Photonics Integrated CIrcuits

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Assignment No. 5
Directional Coupler

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1 Introduction

The whole assignment is mainly centered around directional coupler, which is the most common method of splitting and combining light in photonic systems, especially those in optical fibres. The directional coupler consists of two parallel waveguides, where the coupling coefficient is controlled by both the length of the coupler and the spacing between the two waveguides.

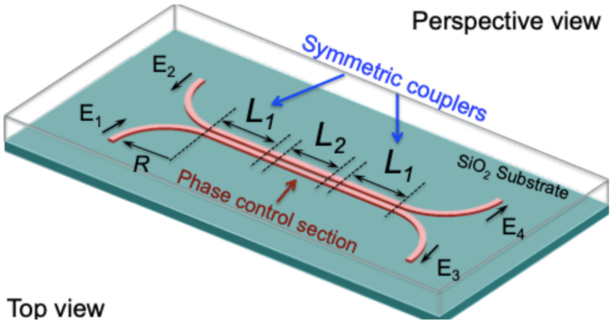


Figura 1: Index variation across the SSC structure

In silicon photonics, directional couplers can be implemented using any type of waveguide, including rib and strip waveguides. This assignment focuses on strip waveguide with quasi-TE polarization. A diagram of a directional coupler is given in Figure 1. The behaviour of a directional coupler can be found using coupled mode theory. The fraction of the power coupled from one waveguide to the other can be expressed as:

$$\kappa^2 = \frac{P_{Crossover}}{P_o} = \sin^2(C.L) \tag{1}$$

where P_o is the input optical power, $P_Crossover$ is the power coupled across the directional coupler, L is the length of the coupler, and C is the coupling coefficient. The fraction of the power remaining in the original "through" waveguide, assuming a lossless coupler $\kappa^2 + \tau^2 = 1$ is,

$$\tau^2 = \frac{P_{Through}}{P_o} = \cos^2(C.L) \tag{2}$$

To obtain the coupling coefficient, we generally use "supermode" analysis, which is primarily based on a numerical calculation of the effective indices, n_1 and n_2 , of the first two eigenmodes of the coupled waveguides.

These two modes, shown in Figure , are known as the symmetric and antisymmetric supermodes.

The supermode approach, and what follows next, is often called the eigenmode expansion method . This approach is more accurate (especially for high-index contrast waveguides with strong coupling) than the traditional Coupled Mode Theory (CMT) approach, where the coupling coefficient is found by perturbation methods. From these two supermodes, the coupling coefficient is found,

$$C = \frac{\pi \Delta n}{\lambda} \tag{3}$$

where Δn is the difference between the effective indices, $n_1 - n_2$. The concept behind the coupler can be explained via the propagation of the two modes with different propagation constants:

$$\beta_1 = \frac{2\pi n_1}{\lambda} \tag{4}$$

$$\beta_2 = \frac{2\pi n_2}{\lambda} \tag{5}$$

As the modes travel, the field intensity oscillates between the two waveguides. With the two modes in phase, the power is localized in the first waveguides. After a π phase shift difference between the modes, the power becomes localized in the second waveguide. This occurs after a distance called the cross-over length, L_x, and is found by:

$$\beta_1 L_x - \beta_2 L_x = \pi \tag{6}$$

$$L_x[\frac{N}{\left(\frac{L}{p}\right) - (m+n)}] = \pi \tag{7}$$

$$L_x = \frac{\lambda}{2\Delta n} \tag{8}$$

2 Simulation Setup

MODE Solutions of Lumerical Suite is used to simulate the directional coupler and the FDE solver is used to find the effective index of the symmetric and asymmetric modes. The directional coupler is designed with two identical Si waveguides having width 0.5 μm and height 0.22 μm and separated by a gap of 0.2 μm with a Si slab of 0.09 μm thickness. The SiO_2 cladding has a thickness of 2 μm. The numerical simulation for calculating the power coupling in the given directional waveguide coupler is performed using Lumerical Suite and MATLAB.

3 Results and Discussions

In this section, I tried to provide a concise and intuitive explanations to the observations obtained according to the objectives that were asked in the given assignment.

3.1 Basic configuration

In the first simulation, I just ran scripts of materials, waveguides and modes in the Eigenmode solver to generate Symmetric (S) and Asymmetric modes (AS) and their effective refractive indices . Using the n_{ef}, I calculated coupling ratio at the two ports (Crossover & Through) and cross-over length. Cross-over length ($L_{Crossover}$)is the length of the coupler after which the two super modes (Sym, ASym) are shifted by 180° (out of phase).

$$L_{Crossover} = \frac{\lambda}{2(neff_{sym} - neff_{asym})} \tag{9}$$

,where $neff_{sym}$ & $neff_{asym}$ are the effective index of Symmetric and Asymmetric modes respectively.
The calculations for the transfer function are done from,

$$\kappa = |\sqrt{\frac{P_c}{P_o}}| = |\sin\frac{\pi}{2}\frac{L_c}{L_{Crossover}}| \tag{10}$$

where L_c & $L_{Crossover}$ are the length of the coupler and crossover length respectively. Here, the operating wavelength is 1550 nm. With Slab thickness 0.09 μm & Directional coupler gap (gap between two waveguides) = 200 nm, I got $neff_{sym}$ = 2.5925 , $neff_{asym}$ = 2.5416 & Cross-over length($L_{Crossover}$) = 1.523e-5 = 15μm

3.2 Changing the slab thickness (Strip waveguide):

In this case, we change the slab thickness in the script to '0' (to simulate coupler with strip waveguides) and observe that the $L_{Crossover}$ increases to 37 μm. With Slab thickness = 0 μm (no slab), Directional coupler gap (gap between two waveguides) = 200 nm, I got $neff_{sym}$ = 2.4544, $neff_{asym}$ = 2.4338, Cross-over length ($L_{Crossover}$) = 3.78 e-5 = 37 μm

$\rightarrow$ *Need more length for coupling of symmetric & asymmetric modes.*

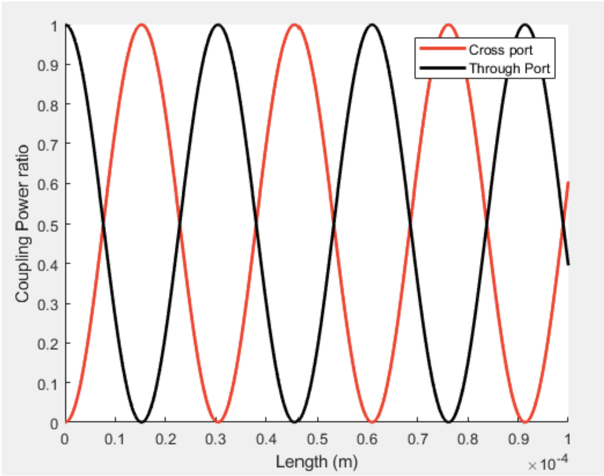
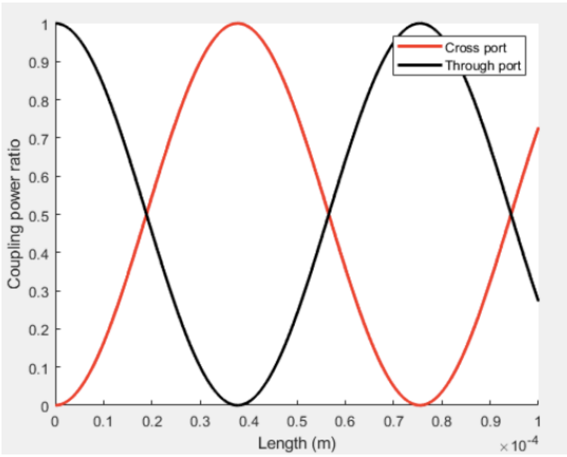
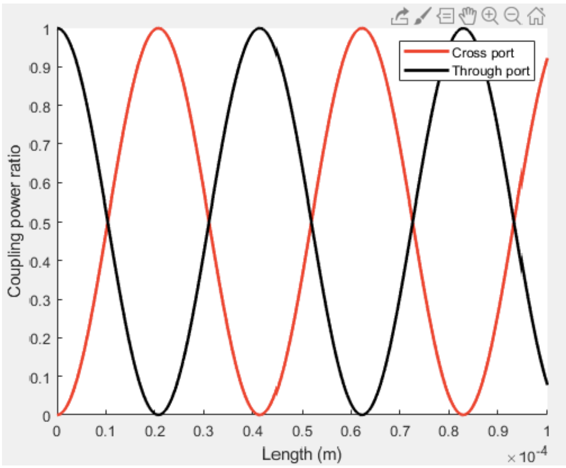


Figura 2: Cross-over length Vs. Coupling ratio



(a) Normal Scale



(b) Logarithmic scale

Figura 3: Cross-over length Vs. gap

3.3 Changing the gap (for strip-loaded ridge)

Now, we change the gap between two waveguides (after reverting the slab thickness) from 200 nm to 250 nm and observe that ($L_{Crossover}$) increases to 20.7 μm. With Slab thickness = 0.09 μm, Increased Directional coupler gap (gap between two waveguides) = 250 nm. I got, $neff_{sym}$ = 2.5845, $neff_{asym}$ = 2.5472 Cross-over length ($L_{Crossover}$) = 2.074e-5 = 20.7 μm

$\rightarrow Need\ more\ length\ for\ coupling\ of\ symmetric\ \&\ asymmetric\ modes(\ in\ comparison\ to\ the\ 1st\ case\ \ in\ which\ gap\ was\ 200\ nm)$

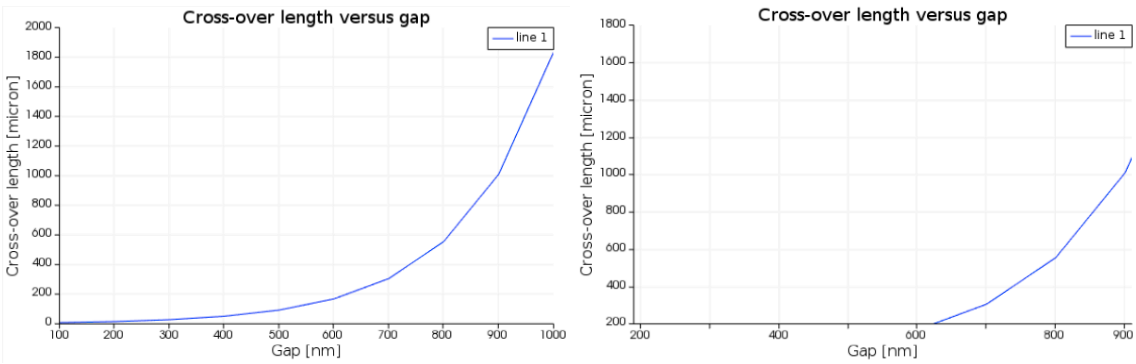
The following table summarizes the simulation results.
Here, S.L.R.W means strip loaded ridge waveguide, while S.W simply means strip waveguide

Waveguide Used	Gap (in nm)	$neff_{sym}$ symmetric	$neff_{asym}$	$L_{Crossover}$ (in μm)
S.L.R.W	200	2.5925	2.5416	15.228
S.W	200	2.4544	2.4338	37.731
S.L.R.W (Increased Gap)	250	2.5845	2.5472	20.746

Tabela 1: Summary of n_eff of super modes and crossover length

3.4 Gap sweep:

In this case, the gap is swept between 0.1 μm and 1.0 μm with 0.1 step and we observe cross over length vs Gap. The inference is that cross-over length increases exponentially with the increase of gap. The figures shown in Fig 4. also show the same thing in different scale types.



(a) Normal Scale

(b) Logarithmic scale

Figura 4: Cross-over length (in μm) Vs. gap (in nm)

3.5 Wavelength Sweep:

Till now, the wavelength of operation was 1.5 μm, in this simulation, we do wavelength sweep from 1.50 μm to 1.60 μm with 10 points in between. Figure. 5. Shows the effective indices of two super modes over the wavelength range. Symmetric mode has higher effective index along the wavelength range.

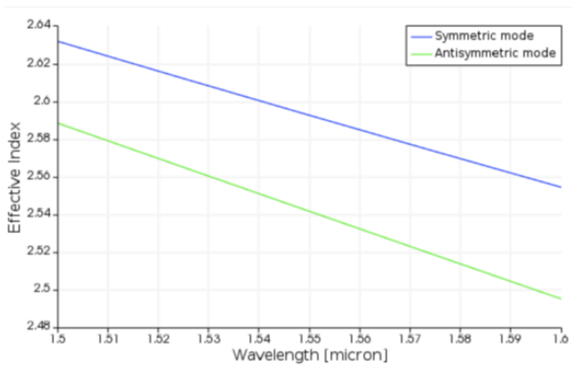


Figura 5: Effective indices of Symmetric & Asymmteric modes over a certain wavelength range

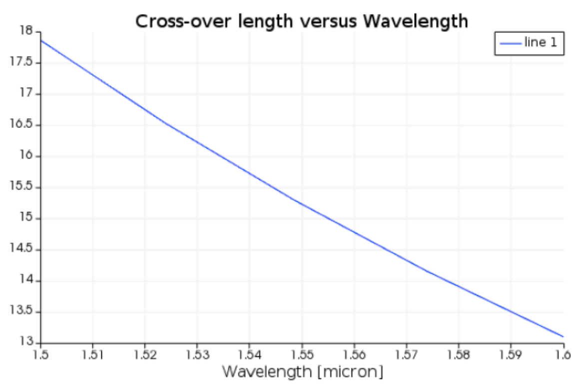


Figura 6: Cross-over length Vs. Wavelegnth

Figure.6. depicts the Cross over length over the wavelengths of 1.5 μm and 1.6 μm. The observation is that, $L_{Crossover}$ is very high at 1.4 μm till 1.55 μm, therefore, coupling is very poor. $L_{Crossover}$ is better from 1.55 μm. Directional coupler is not a broad band device if not designed properly, without considering all these parameters. However it proved out to be a good device over C-Band.

3.6 Simulation using FDTD Lumerical:

Using the scripts in FDTD Lumerical, made a sweep of coupling length (transition zone) from 15.3 μm to 30.6 μm to observe the T-Through port and T-Drop port. Gap =200 nm $thick_Slab$ = 0.09e-6 for strip-loaded ridge waveguides WL=1550 nm.

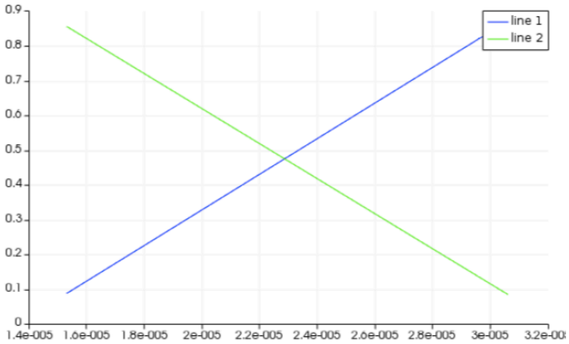


Figura 7: FDTD Analysis

Figure.10. shows the FDTD result, line 1 (blue) is T-through and line-2 (green) is T-Drop. Coupling is better along the transition zone, but decreases when the waveguides are about to separate (at curves of waveguide) and the length of the transition zone should be less to have complete transfer ('1').

4 Conclusion

Designed and simulated Direction coupler with Strip loaded ridge waveguides and Strip waveguides (without slab). Observed the change in cross-over length in both waveguide structures, also by changing the gap between two waveguides of the coupler. Cross-over length ($L_{Crossover}$) is better for Strip loaded ridge waveguides (15.23 μm) $L_{Crossover}$ increases with reduced slab thickness and increased gap. $L_{Crossover}$ should be less as possible to have more coupling. From the wavelength sweeps, it is concluded that, $L_{Crossover}$ is less from 1.55 μm towards higher wavelengths. So, this Direction coupler is not a broad band device, but good at C-band.