Cantilever Inverse Taper Coupler With SiO_2 Gap for Submicrometer Silicon Waveguides

Peng Wang, Aron Michael, and Chee Yee Kwok

***Abstract*— In this letter, we present a cantilever inverse taper coupler with SiO_2 gap for coupling optical beam between an optical fiber and a sub-micron Si waveguide. The result shows that the input spot size of 5 μm can be coupled to 500 nm×240 nm silicon waveguide with a coupling loss less than 0.49 dB/facet and a 3-dB misalignment tolerance larger than ± 1.8 μm for both TE and TM modes. The coupling loss for a standard cleaved fibre with the input spot size of 10.5 μm is 3.72 dB/facet (TE) and 2.12 dB/facet (TM). The couplers have shown improvement in misalignment tolerance for the input spot size of 5 μm and in coupling loss for the input spot size of 10.5 μm due to the introduction of SiO_2 gap in comparison with other reported taper coupler designs. These improvements are achieved without compromising the other performance parameter (coupling loss or misalignment tolerance) and requiring complicated design and fabrication process.**

***Index Terms*— Taper coupler, misalignment tolerance, coupling loss.**

I. Introduction

PHOTONIC Integrated Circuits (PICs) on Silicon-On-Insulator (SOI) substrate have been attracting a lot of attention and developing fast in the last two decades. The unique advantages of SOI substrate include excellent optical properties of silicon, significant device scaling due to silicon's high refractive index and CMOS fabrication process compatibility. Launching light into a sub-micron silicon waveguide (SiW) from a standard single-mode fiber with minimal coupling loss is highly desirable as the traditional butt-coupling approach introduces a significant coupling loss due to large Mode Field Diameter (MFD) mismatch between the SiW and standard single-mode fiber.

Grating and inverse taper couplers are the main approaches that have been employed to improve the coupling efficiency between a SiW and a single-mode optical fiber. Grating couplers exhibit a narrow bandwidth when designed for high coupling efficiency and their fabrication process is relatively complex [1]. In contrast, inverse taper couplers have been demonstrated with wider bandwidth and higher coupling efficiency [2]. But, they are prone to non-smooth coupling facet and fiber-to-coupler misalignment that result in substantial loss. A short SiO_2 gap defined photo-lithographically and reactive ion etched in front of the taper waveguide has been used to achieve a smooth coupling facet. However, the gap is required to be as short as possible to prevent additional loss due to beam divergence in the SiO_2 gap [2]. To further reduce MFD mismatch, lensed fibers with input spot size of 2.5±0.5μm have also been used to demonstrate an inverse taper coupler with a loss of 0.7dB/facet [2]. Although the small spot size from the lensed fiber improves the coupling efficiency, such couplers suffer from misalignment tolerance. Misalignment introduced during packaging process, for example, can easily lead to significant loss. A comprehensive simulation shows that a 3 dB horizontal misalignment tolerance for a single stage linear inverse taper with a 2.5μm spot size lensed fiber is ±1.27μm and ±0.93μm for TE and TM mode, respectively [3].

Cantilever inverse taper couplers have been proposed to confine a beam in a cladding material in order to improve coupling efficiency and misalignment tolerance [4]–[6]. However, the improvement in misalignment tolerance was limited because most couplers were designed for small input spot size of 2.5μm. Although larger spot size can provide better misalignment tolerance, the coupling loss is higher than 4dB/facet for a standard cleaved fibre due to large MFD mismatch. A coupler for larger spot size has been reported in order to improve misalignment tolerance with a coupling loss of about 2dB/facet and 4dB/facet for 5μm and 9.2μm, respectively [5]. However, the coupling structure requires a relatively complicated design and fabrication process. A coupler that reduces coupling loss to 2dB/facet for TE mode input from a standard cleaved fibre with a 10.5μm spot size has been demonstrated [6], but the coupler has to be surrounded by index-matching oil. Therefore, a coupler that reduces coupling loss for large input spot sizes and increase misalignment tolerance for small input spot sizes without requiring index-matching oil or complicated fabrication process is highly desirable. In this letter, we report such a coupler consisting of an inverse taper silicon structure embedded in a SiO_2 cantilever waveguide with a SiO_2 gap.

II. Design

The proposed cantilever inverse taper coupler consists of a 100μm long SiO_2 cantilever waveguide, an inverse linear taper SiW embedded in the middle of the SiO_2 waveguide and a SiO_2 gap between the SiO_2 waveguide facet and the taper end. Figure 1(a) and (b) show the top and side views of the coupler, respectively. The SiW is 500nm wide and 240nm high rectangular structure formed from a 240nm thick active layer of an SOI substrate with the BOX acting as a lower cladding and covered with an identically thick PECVD SiO_2 on top as upper cladding. The waveguide is terminated by

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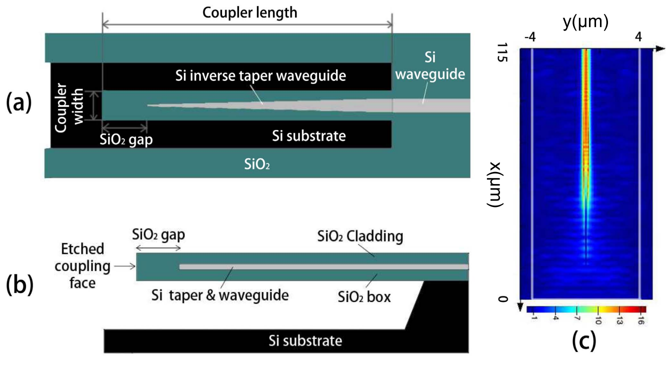

Fig. 1. (a) Coupler schematic top view. (b) Coupler schematic side view. (c) Simulated field distribution along XY plane.

the inverse linear taper structure from the initial width of 500nm to 80nm in a length of 100μm. The taper portion of SiW is located in the middle of the 100μm long SiO_2 cantilever waveguide consisting of the BOX and the deposited PECVD oxide. The SiO_2 gap represents the portion of the SiO_2 cantilever waveguide between the taper end and SiO_2 waveguide facet. The SiO_2 waveguide has identical width and height of either 6μm or 8μm depending on the design for input spot sizes of 5μm or 10.5μm, respectively.

III. Simulation

The cantilever coupler is investigated using a 3D Finite Difference Time Domain simulation. A 1550nm Gaussian mode source is launched at the coupler facet and acts as an input source. Figure 1(c) shows the field distribution along XY plane for 8μm wide coupler with 10μm long SiO_2 gap. The coupling loss of the coupler is calculated from the input power at the source and power measurement in the SiW. Misalignment tolerances are investigated by launching the input source at various positions in vertical and horizontal directions. Both TE and TM modes have been studied with input spot sizes of 5μm and 10.5μm.

In order to obtain optimal SiO_2 waveguide width (same as height), the coupling loss as a function of SiO_2 waveguide with 1μm long SiO_2 gap is simulated and plotted in figure 2(a). The optimal widths for 5μm input spot sizes are 6μm for both TE and TM modes. For 10.5μm input spot size, the optimal widths are 6μm and 8μm for TM and TE, respectively. However, as the SiO_2 gap length is further increased from 1μm, the 6μm wide coupler starts to produce more coupling loss in TM mode than 8μm wide coupler. For example, the simulated loss for 8μm wide coupler is 1.8dB and smaller than 3.4dB for 6μm wide coupler for SiO_2 gap length of 22μm. Coupler width wider than 8μm can be expected to provide better coupling in TM mode. However, the coupling loss in TE mode will increase as the width is made larger than 8μm. Therefore, the width of 8μm is chosen as the optimal width for 10.5μm input spot size.

The 6μm$\times$6μm coupler designed for an input spot size of 5μm is simulated for various lengths of SiO_2 gap to investigate their effect on coupling loss with 0μm and 2μm horizontal misalignments. The result is presented in figure 2(b) and indicates that the coupling loss is relatively constant

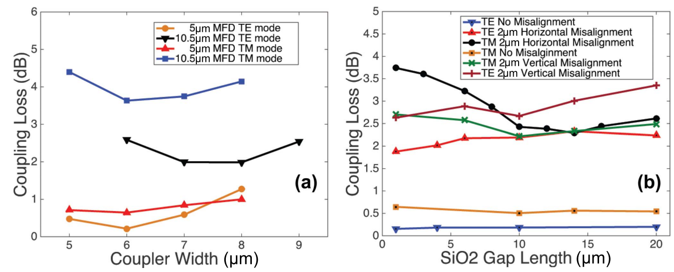

Fig. 2. (a): Coupling loss for 5μm and 10.5μm MFD input source as a function of SiO2 waveguide width with 1μm SiO_2 gap in TE mode. (b): The coupling loss of 6μm$\times$6μm coupler for input spot size of 5μm for various SiO2 gap lengths.

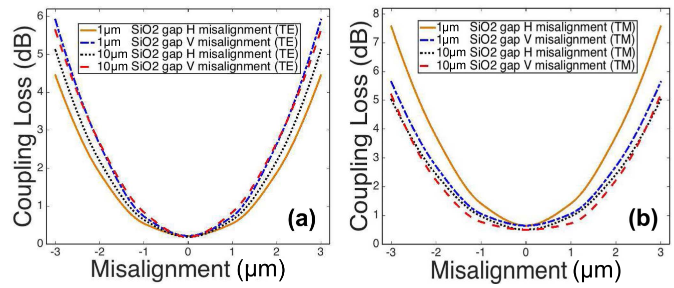

Fig. 3. Misalignment tolerance of 6μm$\times$6μm coupler with 5μm MFD input source: (a) TE mode. (b) TM mode.

with the SiO_2 gap length between 1μm and 20μm for both TE and TM mode when there is no misalignment. With a 2μm horizontal misalignment, the coupling loss drops down from 3.7dB to 2.4dB for TM mode when the SiO_2 gap is increased from 1μm to 10μm, which indicates the SiO_2 gap allows improvement in misalignment tolerance. Further increase in the length of SiO_2 gap above 10μm does not provide any significant advantage as the coupling loss is either maintained or increased. Figure 3 (a) and (b) show the coupling loss as a function of misalignment in both vertical and horizontal directions with SiO_2 gaps of 1μm and 10μm for TE and TM mode, respectively. For TM mode, the 3dB misalignment tolerance in vertical direction for 10μm long SiO_2 gap improves to $\pm$2.5μm as compared to $\pm$2μm for 1μm long SiO_2 gap. However, the improvement of misalignment tolerance for TE mode due to SiO_2 gap is not observed from figure 3 (a).

The coupling behavior and misalignment tolerance of the proposed coupler are also examined for an input spot size of 10.5μm. The input spot size of 10.5μm represents the use of a standard single mode optical fiber. Such fibers are significantly cheaper than lensed fibers and their use is appealing from cost perspective. The coupler width for 10.5μm input spot size is increased from 6μm to 8μm in order to ensure minimal coupling loss. The coupling loss as a function of SiO_2 gap length is obtained and presented in figure 4 for 0μm and 2μm horizontal misalignments. It can be seen from the plot that the coupling loss goes down as the length of SiO_2 gap is increased until it reaches an optimal value. The optimal length for TE mode is 15μm at which the coupling loss is 1.4dB. The coupling loss is higher at 1.8dB for TM mode at the optimal length of 22μm. Figure 5(a) and (b) show the coupler misalignment tolerance for TE and TM mode, respectively,

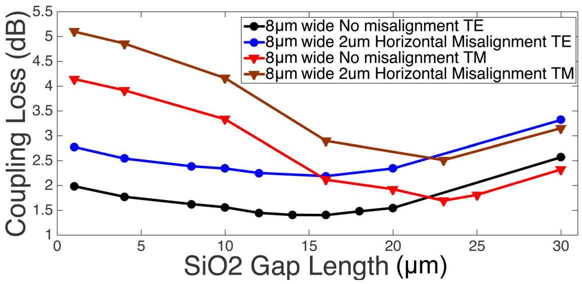

Fig. 4. The coupling loss of 8μm$\times 8\mu$m coupler for input spot size of 10.5μm for various SiO_2 gap lengths.

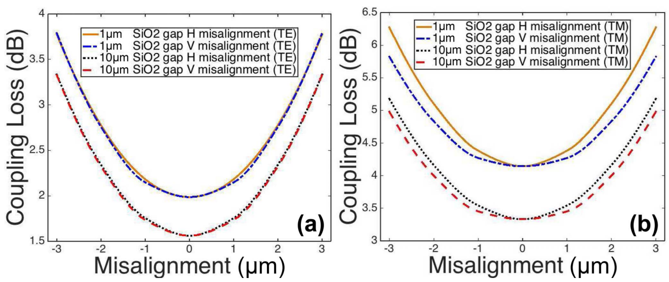

Fig. 5. Misalignment tolerance of 8μm$\times 8\mu$m coupler with 10.5μm MFD input source: (a) TE mode; (b) TM mode.

for 1μm and 10μm long SiO_2 gaps. Coupling loss of 1.7dB for 3μm misalignment in both vertical and horizontal direction can be observed for both 1μm and 10μm long SiO_2 gaps in TE mode. This behavior is fairly similar for TM mode with 1.8dB coupling loss for 3μm misalignment in both directions. The result indicates the misalignment tolerance is not affected significantly by the SiO_2 gap in both TE and TM modes for 10.5μm input spot size. However, significant improvements in coupling losses can be observed from figure 5 when 10μm long SiO_2 gap is introduced.

IV. Fabrication

The inverse taper silicon waveguides are fabricated on an SOI wafer with a 3μm thick buried SiO_2 and 240nm thick active silicon layer. PMMA was spin-coated on the wafer and patterned by electron-beam lithography. Chromium film is evaporated and lifted off to form a pattern that defines the inverse tapered silicon waveguides. Subsequently, the pattern was transferred to the active Si layer using Inductively Coupled Plasma (ICP) reactive ion etching with chromium as a mask. The chromium is removed by wet etch and the SiWs are coated with a 3μm PECVD SiO_2 and 1.5μm thick PECVD amorphous silicon. Photoresist is then spun on top of the amorphous silicon and photo-lithographically patterned to define the SiO_2 waveguide and grooves. The pattern is transferred to the amorphous Si using ICP-RIE with photoresist as a mask. After removing the remaining photoresist in O_2 plasma, the pattern is subsequently transferred to the SiO_2 layer in ICP-RIE system using SF_6/C_4F_8 chemistry. The grooves for the fiber are then deep etched using the Bosch process to 70μm depth with patterned SiO_2 as mask. The silicon underneath the SiO_2 waveguide is removed via Si isotropic etch in ICP-RIE system using SF6 chemistry to form the SiO_2 cantilever waveguide. Using this fabrication approach, we have fabricated a number of devices consisting of input and output couplers connected with a short silicon waveguides. For 5μm spot size input, the input couplers are 6μm wide, 100μm long SiO_2 waveguide cantilever with 1μm and 10μm long SiO_2 gap. For 10.5μm spot size input, 8μm wide and 6μm thick input couplers are fabricated, as the coupler thickness is limited by the SOI box, with a 15μm long SiO_2 gap. The output couplers for all the devices are 6μm wide, 100μm long SiO_2 waveguide cantilever with 1μm long SiO_2 gap.

V. Measurement

Measurements of coupling loss and misalignment tolerance have been conducted on the fabricated couplers. The input beam to the coupler is obtained from the output of a polarization maintaining (PM) lensed fiber that is connected to a polarization controller (Agilent 11896A) coupled to a laser source (Agilent 8164B) generating a beam at a wavelength of 1550nm. The PM lensed fiber is used to produce the required input spot size of 10.5μm and 5μm, respectively, for the measurements. After launching the input beam into the input coupler, the beam propagates through a short silicon waveguide to an output coupler to be collected by the output PM lensed optical fiber which is coupled to an optical power meter. The coupling loss is obtained from the difference in optical power at the input and output ends. The PM fiber at the input side is positioned at various vertical and horizontal locations using micro aligners(Ultralign M561) to measure misalignment tolerance. The TE and TM modes are set by the polarization controller.

The coupling loss and misalignment tolerance measurements for 1μm and 10μm long SiO_2 gap couplers with input spot size of 5μm are plotted in figure 6(a) and (b) for TE and TM mode, respectively. The coupling losses are 0.51dB (TE) and 0.57dB(TM) for 1μm long SiO_2 gap and 0.49dB (TE) and 0.46dB(TM) for 10μm long SiO_2 gap. The coupler with 10μm long SiO_2 gap show a similar coupling loss with 1μm SiO_2 gap, which is well match the simulation result. Furthermore, significant improvement in misalignment tolerance with 10μm long SiO_2 gap as compared to 1μm long SiO_2 gap can be observed and agrees with simulation results. For example, the 3dB vertical misalignment tolerance increases from 1.2μm (1μm gap) to 1.8μm (10μm gap) for TE mode. This demonstrates the benefit of introducing the optimal length of SiO_2 gap. Certain asymmetric characteristics observed in the result are due to fabrication imperfections such as alignment accuracy between masks at various lithography stages. This leads to the difference in misalignment tolerance characteristics in the positive and negative offset directions. Despite the asymmetric characteristics, the coupler with 10μm long SiO_2 gap shows better misalignment tolerance and hence, better tolerance to fabrication imperfections.

Measurements on similar couplers and with 8μm (wide) $\times$ 6μm (thick) couplers using input spot size of 10.5μm have also been conducted. The measured coupling loss with 1μm and 15μm SiO_2 gap are given in figure 6(c) and (d) for TE and TM mode, respectively. Note 15μm SiO_2 gap is chosen as it is found to be the optimal length for 8μm $\times$ 6μm coupler from simulation that gives 2.5dB and 2.1dB coupling losses for TE and TM modes, respectively. The coupling

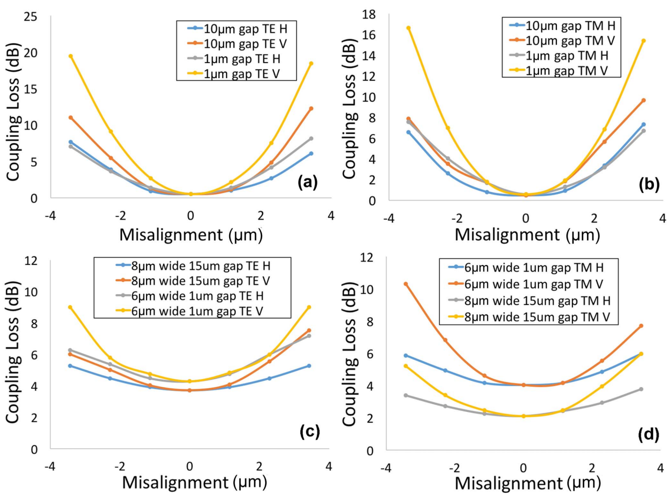

Fig. 6. Measured misalignment tolerance: (a): $6\mu m \times 6\mu m$ coupler with $5\mu m$ MFD input source for TE mode; (b): $6\mu m \times 6\mu m$ coupler with $5\mu m$ MFD input source for TM mode; (c): $6\mu m \times 6\mu m$ and $8\mu m \times 6\mu m$ coupler with $10.5\mu m$ MFD input source for TE mode; (d): $6\mu m \times 6\mu m$ and $8\mu m \times 6\mu m$ coupler with $10.5\mu m$ MFD input source for TM mode.

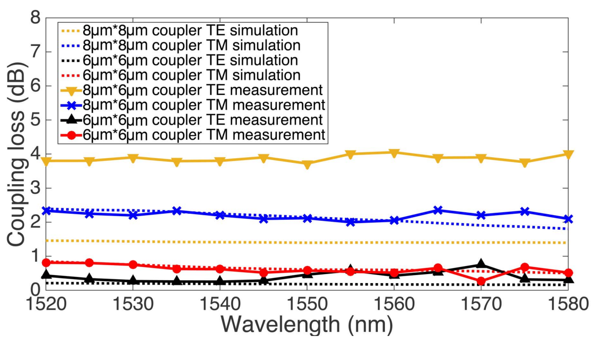

Fig. 7. Measured and simulated Coupling losses of the fabricated and designed couplers over the wavelength range of 1520nm to 1580nm.

loss is 4.29dB/facet and 4.05dB/facet with $1\mu m$ SiO_2 gap and $6\mu m$ wide coupler for TE and TM mode, respectively. However, the coupling loss decreases to 3.72dB/facet (TE) and 2.12dB/facet (TM) for $8\mu m$ wide coupler with $15\mu m$ long SiO_2 gap. The significant decrease in coupling losses with TM mode agrees with the simulation result and represents a superior coupling efficiency in comparison to other reported couplers. Hence, the results clearly demonstrate improvement in coupling loss while maintaining similar large misalignment tolerance when SiO_2 gap is introduced into a cantilever inverse taper coupler.

Figure 7 shows the simulation and measurement of the coupling loss for the designed and fabricated couplers over the wavelength range of 1520nm to 1580nm. It can be seen that the coupling loss is almost constant over the 60nm wavelength range for both fabricated $6\mu m \times 6\mu m$ and $8\mu m \times 6\mu m$ coupler. The simulation and measurement results agree quite well as seen from the $6\mu m \times 6\mu m$ coupler. For symmetric coupler dimensions of $8\mu m \times 8\mu m$, simulation shows that the coupling loss is constant over the wavelength range with slight decrease for TM mode as the wavelength increases.

VI. Conclusion

In this letter, we demonstrate that misalignment tolerant and low loss cantilever inverse taper couplers can be designed by introducing a SiO_2 gap with an optimal length and width in front of a tapered end of silicon waveguide for a desired input spot size. A $6\mu m$ x $6\mu m$ coupler with $10\mu m$ SiO_2 gap shows that coupling loss less than 0.49dB and misalignment tolerance larger than $\pm 1.8\mu m$ for 3 dB additional loss with a $5\mu m$ input spot size can be achieved in both TE and TM modes. Introduction of the $15\mu m$ SiO_2 gap with $8\mu m$ wide coupler improves TM mode coupling loss from 4.05dB/facet to 2.12dB/facet while maintaining large misalignment tolerance for input spot size of $10.5\mu m$. The proposed couplers are superior in comparison to other reported couplers in that they improve misalignment tolerance or coupling loss without significantly compromising the other, requiring complicated design and fabrication process.

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