Low polarization-dependent-loss silicon photonic trident edge coupler fabricated by 248 nm optical lithography

Xin Tu 1, Patrick Dumais 2, Ming Li 1, Dominic Goodwill 2, Hongyan Fu 1, Dongyu Geng 1, Eric Bernier 2

1 All-Optics Laboratory, Huawei Technologies Co. Ltd., Shenzhen, 518129, China
2 Huawei Technologies Canada Co. Ltd., Ottawa, K2K 3J1, Canada

Abstract: Trident edge couplers were fabricated using optical lithography. TE and TM coupling loss with lensed fiber were improved by 0.2 dB and 0.3 dB compared to a single-taper coupler. PDL was improved by 0.1 dB.

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I. INTRODUCTION

Edge coupling of silicon nanophotonics requires coupling a fiber mode of approximately 10 μm diameter, to a single mode silicon waveguide with mode size approximately 500 nm by 200 nm. This challenge has been approached in many ways, frequently using a nano-taper to create a larger mode at the edge of the silicon die, and a lensed fiber to reduce the fiber mode size.

Hatori et al [1] demonstrated that performance equivalent to a single taper could be achieved by using a trident-shaped silicon edge coupler, fabricated with e-beam lithography. The conventional single-mode waveguide is tapered down within the die, and coupled laterally to a pair of narrow single-mode waveguides forming a shape similar to a fishing trident (more correctly: a bident). The outer waveguide pair then tapers down to the narrowest allowed feature at the edge of the die. The outer waveguide pair supports a supermode that is larger laterally and vertically than the mode of the original single mode waveguide. As reported in [1], the supermode is relatively insensitive to the tip width, and thus manufacturing repeatability should be better than a single tip edge coupler.

Katayose et al [2] have reported a similar device in silica, where all three waveguides of the trident were extended to the edge of the die. They called this element a triple-branched spot size converter. A multi-waveguide silicon edge coupler based on mode beating was reported in [3].

We have found no previous report of a supermode trident edge coupler fabricated by optical lithography in silicon.

II. DEVICE FABRICATION

We designed trident edge couplers, as shown in Figure 1, and conventional single-taper edge couplers. They were fabricated on the same die at IME A*STAR. The fabrication comprised 220 nm thickness of silicon on insulator with 2μm buried SiO₂ and 2.7μm cladding SiO₂. The device was fabricated in a silicon photonics wafer that included metallization, doping and Ge photodetectors. The edge facet is a 100μm deep vertical etch without undercut that provides an optically flat facet and allows the fiber to approach arbitrarily close to the facet. There is 1 μm of SiO₂ between the silicon taper tip and the edge facet, to protect the silicon. Total coupler length is around 300μm, core setback is ~30% of the length, and tip spacing is 1.0 to 1.4μm. Pairs of identical trident couplers are at opposite edges of the die, connected by 3mm of single mode ridge waveguide, with a chicane of two 90º bends to improve measurement accuracy by removing weakly guided light.

248nm optical lithography with binary-intensity mask was used to pattern the silicon. 20 designs were fabricated and tested, with varying tip spacing and taper overlap. The nominal waveguide tip was 180 nm, which is rendered as ~150 nm in the fabricated die. Single-mode waveguide nominal width was 500nm. Figure 2 shows SEM photos provided by IME of the three transition regions, on a companion wafer that was fabricated without top cladding. The bending of the trident termination toward the core waveguide is believed to be real, not an SEM artifact. Its cause was not investigated. It will have a small effect on overall loss, but no effect on the trident supermode at the die edge.
III. COUPLING EFFICIENCY MODELING

The trident edge coupler supports one supermode of each polarization. TE is shown in Figure 3. Three factors affect device efficiency: coupling from fiber spot to/from trident supermode; taper-assisted transition of supermode to/from core mode; substrate effects.

Fiber coupling is primarily dependent on trident tip spacing and, as shown in [1], weakly dependent on tip width. Despite the non-circular shape of the supermode, 3D FDTD modelling indicated the lowest theoretical loss is 0.7 dB for TE and 1.4 dB for TM at a tip spacing of ~1.2 μm. All modeling assumed a perfect Gaussian spot created in a semi-infinite silica incident medium, while measurements were done with air between a lensed fiber and the die. Measured PDL is expected to be smaller than the model, as the TE mode will suffer larger loss in the taper-assisted transition of supermode to/from core mode, due to sidewall roughness or distortion of the waveguides.

The loss of a supermode-to-core transition is dominated by the taper tip width, with small effects due to coupler spacing, slope shape and slope length.

The use of 193 nm lithography would create narrower tips, which would improve the transition loss and make the supermode more circular. This may give lower loss for TM, estimated as 0.6 dB improvement, as shown in Table I.

Modeling indicates that supermode propagation loss with 2 μm BOX is negligible, with no discernible substrate effects. However, some tests showed faster roll-off in coupling efficiency as the input fiber was moved down toward the substrate, compared to moving the fiber up toward the air, which may be due to a Lloyd’s mirror effect at the BOX-to-substrate interface.

FIG. 3. 3D-FDTD TE mode profiles of (a) incident lensed fiber spot and (b) trident edge coupler cross-section. (c) TE mode profile in the wafer plane.

<table>
<thead>
<tr>
<th>Simulated coupling loss (dB)</th>
<th>248nm lithography 180nm feature size</th>
<th>193nm lithography, 130nm feature size</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>TM</td>
<td>1.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

TABLE I Simulated coupling loss for the tip spacing of 1.2μm

IV. EXPERIMENTAL RESULTS

Devices were tested using a pair of lensed fibers on nano-positioners, using a polarization synthesizer to scan the TE and TM insertion loss. Table II shows the fiber spot size 1/e^2 intensity diameter specified by the fiber manufacturer. The measurement cannot distinguish input versus output coupling. Table II shows the measured coupling loss per facet, defined as ½(fiber-to-fiber transmission – on-chip loss), at optimum fiber position. On-chip loss was calibrated using cut-back straight waveguides and chains of bends. Any polarization mixing created by the device was below the ~20dB polarization measurement sensitivity. Figure 4 shows the spectrum of the best design. After filtering the measurement noise, the coupling loss is <1.5dB for TE mode and <1.7dB for TM mode over the 35nm C-band. The PDL is <0.3dB. TE loss varies ±0.1dB without a wavelength trend. TM loss increases nearly linearly by 0.3 dB from 1530nm to 1565nm. Similar wavelength trends were observed for all designs.

In agreement with the modeling, the best trident edge coupler has small improvement on the coupling efficiency compared to the single taper. Table II shows the measured coupling efficiency for different spot sizes of lensed fibers at 1550 nm. The result of
experiment for TE is worse that the modeling data, which may be caused by the distortion of the incident beam spot, reflection loss at the air/silica interface and the bending of the trident termination. Measured PDL is only 0.1dB for 3.2µm fiber spot at 1550 nm. TM loss is within 0.1dB of the model, and TE loss is 0.7dB worse than the model.

Figure 5 shows the measured loss versus input fiber alignment, normalized to the optimal-alignment coupling loss. For 1.0 dB excess loss due to misalignment, some tridents were 0.1 to 0.2 µm less sensitive to position than the single taper. This difference is comparable to the testing step of 0.15 µm, which was challenging to measure repeatedly. Position tolerance in the longitudinal direction was more than 5 times larger than in the lateral and vertical directions.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>Measured coupling loss, 1550 nm. Absolute calibration ±0.1dB</th>
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</thead>
<tbody>
<tr>
<td>Loss per facet (dB) measured at optimal alignment, 1550 nm</td>
<td>2.5±0.1µm-spot lensed fiber</td>
</tr>
<tr>
<td>TE, TM, PDL</td>
<td>TE, TM, PDL</td>
</tr>
<tr>
<td>Single taper edge coupler</td>
<td>1.7, 2.2, 0.5</td>
</tr>
<tr>
<td>Best trident edge coupler design</td>
<td>1.6, 1.9, 0.3</td>
</tr>
<tr>
<td>Worst trident edge coupler design</td>
<td>2.1, 3.0, 0.9</td>
</tr>
</tbody>
</table>

FIG. 4. Wavelength-dependent coupling loss of the best design, 3.2µm-spot.

FIG. 5. Normalized coupling loss vs. input misalignment, 3.2µm-spot.

V. CONCLUSION

Trident edge couplers were fabricated in 220 nm silicon photonics using 248 nm optical lithography. The trident couplers have lower coupling loss and PDL than single tapers.

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REFERENCES

