Silicon Photonic 2 X 2 Power Splitter with S-Bend Configuration

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Abstract The power splitting ratio of a symmetric 2x2 directional coupler which is based on the silicon-on-insulator (SOI) platform is explored by varying the coupling length (l_c) and the waveguide gap (g_c) using the Wave Optics Module in COMSOL Multiphysics®. This work also serves as a comparative study to validate COMSOL's ability to reproduce results from Lumerical Mode Solutions®, a popular integrated photonics modelling platform in simulating directional couplers with various power splitting ratios.

Keywords: Directional Coupler, Silicon-on-Insulator, Silicon Photonics, Power splitter.

1. Introduction

Directional couplers are used for the purpose of redirecting, splitting, and combining light in silicon photonic circuits. They are used extensively in data communication applications such as wavelength-division-multiplexing and signal switching [1]. Their functionality is an integral building block for devices such as Mach-Zehnder interferometers (MZIs), polarization filters , and distributed Bragg reflector (DBR) based wavelength filters [2]. Their functionality is an integral building block for devices such as Mach-Zehnder interferometers (MZIs), polarization filters , and distributed Bragg reflector (DBR) based wavelength filters [2].

Although the directional coupler has a flexible design, resulting power splitting ratios are very sensitive to variations in their geometry and operating wavelength [3]. So, the ability to capture the resulting power distributions is very important subsequent fabrication. In this paper, various geometries and operating wavelengths of a power splitter will be simulated using both COMSOL Multiphysics and Lumerical Mode Solutions® to validate results.

2. Theory

The simulated 2x 2 power splitter is based on a 220 nm silicon-on-insulator (SOI) waveguide platform where Si is buried within SiO_2 cladding. The high refractive index contrast between Si in comparison to the surrounding cladding acts to optically confine propagating light in waveguide structures [4]. As depicted in the schematic in Figure 1, the power splitter consists of 4-ports, two inputs, a through port, and a cross port. The waveguides have s-bend regions which transition to a straight coupling length denoted as (l_c). They are separated by a gap (g_c). In the cross-section view, the 220 nm thick, 400 nm width geometry is chosen to maintain single TE mode propagation in both waveguides. As light is launched into the input port, which is demonstrated by the direction of the white arrows, it travels through the top waveguide and out to the through and cross port. Depending on the proximity and interaction length a fraction of light will be evanescently coupled between waveguides.

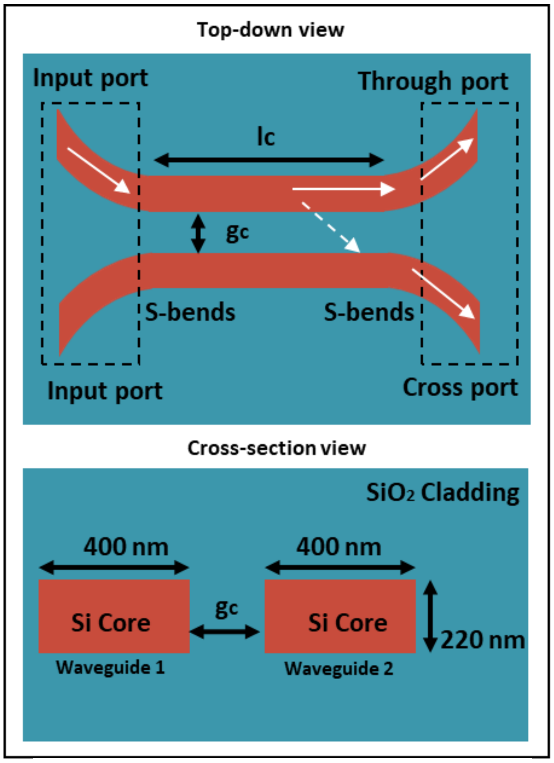

Figure 1. Schematic of power splitter

3. Power Splitter Simulation

In the 2D 4-port directional coupler, power splitter is simulated using COMSOL's Electromagnetic Waves, Beam Envelopes (ewbe) physics interface in the Wave Optics Module [5]. To study the wavelength dispersion of the power splitter, a parametric sweep over the wavelength range of 1.50 $um \le \lambda \le 1.60$ um is included. Figure 2 and Figure 3 represent the refractive index of Si (n_{Si}) and SiO_2 (n_{SiO2}) as wavelength dependent interpolated functions.

3.1 Governing Equations

In order to simulate mode propagation through the Si core, the Electromagnetic Waves, Beam Envelopes (ewbe) physics interface in the Wave Optics Module was used. This interface, which is based on the below equation is used when the model has a length that is much longer than the wavelength [5].

$$E(r) = E_1(r)e^{(-jk_1 \cdot r)}$$

Where E_1 is the in-plane electric field, $e^{(-jk_1 \cdot r)}$ is the phase, and k_1 is the wave vector.

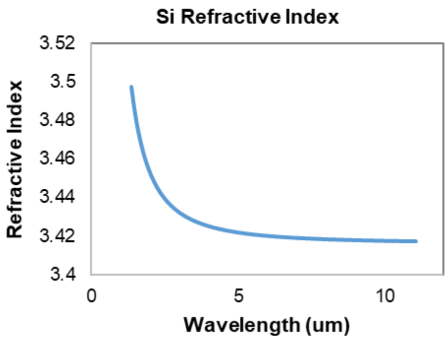

Figure 2. Interpolation plot of n_{Si} spanning a wavelength range of 1.357 to 11.04 um.

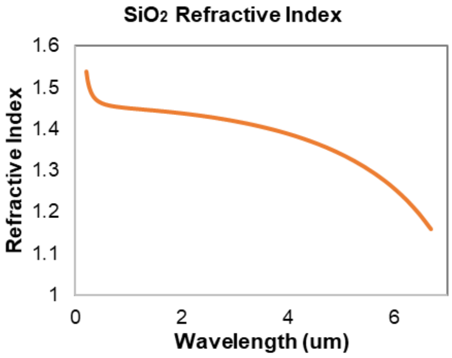

Figure 3. Interpolation plot of n_{SiO2} spanning a wavelength range of 0.21 to 6.7 um.

4. Results and Discussion

Simulation results in Figure 4 show the normalized electric field distribution at a wavelength of 1.55 um while operating in the TE mode. As the lc is varied from 0 um to 30 um in Figure 4 a. - 4 d., the amount of evanescent coupling from the top waveguide to the bottom becomes more pronounced.

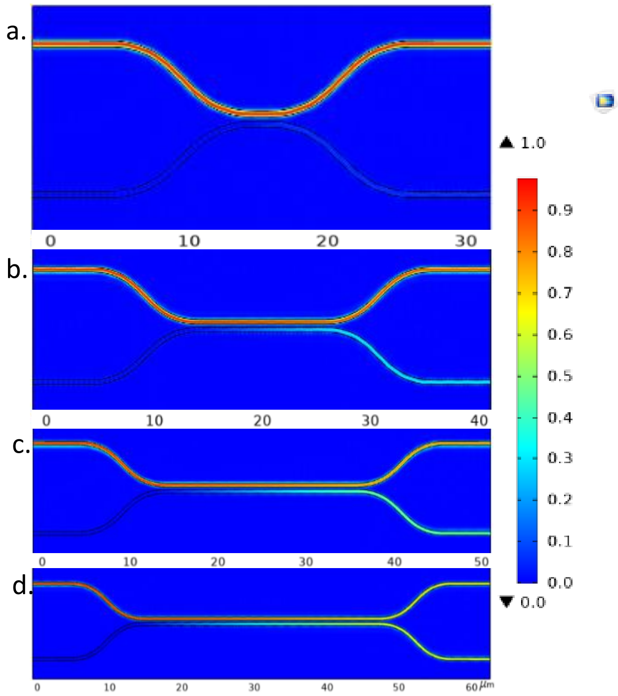

Figure 4. Normalized power distribution of directional couplers for various coupling lengths operating at a 1.55 um wavelength. a. lc= 0 um, b. lc = 10 um, c. lc = 20 um, d. lc= 30 um.

At lc = 0 um, all the power remains in the top arm while at lc = 30 um, the power is equally split. Figure 5 shows the power splitting ratios as the operating wavelength is swept from and lc is varied at the through and cross port. At a lc of 0 um, no power is coupled resulting in a 100/ 0% splitter. At a lc of 30 um, the power in the cross port exceeds that of the through after ~ 1.54 um.

In Figure 6, the power distribution as gc is decreased from 0.4 um to 0.1 um is shown. In Figure 6. a., no power is coupled from the top waveguide. While in Figure 6. d., the waveguides can couple light back and forth several times before reaching the through and cross port. Figure 7 shows the power splitting ratios as the gc is between the waveguides is minimized and the operating wavelength is swept.

When gc is largest at 0.4 shown with blue solid and dotted lines, there is minimal power transfer for most of the wavelength range. When gc is smallest at 0.1 shown with purple solid and dotted lines, the power at the cross port exceeds that in the through port. A 50/50% power ratio is obtained at a wavelength of ~ 1.54 um.

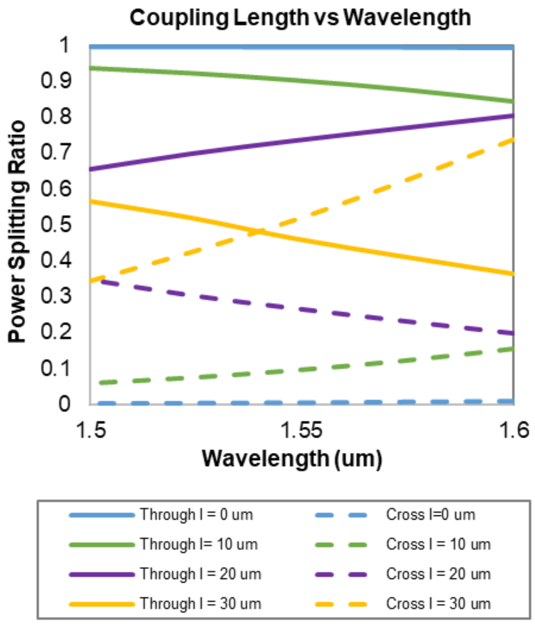

Figure 5. Simulated power splitting ratio of the through and cross port across a wavelength range of 1.5 um to 1.6 um. The blue solid and dashed line correspond to a coupling length of 0 um. The green solid and dashed line correspond to a length of 10 um. The purple solid and dashed line correspond to a length of 20 um. And the yellow solid and dashed line correspond to a length of 30 um. The corresponding waveguide gap for the above simulations is 0.1um.

Figure 7 shows the power splitting ratios as the *gc* between the waveguides is minimized and the operating wavelength is swept. When *gc* is largest at 0.4 *um* shown with blue solid and dotted lines, there is minimal power transfer for most of the wavelength range. When *gc* is smallest at 0.1 *um* shown with purple solid and dotted lines, the power at the cross port exceeds that in the through port. A 50/50% power ratio is obtained at a wavelength of ~ 1.54 *um*.

In order to provide further validation to the results obtained, the power splitter is simulated using Lumerical Mode Solutions®. Figure 8 shows the change in the power splitting ratio as *lc* is increased from 0 *um* to 30 *um*. The results from the two software are in good agreement with only small deviation towards the larger *lc* values. In Figure 9., the simulation results from Lumerical follow the trend of the splitting ratio as *gc* is changed.

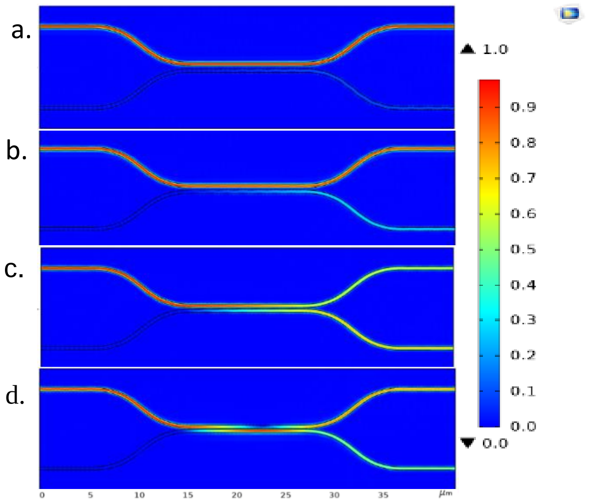

Figure 4. Normalized power distribution of a power splitter for various wavelength gaps operating at a 1550 nm wavelength. a. gc= 0.4 um, b. gc = 0.3 um, c. gc = 0.2 um, d. gc= 0.1 um.

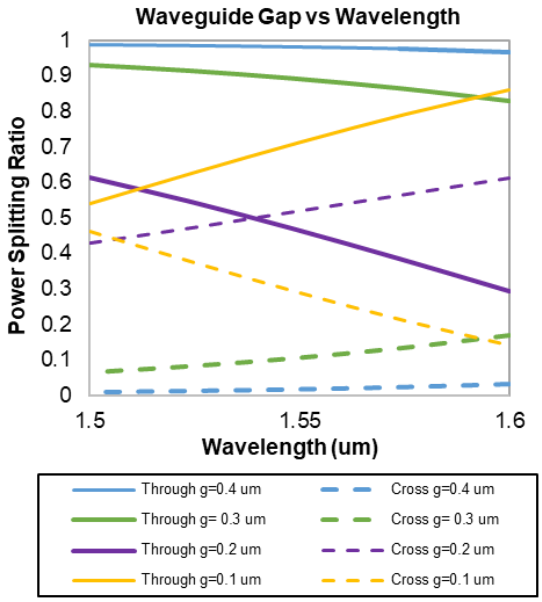

Figure 7. Simulated power splitting ratio of the through and cross port across a wavelength range of 1.5 um to 1.6 um. The blue solid and dashed line correspond to a gap of 0.4 um. The green solid and dashed line correspond to a gap of 0.3 um. The purple solid and dashed line correspond to a gap of 0.2 um. And the yellow solid and dashed line correspond to a gap of 0.1 um. The corresponding coupling length for the above simulations is 10 um.

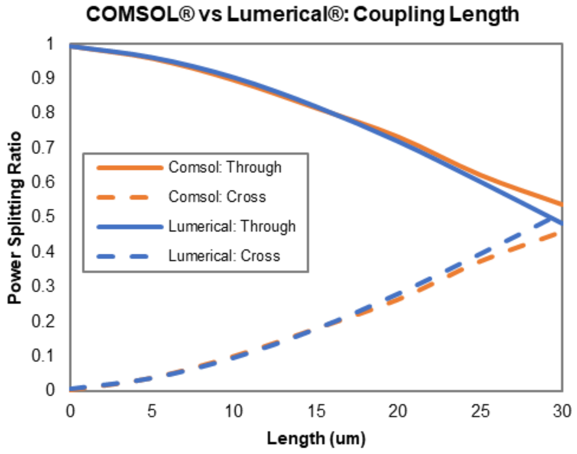

Figure 8. Simulated power splitting ratio of the directional coupler as the coupling length is increased from 0 um to 30 um. The solid and dashed blue line correspond to simulated COMSOL results. The solid and dashed orange line correspond to Lumerical results.

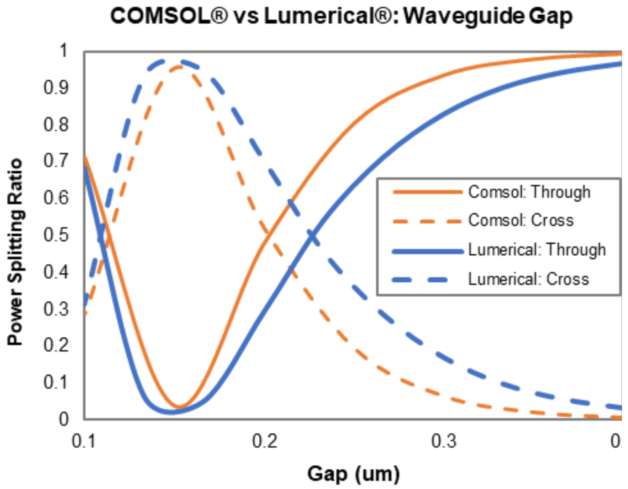

Figure 9. Simulated power splitting ratio of the directional coupler as the waveguide gap is increased from 0.1 um to 0.4 um. The solid and dashed blue line correspond to simulated COMSOL results. The solid and dashed orange line correspond to Lumerical results.

5. Conclusions

We have demonstrated COMSOL's ability in reproducing optical results. As the *lc* is increased from 0 *um* to 30 *um*, both software show that the power through and cross port become equally split. When *gc* is decreased, both software have the same coupling phenomena. While Lumerical is highly capable of solving simulation problems that are solely optics based, it does not allow users to include to real world physics contribution [6] in the way COMSOL can.

6. Acknowledgement

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7. References

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