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Efficient edge coupler for higher order mode fiber-to-chip coupling

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Abstract: An edge coupler composed of two tapered waveguides and a Y-branch for LP_{11} - TE_1 mode coupling and mapping is proposed on silicon-on-insulator platform. An average 3 dB coupling loss can be acquired within 100 nm bandwidth.

OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides.

1. Introduction

The silicon-on-insulator (SOI) platform has become a mature and promising method for photonic integrated devices to fulfill the target of a compact footprint, a complex function with relatively low cost and power consumption. One of the most vital tasks that should be carried in the limelight is the high-efficiency coupling schemes between optical fiber and photonic integrated circuit (PIC) chip. In order to effectively reduce the mode mismatch and meet the expectation of large bandwidth and high coupling efficiency, many approaches are raised for both vertical and edge coupling. Grating couplers (GCs) [1-3] are widely used for vertical coupling scheme since they have advantages in large misalignment tolerance at chip surface without cleaving and polishing the cross section, low packaging cost and potential for multi-channel coupling with multi-core fibers (MCFs). However, the limitation of bandwidth and the nature of polarization dependence drag the usage of GCs in multiplexing system. On the other hand, the traditional taper couplers [4-6] for edge coupling scheme may have solved the problems above since the mode field adiabatically propagates in the waveguide core with proper refractive index cladding covered rather than diffraction. To further improve the misalignment tolerance and coupling efficiency, several new structures including multi-stage tapers [7], cantilever beams [8], double-tip inverse tapers [9,10] and trident waveguides [11] are proposed for coupling with both cleaved and lensed fibers. Nevertheless, the reported edge coupling methods are mainly focused on fundamental mode. To the best of our knowledge, there is no previous report on higher order mode edge coupling, while the mode multiplexing technique is receiving increasing research interests recently.

In this work, we propose and theoretically demonstrate an efficient edge coupling scheme for first order linearly polarized mode (LP_{11}). A double-tip inverse taper combined with Y-branch are utilized for the coupling and LP_{11} to first order transverse electric (TE_1) mode mapping between a cleaved few mode fiber (FMF) and SOI chip, through two-petal separation and combination. The simulated coupling loss at 1550 nm is 3.06 dB with a fluctuation less than 0.45 dB in the wavelength range of 1500-1600 nm, while the misalignment-tolerance is also calculated in both horizontal and vertical directions.

2. Principle and device design

Fig. 1. Schematics of edge coupler (not in scale) in (a) 3D-view (b) Top view with geometric parameters and transmission symbols.

Figure 1(a) shows the schematic of the designed edge coupler with a cascade of two identical inverse-tapered channel waveguides and a rib waveguide Y-branch structure, for the purpose of reducing the propagation loss caused by the sidewall roughness in fabrication. The silicon dioxide upper cladding with finite width is decided for a better confinement of mode field that travels in it. When the LP_{11} mode ($LP_{11a,x}$ is selected in this work) couples into the upper cladding of SOI chip from FMF (which is not shown in schematics for simplicity), the two petals with a

phase difference of π would split up into two inverse tapers (with a proper design of taper gap W_g) and propagate independently, as Fig. 1(b) shows. Since the two petals travel through the exactly same optical path thanks to the symmetric structure, the phase difference is maintained in the single mode rib waveguide arms of Y-branch. Thus, the mode fields in the arms can therefore be regarded as the quasi first-odd supermode and finally combined into a TE_1 mode with the superposition in the multimode stem of Y-branch. The cladding width W_c and tip width W_t can be optimized for a larger mode field overlap and a better capture of incoming beams. The taper length L_t , the length of transitional waveguide between channel and rib waveguides L_{swg} and the Y-branch length L_b can also be optimized comprehensively in order to achieve a better adiabatic transmission.

3. Results and discussion

We analyze the mode field characteristics and propagation features of the proposed edge coupler using eigenmode expansion (EME) algorithm. In this model, the thickness of buried oxide layer and upper cladding layer of SOI chip are set to be 2 and 3 μm , with the refractive indexes of silicon and silicon dioxide assumed to be 3.476 and 1.444 at 1550 nm, respectively. The single mode waveguide of the Si layer has 220 nm height and 500 nm width, and 1 μm width and 130 nm rib height are set for the multimode rib waveguide. The taper tip is chosen to be 200 nm in order to match the resolution of 248-line lithography. The FMF used in the simulation has a core radius of 9.5 μm with the refractive indexes of core and cladding defined to be 1.464 and 1.456, respectively.

The optimization and simulation procedure can be mainly divided into two steps: firstly the mode mismatch loss needs to be minimized while the lengths of tapers and Y-branch would be preset with conservative values, in order to guarantee an adiabatic propagation. Then, a more accurate optimization is performed to target a compact footprint. In the first step, W_c is optimized to be 16 μm to acquire the largest mode field overlap between FMF and chip cladding based on the integration calculation. Figure 2 shows the coupling loss induced by different taper gaps, the best coupling efficiency appears at 9 μm and it decreases with the deviation. In the second step, L_{swg} is optimized to be 20 μm which goes well with fabrication standard. Figure 3 presents the coupling loss with different lengths of taper and Y-branch, respectively. The maximum sweeping length for Y-branch is set to be 100 μm which could ensure a stable transmission, while with consideration of 200 μm for tapers. The curve goes drastically with fluctuation for Y-branch at short lengths since the steep converge of the two arms excites higher order modes which largely degrades the coupling efficiency. The curve of taper length changes slowly at around -3 dB as length increases. Taking the compactness of device, the coupling efficiency and fabrication feasibility into consideration, the optimal parameters of the designed edge coupler are decided and presented in Table 1.

Fig. 2. Coupling loss vs. taper gap.

Fig. 3. Coupling loss vs. taper and Y-branch lengths.

Table 1. The optimal parameters of the designed edge coupler

Items	W_t	W_g	W_c	L_t	L_{swg}	L_b
Unit/ μm	0.2	9	16	60	20	50

Figure 4 shows the simulated transmission spectrum of our designed edge coupler with a total length of 130 μm . The total coupling loss fluctuates less than 0.45 dB in the wavelength range of 100 nm, which is far below the 1-dB bandwidth threshold. A 3.06 dB coupling loss is acquired at 1550 nm. The loss is mainly limited by the poor mode field overlapping, and the value would be further optimized if a lensed FMF could be used. The inset (a) presents the

mode field distribution along the propagation in x-y cross section while insets (b)-(e) show the mode profiles in x-z cross section at different positions of y-axis. It is obvious that an adiabatic mode conversion and power equalization in the two waveguide paths are achieved.

To further test the robustness of the edge coupler, we studied the misalignment tolerance in both vertical and horizontal directions, as Fig. 5 shows. The curves of coupling efficiency drops quickly as the deviation increases, with a 1-dB degradation for the misalignment range of ± 1.5 and ± 2.5 μm in horizontal and vertical direction, respectively. The results demonstrate a reasonable performance.

Fig. 4. Simulated transmission spectrum of edge coupler for LP₁₁-TE₁ mode. Insets: (a) mode profile in x-y cross section (b)-(e) mode profiles in x-z cross section with (b) $y=1$ μm (c) $y=3$ μm (d) $y=110$ μm (e) $y=130$ μm at 1550 nm.

Fig. 5. Misalignment tolerance of edge coupler at 1550 nm.

4. Conclusion

We have proposed an efficient edge coupler based on double-tip inverse tapers for the coupling and mapping between LP₁₁ in FMF and TE₁ modes in SOI chip. The method of two-petal separation and combination is discovered and demonstrated theoretically without any complex design compared against fundamental mode. In the 130 nm device length design, a 3.06 dB coupling loss at 1550 nm with a fluctuation less than 0.45 dB in 100 nm range is achieved. A good power equalization and large misalignment tolerance are also demonstrated.

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