Investigation of Silicon Slot-based Directional Couplers

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Abstract: *A theoretical investigation of optical directional couplers based on silicon slot waveguides is carried out. The influence of various geometrical parameters on the coupling length is studied. A number of interpolation curves are extracted and presented for design purposes. Although the results are obtained for a specific technology, the theoretical approach is very general.*

Introduction

Silicon Photonics is increasingly important in integrated optics for technology and cost reasons. Silicon is transparent in the range of optical telecommunication wavelengths (1.3 and 1.55 µm) and is a well understood and robust material, available in large size, good quality and low price. Recently, several silicon based active and passive devices with high performance have been demonstrated.

Moreover, there is a current trend in silicon photonic circuits to move to smaller device dimensions for improved cost efficiency and device performance. In this scenario, very recently slot waveguides are attracting much attention [1].

A slot waveguide structure is based on a low index (air or SiO_2) sub-micrometer slot embedded between two silicon wire waveguides. In such waveguide geometry, the optical field in the low refractive index region is enhanced with respect to the silicon ones, because of the electric field discontinuity at the high index contrast interfaces.

Using slot waveguides, many optical devices have been already realized and proposed, including directional couplers [2], all-optical logic gates [3], beam splitters [4], ring resonators with high quality factor [5], optical modulators [6], light emitting devices with strong light confinement and enhanced emission properties [7]. A finite element method modal investigation has been performed [8] to show the possibility of confining more than 50% of optical power in the low-index gap region of a SOI slot waveguide, by optimizing its geometrical parameters.

Directional couplers are routinely used for a large variety of applications and functions related to lightwave technology. Directional couplers composed of two parallel slot waveguides have been experimentally demonstrated [9], but a detailed theoretical investigation on these devices has never been carried out.

In this paper, we use the Coupled Mode Theory (CMT) and the Finite Element Method (FEM) to investigate directional couplers based on slot waveguides. We have also compared our approach with simulation results obtained in other papers using different methods.

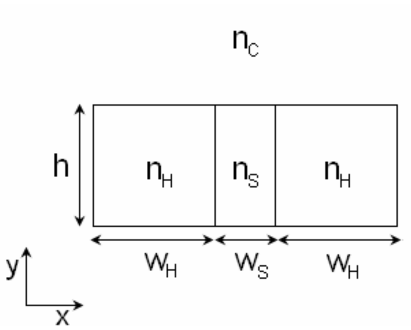

Fig. 1: Slot waveguide cross section.

Slot waveguide investigation

In this paper a horizontal slot waveguide geometry is assumed, in which the quasi-TE modes, polarized along *x* axis (see Fig. 1), are strongly confined in the slot region. The operating wavelength is 1550nm. There exist also quasi-TM modes, but they are not only confined in the slot region but mainly in the whole waveguide (including the two high index regions).

The slot waveguide is formed by a silicon oxide slot (n_S = 1.46) embedded by two silicon wires (n_H = 3.48). The whole waveguide is surrounded by silicon oxide (n_C = 1.46).

First, we have employed FEM [10] to study the birefringence of the slot waveguide in Fig. 1. Our analysis started with the following dimensions: waveguide height h = 250nm and high index region width w_H = 200nm. The slot width w_S has been varied from tens of nanometers to 200nm.

Fig. 2 shows a graph of the variation of the TE/TM fundamental mode effective index difference ($\Delta N=N_{TE}-N_{TM}$) versus the slot width for various waveguide heights, namely 250nm, 300nm and 350nm. In the first case, the slot width for zero birefringence (ZBR) is 75.2nm, in the second it is 17.7nm, and in the third case it is smaller than 10nm. For larger values, the slot width has less influence on the mode birifrangence in all cases, especially for larger waveguide heights.

We have also evaluated the fraction of optical power confined in the slot (Fig. 3). For h = 250nm, the ZBR slot width provides also a good power confinement, close to the maximum (nearly 26%). Increasing the waveguide height, the maximum power confinement becomes higher, but the relevant slot widths are far from ZBR points.

Directional coupler investigation

We have investigated directional couplers formed by two parallel slot waveguides, as described above. We have denoted with d the distance between the centers of the two slot waveguides. The theoretical approach is based on CMT and FEM.

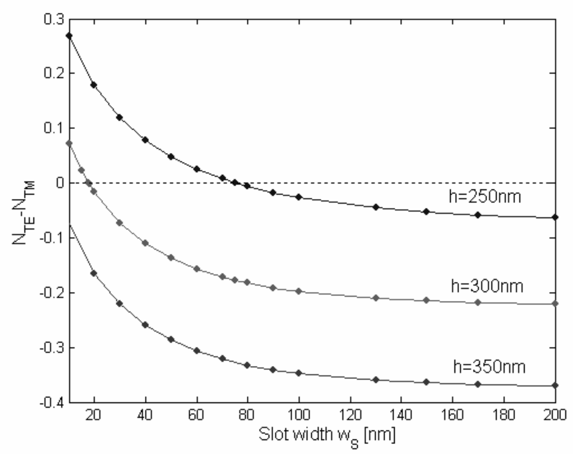

Fig. 2: Birefringence of slot waveguide for various slot heights and widths.

According to CMT, the coupling coefficient between two optical modes propagating in two adjacent optical waveguides can be expressed as

$$\kappa = \frac{1}{2}(\beta_s - \beta_a) \quad (1)$$

where β_s and β_a are the propagation constants of symmetric and anti-symmetric modes within the directional coupler, respectively. Using 2D full-vectorial FEM to perform modal analysis of the coupler cross-section, it is possible to calculate β_s and β_a with great accuracy.

The coupling length L_C is related to coupling coefficient by the following formula:

$$L_C = \frac{\pi}{2\kappa} \quad (2)$$

To validate our modeling, we have studied two couplers proposed in [2]. These couplers, having h=250 nm, w_H=200 nm, w_s=100 nm, d =1 µm and 1.5 µm, respectively, and n_C fixed to obtain polarization-independence, were investigated in [2] by full-vectorial FEM and beam propagation method. Coupling lenghts for quasi-TE and quasi-TM modes, calculated by our modeling and by the other method [2], are summarized in Table I. The comparison shows a very good agreement (maximum shift around 5%).

Therefore, our analysis started with height h = 250nm, slot width w_S=100nm, and high index regions width w_H=200nm. With these dimensions, we have investigated the dependence of the coupling length L_C on the separation distance d between the slots. Coupling coefficient κ is proportional to the overlapping of the electric fields in both slot waveguides, therefore it is related to the gap d as $\kappa(d) \propto \exp(-\gamma d)$, where γ is the decay rate of the optical field in the cladding region. As expected, we have obtained an exponential relationship between L_C and d, namely:

$$L_C^{TE} = 0.346 \times \exp(4.441d) \quad (3)$$

$$L_C^{TM} = 0.236 \times \exp(4.58d) \quad (4)$$

with d >0.7µm. These dependences are sketched in Fig. 4.

Table 1: Comparison for couplers designed in [2].

	Our method		Literature [2]	
	L_C (TE) [µm]	L_C (TM) [µm]	L_C (TE) [µm]	L_C (TM) [µm]
d = 1 µm n_C=1.30655	22.18	22.21	22.23	22.23
d = 1.5 µm n_C=1.41545	201.82	201.93	203.0	203.0

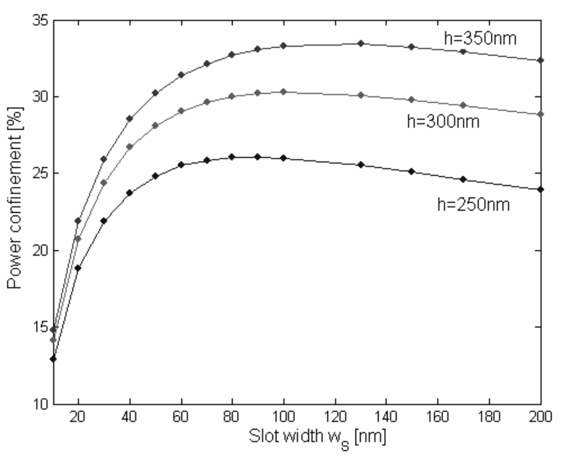

Fig. 3: Power confinement in the slot region.

All the successive calculations have been carried out for d = 1 µm, i.e. in the worst case.

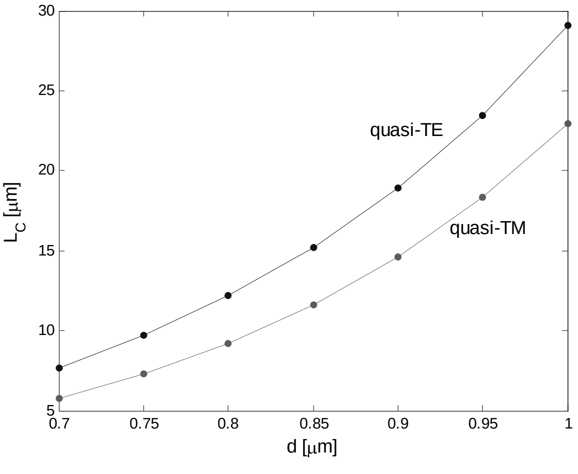

Fig. 4: Coupling length versus separation distance d.

We have analyzed the influence of height h of coupled waveguides on quasi-TE and quasi-TM coupling lengths. As it can be observed in Fig. 5, the former shows a linear dependence, while the latter has a fourth degree polynomial behavior. Thus, by increasing the waveguide height h, the coupling length for quasi-TM increases more rapidly than for quasi-TE polarization.

The two curves intersect at h=274 nm, providing the same coupling lengths for both polarizations.

For the same geometrical configuration, we have also evaluated the height h corresponding to the ZBR condition for quasi-TE and quasi-TM symmetric modes of directional coupler. This height is about 239.9 nm.

Then, we have studied the influence of high index symmetric region width on coupling length. We have performed the calculations for three waveguide heights, namely 250nm, 350nm and 400nm. The three corresponding graphs are sketched in Fig. 6,7,8.

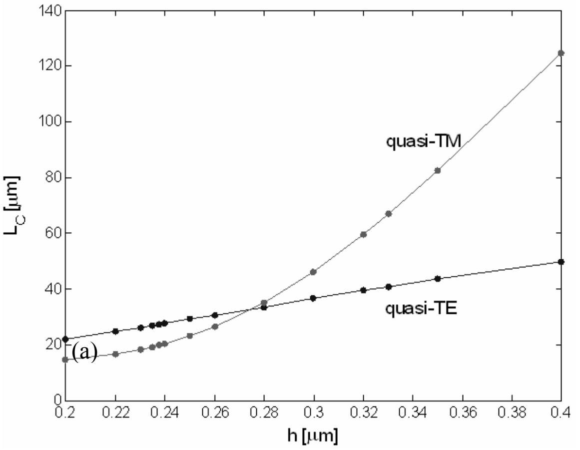

Fig. 5: Coupling length versus height h.

In the first case, for h=250nm (Fig. 6), the coupling lengths for both polarizations show a parabolic behavior. The two curves do not intersect for any value of the parameter w_H.

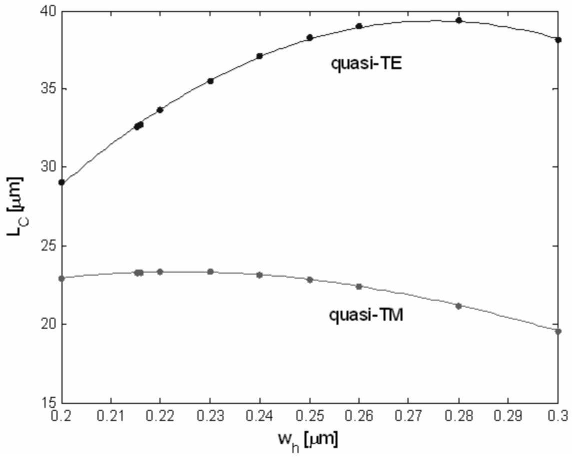

Fig. 6: Coupling length versus w_H for h = 250nm.

For this configuration, ZBR condition for quasi-TE and quasi-TM symmetric modes of directional coupler corresponds approximately to w_h = 215.5nm.

For larger h values, the situation changes significantly, as sketched in Fig. 7 and 8. The coupling lengths for quasi-TE and quasi-TM polarizations show a third order polynomial behavior, and it is possible to find a w_H value where the coupling lengths are the same for both polarizations. For h=350 nm and 400 nm, the intersection points are obtained for w_H=284 nm (L_C =55.61µm) and w_H=303 nm (L_C =59.03µm), respectively. Besides, for higher waveguide heights, coupling lengths for quasi-TM shows a stronger dependence on w_H with respect to those for quasi-TE polarization.

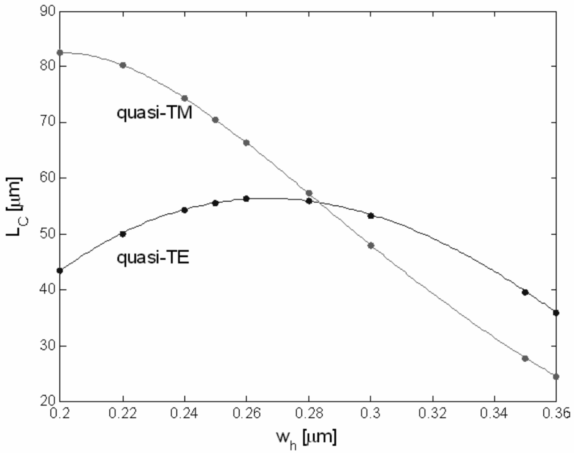

Fig. 7: Coupling length versus w_H for h = 350nm.

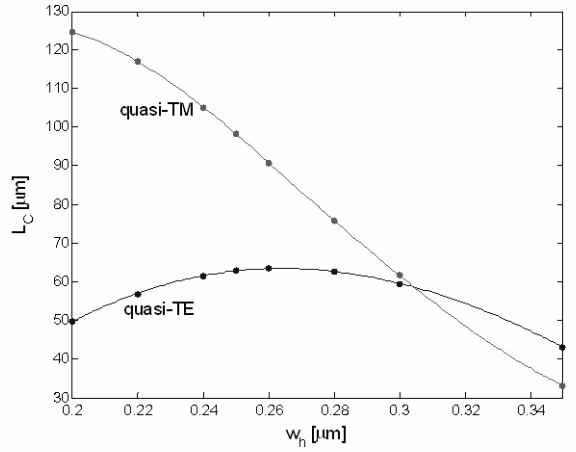

Fig. 8: Coupling length versus w_H for h = 400nm.

Either for quasi-TE or for quasi-TM modes, coupling length dependence on high index regions width can be expressed as:

$$L_c = p_0 + p_1 w_H + p_2 w_H^2 + p_3 w_H^3 \tag{5}$$

where p_0, p_1, p_2 and p_3 are fitting parameters whose values are collected in Table 2, for considered values of h and both polarizations.

Conclusions

In this work, we have investigated directional couplers formed by two parallel symmetrical silicon slot waveguides. The adopted modeling approach, validated by comparisons with other numerical results reported in literature, is based on Coupled Mode Theory and Finite Element Method, and results very fast and accurate. Our work is a starting point for future investigations and optimizations. Many devices can be realized based on slot waveguides and directional couplers, also employing different materials.

Table 2: Fitting parameters for coupling length.

h [nm]	Mode	p_3	p_2	p_1	p_0
250	TE	0	-1851	1019	-100.9
	TM	0	-639.3	285	-8.42
350	TE	3622	-5590	2208	-203.6
	TM	17020	-14880	3857	-229.7
400	TE	4056	-6309	2483	-227
	TM	25490	-21190	5115	-254.7

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