Ultra-compact and broadband orthogonal coupler between strip and slot silicon waveguides

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ABSTRACT

We propose an ultra-compact and broadband orthogonal coupler between a strip waveguide and a slot waveguide. Numerical simulations show that a 700-nm wide (full width at half maximum) coupling spectrum can be theoretically achieved and a high coupling efficiency of 73% around 1500-nm wavelength can be obtained. The coupling length is only about 475 nm. This configuration does not include a tapering section and has a high tolerance to the waveguide height, alleviating the stringent fabrication requirements.

Keywords: orthogonal coupler, slot waveguide, strip waveguide, silicon photonics

1. INTRODUCTION

Silicon photonics, due to its fabrication compatibility to the standard CMOS microelectronics technology, has become a promising platform for the next-generation photonic integrated circuits (PICs). Silicon based nano-scale waveguides are essential elements of high-density PICs because of their strong optical confinement. A conventional strip waveguide is made of a high-index core surrounded by low-index claddings based on total internal reflection. It is promising for mass production and the optical loss measured from fabricated devices is only 1-2 dB/cm[1], but the device size is limited by the diffraction limit of light. Silicon based slot waveguide, where a nano-scale low-index slot is embedded between two high-index slabs, has attracted much attention recently due to its unique capability in enhancing and confining the optical field in the nano-scale slot[2]. However, direct excitation of the eigen-mode of the slot waveguide through coupling light from an optical fiber or external source is inefficient owing to the large mismatch of k vectors and field profiles of the two modes. In addition, the optical loss of the slot waveguide is much larger than that of the strip waveguide[1]. Therefore, it is expected that the slot waveguide is only used to implement certain particular functions, e.g., modulators, while the strip waveguide is employed as the low-loss interconnects on a single high-density silicon chip. To this end, efficient and ultra-compact coupling between these two types of waveguides is of great significance. In previous schemes[3-5], tapering structures have been utilized to achieve high coupling efficiency. However, all these couplers have a coupling length of several or even tens of micrometers, increasing the structure dimension, the loss, and the fabrication complexity. Also, reducing the length of the tapering section may cause resonance effects, leading to a smaller coupling bandwidth[6].

Here, we propose an ultra-compact orthogonal coupler for broadband coupling from the strip waveguide to the slot waveguide. Finite difference time domain (FDTD) simulation results show that our scheme has a coupling length of only about 475 nm, which is one order of magnitude smaller than that of the previous taper-introduced schemes, and a 3-dB coupling bandwidth of as large as 700 nm. The coupling efficiency reaches the maximum value of 73% around the 1500 nm wavelength. Furthermore, this configuration is very easy to fabricate and has a large tolerance to the waveguide height.

2. COUPLER CONFIGURATION

A schematic diagram of the proposed ultra compact and broadband orthogonal coupler is shown in Fig. 1 (a). Silicon on insulator (SOI) structure is assumed. The strip silicon waveguide and the slot waveguide are orientated orthogonally. The cross sections of the strip waveguide and the slot waveguide along the B-B' and A-A' cut lines are illustrated in Fig. 1 (b) and (c), respectively. The strip waveguide is utilized as the access waveguide, with its width W_s set to be 450 nm. The structural dimensions of the slot waveguide are chosen as 180 nm for the two silicon slabs and 50 nm for the poly(methylmethacrylate) (PMMA)-filled slot. The heights of both waveguides are 250 nm. The entire structure is covered by air. We also plot the fundamental quasi-transverse electric (TE) modes of the strip waveguide and the slot waveguide at wavelength λ = 1550 nm in Fig. 1 (b) and (c), respectively, using commercial software Lumerical MODE Solutions 4.0.4[7]. The refractive indices of the silicon and silica are set according to a Palik model included in the default material database of the software[7], which is fitted with experimental data. The refractive index of PMMA is 1.605 at λ = 1550 nm[8].

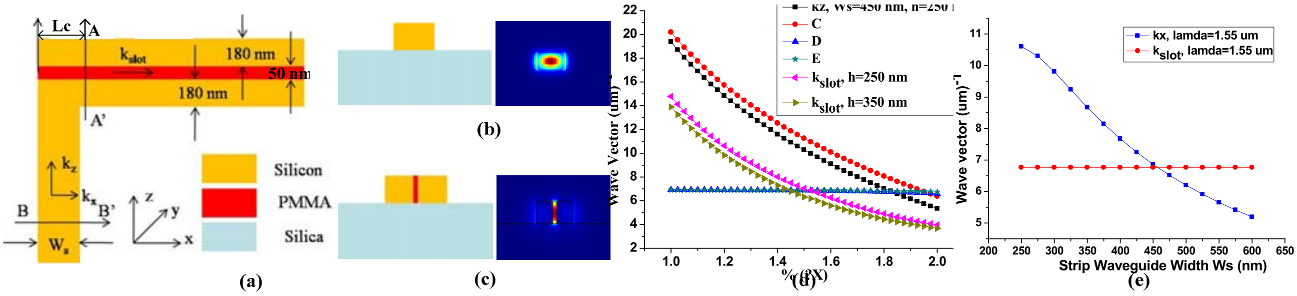


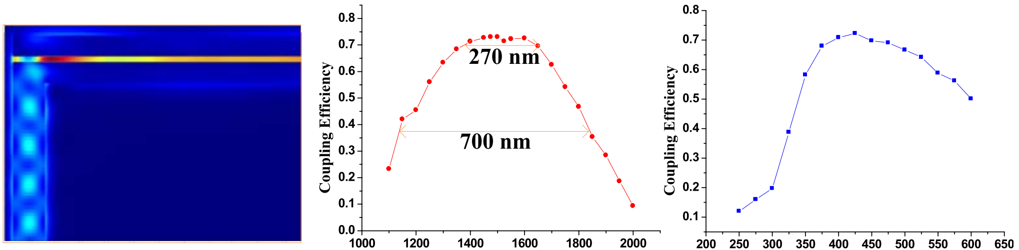
Figure 1. (a) Schematic diagram of proposed ultra-compact broadband orthogonal coupler. (b) The cross section of the strip waveguide at B-B' cut line and its fundamental quasi-TE mode. (c) The cross section of the slot waveguide at A-A' cut line and its quasi-TE mode. (d) The dispersion characteristics of the strip waveguide and the slot waveguide for different heights of the whole structure when W_s = 450 nm. (e) The wave vector component k_x varies as a function of the strip waveguide width W_s.

Rather than reduce the mismatch between propagation constants of these two types of waveguides using tapering structures in previous schemes[3-5], our coupling scheme is based on matching the lateral wave vector component of the strip waveguide, k_x, with the propagation constant of the slot waveguide, k_{slot}[6]. This k_x component has a small mismatch with k_{slot} over a large bandwidth, which can be seen from Fig. 1 (d), allowing for highly efficient broadband coupling and avoiding any significant resonance effects which exist in direct butt coupling schemes[6]. In addition, with the increase of the height h of the whole structure, k_z increases and k_{slot} decreases, leading to a larger mismatch between k_z and k_{slot}, while the k_x component keeps almost the same. It reveals that the orthogonal configuration is tolerant to the variance of the height of the whole structure. The k_x component shares the same value with k_{slot} at 1500-nm wavelength for W_s = 450 nm and h = 250 nm. At this wavelength the coupling efficiency is maximized. For butt coupling, there exists an upper bound to the strip waveguide width because of the size mismatch between the two types of sections. However, this issue no longer exists in the orthogonal configuration. Fig. 1 (e) shows the k_x component varies with the strip waveguide width at wavelength λ = 1550 nm. It can be seen that at a particular strip waveguide width, the difference between the k_x component and the k_{slot} is zero. The highest coupling efficiency is expected to be obtained at this W_s value.

3. SIMULATIONS AND RESULTS

The commercial software Lumerical FDTD solutions 7.5.3[7] is employed to perform simulations of coupling from the strip waveguide to the slot waveguide. Material parameters are the same as those set in section 2. To measure the transmission, a power monitor is placed at the A-A' cut line 25 nm away from the strip waveguide right sidewall, as shown in Fig. 1 (a). The output power through the monitor is calculated and normalized with respect to the source power and thus we can analyze the coupling efficiency. Coupling length, L_c, is defined as the distance from the left sidewall of the strip waveguide to the A-A' cut line. Here we use a strip silicon waveguide quasi-TE mode as the launch field as shown in Fig. 1 (b), 2 µm away from the slot waveguide.

Fig. 2 shows the simulation results. The transforming process can be clearly observed in the field evolution pattern illustrated in Fig. 2 (a), where electric field intensities are plotted along the coupler structure central XZ plane. Because of the large effective refractive-index mismatch between the strip waveguide and the slot waveguide, a cavity is formed, inducing slight resonance effects in the strip waveguide as shown in Fig. 2 (a). However, these effects do not affect the mode field in the slot waveguide due to the orthogonal configuration. Fig. 2 (b) shows the coupling efficiency over a wavelength span of 1 µm at the strip waveguide width W_s = 450 nm. The coupling efficiency reaches the maximum value of 73% at λ = 1500 nm and varies less than 3% over a wavelength span of about 270 nm. The 3-dB coupling spectrum is as broad as 700 nm. The dependence of the coupling efficiency on the strip waveguide width W_s at λ = 1550nm is also simulated and the results are plotted in Fig. 2 (c). It is found that the peak coupling efficiency can reach 72.5% for a strip waveguide of 425 nm wide. These results are consistent with the analysis above.



(a) (b) (c)

Figure 2 (a) Electric field distribution along the central XZ plane of the coupler structure (b) Coupling efficiency as a function of wavelength at W_s = 450 nm. (c) Coupling efficiency as a function of strip waveguide width W_s at λ = 1550 nm.

4. CONCLUSION

We present an ultra-compact and broadband orthogonal coupler between the strip waveguide and the slot waveguide by matching the wave vector component k_x of the strip waveguide and propagation constant k_{slot} of the slot waveguide. Our simulation results show that with very short coupling length of only 475 nm, the coupling efficiency can reach 73% around 1500 nm wavelength. This coupler configuration is very easy to fabricate and tolerant to the variance of the height of the whole structure. These features make the coupling scheme a feasible platform and promising candidate for high density PICs.

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