Proposal and analysis of a double-tip coupler for efficient coupling fiber to slot and strip waveguides

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ABSTRACT

High efficiency coupling from fiber to slot and strip waveguides using a double-tip coupler is presented. The double tips are inverse tapered, while their distance is decreased. The coupling efficiency reaches 90.9% with a taper length of only 30μm for coupling fiber to slot waveguides. With a mode transformer, the slot waveguide mode can be converted to strip waveguide mode with an efficiency of 99.3% in a length of 15μm. The impact of several parameters, such as distance between tips, taper length, and tip-end width, are simulated and optimized to improve the coupling efficiency.

Key words: fiber-to-waveguide coupler, slot waveguide, strip waveguide, silicon-on-insulator

1. INTRODUCTION

Recently, slot waveguides were theoretically investigated and experimentally realized [1-5], which can confine the fundamental mode highly in a slot region of low index material. Together with strip waveguides, they are promising for high-density integrated optical circuits, due to the cross section of less than a micrometer and small bending radius. However, the large mode mismatch between a single-mode fiber and a slot/strip waveguide leads to considerable coupling loss.

In a recent work, the authors of [6] proposed a highly efficient coupling between optical fibers and sandwiched slot waveguides based on the inverse taper approach. In addition, double-tip coupler to connect a fiber and a strip waveguide was presented in [7], and then verified in [8], with a coupling loss reduction of 2dB per coupling facet, compared with that of a single tip. However, the Y junction between slot waveguide and strip waveguide brings a fabrication challenge and large conversion loss.

In this paper, we design and investigate on a novel double-tip coupler for coupling fiber to slot and strip waveguides. Mode transformers [9, 10] are employed for coupling strip waveguides. Several factors also have been analyzed, including the distance between tips, taper length, and tip-end width. High coupling efficiency has been obtained in a short propagating length, suggested by the three-dimensional beam propagation method simulation.

2. CONFIGURATION AND SIMULATION

The device is based on the silicon-on-insulator (SOI) material platform. The index contrast between core (n_{Si}=3.477) and cladding/substrate (n_{SiO2}=1.444, n_{air}=1) is high and enable device compactness. The schematic of our design is shown in Fig.1. It is divided into two parts: one is a double-tip coupler that effectively couples the fiber and the slot waveguide,

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the other is a mode transformer, which is necessary for the strip waveguide coupling. The thickness of silicon layer is H=300nm, the strip width is W_{r0}=300nm. Two identical tips of W_{c0}=100nm are designed and then inversely tapered to W_{s0}=200nm, while the distance between the two tips (W_{c1}) is tapered to W_{s1}=100nm in length L_{cs}. The top cladding of device is silica. The transformer length and tip-end width are denoted as L_{sr} and W_{te}, respectively.

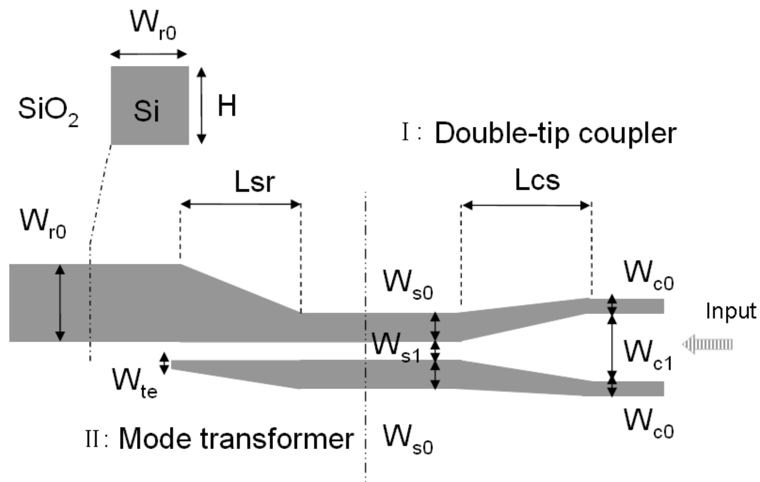

Fig.1 The schematic of a double-tip coupler together with a mode transformer

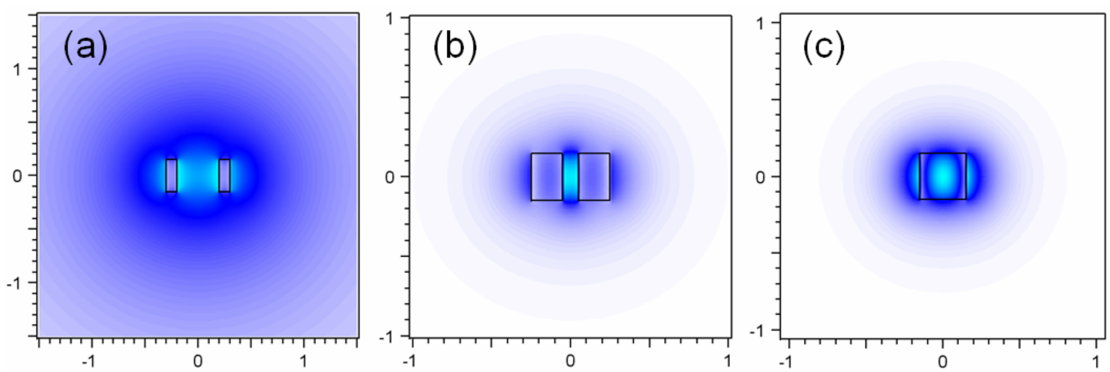

Fig.2.Fundamental mode distributions of a double-tip waveguide (a), a slot waveguide (b), and a strip waveguide (c)

The fundamental mode of a double-tip waveguide can be obtained using three-dimensional mode solver based on beam propagation method. Note that only the transverse-electric (TE) polarization is considered, and input wavelength is 1550nm. A lensed fiber with a mode field diameter of 3μm is chosen here. Then, we can evaluate the coupling efficiency between the fiber and double-tip waveguide by overlap integrating their fundamental modes. As seen in Fig.2 (a), the mode profile of double-tip waveguide is large and comparable with that of a lensed fiber, ensuring a low mode mismatch loss. The mode of double-tip waveguides can be converted to that of conventional slot waveguides (see Fig. 2(b)) through a taper. We also observe that the mode mismatch of slot and strip waveguide is notable, indicating that a low-loss mode transformer is necessary.

By introducing the configuration in Fig. 3(a), we evaluate the transmission efficiency in slot waveguide tapers and converting efficiency in mode transformers. The structure begins and ends both with a strip waveguide. The transmission process is reciprocal, the two transformers and tapers are all the same. Therefore, the transmission efficiency and converting efficiency can be calculated by $\eta_1 = (P_{out}/P_{in})^{1/2}$ and $\eta_2 = (P'_{out}/ P_{out})^{1/2}$, respectively. The simulation is carried out by using beam propagation method. Fig.3 (b) illustrates the optical field evolution in the configuration with slot waveguide tapers. Due to efficient converting, minor loss can be observed.

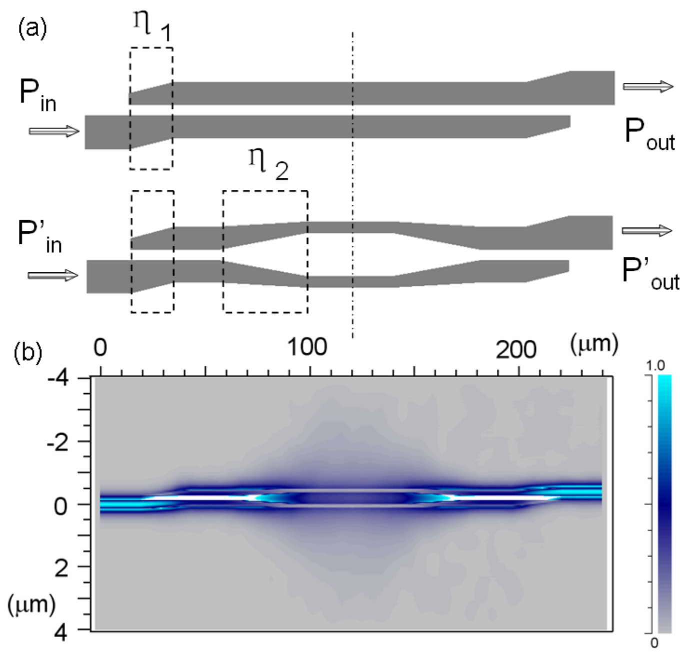

Fig.3 (a).Schematics of mode transformers w/o slot waveguide tapers, (b).Field evolution in the mode transformers with slot waveguide tapers

3. RESULTS AND DISCUSSION

As the distance between two tips increases, the mode effective index decreases monotonously, as shown in Fig.4. The mode profile is also enlarged, whereas it is a non-Gaussian-like mode. By means of overlap integral of the double-tip mode and fiber mode, the coupling efficiency is obtained under varied tip distance, as shown in Fig.4. We can see that the coupling efficiency achieves the maximum of 92.4% with a distance of 350nm, corresponding to a coupling loss of only 0.34dB. Further increase the distance, the coupling efficiency will fall slightly, because of the aggravated mode mismatch between the fiber mode and enlarged double-tip mode.

The transmission efficiency in the slot waveguide tapers is simulated, considering the impact of taper length and distance between the two tips, as shown in Fig.5. Under the same taper length, double-tip with a large distance has low transmission efficiency. We can see that the transmission efficiency increases with the taper length. At the distance of 400nm, the transmission efficiency exceeds 98.4% with a taper length of no less than 30μm. Since the coupling efficiency between the double-tip and fiber is 92.4%, the total coupling efficiency between the slot waveguide and fiber reaches as high as 90.9% in a length of 30μm, corresponding to a coupling loss of 0.41dB.

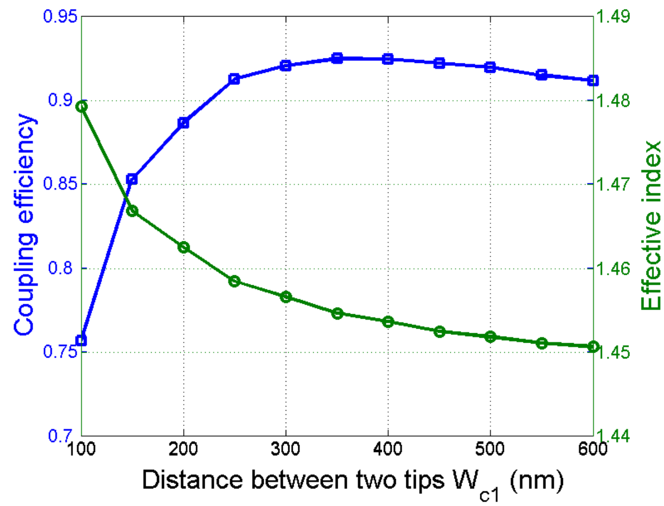

Fig.4. Coupling efficiency between the double-tip and fiber and effective index of double-tip mode with the distance between two tips varied from 100nm to 600nm.

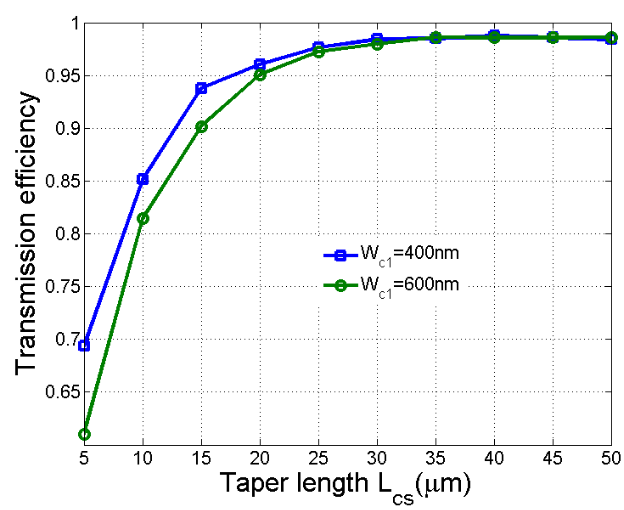

Fig.5. Transmission efficiency through a slot waveguide taper with varied length

As seen in Fig.2, the mode mismatch between slot and strip waveguide modes is notable. Direct coupling of the slot and strip waveguides may cause a conversion loss of 0.69dB, while the conversion loss is only 0.03dB as the mode transformer is employed. We can find that the conversion loss of the mode transformer is much lower than that of direct coupling, as compared in Fig.6. The mode converting efficiency is influenced by the transformer length and tip-end width. The simulation results are depicted in Fig. 7. With the tip-end width of zero, the converting efficiency increases with the transformer length L_{sr}, and achieves as high as 99.3% in a length of 15μm. We choose the transformer length as 15μm, and calculate the effect of tip-end width W_{te}. As the width increases to 200nm, the converting efficiency is reduced to 97.1%, corresponding to a conversion loss of 0.13dB. Due to the fabrication limits, tip-end width above zero is practical, whereas it deteriorates the efficiency only slightly.

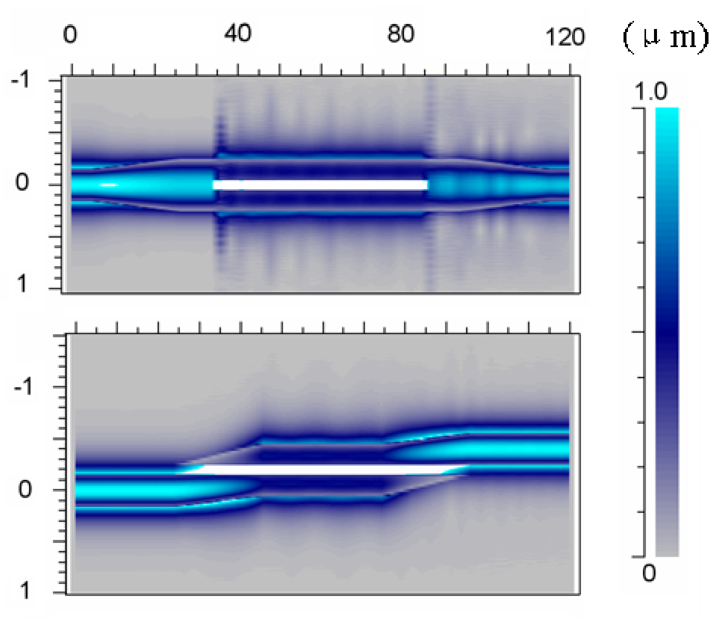

Fig.6. Field revolutions of direct coupling and coupling by mode transformer

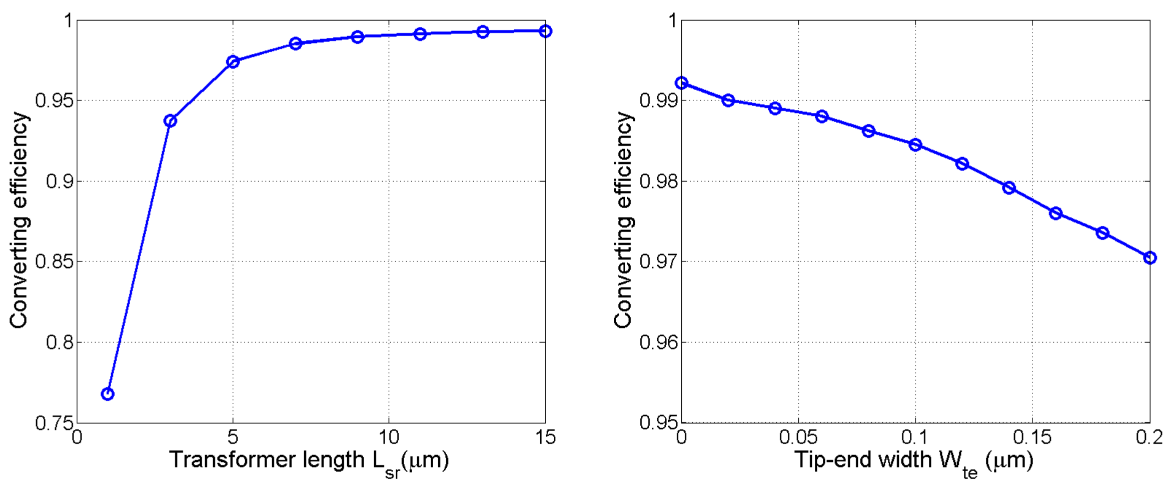

Fig.7. Mode converting efficiency with varied transformer length L_{sr} and tip-end width W_{te}

4. CONCLUSION

In summary, we have proposed efficient coupling from the fiber to slot and strip waveguides based on silicon-on-insulator using a double-tip coupler. The double-tip waveguide shows high coupling efficiency with fiber and low loss connecting to slot waveguides through a taper. The total fiber coupling efficiency for slot waveguides reaches 90.9% with a taper of 30μm in length, while it is 90.3% for strip waveguides, by employing a mode transformer of converting efficiency about 99.3%. The designs are very useful for coupling fiber to slot and strip waveguides under the present fabrication processes.

5. ACKNOWLEDGMENTS

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