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

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***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 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 bandwidths 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 SiO_2 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 SiO_2 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

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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 the wavelength of 1596 nm. 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.

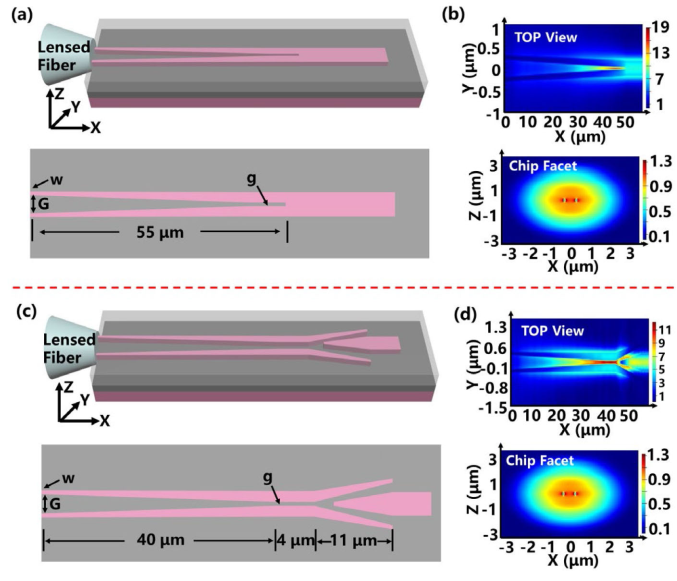

Fig. 1. The structure schematics and the electric field distribution of the (a, b) fork1 and (c, d) fork2 edge couplers, respectively.

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]:

$$\text{Overlap} = \frac{\left|\int E_1 E_2 dA\right|^2}{\int |E_1|^2 dA \int |E_2|^2 dA} \tag{1}$$

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.

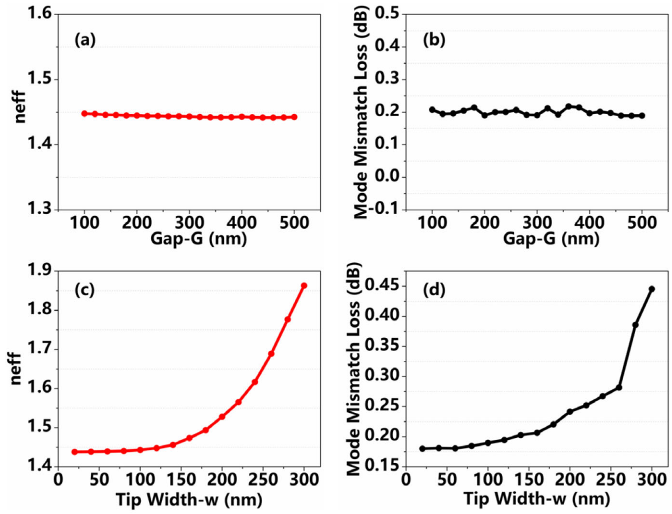

Fig. 2. The effective indexes and mode mismatch losses from an optical fiber to the fork1 edge coupler vs. (a, b) gap and (c, d) tip width, at 1550 nm.

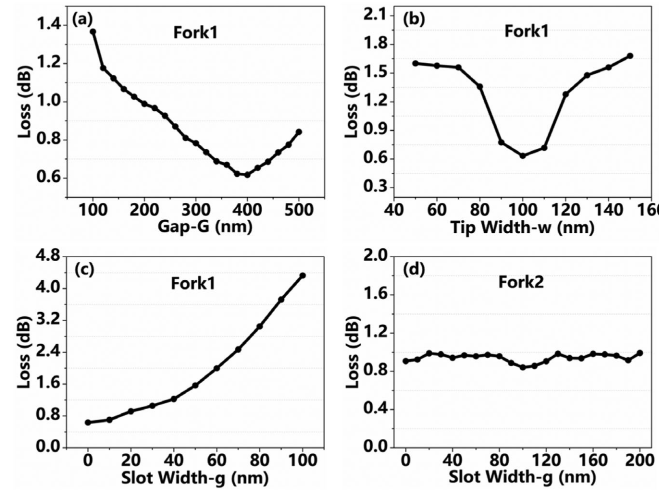

Fig. 3. The simulated fabrication tolerance of the fork shape edge couplers at the wavelength of 1550 nm. (a-c) The influences of gap, tip width and slot width on the coupling loss for the fork1 structure. (d) The influences of the slot width on the coupling loss for the fork2 structure.

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 in Fig. 1), are theoretically analyzed and optimized by the 3D-FDTD simulation.

Mode mismatch losses between the 6 μm 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 (neff) 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 neff 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 μm. 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)], which can be easily fabricated by the CMOS process. However, according to the simulation, the loss depends on the slot width (g) heavily, the loss increases as the g increases [Fig. 3(c)]. The optimal slot width is 0 nm, but this structure is scarcely possible for the fabrication. The loss reaches 2 dB when the slot width is 60 nm, which may still cause the low yield in the fabrication, so there will be a compromise.

Hence, to efficiently convert the light from wider slot waveguide to the strip waveguide, an eased fabrication of slot-to-strip mode converter should be added. Based on the analysis of the fork1 edge coupler and considering the fabrication tolerance, an improved fork shape edge coupler (fork 2) is proposed [Fig. 1(c)]. The tip width (w) and the gap (G) are 100 nm and 400 nm which are the same as fork1, the length of the two tapers is 40 μm, which converter the light from the facet to the 4 μm long slot waveguide. Finally, the light is transferred into a 600 nm wide strip waveguide through the slot-to-strip mode converter [27]. The fork2 edge coupler improves the fabrication tolerance of the slot width (g). As shown in Fig. 3(d), the coupling losses are all below 1 dB with the slot width increasing from 0 nm to 200 nm. And the fluctuation between the maximum and minimum losses is only 0.2 dB. In the design layout, the slot width is set as 100 nm.

B. Fabrication and Measurement

The structures of the proposed edge couplers are fabricated on an SOI wafer with the top silicon layer thickness of 220 nm and the buried SiO_2 layer thickness of 3-μm. Based on the E-beam lithography (EBL) process, the coupler structures are firstly defined on an E-beam photoresist layer (ZEP-520). Following the EBL process, to transfer the structures onto the silicon layer, the top silicon layer is etched utilizing an inductively coupled plasma (ICP) etching process. Then, the E-beam photoresist is removed. Finally, a 2-μm-thick SiO_2 cladding layer is deposited by plasma enhanced chemical vapor deposition (PECVD). The eased fabrication process of single EBL and ICP etching is of great feasibility and repeatability. Fig. 4 exhibits the SEM pictures of the fabricated fork1 and fork2 edge couplers.

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 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

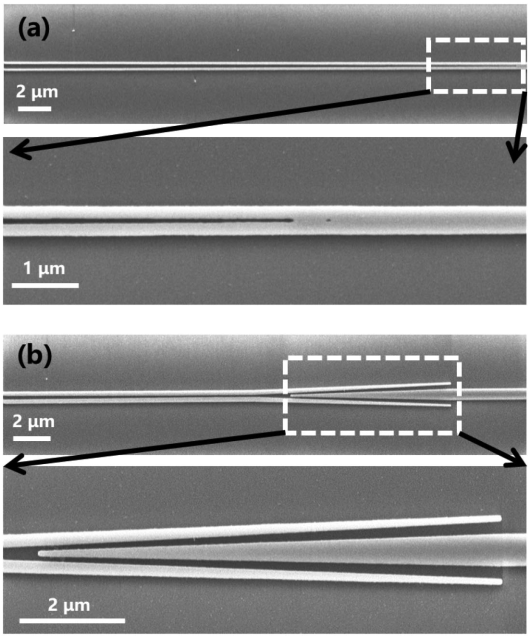

Fig. 4. The SEM pictures of the fabricated fork1 and fork2 edge couplers.

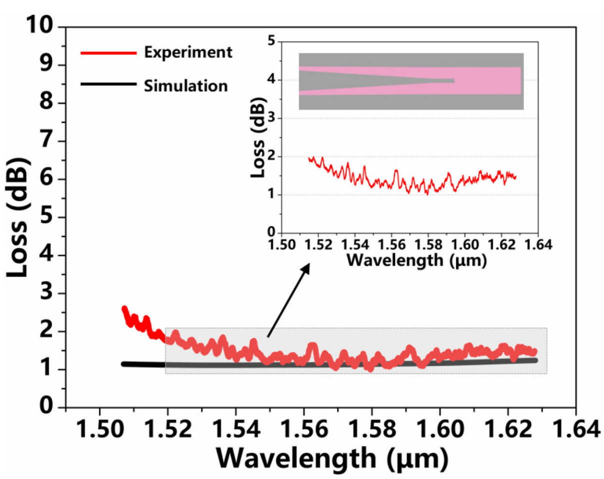

Fig. 5. The simulated and measured coupling losses for fork1 edge coupler. The inset means the loss is below 2 dB from 1514 nm to 1628 nm.

output. Input and output lensed optical fibers with MFD of 6 μm are utilized. For the silicon strip waveguide, the linear propagating loss is 3.6 dB/cm. The measured spectra of the fork1 edge coupler is shown in Fig. 5. The minimum slot width in the design layout is 0 nm, but due to the deviation of the fabrication, the fabricated slot width is characterized as 40 nm [Fig. 4(a)]. The spectra look slightly noisy due to reflection introduced at fiber/chip interface and the oscillation of testing platform. At the wavelength of 1.55 μm, the measured loss is 1.25 dB/facet. The minimum loss is 1 dB/facet, appearing at 1579 nm. As shown in the inset in Fig. 5, the loss is below 2 dB/facet from 1514 nm to 1628 nm, indicating a wide bandwidth of 114 nm. Compared with the simulation, higher losses in the short wavelength range and slight fluctuations are observed in the measured spectra,

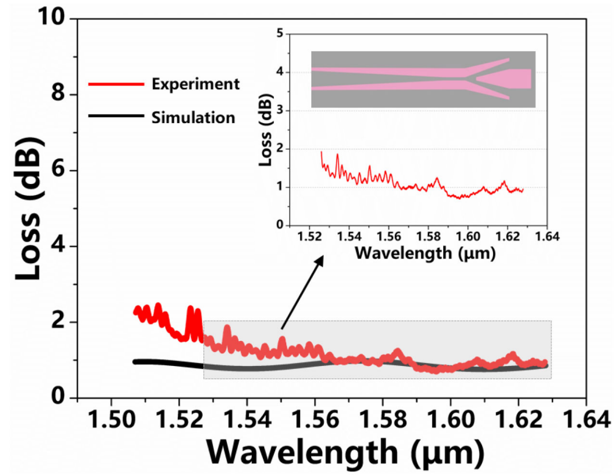

Fig. 6. The simulated and measured coupling losses for fork2 edge coupler. The inset means the loss is below 2 dB from 1526 nm to 1628 nm.

which may be attributed to the imperfections introduced by the fabrication and measurement.

Fig. 6 demonstrates the measured coupling loss of the fork2 edge coupler. The ripples of the spectra are mainly due to the oscillation caused by the fabrication deviation and measurement. The minimum feature structure is characterized to be about 100 nm [Fig. 4(b)], which is of great feasibility and repeatability margin in the fabrication. The measured loss is 1.49 dB/facet at the wavelength of 1.55 μm. The minimum loss is 0.7 dB/facet at 1596 nm. The 2-dB bandwidth is 102 nm, from 1526 nm to 1628 nm, as shown in the inset in Fig. 6. The experimental results agree well with the simulation results.

Higher speed datacom applications in Si photonics bending toward the O-band are emerging as the current tendency in the industry to tackle the ever-increasing demand in terms of data rates and capacity. Due to the limitation of the laser wavelength range in our equipment, the experimentally measured loss cannot be obtained for the O band, but the simulation results are demonstrated in Fig. 7. The coupling losses of fork1 and for2 edge coupler at 1310 nm are 1.51 dB and 1.60 dB, respectively. These reasonable low losses mean that the fork1 and fork2 edge coupler can be applied in the O band.

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.

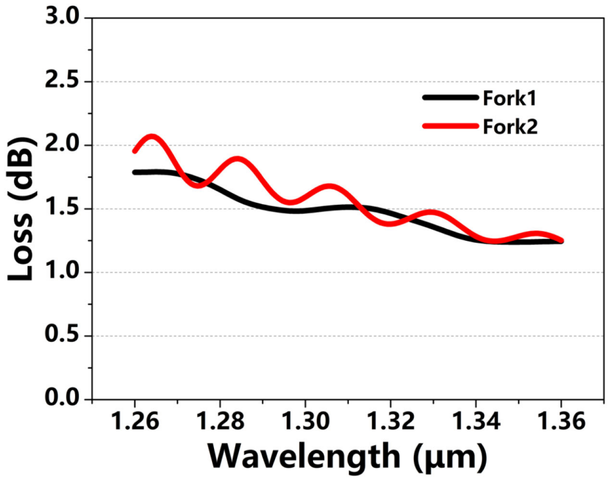

Fig. 7. The simulated coupling losses for fork1 and fork2 edge coupler in the O band with the wavelength from 1260 nm to 1360 nm.

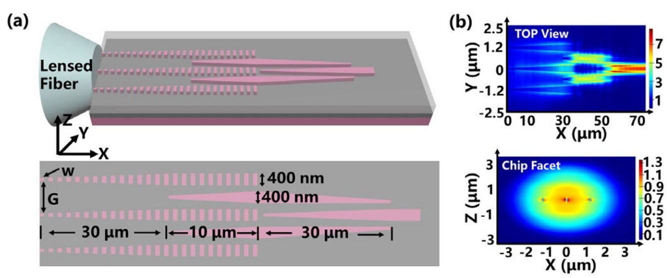

Fig. 8. The (a) structure schematics and the (b) electric field distribution of the dual-trident SWG edge couplers.

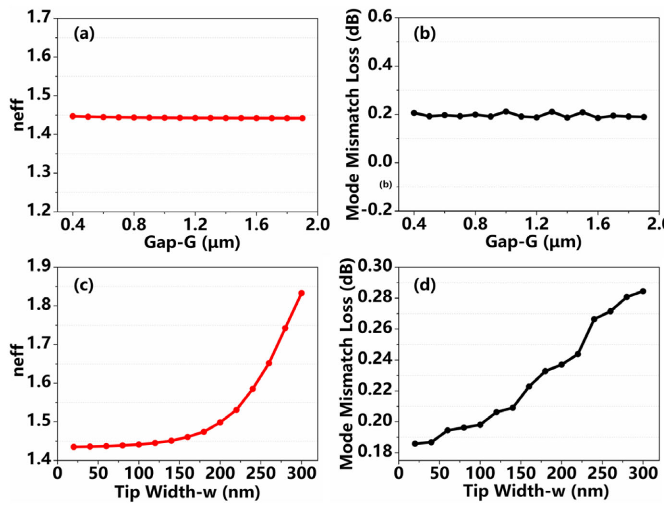

Fig. 9. The effective indexes and mode mismatch losses from an optical fiber to the dual-trident SWG edge coupler vs. (a, b) gap and (c, d) tip width.

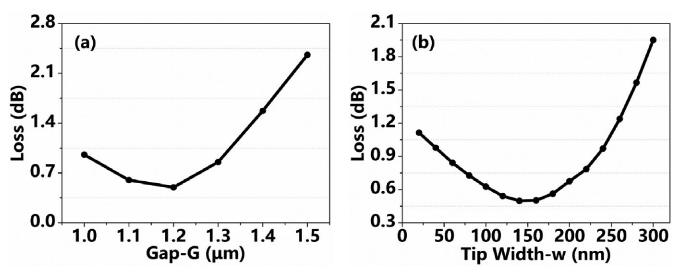

Fig. 10. The simulated fabrication tolerance of the dual-trident SWG edge couplers at the wavelength of 1550 nm. The influences of (a) gap and (b) tip width on the coupling loss.

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 vectoral 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 neff 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 neff 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.

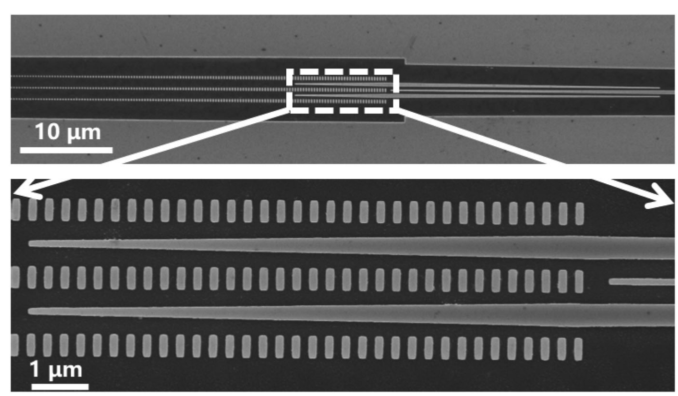

Fig. 11. The SEM pictures of the fabricated dual-trident SWG edge coupler.

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 μm 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

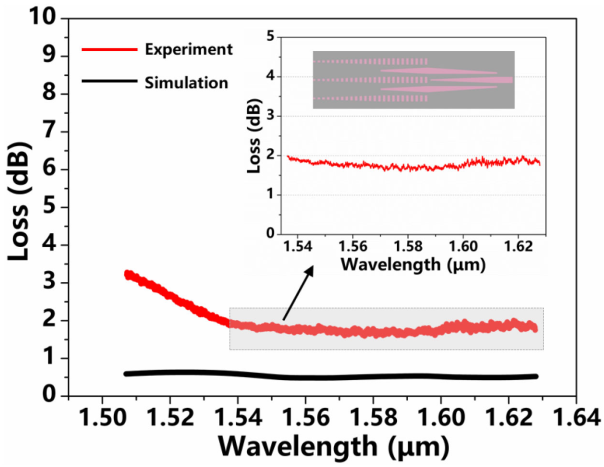

Fig. 12. The simulated and measured coupling losses for dual-trident SWG edge coupler. The inset means the loss is below 2 dB from 1536 nm to 1628 nm.

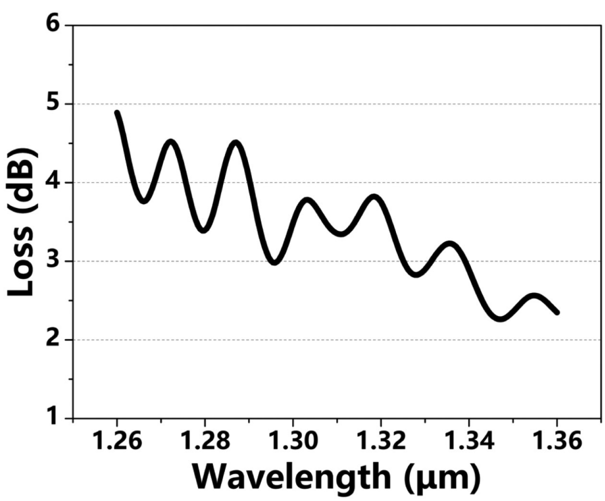

Fig. 13. The simulated coupling losses of the dual-trident SWG edge coupler in the O band with the wavelength from 1260 nm to 1360 nm.

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.

TABLE I
COMPARISON OF THE COUPLING PERFORMANCE AND THE FABRICATION DIFFICULTY OF EDGE COUPLER. THE FIRST THREE LINES REPRESENT THE THREE COUPLERS PROPOSED IN THIS PAPER. THE LOSSES WERE MEASURED AT 1550 NM

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

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 between the proposed edge couplers in this paper and other structures. Our proposed edge couplers own greater superiority in the bandwidth and eased fabrication process, while the coupling loss is not compromised.

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 completive in silicon photonics.

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