Design and modeling of a fabrication tolerant and broadband directional coupler

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We present a design for a fabrication tolerant and broadband directional coupler in photonic integrated circuits based on IMEC's iSiPP50G silicon photonics platform. We demonstrate that such a design can be tolerant to fabrication errors on waveguide width and at the same time has a uniform coupling ratio around the operating wavelength of 1550 nm. Based on the finite difference eigenmode and finite-difference time-domain simulation results, we analyze the effects of fabrication errors on the coupling of these directional couplers.

1 Introduction

Photonic Integrated Circuits (PIC) route light between different optical functions on a chip, and these circuits are becoming increasingly complex with the growing maturity of the fabrication technology and the design/simulation platforms. The high refractive index contrast between the waveguide core and the cladding on the one hand facilitates the high integration of chip fabrication, but on the other hand, makes the transmission characteristics of the on-chip optical components more sensitive to fabrication errors [1]. For example, fabrication errors in waveguide width of a directional coupler (DC), one of the most fundamental components on a chip, can lead to very large errors in the power coupling. Therefore, designing and manufacturing on-chip components that are insensitive to manufacturing errors is of great significance for improving product yield and reducing manufacturing costs.

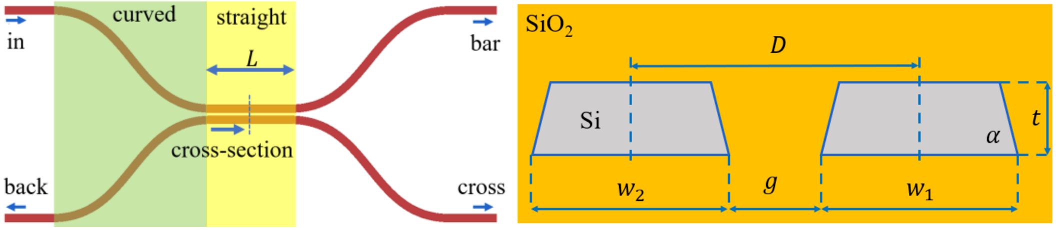
2 Structure model of the directional coupler

A DC consists of two waveguides that are brought in close proximity, so the evanescent fields can couple the light from one waveguide to the other. The model [2] that describes the cross-transmission characteristics of the coupler:

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

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 curved section.

The corresponding schematic diagram is as figure 1(a)



(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.

3 Waveguide width fabrication errors

Figure 1(b) shows the cross-section through the straight section of a directional coupler with silicon waveguides and silica cladding all around. D is the distance between the center lines of the two waveguides; w_1, w_2 are the widths of two waveguides; t is waveguides thickness; g demonstrates the base gap of the waveguides; the sidewall angle α is 85°.

Based on IMEC's silicon photonics platform iSiPP50G, we use some approximations here: both waveguides are symmetrical trapezoids (side angle (α) is same on the outside and in the gap), and we assume that when the width changes due to a fabrication variation, the change is the same (in absolute numbers) 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.

When the waveguides become wider, the mode confinement in the waveguide becomes stronger, which will lead to lower coupling strength. But on the other hand, widening the waveguides will make the gap between the two waveguides smaller (for constant D), which will lead to a larger coupling strength. Therefore, if these two factors that affect the coupling can achieve balance in the range of waveguide widths that we can fabricate, then we can achieve an equilibrium region where the coupling strength is not sensitive to a change in the waveguide width.

4 Tolerant coupler

We performed a set of simulations to validate the idea of this tolerant design, and to identify the tolerant design space. For a given D of a symmetric directional coupler, we scanned the width of the waveguides and observed how the transmission changed with the width of the waveguides.

4.1 Finite difference eigenmode simulations

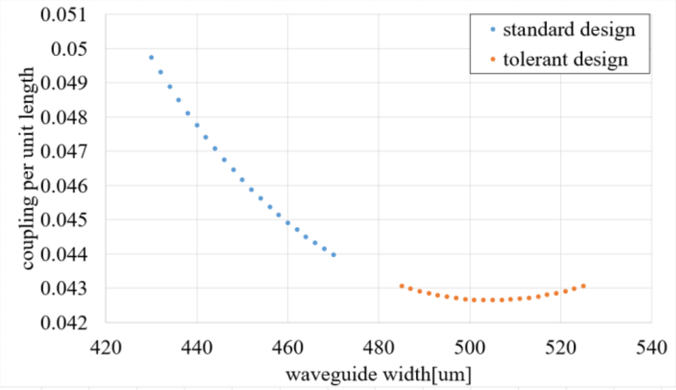


Figure 2 Calculated coupling per unit length (κ') using finite difference eigenmode (FDE) solver for different waveguide widths of both the standard and the tolerant designs.

We first present a fast and accurate simulation result using the finite difference eigenmode (FDE) solver from Ansys Lumerical Mode. It is worth noting that the simulation result only represents the coupling strength per unit length (κ') from the straight coupler section, not the total power coupling after a given length.

Figure 2 shows the simulation results calculated by the FDE solver. The standard design we used is $D = 700\text{nm}, w_1 = w_2 = 450\text{nm}, \text{and t} = 214\text{nm}$.

We can see that within a width variation of $\pm 20\text{nm}$ around 450nm, the standard design leads to a 6% relative difference$\left(\frac{\text{max}-\text{min}}{\text{max}+\text{min}}\right)$, while we observe a tolerant region around 505nm which only has a 0.5% relative difference. After a quick simulation with the FDE solver, we were able to ascertain that this tolerant design is feasible. The next step is to simulate the complete coupler with the curved sections. We do not expect the results to be quite different from the straight waveguide section, since the coupling strength is dominated by the straight waveguide section, except when the coupler is very short.

4.2 Finite-difference time-domain simulations

We used Ansys Lumerical finite-difference time-domain (FDTD) to simulate the complete coupler with the bend sections shown in Figure 1(a). We have simulated different lengths of the DC to find out the influence of the curved section on the tolerant region.

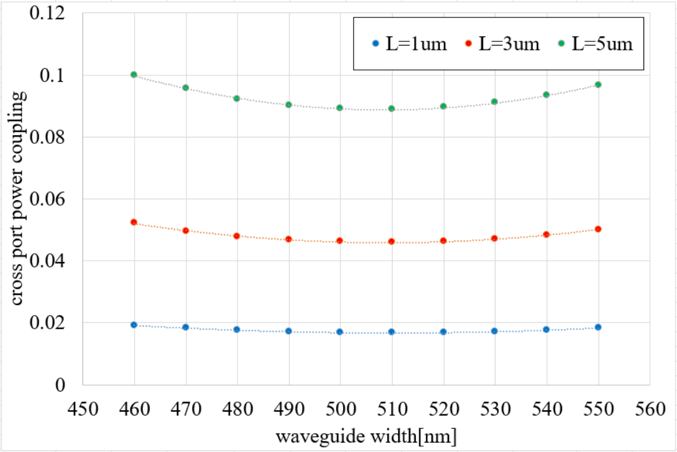


Figure 3 Calculated cross port power coupling using finite difference time domain (FDTD) solver for different waveguide widths and lengths of the tolerant design.

From the simulations, we can see that the tolerant region of the complete coupler has several nano-shifts compared with that of the straight section. The relative differences for a width variation of $\pm 45\text{nm}$ are 9.9%, 6.5%, and 6.4% for $L = 1,3,$ and $5\mu\text{m}$ respectively. The relative differences decrease with increasing coupler lengths. We think the reason might be that the curved section of coupler is more sensitive to the width variations.

5 Broadband-tolerant coupler

We want our directional coupler to be both fabrication tolerant, and broadband, i.e., it has a constant coupling strength over a wide wavelength range. For that, we make the directional coupler asymmetric: $w_1 \neq w_2$ [3]. We use the simplest and most easily fabricated asymmetric coupler as the basis for our design of the broadband-tolerant coupler. The asymmetry will lead to a maximum power cross-coupling of less than 1. We can use the asymmetry to get the desired maximum cross coupling for the center wavelength; as the power coupling follows a sinusoidal response as function of length, the top of this sine curve (at max cross coupling) is also quite tolerant to wavelength variations. It is worth noting that for these simulations, we use a rectangular waveguide, so the sidewall angle α is 90°.

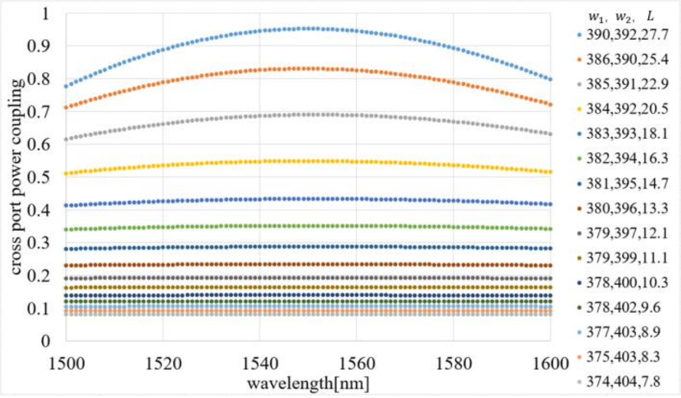


Figure 4 Calculated cross port power coupling for the designed tolerant-broadband coupler.

We show one group of tolerant-broadband design parameters for different desired power coupling in figure 4. The center line distance (D) between two waveguides is fixed at 700nm. The legend shows the used design parameters, the first two numbers are the widths [nm] of the waveguides (w_1, w_2) and the third number is the length[um] of the straight section waveguides (L).

From figure 4, we can see that the larger the mismatch between the waveguide widths is, the lower is the maximum power coupling, but broader is the bandwidth. The relative difference within the $\pm 50\text{nm}$ wavelength band around 1550nm changes from 10% to 0.2% when the maximum coupling efficiency changes from 95% to 8%.

Figure 5 shows the relationship between desired maximum cross power coupling, width difference between two waveguides and the coupler length. We can see that, for a particular desired coupling, we need the specific width difference and coupler length.

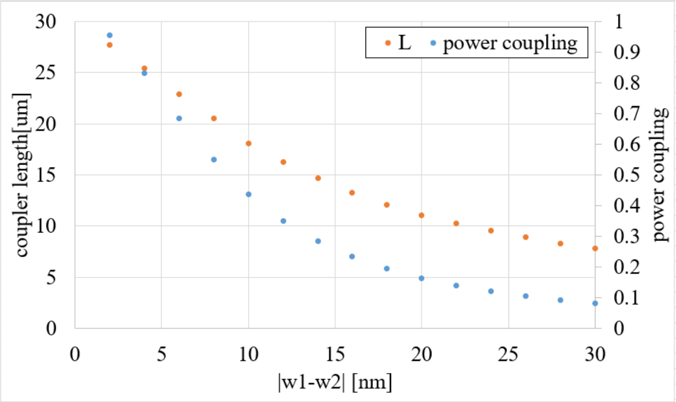


Figure 5 Relationship between desired maximum coupling, width difference and the coupler length

We select one of the designs in this group and scan the waveguide widths to test the fabrication tolerance. During the sweep, the mismatch between the two waveguides is fixed at 10nm. The horizontal axis below shows the shifts between averaged waveguide width and 388nm.

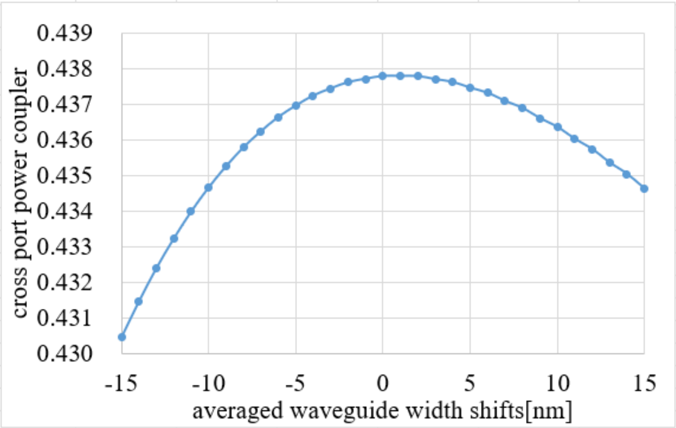


Figure 8 Waveguide width sweep for the tolerant-broadband coupler.

We can see that the relative difference within $\pm 15\text{nm}$ width variation around the tolerant region ($w_1 = 383\text{nm}, w_2 = 393\text{nm}$) is 0.84%. Unlike the symmetrical coupler (non-broadband coupler simulation results shown in Figure 2), the tolerant region of the non-broadband coupler shows a minimal value while the tolerant region of the broadband coupler shows a maximal value.

The reason is that the tolerance of the non-broadband coupler is the optical confinement of the waveguide and the effect of the waveguide gap that cancel each other. We should consider that a broadband coupler requires a particular coupler length and waveguide width to get maximal coupling efficiency. The change in width will reduce the coupling efficiency.

6 Conclusions

To conclude, the design of the tolerant-broadband directional coupler is presented and validated using FDE and FDTD simulations. We validated the design space and identified regions of broadband and tolerant operation. We currently do not have an experimental verification, but this is planned for the near future. If the measurement results support the simulation results, the presented design parameters can be used in our future manufacturing platform.

References

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