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Coupling Efficiency of A Spot Size Converter For Optical Fiber-Chip Connections

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ABSTRACT

The light propagation in optical waveguide must be able to maintain low propagation loss, low coupling loss and scattering loss condition, especially in the junction. In this research, a spot size converter is proposed to preserve the lowest coupling loss. This optical converter is composed of a single mode optical fiber (SiO_2) including inversed taper. The optical input signal from the optical fiber is launched into photonic integrated circuits and then coupled into the Si-Slab waveguide. Furthermore, linear form with the length dependence has been studied to obtain the optimal position of optical fiber and the chip and analyzed the coupling efficiency of it. The purpose of this research is to procure the optimal form of spot size converter. The simulation result shows the coupling loss of linear form is 0.62 dB and 0.24 dB on TE and TM mode condition respectively. Along with the increase in the taper length, the coupling loss obtained tends to decrease as well. So that, it can be assumed the design of a linear form with 100 µm taper length provides the highest coupling efficiency.

1. Introduction

Nowadays, internet services such as mobile application, video streaming, e-commerce, and social media have become a part of daily life. Consequently, it will result in the massive growth of data exchanged over networks which makes modern telecommunications require significant technological advancement. Moreover, one of the most important things on telecommunications is optical waveguide. Advancements in optical technology have already revolutionized the communications field, allowing for modern high-bandwidth trans-oceanic transmission through optical fibers [1].

There are so many cases where a communication system requires various optical waveguide. One of the most important things in the simultaneous usage of various optical waveguide is the coupling connections. We have to pay much attention to reduce the coupling losses caused by the mismatch of optical waveguides used in the system. The coupling loss is a dominant factor compared to another type of losses [2]. Therefore, introducing a spot size converter (SSC) in the end facet of the optical waveguide is an effective way to reduce the coupling loss. A common approach in the edge coupling is the usage of an inversed taper. The light from the optical fiber is coupled to a narrow waveguide tip which can expand the mode field size [3], [4].

Most SSC solutions deployed in the field are constructed with the same material as the optical fibers, which is SiO_2. Etching is one of the most common methods used in SSC development. Since photonics mode expansion needs lateral and vertical dimension tapering as well for a universal SSC design, it should give the designers a flexibility to control the SSC size for different edge coupled components. Although, silicon waveguide can now be considered as a proven technology, its compatibility with optical fiber components is still relatively limited, mainly due to the large size mismatch between the optical fibers and silicon waveguide modal distributions. Because of this, coupling method to and from silicon waveguide components with large efficiencies is still a relevant challenge [5].

Besides, various coupling techniques are currently being explored, including grating coupling [6] and end-firing from macroscopic fibers [7], where coupling efficiencies up to 70%–80% to on-chip waveguides have been achieved. More recently, on-chip silicon waveguides have been coupled to the waist of a biconical fiber taper [8] with an efficiency over 93%.

2. Design and Simulation Parameters
Design of SSC
Since an SSC design is located in the corner of optical fiber, SSC materials are made by the SiO_2 as well. Compared to other materials, the major advantage of SiO_2 converter is the improvement in transmission and reduction in return loss from optical fiber to converter. In order to confine the optical mode within the $SiO2$, it is necessary to etch and isolate the SSC from the other materials substrate (cladding).

The coupling loss is the highest loss in the direct coupling between optical fiber and the photonic integrated circuits [2]. At the same time, one of the most important parameters in the coupling is the alignment tolerance which should be small in its value. Due to the effect of alignment tolerance in the coupling efficiency, there is a challenge in packing a silicon-based integrated circuit with optical fibers in a same package. Hence, it demands an optical mode size converter between the optical fiber and silicon waveguide. In other words, the interface between optical fiber component and a silicon photonics typically includes a section of fiber that is either a standard straight-polished fiber or a specialized device that, on some occasions, makes it possible to improve the overall coupler efficiency.

Here, utilizing the double-tip inversed taper is one of the most effective ways to achieve good coupling efficiency. Although, when fabrication process degrades one of the tips, the coupling efficiency does not differ too much [9], [10]. Under such context, we designed and simulated a novel method to efficiently couple an optical fiber to a silicon waveguide (chip) using a conical tapered fiber tip. We note that coupling techniques and technology have a strong impact on chip-packaging solutions; therefore, we also review the most relevant packaging techniques and trends.

Fiber-chip edge couplers accommodate the mode size matching between the optical fibers and the edge of silicon photonics, thus can provide a substantially increased coupling efficiency, broad coupling bandwidth, and low polarization dependence. To efficiently excite the mode in the silicon photonics waveguide, the incident mode field in fiber should spatially overlap the mode field in the waveguide as close as possible [11].
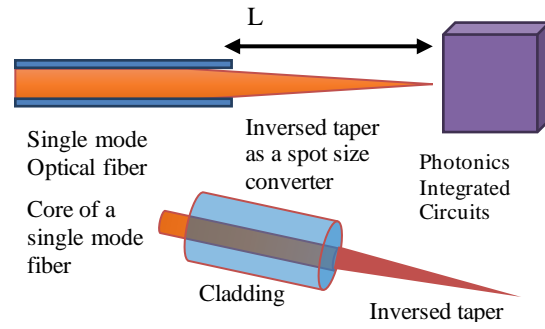

Fig. 1: The schematic of spot size converter mechanism. The input port is the optical fiber. The taper length (*L*) is the important parameter to obtain the high coupling efficiency. Some part of core layer will be made sharp (fiber lens).

Figure 1 shows the schematic diagram of SSC used to couple an optical fiber and a silicon waveguide. It is composed of a suspended SSC SiO_2 and a silicon waveguide. In order to compress the mode size in the vertical direction (Y-axis), a clad material with SiO_2 (different refractive index with a core material) is used to coverlid an optical fiber and an SSC design termination, forming a terminated taper [12],[13]. The suspended SSC is also laterally tapered (X-axis) such that the dimensions are larger at the input facet and smaller at the inversed taper. This lateral taper serves to compress the input optical mode size to match the silicon waveguide mode size in the horizontal direction.

Parameter Simulation by FDTD
SSC design is directly connected to the optical fiber as shown in Fig. 2. Meanwhile, the silicon waveguide is attached very close to the end of SSC designed. In this simulation, the power analysis is obtained by introducing a power monitor. Furthermore, analysis of the power monitor before and after the SSC positions aids in obtaining the value of the loss due to the coupling that occurs between optical fibers and silicon waveguide.

One can use modal overlap (or mode mismatch) to determine coupling loss between the optical fiber and the chip facet, where the modal overlap is defined as [4]:

$$\beta = \frac{\int E_1 E_2 \, dA|^2}{\int |E_1|^2 dA \int |E_2|^2 dA} \qquad (1)$$

where β is a modal overlap, A is the modal distribution area, the complex electric field of lensed fiber mode is represented by E_1 whilst E_2 is for the on-chip waveguide mode (at the chip facet). Overlap measures the fraction of electromagnetic fields between the modes of lensed fiber and chip facet. The mode at the facet of the silicon waveguide overlaps the lensed fiber mode to the maximum extent, to get a high coupling efficiency. The mode electric field distribution at the coupler facet is
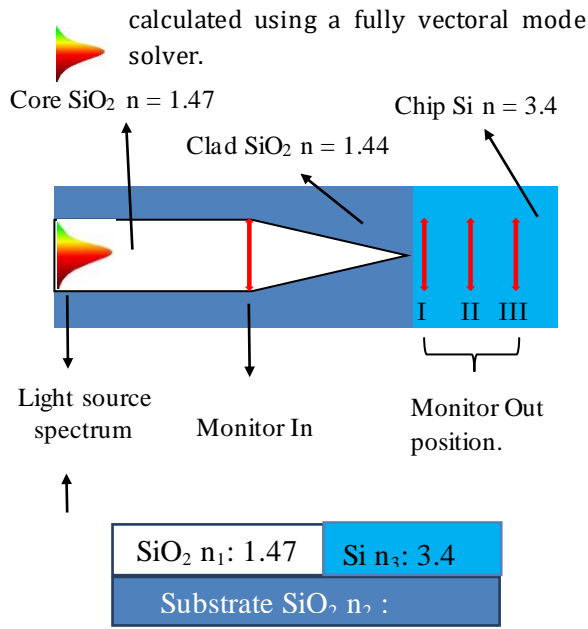
calculated using a fully vectorial mode solver.

Core SiO₂ n = 1.47
Clad SiO₂ n = 1.44
Chip Si n = 3.4

I   II   III

Light source spectrum
Monitor In
Monitor Out position.

SiO₂ n₁: 1.47   Si n₃: 3.4
Substrate SiO₂ n₂ :

Fig. 2: Schematic of inversed taper for SSC on FDTD simulation. Side view of optical waveguide on the simulation.

The mode mismatch (coupling) loss are hardly affected by the gap between the tips at the facet. But the propagation loss and mode conversion loss from facet mode to silicon waveguide mode is influenced by the gap. The increasing of the tip width, meaning the n_{eff} at the chip facet is increased, leads to the increasing of the mode mismatch loss. Here, the influence of the taper length (L) and gap on coupling loss is studied.

In our simulation, we have analyzed TE mode and TM mode respectively and find the lowest coupling between them. Also, in our simulation, the symmetric (*perfectly matched layer*, PML) boundary condition is used. It means that all of incident light will be absorbed perfectly in the boundary condition since normally the field has faded away when it spreads out laterally on the gap. The computation FDTD region is 50μm × 300μm, and the grid size (mesh setting) is 0.025μm.

3. Results and Discussion

The fundamental factors that lead to the high coupling loss between the SSC taper and the silicon waveguide are the gap (between optical fiber and silicon waveguide) and the mode size mismatch. So, in order to cut down the high coupling loss, the gap must be diminutive, and the mode size of the inverse tapers should be much more alike with that of the SSC taper.

FDTD simulations are used to investigate the effect of the tapered design, as shown in Fig. 3. This design sustains the parallel pattern of the light with a small divergence angle. The taper keeps the divergence angle of incident light small. Figure 3 also shows that the light propagation is detected not only in the optical fibers but also at the silicon waveguide.
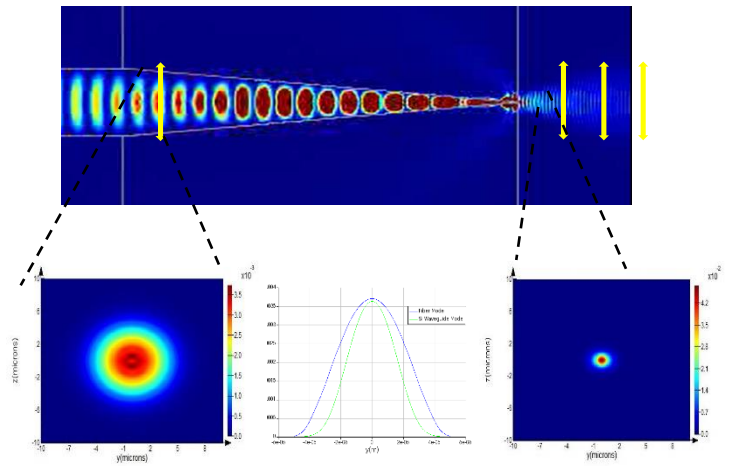

Fig. 3: Propagation light on the inversed taper fiber through to the photonic integrated circuits. (left) Mode propagation in the middle of fiber and (right) in the corner of inversed taper.

Coupling efficiency definition

The coupling efficiency between SSC taper and silicon waveguide is determined by the overlap integration of their optical fields as shown in Eq. (1). Besides, in our simulation, the loss of mode mismatch, and the influence of taper length (L) have been considered. So, the total coupling efficiency (in dB) is expressed in Eq. (1).

Comparison between power monitor input and power monitor output (I, II, and III position) could generate the coupling loss. All coupling losses and coupling efficiency has been analyzed as shown in Fig. 4, 5, 6, and 7.

The coupling losses and coupling efficiency are shown separately by the TE and TM modes, various of wavelength, various of taper length and the power monitor position.
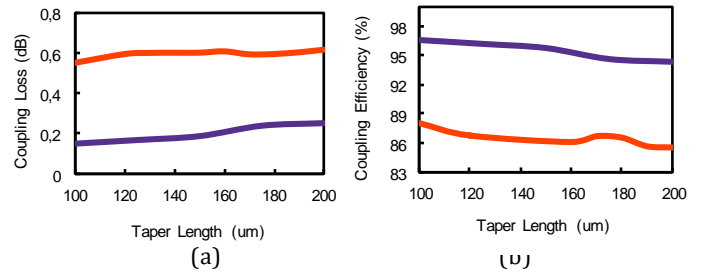

Fig. 4: (a)Taper length dependence of coupling efficiency. (b) Taper length dependence of coupling loss. Red and purple lines are the TE and TM mode condition respectively.
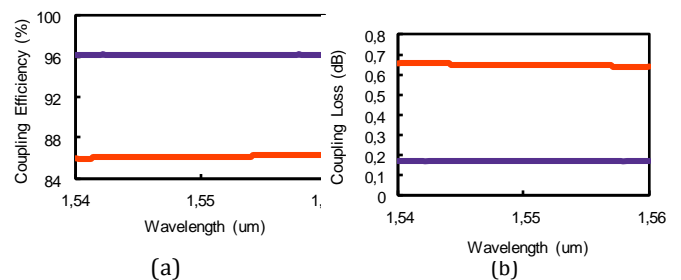

Fig. 5: (a) Wavelength dependence of coupling loss. (b) Wavelength dependence of coupling efficiency. Red and purple lines are the TE and TM mode condition respectively

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Along with the increased of taper length, the coupling loss slowly begins to increase as well as shown in Fig. 4(a). This condition applies to TE and TM mode. Meanwhile, the coupling efficiency gradually decreases with the increase of taper length as well. According to Fig. 4, the lowest coupling loss and highest coupling efficiency is obtained by L=100 μm. Then, the shortest taper length provides an optimal design as well.

The data carrier requires a specific wavelength, so that, the effect of changing wavelength has been studied as shown in Fig. 5. Here, wavelength dependance does not really change the coupling loss and coupling efficiency. Likewise for the TE and TM mode condition, there are no significant changes.

Figure 6 shows wavelength dependance of and coupling efficiency. Therefore, monitor position has shown different changes of coupling efficiency in TE and TM mode. The first monitor is in front of the inversed taper. While the second and third monitors are 10 μm next to is. For λ = 1.55μm in TE mode, the coupling efficiency in first monitor is 86.16 %, while second monitor is 85.45 % and the third monitor is 83.52 %. Furthermore, the coupling efficiency in the first monitor is 96.20 %, while second monitor is 96.19 % and the third monitor is 96.05 % in TM mode.
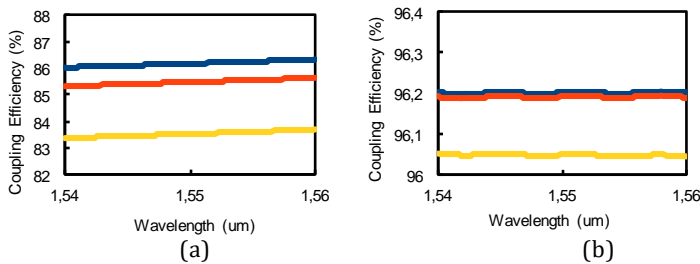

Fig. 6: (a) Wavelength dependence of coupling efficiency on TE mode. (b) Wavelength dependence of coupling efficiency on TM mode. The blue, red and yellow lines are monitor positions (I, II and III). The distance between two monitors is 10 μm.
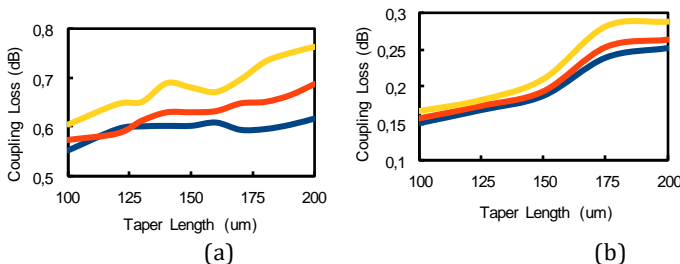

Fig. 7: (a) Taper length dependence of coupling loss on TE mode. (b) Taper length dependence of coupling loss on TM mode. The blue, red and yellow lines are monitor positions (I, II and III). The distance between two monitors is 10 μm.

Taper length dependance measured by different monitors gives a significant value of coupling loss. Both were measured under TE and TM mode condition. On average, the lowest coupling loss is obtained by the first monitor. The highest coupling loss is obtained by the third monitor at the longest taper length. The taper length dependance of

coupling loss tends to increase slowly, Then, there are some points with suddenly changes as shown in Fig 7.

4. Conclusion

We simulated and analyzed the inversed taper as a spot size converter to connect optical fiber and photonics integrated circuits. The function of SSC is to control the divergence angle of the propagation light after crossing the other materials. We proposed the design with linear inverse taper on the fiber and calculate the coupling loss and coupling efficiency. This value is the shortest taper length that can be used to get the smallest coupling loss and the highest coupling efficiency during propagation in the waveguide. By using this structure, the divergence angle of the input light of the silicon waveguide is minimum. This result can apply to be connecting bridge between optical fiber and silicon waveguide.

5. Conflict of Interest

The authors declare that they have no conflict of interest.

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