: *fabrication tolerant, directional coupler, photonic intergrated circuit*

INTRODUCTION

Components on a photonic integrated chip (PIC) control the propagation of light on the chip. With the maturity of manufacturing technology, people's needs for chip functions are becoming more and more diverse, the circuits are becoming more complex. The high refractive index contrast between the waveguide core and cladding ensures high integration in chip fabrication, but also makes the performance of on-chip optics more sensitive to fabrication errors [1][2]. For example, a directional coupler (DC) is an essential component of almost all chips, and the manufacturing error of its waveguide width will cause a large error between the actual coupling ratio and the design value, which will affect all components that contain DC. Therefore, designing and manufacturing on-chip components that are insensitive to manufacturing errors at a low cost is of great significance for improving product yield and reducing manufacturing costs.

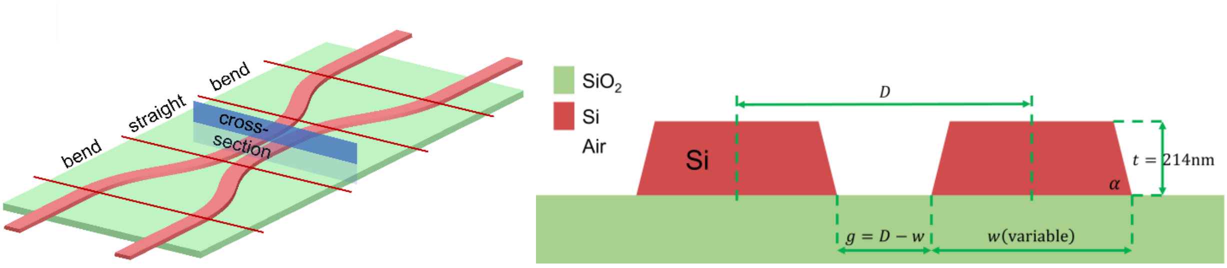
STRUCTURE MODEL OF THE DIRECTIONAL COUPLER

A DC usually consists of two waveguides in close proximity, so that the evanescent field of electromagnetic waves can couple the energy of light from one mode to the other. The math model [3] that describes the cross-transmission characteristics of the coupler is shown in Equ.(1):

$$P = \sin^2(\kappa' L + \kappa_0) \tag{1}$$

Where P is the overall power coupling, κ' is the coupling per unit length of the straight coupler section, L is the length of the straight section of the DC, and κ_0 is the coupling from the bend section.

The corresponding schematic diagram is as figure 1(a). Figure 1(b) shows the cross-section through the straight section of a directional coupler with SiO_2 base and air cladding.



(a) (b)

Figure 1: (a) Schematic diagram of a directional coupler showing the straight and the curved sections. (b) Diagram showing the cross-section through the straight section of the directional coupler.

In IMEC's iSiPP50G silicon photonics platform, the base angle $\alpha > 85°$; the thickness t is 214nm; the default value of centre line distance D is 700nm; the default value of waveguides base width w is 450nm, g demonstrates the base gap of the waveguides. The waveguides are made of Si and the DC can be SiO_2 cladding or air cladding.

Based on the current manufacturing process, we use the following approximations when the width changes due to a fabrication variation:

- both waveguides are symmetrical trapezoids
- the absolute change is same for both waveguides and it occurs symmetrically on the left and right sides of the waveguide. That means that we assume that D is invariant under fabrication variations.

Now we consider the result of the manufacturing error of the waveguide width. As the waveguide becomes wider, the waveguide confines the modes more strongly, which leads to a decrease in the coupling strength. But on the other hand, a wider waveguide will make the gap between the two waveguides smaller (if we consider D as constant), which will lead to a larger coupling strength. Therefore, over the range of waveguide widths we can fabricate, if these two factors affecting coupling can be balanced, then we will obtain the waveguide insensitive to fabrication errors.

TOLERANT COUPLER SIMULATION RESULTS

We perform a set of simulations to validate the idea of this tolerant design. For a given D of a symmetric directional coupler, we scan the width of the waveguides and calculate how the transmission changed with the width of the waveguides.

We first use Ansys Lumerical finite difference eigenmode (FDE) to calculate the coupling per micrometre (κ') in the straight section of the DC (figure 1 (b)). Because FDE is an algorithm applied to two-dimensional structures, it is relatively faster than three-dimensional structures. In the sweep, the waveguide width changes from 478nm to 548nm, while keep D=700nm. As shown in figure 2(a), we can find that the tolerance region for the DCs we simulate is $520\text{nm} < w < 530\text{nm}$. Through the quick simulation of FDE, we can know that our design ideas are generally correct. This makes it meaningful that we use FDTD to calculate the coupling ratio across DC.

Then we use Ansys Lumerical Finite-Difference Time-Domain (FDTD) method to simulate the complete coupler with the bend sections shown in Figure 1(a). We simulate different lengths of the DC to see whether the length of straight sections have large influence on the tolerant region.

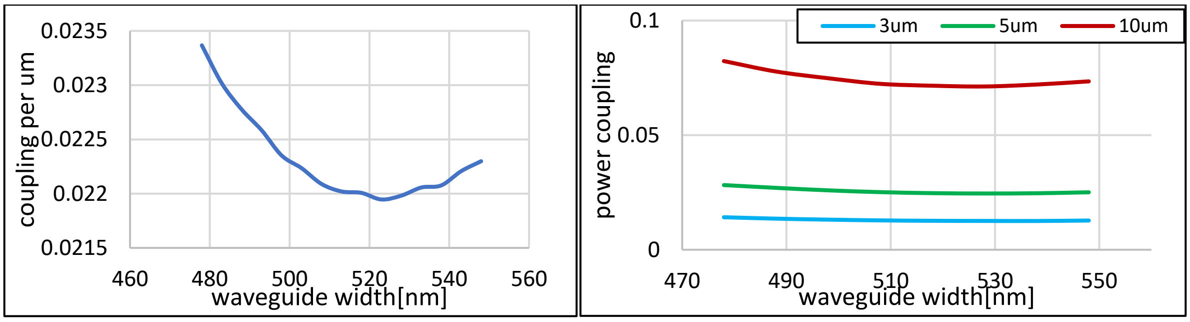


Figure 2 (a) Calculated $\boldsymbol{\kappa}'$ using FDE solver for different waveguide widths, with D=700nm. (b) Calculated cross port power coupling using FDTD solver for different waveguide widths and lengths of the tolerant design, with D=700nm

From the simulations results in figure 2(b), we can see that with a width variation of $\pm 35\text{nm}$ around 513nm, the relative differences $\left(\frac{\max-\min}{\max+\min}\right)$ of these DCs are 6.1%, 7.0%, and 7.2% for $L = 3, 5$ and $10\mu\text{m}$ respectively. The tolerance region for the DCs we simulate is $520\text{nm} < w < 530\text{nm}$. The tolerance region of these DCs with different lengths calculated by FDTD are very close, we think this is because the coupling strength of DC is mainly provided by the straight section if this DC is not particularly short. The tolerance intervals calculated by FDTD and FDE algorithms are also close. This means that, based on our idea, we don't necessarily need to use the time-consuming FDTD for the calculation.

TOLERANT COUPLER MEASUREMENT RESULTS

In this chapter, we present the preliminary design and experimental measurement results of the tolerant couplers. We did not measure the couplers directly, because the transmission $T_c(\lambda)$ of the coupler is close to that of the grating $T_g(\lambda)$, and we do not have a very accurate method to calculate the influence of the grating from the measurement results.

So, we use Mach–Zehnder interferometers (MZIs) for measurement. The two DCs in each MZI are designed to be identical. It should be mentioned that in our experiments all elements are purely passive elements with air cladding.

To calculate the coupling strength, we use the following lossless MZI mathematical model:

$$F = \begin{bmatrix} \sqrt{1-P(\lambda)} & i\sqrt{P(\lambda)} \\ i\sqrt{P(\lambda)} & \sqrt{1-P(\lambda)} \end{bmatrix} \begin{bmatrix} e^{-i\frac{2\pi n_{eff}(\lambda)\Delta L}{\lambda}} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \sqrt{1-P(\lambda)} & i\sqrt{P(\lambda)} \\ i\sqrt{P(\lambda)} & \sqrt{1-P(\lambda)} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{2}$$

In the equation above, $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ is the normalized input field and TE polarized; $P(\lambda)$ is the cross-port power coupling of DCs; ΔL is MZI arm length difference; λ is the wavelength; $n_{eff}(\lambda)$ is the effective index of the waveguide; F is the output complex Rayleigh coefficient of each port. The cross/bar port power coupling is the square of the absolute value of each element.

One of our measurements with $w = 548\text{nm}$ is shown in figure 3. We show this measurement result since the bar port has a maximal extinction ratio which means the 50% power coupling at the corresponding wavelength. So, the bar/cross ports power is comparable and makes the picture look nice.

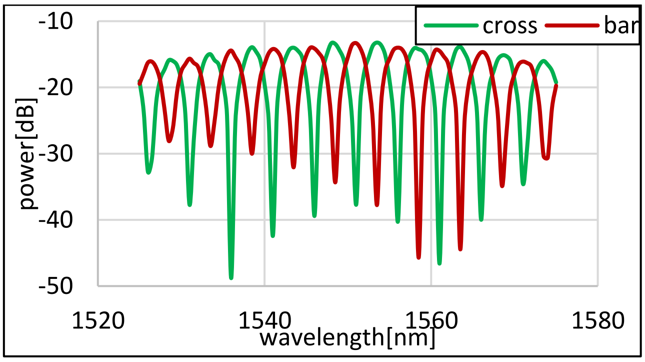


Figure 3 Measurement results of two MZI ports with waveguide width 548nm.

After data processing steps and fit the power coupling $P(\lambda)$ with equation (2), we obtain the cross-port power coupling of these DCs with different waveguide widths.

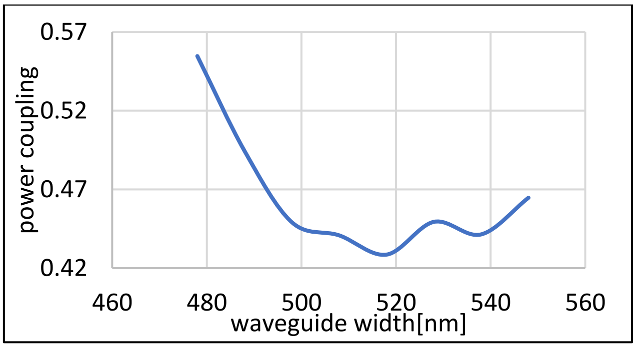


Figure 4 Cross-port power coupling of DCs with different waveguide width, 9.98um straight section length

From the results shown in figure 4, we find that the tolerance region of these DCs is around 520nm. There could be a deviation of several nanometres compared with the simulation results. This may be due to two main reasons: the thickness of the manufactured waveguide is different from the design value (214nm); the side wall angle of the waveguide is not 85°. But generally, we can find the waveguide width tolerant region of DCs. In this region, the DCs transmission characteristics are insensitive to changes in waveguide width.

CONCLUSIONS

To conclude, the design of the tolerant directional coupler is presented and validated by FDE simulation, FDTD simulation and measurements. Our experimental measurements are in good agreement with the FDTD simulation results. Since this was a preliminary experiment to evaluate the idea, we didn't scan the waveguide width over a wide range. In the following experiments and measurements, we will apply a wider range of scanning and more sweep steps of the waveguide width. In the future, we will combine the ideas of tolerance DC and broadband DC to design and manufacture tolerance and broadband DC.

References

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