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TAPER COUPLERS FOR COUPLING BETWEEN LASER AND SILICON WAVEGUIDE WITH LARGE ALLOWABLE TOLERANCE

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ABSTRACT

A taper coupler with multimode input and single mode output is presented for coupling between edge emitting laser diode and silicon waveguide. The tapered coupler structure is optimized and tolerance for laser diode placement is studied. A typical coupling efficiency of -2dB is achieved from laser diode to silicon waveguide. With tolerance of +/-4 μ m laterally or vertically, the variation of the coupling efficiency is about 3dB. The tolerance is large compared with other methods. Tilting angle at laser diode and the small gap between tapered coupler and silicon waveguide also affect the overall coupling. From our studies, horizontal and vertical offsets are more critical for laser diode placement in order to have a good coupling. The new design can be applied to photonics packaging because it will make passive assembly easier by having larger tolerance for packaging compared with the conventional method with lens.

Keywords: Coupling efficiency, Laser diode attachment, Silicon waveguide, Taper coupler, Tolerance

1. INTRODUCTION

Silicon photonics attracts much attention in recent years. Waveguides, various passive optical components, and photo detectors have been realized and can be integrated on silicon using standard CMOS techniques. However, silicon laser still has a long way to go. Presently, we still need to couple laser from an external laser source to silicon photonics devices. A typical DFB laser diode has a small beam spot at the output with wide divergence angles of horizontal 20 degrees and vertical 40 degrees. A silicon waveguide is about 0.35 μ m (height) * 0.4 μ m (width). Compared with laser diode to single mode fiber coupling [1][2], optical coupling between laser diode to waveguide is even more challenging. Direct coupling (butt coupling) will have large loss. Coupling with focusing lenses of different mechanisms is intolerant of small misalignment (0.5 μ m) between the laser and waveguide tip. M. Oguro et al from NEC used mode size converter to couple light from laser diode to a 4.5 μ m (height) * 8 μ m (width) planar waveguide with 6.5dB coupling loss [3]. Bookham claimed a tapered rib waveguide to transit light from relatively large cross-section waveguide, eg. fiber, to a smaller cross-section waveguide [4]. In this paper, we propose a taper coupler with larger tolerance (+/-3 μ m) with good coupling efficiency (\geq -3dB to -6dB) for laser and silicon waveguide coupling. Rather than the adiabatic mode size converter, it starts with an input size larger than the mode size of laser diode. Because of the larger input size, the light can be coupled into the taper structure with larger tolerances. The design is optimized and tolerance is studied.

2. TAPER COUPLER DESIGN AND SIMULATION FOR LASER AND SILICON WAVEGUIDE COUPLING

A taper coupler with mode size matching at both sides will convert the mode from one waveguide to another waveguide. But the mode size converter needs to be aligned with the both the waveguides precisely, as otherwise, most of the light

will be lost [5][6]. In order to achieve a more generous tolerance for passive alignment in low cost assembly, a taper coupler with relative large input opening is designed to couple the light from laser diode to silicon waveguide. In order to make the fabrication simpler, the coupler is designed to have symmetric lateral taper and pseudo-vertical taper shape. The laser diode active waveguide faces the center of the entrance facet of taper coupler. Figure 1 and figure 2 show the top view and cross-sectional views of the designed tapered coupler structure.

The design of the coupler includes considerations of assembly. Considering the placement of laser diode will be at least a distance from the taper coupler, the laser beam will diverge to a beam spot of several micrometers diameter. Thus, we designed the opening at input side to be $12\mu\text{m} \times 12\mu\text{m}$ which is larger than the laser diode mode size. Considering the divergence angle of 32 degree, the distance between the laser diode and the taper coupler should be less than $21\mu\text{m}$. This helps in coupling the light into the coupler even if the laser diode has a few micrometers displacement. The designed taper waveguide has a core refractive index of 1.51 and clad refractive index of 1.46. This results in a multi modal tapered coupler. Higher order modes will be lost during the propagation through the coupler. However, most of the light will be coupled into the waveguide by design optimization. The taper coupler has two layers to form the pseudo-vertical tapering structure as depicted in figure 2. The bottom layer is $11\mu\text{m}$ thick and top layer is $1\mu\text{m}$ thick. The length of the bottom layer is optimized so that most of the light will be coupled into the top layer. The output end of the taper coupler tapers down to $1\mu\text{m} \times 1\mu\text{m}$ whose fundamental mode matches with propagation constant of the mode in silicon waveguide. The length of the coupler is 1.7mm. The length of the top layer is optimized to achieve the best coupling between the taper coupler and silicon waveguide. Figure 3 shows the horizontal light propagation from laser diode to a silicon waveguide through taper coupler. Figure 4 shows the vertical light propagation. By using such a taper coupler, a typical -2dB coupling efficiency is achieved.

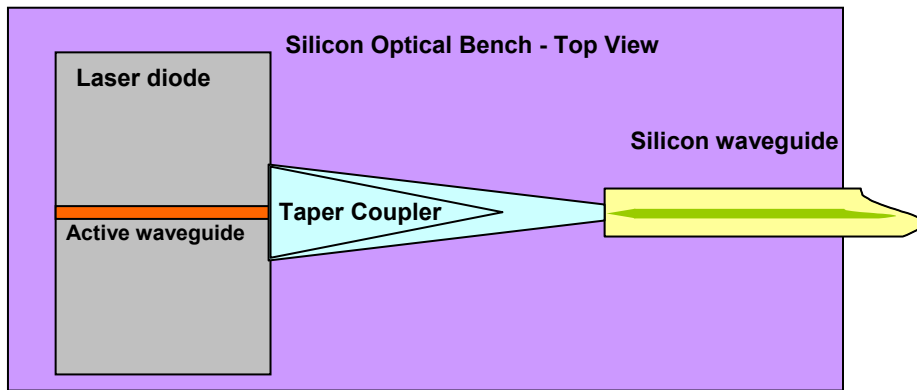


Fig. 1 Top view of a taper coupler between laser diode and silicon waveguide.

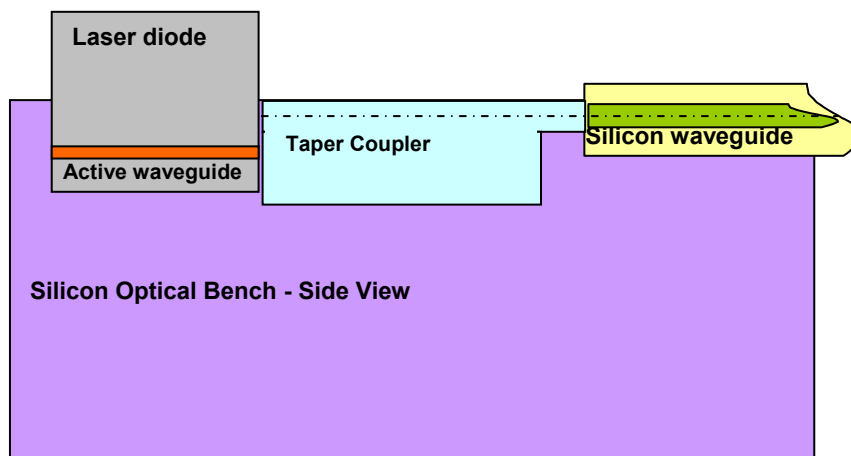


Fig. 2 Side view of a taper coupler between laser diode and silicon waveguide.

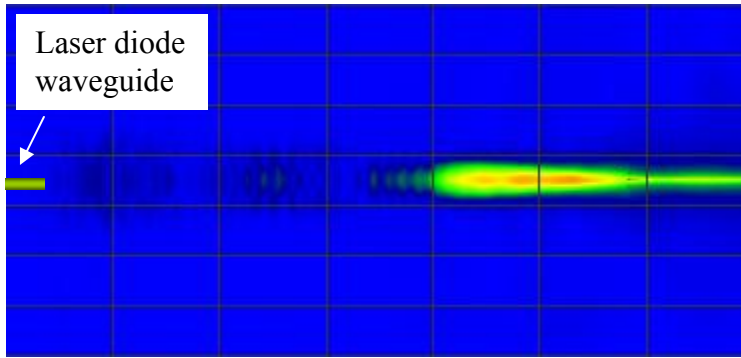


Fig. 3 Light propagation from laser diode to silicon waveguide through taper coupler (horizontal slice).

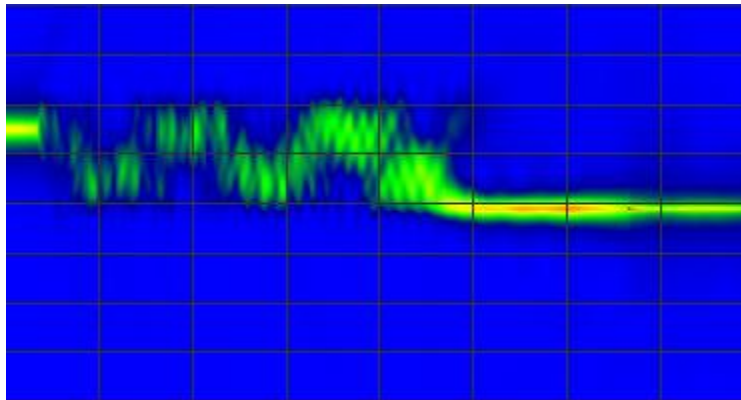


Fig. 4 Light propagation from laser diode to silicon waveguide through taper coupler (vertical slice).

3. LASER DIODE TOLERANCE STUDY DURING DESIGN

To study the possible tolerance values of laser diode placement, simulation studies were carried out by shifting the input to the tapered coupler in both horizontal and vertical positions. The placement tolerances were studied from $-4\mu\text{m}$ to $+4\mu\text{m}$ offset laterally and from $-4\mu\text{m}$ to $+4\mu\text{m}$ vertically. The coupling efficiency varies from -1.9dB to -5dB within $\pm 4\mu\text{m}$ lateral offset (Fig. 5), which means the variation is about 3dB . Figure 6 shows the light propagation in the tapered coupler when the laser diode is offset by $4\mu\text{m}$ laterally. The coupling variation is less than 3dB when the vertical position of the laser waveguide offsets from $-4\mu\text{m}$ to $+4\mu\text{m}$ (Fig. 7). In these two sets of simulations, we assume there is not tilting at the active waveguide of laser diode relative to the optical axis of taper coupler and silicon waveguide.

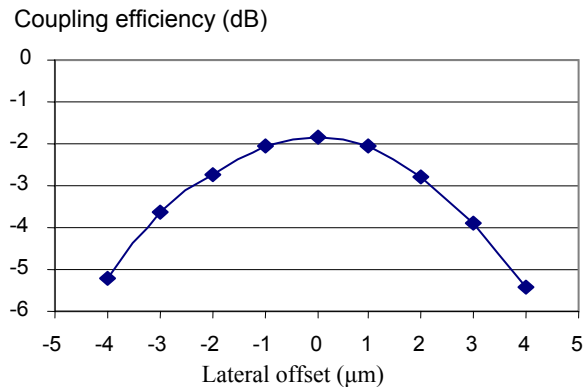


Fig. 5 Coupling efficiency vs. lateral offset.

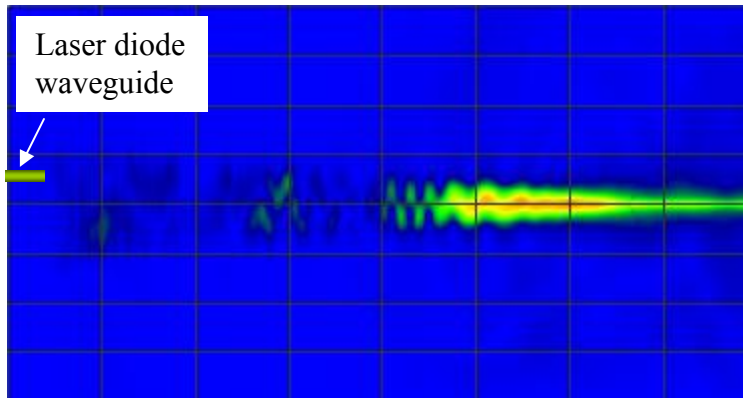


Fig. 6 Light propagation from laser diode to silicon waveguide through taper coupler with 4 μm horizontal offset.

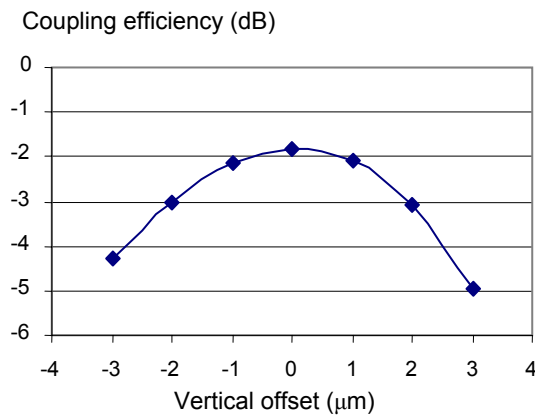


Fig. 7 Coupling efficiency vs. vertical offset.

It's also possible that the laser diode is tilted relative to the optical axis of tapered coupler and silicon waveguide. The coupling property at tilting condition is studied. The schematic configuration of tilting between laser diode and coupler is shown in Fig. 8. The coupling efficiency results over a range of tilting angle are presented in Fig. 9. When there is a deliberate tilt of ± 2 degrees, the coupling efficiency improves from -1.9dB to -2.8dB . Hence, the coupling efficiency variation due to tilting of laser diode is less than 1dB . Figure 10 shows the light propagation from laser diode to silicon waveguide through taper coupler with 2 degree tilting at laser diode. It can be seen that the modes are launched asymmetrically in tapered coupler. The light propagation is very similar to horizontal offset of laser diode.

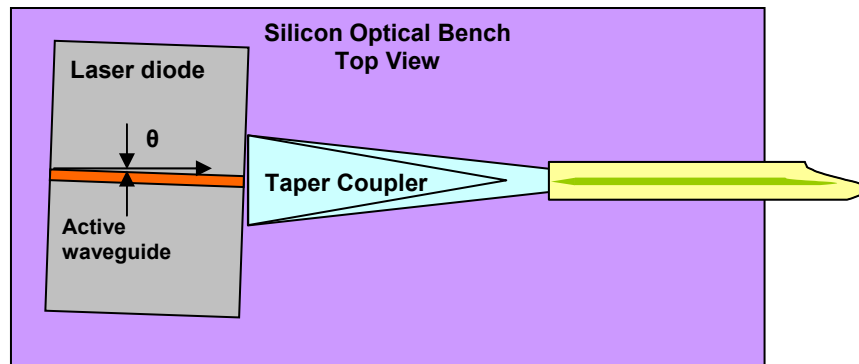


Fig. 8 Top view of a taper coupler between a lateral tilting laser diode and silicon waveguide.

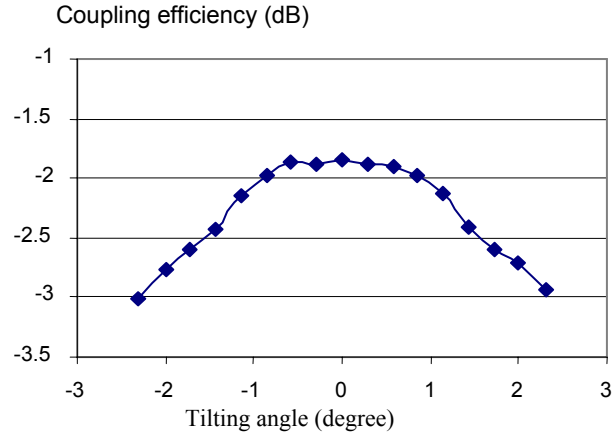


Fig. 9 Coupling efficiency vs. lateral tilting angle.

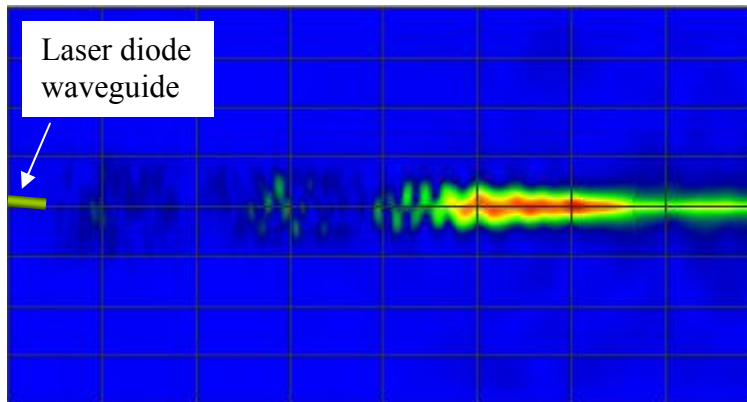


Fig. 10 Light propagation from laser diode to silicon waveguide through taper coupler with 2 degree tilting.

4. CONCLUSIONS

In this paper a coupler is designed for coupling the light from laser diode to silicon waveguide with large alignment tolerances. The coupler has a pseudo vertical tapered structure. Laterally, it has a linear taper. The input aperture is much larger than the size of the laser waveguide cross-section. The tapered coupler provides single mode output and matches the mode propagation constant with that in silicon waveguide. The tapered coupler is fabricated on the same substrate with the silicon waveguide through the silicon micro-fabrication process. The misalignment between the silicon waveguide and taper coupler can be very small since this is controlled by high precision silicon optical bench patterning processes. The coupler relaxes the laser diode placement accuracies and eliminates the need for a coupling lens. Design Studies showed that the tolerance between the laser diode and taper coupler can be more than $\pm 4\mu\text{m}$ misalignment at x-y, and more than ± 2 degree tilting angle tolerance. The laser to silicon waveguide coupling tolerances is greatly improved and passive alignment for laser diode and silicon waveguide becomes possible. The technology is suitable for functional integration for silicon photonics. Important results are summarized as followings:

1. A taper coupler is designed for larger tolerance laser diode and silicon waveguide light coupling;
2. The optimized structure can achieve -2dB coupling efficiency by simulation;
3. With $\pm 4\mu\text{m}$ laser diode offset, the coupling efficiency varies only 3dB;
4. ± 2 degree tilting at the laser diode varies the coupling efficiency by only 1dB.

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