Low Loss, Large Bandwidth Fiber-Chip Edge Couplers Based on Silicon-on-Insulator Platform

An He, Xuhan Guo, Member, IEEE, Member, OSA, Kangnian Wang, Yong Zhang, and Yikai Su, Senior Member, IEEE, Member, OSA

Abstract—Fiber-chip edge couplers are extensively used in integrated silicon photonic for the coupling of light between optical fibers and planar silicon waveguide circuits. Here, we experimentally demonstrate three kinds of edge couplers with eased fabrication process, two fork shape, and one dual-trident SWG shape, based on Silicon-on-Insulator platform. A commercial lensed fiber with mode field diameter of 6.0 μm is used. The coupling performance and fabrication tolerance are theoretically analyzed and verified by 3D-FDTD simulation. The experimental results show that these edge couplers pose low coupling losses and large bandwidth simultaneously. At the wavelength of 1.55 μm, the coupling losses are 1.25 dB/facet, 1.49 dB/facet, 1.82 dB/facet for fork1, fork2, and dual-trident SWG couplers, respectively. The measured wavelength bandwidths in which the loss below 2 dB are 114 nm, 102 nm, 92 nm, respectively.

Index Terms—Edge couplers, fiber-to-chip coupling, photonic integrated circuits, silicon photonics.

I. INTRODUCTION

Silicon photonics has revolutionized the field of integrated optics, and provided a vigorous platform to build mass-producible silicon-based optical circuits with low cost. Silicon-on-insulator (SOI) is a prominent platform for the integration of optical and electrical devices. The high contrast of refractive index between the silicon and silicon dioxide in SOI realizes the highly integrated optical devices with sub-micrometer dimensions [1]–[3]. However, light coupling between the optical fibers and SOI waveguides arises a challenge due to the large mode size mismatch, given the mode size of an optical fiber is about two orders of magnitude larger compared to a typical silicon wire waveguide.

To alleviate this problem, two types of approaches have been intensively investigated, specifically surface grating couplers and edge couplers. Surface grating couplers diffract the light in or out the planar silicon waveguide, with the optical fiber positioned at near-vertical incidence above the chip [4]–[6]. A notable drawback of grating couplers is the dispersive operating principle that limits their coupling efficiency, operating bandwidth and typically makes them polarization/wavelength sensitive. Fiber-chip edge couplers accommodate the mode size matching between the fibers and the edge of SOI chips, thus can provide a substantially increased coupling efficiency, broad coupling bandwidth, and low polarization dependence. To efficiently excite the mode in the SOI waveguide, the incident mode field in fiber should spatially overlap the mode field in the waveguide as closely as possible [7].

Generally, a commonly-practiced approach in edge coupling is based on inverse tapers. The light from the optical fiber is coupled to a narrow waveguide tip which can expand the mode field size [8], [9]. Almeida et al. [9] presented a compact tapered edge coupler, in which a single mode silicon waveguide was tapered down to a 100 nm wide tip. The experimental coupling loss between the 5 μm mode field diameter (MFD) fiber and the taper was 6.0 dB for TE polarization, at wavelength of 1.55 μm. The relatively high loss is mainly caused by the still high mode size mismatch presenting between the fiber and the chip facet.

To reduce the mode mismatching loss, edge couplers with multiple layers [10]–[12] or suspended structures [13]–[15] are proposed. Arnab et al. [10] demonstrated an edge coupler with bilayer inverse tapers. The coupling loss from a fiber with 5 μm MFD is 1.7 dB. The bandwidth with the loss below 2 dB is about 40 nm. Fang et al. [11] proposed an edge coupler composed of bilayer Si tapers located in the center of suspended SiO2 waveguide. The measured coupling loss from a lensed fiber with 5 μm MFD is 1.7~2.0 dB for TE mode in the wavelength range of 1520~1600 nm. Sun et al. [15] showed a cantilever shape edge coupler. The SiO2 cantilevers wrapping 250 nm thick silicon inverse taper are deflected out of plane by residual stress. The coupling efficiency of 1.6 dB for TE polarization at 1.55 μm is achieved. The measured spectrum shows wavelength dependence, with about 1.6 dB fluctuation from 1500 nm to 1560 nm.

Although the coupling loss is dramatically reduced by the bilayers and suspended structures, it would appreciably increase the complexity and difficulty of fabrication and packaging, especially in a standard complementary metal-oxide-semiconductor (CMOS) foundry. Edge coupler with planar silicon taper combining intermediate polymer shows decent experimental coupling performance [16], but it has not been widely adopted by

industry due to the limitations of polymer material (reliability, integration challenge, etc.). Therefore, continuing pursuit of edge coupling schemes to achieve low coupling loss, large bandwidth and eased fabrication remains highly desirable.

One such scheme is to employ the double-tip inverse taper, even if one of the tips is degraded due to fabrication imperfection, satisfactory coupling efficiency still could be achieved [17]. Edge couplers with double taper tips often perform better compared to those with the single taper only [18], [19]. Moreover, the coupler with double-tip taper provides a new design parameter, the gap between the two tips, which can offer another degree of freedom to improve the coupling performance. Wang et al. [20] presented an edge coupler with two tapered tips and a multimode interference combiner on an SOI platform. The coupling loss between a lensed fiber with MFD of 3.3 µm and the edge coupler is 1.1 dB at 1.55 µm. Han et al. [21] used three inverse tapers to form the asymmetric double slot waveguide, which can maximize the initial mode overlap with the 2.5 µm MFD fiber mode. The experimental results show that the minimum insertion loss is 1.8 dB for both TE and TM polarization. But the minimum slot widths both of the double slot waveguide are only 50 nm, which is difficult for the fabrication. Another alternative solution to implement efficient planar edge couplers relies on the employment of subwavelength grating (SWG) [22]–[24]. According to the effective medium theory, if the period of the grating is smaller than the light wavelength and is small enough to avoid Bragg diffraction, the SWG can be considered as a material with uniform effective index [25]. By changing the duty cycle and period, the mode distribution and effective refractive index of the SWG can be varied. Employing an SWG structure offers an additional degree of freedom that is beneficial at the design of edge coupler because the mode size at the coupler tip can be controlled by both the gap between the tips and the waveguide effective refractive index, which can be tuned by modifying the SWG structure. Pavel et al. [22] demonstrated a subwavelength refractive index engineered structure to ease the loss and wavelength resonances by suppressing diffraction effects. Although a low coupling loss of 0.32 dB is obtained, the use of relatively expensive lensed fibers with mode beam waist about 3 µm for mode-matching is indispensable in the measurement. Teng et al. [26] proposed an edge coupler based on trident-shaped SWG dielectric metamaterial. The pure coupling loss from a 4 µm MFD lensed is about 1.5 dB. The 2-dB bandwidth is about 50 nm.

In this paper, to achieve low coupling loss, broad bandwidth and ease of fabrication, we experimentally demonstrate two fork shape (fork1, fork2) and a dual-trident SWG shape edge couplers based on SOI platform with single E-beam lithography (EBL) and inductively coupled plasma (ICP) etching process. For fork1 coupler, the coupling loss is 1.25 dB/facet at 1.55 µm, and the 2-dB bandwidth is as wide as 114 nm. The minimum loss for fork2 coupler is only 0.7 dB/facet at 1.55 µm. The 2-dB bandwidth is 102 nm. The deviation of the dual-trident SWG coupler is only 0.4 dB from 1536 nm to 1628 nm with the minimum loss of 1.59 dB/facet. The edge couplers are optimized for TE polarization with the lensed fiber MFD of 6 µm at the facet.

II. FORK SHAPE EDGE COUPLERS

Edge couplers with multiple taper tips often perform better than those with only single taper [18], [19], fork shape edge couplers with double inverse tapers are hence proposed considering the good performance and eased fabrication. Except for the tip width, the double-tip taper offers a new design parameter, the gap between the tips, which can be designed to expand the mode field. In this section, the mode mismatch losses between the lensed fiber and the chip facets of the two fork shape edge couplers (fork1 and fork2 in Fig. 1) are firstly theoretically analyzed. Then the coupling performance and fabrication feasibility are studied by the 3D Finite-Difference Time-Domain (3D-FDTD) simulation. At last, the fabrication and measured results are presented.

A. Designs and Simulation

When the light is injected from an optical fiber to an SOI chip through an edge coupler, the fiber mode is expanded preferentially into the chip facet with large modal overlap and then adiabatically transferred to the highly confined strip waveguide. Hence the coupling loss of the edge coupler is mainly determined by the mode overlap (mode mismatch) between the optical fiber and the chip facet. The modal overlap can be defined as [7]:

\[
\text{Overlap} = \frac{|\int E_1 E_2 dA|^2}{\int |E_1|^2 dA \int |E_2|^2 dA}
\]

where \(E_1\) and \(E_2\) are the complex electric field amplitudes of the optical fiber mode and the on-chip waveguide mode (at the chip facet), respectively. To obtain the high coupling efficiency, the mode at the facet of the SOI chip should spatially overlap the fiber mode to the utmost extent.

Fig. 1. The structure schematics and the electric field distribution of the (a, b) fork1 and (c, d) fork2 edge couplers, respectively.
The structures of the proposed fork shape couplers are demonstrated in Fig. 1(a) and (c). The mode transmissions along the couplers are illustrated in Fig. 1(b) and (d). Three main parameters, the gap, tip width, and slot width (G, w, and g), are theoretically analyzed and optimized by the 3D-FDTD simulation.

Mode mismatch losses between the $6 \mu m$ MFD lensed fiber and the chip facets are calculated using (1). As shown in Fig. 2(a) and (b), the gap between the two tips at the facet barely change the mode effective index ($n_{eff}$) and the mode mismatch loss. But the gap will influence more on the propagation loss and mode conversion loss from the facet mode to the strip waveguide mode. The increasing of the tip width, results in the difference of $n_{eff}$ between fiber and chip facet, and leads to the augment of the mode mismatch loss [Fig. 2(c) and (d)]. Similarly, the tip width will affect the mode propagation and mode conversion in the same way.

For the fork1 coupler, the light from the lensed fiber is firstly coupled into the double-tip edge facets with optimized matching modal size. Then the light is transferred to the strip waveguide directly from the slot waveguide mode [Fig. 1(b)]. The length of the two tapers which transfer the light from the facet to the 350 nm wide strip waveguide is set as 55 $\mu m$. As shown in Fig. 3(a), the minimum loss occurs when the gap is 400 nm. For the influence of tip width, the smallest coupling loss is 0.63 dB at the tip width of 100 nm [Fig. 3(b)]. Similarly, the tip width will affect the mode propagation and mode conversion in the same way.

In order to characterize the performance of the fabricated edge coupler, a tunable laser (Keysight 81960A) with wavelength from 1507 nm to 1628 nm is chosen as the light source. An optical power meter (Keysight 81636B) is used to record the transmission spectra. The input light polarization is tuned by a polarization controller and set to TE mode. Light coupled in and out of the chip from the tunable laser is implemented by two identical edge couplers, one at the input and one at the output.
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Fig. 4. The SEM pictures of the fabricated fork1 and fork2 edge couplers.

Fig. 5. The simulated and measured coupling losses for fork1 edge coupler. The inset means the loss is below 2 dB from 1514 nm to 1628 nm.

Fig. 6. The simulated and measured coupling losses for fork2 edge coupler. The inset means the loss is below 2 dB from 1526 nm to 1628 nm.

III. DUAL-TRIDENT SWG EDGE COUPLER

On the premise of eased fabrication shown above, to further reduce the coupling loss and enlarge the bandwidth, SWG [22], [29] and trident shape [26], [30] structures could be adopted to take advantage of the flexible effective refractive index. In this section, a dual-trident SWG edge coupler is proposed (Fig. 8) to expand the modal profile in the chip facet. The same methodology is used to characterize this structure as before. The mode mismatch losses between lensed fiber and the chip facets are firstly theoretically analyzed. Then the coupling performance and fabrication tolerance are studied by the 3D-FDTD simulation. Finally, the measured results are presented and discussed.
A. Design and Simulation

As shown in Fig. 8(a), the upper tapered SWG, the upper conventional taper and the middle tapered SWG form one trident SWG structure. The lower tapered SWG, conventional taper and the middle tapered SWG form the other trident SWG structure. The two trident SWG structures compose the dual-trident SWG edge coupler as proposed. The period and the duty cycle of the SWG part are set to be 300 nm and 0.5, respectively. Fig. 8(b) shows the 3D-FDTD calculated mode evolution. The input beam is initially captured by the triple-tapered SWG arms, and smoothly transformed into the 400 nm wide strip waveguide by evanescent coupling.

Mode mismatch losses between the lensed fiber and the chip facet are calculated using (1) in the same way. The mode electric field distribution at the coupler facet is calculated using a fully vectorial mode solver. At this design step, the SWG tip is treated as a homogeneous medium. As shown in Fig. 9(a) and (b), the mode $n_{eff}$ and the mode mismatch 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 strip waveguide mode will be 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 [Fig. 9(c) and (d)]. Similarly, the tip width will affect the mode propagation and mode conversion.

Mode mismatch losses between the lensed fiber and the chip facet are calculated using (1) in the same way. The mode electric field distribution at the coupler facet is calculated using a fully vectorial mode solver. At this design step, the SWG tip is treated as a homogeneous medium. As shown in Fig. 9(a) and (b), the mode $n_{eff}$ and the mode mismatch 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 strip waveguide mode will be 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 [Fig. 9(c) and (d)]. Similarly, the tip width will affect the mode propagation and mode conversion.

The influence of the tip width and gap [$w$ and $G$ in Fig. 8(a)] on coupling loss is studied. The optimal coupling performance is found to be 0.5 dB at the gap of 1.2 $\mu$m and the tip width of 140 nm (Fig. 10), which is 0.35 dB less than the fork2 coupler. The simulated coupling loss is no more than 0.6 dB from 1507 nm to 1628 nm, and the fluctuation is only 0.1 dB (Fig. 12), which is more stable compared with fork2 coupler. Notably, the losses are all less than 1 dB while the tip width varying from...
Fig. 12. The simulated and measured coupling losses for dual-trident SWG edge coupler. The inset means the loss is below 2 dB from 1536 nm to 1628 nm.

Fig. 13. The simulated coupling losses of the dual-trident SWG edge coupler in the O band with the wavelength from 1260 nm to 1360 nm.

40 nm to 200 nm, which indicates a much higher fabrication tolerance.

**B. Fabrication and Measurement**

The fabrication process is the same as the fork shape edge couplers on the SOI platform. The SEM pictures of the fabricated planar dual-trident SWG edge coupler is shown in Fig. 11. It is worth mentioning again that the eased fabrication process is a competitive advantage compared to other structures. The setup for measurement is also the same as used for the fork shape edge coupler.

Fig. 12 shows the simulated and experimentally measured spectra of the coupling loss. The simulated loss at 1.55 μm is 0.5 dB and the minimum loss is 0.48 dB at 1566 nm with the fluctuation of only 0.1 dB over a 121 nm range. The measured loss is 1.82 dB/facet at 1.55 μm, and the minimum loss is 1.59 dB/facet at 1581 nm. From 1536 nm to 1628 nm, the coupling loss is less than 2 dB/facet, means the 2-dB bandwidth is 92 nm.

The deviation between the maximum loss minimum loss is only 0.4 dB, which displays the independence of wavelength. The difference between the simulated and measured results may be mainly induced by the fabrication and test errors.

Fig. 13 presents the simulated loss of the dual-trident SWG edge coupler in the O band. Compared to the C band, the coupling loss increases observably. The loss is 3.36 dB at the wavelength of 1310 nm. This higher loss may restrict the application of dual-trident SWG edge coupler in the O band.

Table I gives the comparison of the coupling performance and fabrication difficulty of edge coupler. The first three lines represent the three couplers proposed in this paper. The losses were measured at 1550 nm.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Loss (dB)</th>
<th>Bandwidth (nm)</th>
<th>Fluctuation (dB)</th>
<th>Fiber MFD</th>
<th>Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fork1</td>
<td>1.25</td>
<td>114</td>
<td>1</td>
<td>6</td>
<td>SOI, Planar</td>
</tr>
<tr>
<td>Fork2</td>
<td>1.49</td>
<td>102</td>
<td>1.23</td>
<td>6</td>
<td>SOI, Planar</td>
</tr>
<tr>
<td>Dual-Trident SWG</td>
<td>1.82</td>
<td>92</td>
<td>0.4</td>
<td>6</td>
<td>SOI, Planar</td>
</tr>
<tr>
<td>Taper [9]</td>
<td>6</td>
<td>NA</td>
<td>NA</td>
<td>5</td>
<td>SOI, Planar</td>
</tr>
<tr>
<td>Taper [11]</td>
<td>1.7</td>
<td>40</td>
<td>1.5</td>
<td>5</td>
<td>SOI, Biaxial taper</td>
</tr>
<tr>
<td>Double-slot [21]</td>
<td>1.8</td>
<td>70</td>
<td>0.4</td>
<td>2.5</td>
<td>SOI, Planar</td>
</tr>
<tr>
<td>Cantilever [15]</td>
<td>1.6</td>
<td>60</td>
<td>1.6</td>
<td>1.5</td>
<td>Suspended, bent</td>
</tr>
<tr>
<td>SWG-trident[26]</td>
<td>1.5</td>
<td>50</td>
<td>0.2</td>
<td>4</td>
<td>SOI, Planar</td>
</tr>
<tr>
<td>Double-tip [20]</td>
<td>1.1</td>
<td>150</td>
<td>0.3</td>
<td>3.3</td>
<td>SOI, Planar</td>
</tr>
</tbody>
</table>

IV. CONCLUSION

Three kinds of edge coupler structures, two fork shape and one dual-trident SWG shape, are theoretically studied and experimentally demonstrated. These edge couplers show low coupling losses and possess large bandwidths simultaneously. At 1.55 μm, the coupling losses are 1.25 dB/facet, 1.49 dB/facet, 1.82 dB/facet for fork1, fork2 and dual-trident SWG edge couplers, respectively. The minimum losses are 1 dB/facet, 0.7 dB/facet and 1.59 dB/facet, respectively. The 2-dB bandwidths are 114 nm, 102 nm, 92 nm, separately. The loss deviation of the dual-trident SWG coupler is only 0.4 dB from 1536 nm to 1628 nm, which shows low wavelength dependence. According to the simulation, these three designs all have pros and cons in different application scenarios. The fork1 structure is the simplest and the most straightforward design but sensitive to the slot width. The fork2 coupler shows a little higher loss, but the loss is independent on the slot width. The fork1 and fork2 edge couplers can also be used in the O band. The dual-trident SWG coupler presents significantly high loss in the O band, but shows a better coupling performance in the C band compared to the fork1 and fork2 couplers. We believe these low-loss, large bandwidth edge couplers with eased fabrication process are desirable and complete in silicon photonics.
REFERENCES


An He received the B.S. degree in applied physics from the Suzhou University of Science and Technology, in 2015 and the master’s degree from Wenzhou University, in 2018. In 2018, he joined Shanghai Jiao Tong University as a Doctoral Student. His research interests include silicon photonics devices and heterogeneously integrated silicon lasers.

Xuhan Guo received the B.S. degree from the Huazhong University of Science and Technology, Wuhan, China in 2009 and the Ph.D. degree from the University of Cambridge, Cambridge, UK in 2014. He has worked as a Research Associate at the University of Cambridge until 2017, then he moved to Shanghai Jiao Tong University, China, where he is currently an Associate Professor of photonics. He is the author or co-author of more than 30 publications. His current research interests include hybrid silicon lasers, silicon photonics devices and circuit, and PON. He also serves as a TPC member of a number of international conferences including ECOC (2018–), CLEO Pacic Rims (2018–), IEEE GPP (2019–), IEEE GLOBECOM (2016–2017), the Secretary (2018–) of IEEE Photonics Society Shanghai chapter ECIO (2010). Dr. Guo is a member of IEEE and a member of OSA.

Kangnian Wang received the B.S. Degree in applied physics from the Nanjing University of Posts and Telecommunications in 2017. In September 2017, he joined Shanghai Jiao Tong University as a Postgraduate student.

Yong Zhang received the B.S. degree from Northwestern Polytechnical University, Xi’an, China, in 2010, and the Ph.D. degree from the Huazhong University of Science and Technology, Wuhan, China, in 2015. He joined Shanghai Jiao Tong University, Shanghai, China, as a Research Faculty Member in July 2015. His research interests include Silicon Photonics Devices and Circuit, Microcavity Devices, E-beam Lithography, and ICP etching process.

Yikai Su received the B.S. degree from the Hefei University of Technology, China, in 1991, the M.S. degree from the Beijing University of Aeronautics and Astronautics (BUAA), China, in 1994, and the Ph.D. degree in EE from Northwestern University, Evanston, IL, USA in 2001. He worked at Crawford Hill Laboratory of Bell Laboratories before he joined the Shanghai Jiao Tong University, Shanghai, China, as a Full Professor in 2004. His research areas cover silicon photonic devices for information transmission and switching. He has over 400 publications in international journals and conferences, with more than 3700 citations (scopus search). He holds 6 US patents and ~50 Chinese patents. Prof. Su served as an associate editor of APL Photonics (2016-2019) and Photonics Research (2013-2018), a topical editor of Optics Letters (2008-2014), a guest editor of IEEE JSTQE (2008/2011), and a feature editor of Applied Optics (2008). He is the chair of ACP 2012, a TPC co-chair of ACP 2011 and APCC 2009. Prof. Su is a senior member of IEEE and a member of OSA.