

# Ultracompact Fiber-to-Chip Metamaterial Edge Coupler

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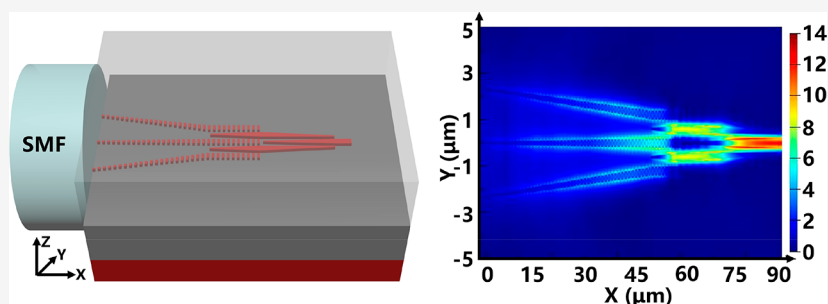
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**ABSTRACT:** Compact fiber-to-chip light coupling with low loss and large bandwidth, SMF-to-chip edge coupler in particular, is extensively demanded in integrated photonics. The inescapable challenge of edge coupler is the difficulty and complexity in fabrication and packaging. During the past decades, metamaterials have manifested marvelous talent in integrated photonics. Here, we experimentally demonstrate an ultracompact edge coupler via metamaterial for SMF with a mode field diameter of  $10\ \mu\text{m}$ , which is fully based on silicon-on-insulator material and a CMOS compatible fabrication process. In this work, we theoretically analyze the coupling performance and the fabrication difficulty. The experimental results show that this metamaterial-based coupler possesses low coupling loss and broad bandwidth simultaneously with the coupling length of only  $90\ \mu\text{m}$ . At  $1550\ \text{nm}$ , the coupling losses are  $2.22/2.53\ \text{dB/facet}$  for the fundamental TE/TM mode, while the minimum average loss could reach  $1.81\ \text{dB/facet}$ . The measured bandwidth with a loss below  $3\ \text{dB}$  is as broad as  $120\ \text{nm}$ , covering the entire C/L band. Moreover, this prominently eased fabrication process potentially exhibits significant superiority in both research and industrial applications.

**KEYWORDS:** silicon photonics, integrated photonics, edge coupler, metamaterial

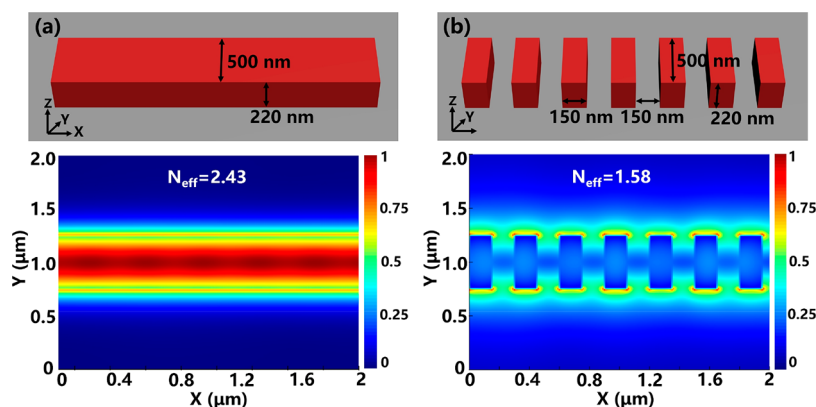
The tremendous technological advancements of 5G telecommunication, cloud services, and artificial intelligence are revolutionizing the lifestyle and the data exchange over networks. The capability of the data processing of the data center is confronted with unprecedented challenges. The silicon (Si)-based integrated circuits, benefiting from their various merits, including low cost, high integration density, large bandwidth, energy efficiency, and complementary metal-oxide-semiconductor (CMOS) compatibility, have attracted increasing attention from the scientific research community and industry.<sup>1–3</sup> Optical interconnect for transmitting light is significant in Si photonic integrated circuits (PICs), and the optical coupling between fiber and chip is vital in data centers and optical transmission systems. Off-plane grating coupling and in-plane edge coupling are the main two schemes to accomplish the fiber-to-chip optical coupling.<sup>4,5</sup> Relatively, the grating coupling is a common solution; however, the unavoidable drawbacks caused by their inherent diffractive characteristics produce several limitations in application. The loss is high, the bandwidth is narrow, and the polarization dependence generates a considerable cost in transmission efficiency. Fiber-to-chip edge couplers provide an accommodation of the mode field size between the fiber and the edge facet of Si-on-insulator (SOI) chip, thus, improving coupling

efficiency, enlarging the bandwidth, and substantially reducing the polarization dependence.

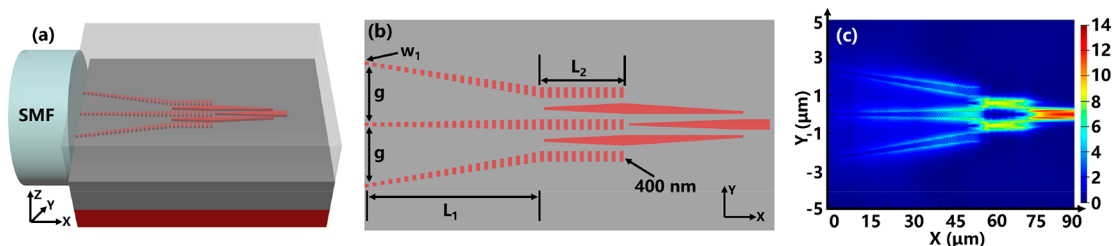
The low loss fiber-to-chip optical edge coupling is usually realized between a lensed fiber and an SOI chip, profiting from the small fiber mode field (less than  $2\ \mu\text{m}$ ).<sup>6–8</sup> But the alignment difficulty of the high-cost lensed fiber itself arises from obstruction in the practical application. Efficient optical coupling between a standard single-mode fiber (SMF) and nanophotonic waveguides based on the SOI platform is strongly desired.

Sanchis et al. have demonstrated a  $130\ \mu\text{m}$  long parabolic inverse taper to couple an SMF with a mode field diameter (MFD) of  $8.2\ \mu\text{m}$  to an SOI chip.<sup>9</sup> The coupling loss is  $2\ \text{dB}$  for the TE mode, with the  $60\ \text{nm}$   $3\ \text{dB}$  bandwidth in the O band. This structure demands two air trenches, requiring excessive deep etching in order to assist the light coupling and

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**Figure 1.** Contrast of  $N_{\text{eff}}$  and mode field distribution between strip and SWG-metamaterial Si waveguides. The width and thickness of these two waveguides are both 500 and 220 nm, respectively.



**Figure 2.** Structure of the SWG metamaterial edge coupler: (a) 3D view, (b) top view, and (c) the electric field distribution.

transmission. Shi et al. reported an arrayed waveguide with four tips to achieve a 1.7 dB coupling loss for the  $\text{TM}_0$  mode between an SMF and SOI-based chip.<sup>10</sup> The 3 dB bandwidth is 64 nm at the C-band. But the cladding layer is 10  $\mu\text{m}$  thick SU-8, which lacks robustness in the highly integrated domain. In addition, the length of this coupler is 1200  $\mu\text{m}$ , which is not competitive for an exorbitant chip. Tummidi et al. demonstrated a 500  $\mu\text{m}$  long multilayer  $\text{Si}_3\text{N}_4$  coupler, while the loss is below 1 dB with the assistance of matching oil.<sup>11</sup> Maegami et al. also utilized the  $\text{Si}_3\text{N}_4$  waveguide to couple the light from an SMF to a Si waveguide.<sup>6</sup> The length of the coupler is 300  $\mu\text{m}$ , with a coupling loss of 2.9/2.1 dB for the TE/TM mode, which helps with the matching oil.

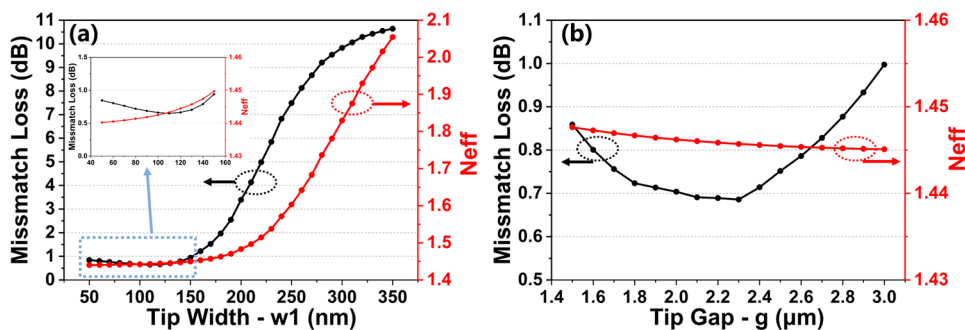
In recent years, metamaterial Si structures have drawn significant attention in the development of highly compact edge couplers. The optical properties of metamaterials considerably exceed the parameter freedom accessed from natural materials, which has been stimulating strong research enthusiasm in nanophotonics. In particular, Si has arisen as a widely employed material choice not only due to the low absorption loss and high refractive index in the communication spectral range, but also due to the principal technological relevance.<sup>12–14</sup> By virtue of the engineering of the refractive index, the metamaterial waveguide initiates a new occasion in device design and optimization. Despite the additional structure complexity, the index contrast can be effectively reduced by creating a metamaterial Si waveguide, thus, the fabrication tolerances of metamaterial structures are comparatively high in contrast to conventional Si tapers.

Barwicz et al. demonstrated the first O-band metamaterial edge coupler between a nanophotonic waveguide and an SMF.<sup>15</sup> The coupler consists of three taper structures, a metamaterial taper, a hybrid taper, and a solid waveguide taper, suspended above an undercut region. The peak transmission efficiency is 1.3 dB. Cheben et al. utilized a subwavelength

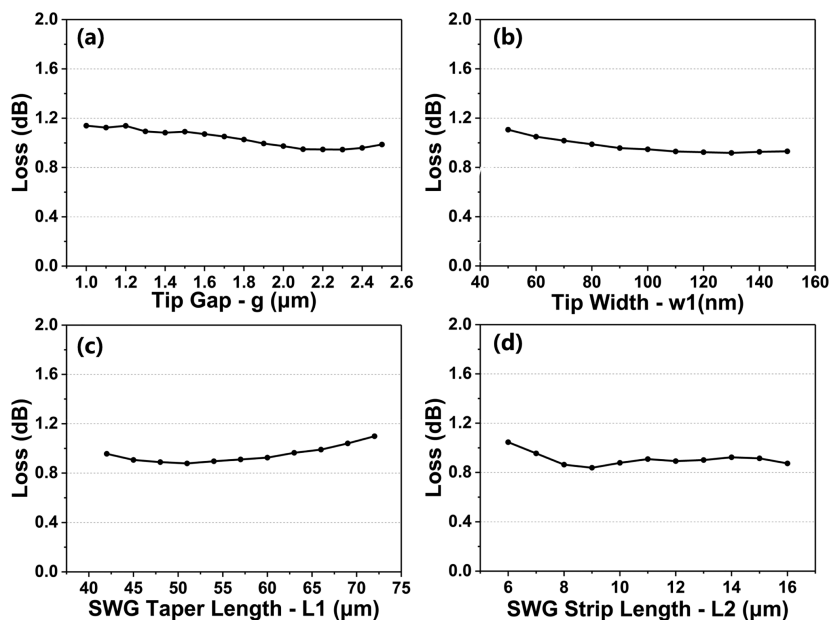
grating (SWG) metamaterial to engineer the refractive index, enabling a 0.32 dB loss from a lensed fiber with 3.2  $\mu\text{m}$  MFD to the SOI chip.<sup>16</sup> Qi et al. proposed a trident-shaped edge coupler based on metamaterial structure.<sup>13</sup> Experiments show that the loss over the C band with a 2.5  $\mu\text{m}$  MFD fiber is less than 2 dB/facet. Peng et al. proposed a metamaterial edge coupler with the measured loss of 1.3/1.5 dB for the TE/TM mode,<sup>17</sup> but this structure needs a more intricate process, while the Si coupler is required to be suspended with a V-groove at the chip facet.

Employing the bilayers and suspended schemes, the coupling efficiency can be distinctly improved. However, the excrement complexity and difficulty create an enormous challenge in the fabrication and packaging, especially in a standard CMOS foundry.<sup>18–21</sup> By combining an intermediate polymer material and a single layer Si inverse taper can also achieve acceptable coupling performance, but owing to the physical boundedness of the polymer itself (reliability, robustness, integration difficulty, etc.), this scheme has not realized extensively application. Therefore, continuing the design and optimization of edge coupling to achieve decent performance and eased fabrication remains challenging.

In this work, to achieve the excellent performance of loss, bandwidth, compactness, and fabrication, we experimentally propose a SWG metamaterial edge coupler, which is fully based on the standard fabrication process on an SOI platform. The coupler is fabricated by a single step of e-beam lithography (EBL) and inductively coupled plasma-reactive ion etching (ICP-RIE) process. The coupling loss between the SMF and SOI chip can reach 2.22 dB/facet at 1550 nm, the bandwidth with the loss of no more than 3 dB is as broad as 120 nm. To notice, the total length of the edge coupler is below 90  $\mu\text{m}$  and fully compatible with the CMOS process, which can be further implemented in highly integrated PICs.



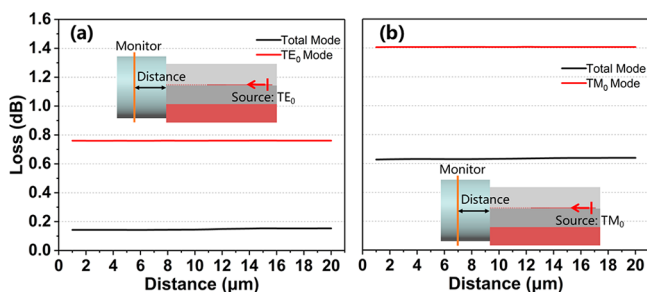
**Figure 3.** Effect of (a) tip width and (b) tip gap on the losses induced by a mode mismatch between SMF and the metamaterial edge coupler; the wavelength is 1550 nm. The inset represents the tip width from 50 to 150 nm.



**Figure 4.** Fabrication tolerance of the (a) tip gap, (b) tip width, (c) SWG taper length, and (d) SWG strip length; the wavelength is 1550 nm.

## DESIGN AND SIMULATION

In the past few years, metamaterials have been implemented in optical components and integrated systems with the capability



**Figure 5.** Loss from the SOI chip to SMF with the light source of (a)  $\text{TE}_0$  and (b)  $\text{TM}_0$  mode.

of transcending those conventional photonic devices. SWGs are sometimes referred to as metamaterial waveguides. Typically, SWG-metamaterials optical elements are subwavelength scale, exhibiting planar configuration, while can be fabricated in batch using the standard micronano fabrication processes at potentially low cost.<sup>14,22,23</sup> In contrast with a conventional strip waveguide, the effective refractive index

( $N_{\text{eff}}$ ) of the SWG-metamaterial waveguide can be effectively engineered by simply controlling the duty cycle and waveguide width. As shown in Figure 1, the  $N_{\text{eff}}$  of the 500 nm wide and 200 nm thick strip Si waveguide is 2.43, as the mode field is mainly confined in the waveguide. However, for the SWG waveguide with the same width, the  $N_{\text{eff}}$  is only 1.58 due to the mode field distribution being more capacious. Moreover, these two momentous properties for the coupling between the fiber and the chip can be effectively regulated. Increasing the tip number of the edge couplers often makes improvements to the coupling performance. Hence, in consideration of the stringent requirement of performance and fabrication, edge couplers with multitips such as fork shape and trident shape are proposed.<sup>13,24–27</sup> Except for the tip width, a new design freedom, the distance between tips and waveguides can also optimize the mode field distribution to improve the coupling performance.

The mode field area of a single mode Si waveguide is normally 100 $\times$  smaller than that of SMF. When an optical mode enters the SOI waveguide, the huge mode mismatching between the fiber and waveguide creates the radiation mode and some scattering loss. The difference of the  $N_{\text{eff}}$  causes the reflection loss. Enhancing the spatial mode overlap of the fiber and waveguide can effectively stimulate the SOI waveguide mode. When light enters an SOI chip from an SMF, the light

preferentially expands into the chip facet with optimal modal overlap, then transfers into the connecting strip waveguide adiabatically. Thus, the mode overlap (mode mismatch) determines the coupling performance predominantly. The overlap between two modes is defined as<sup>28</sup>

$$\text{overlap} = \frac{\left| \int E_1 E_2 \, dA \right|^2}{\int |E_1|^2 \, dA \int |E_2|^2 \, dA} \quad (1)$$

where  $E_1$  is the complex electric field amplitude of the fiber mode, and  $E_2$  is the complex electric field amplitude of the chip facet mode. To achieve the optimum coupling performance, the mode field at the SOI chip facet should overlap the mode field in fiber at full steam.

The structure of the proposed SWG metamaterial edge coupler is illustrated in Figure 2. The coupler is composed of three sections. The first section is the SWG metamaterial; the width of the Si block increases along the light propagation direction. The period of the SWG metamaterial part is set as 300 nm, and the duty cycle is 0.5. Connected to section 1 is the second section, three SWG strip waveguides, guiding light into the two solid tapers. Finally, the beam evanescently transforms into the strip waveguide with a 400 nm width through the third section (Figure 2c). By using the metamaterial, the planar coupler structure is realized, which tremendously simplified the fabrication process. Four main parameters, the gap, tip width, meta-taper length, and SWG strip length ( $g$ ,  $w_1$ ,  $L_1$ , and  $L_2$  in Figure 2b), are analyzed in theory and optimized by the Lumerical 3D-FDTD.

The mismatch losses of the modes between SMF and the chip facet are analyzed using eq 1. The fully vectorial mode solver is used to calculate the mode electric field distribution. In this condition, the tip section of the SWG-metamaterial is regarded as a uniform medium. In Figure 3a, the increment of the tip width from 50 to 350 nm, meaning the increasing of  $N_{\text{eff}}$  at the chip facet (red line), causes the increased loss induced from a mode mismatch (black line). But in the range from 50 to 150 nm the deviation can be neglected; this can be confirmed from the FDTD simulation (Figure 4b).

The effect of the tip gap between two meta-taper tips at the facet is demonstrated in Figure 3b; the gap barely changes the mode  $N_{\text{eff}}$  (red line) and the mode mismatch loss (black line). However, during the mode propagation and conversion from the chip facet, through metamaterial structure, to the strip waveguide, the gap will cause more influence on the loss.

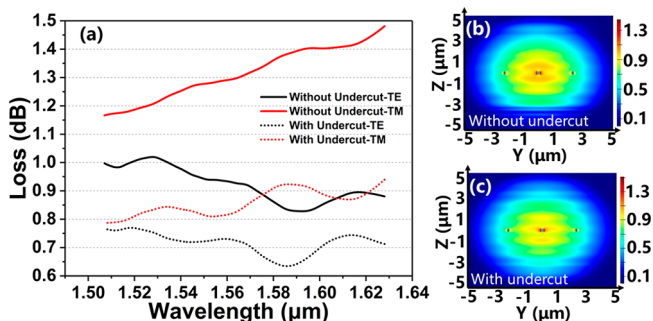
The influences of the tip gap, tip width, meta-taper length, and SWG strip length on coupling loss and mode conversion loss are studied by FDTD. The simulated results are shown in Figure 4. The optimal loss is 0.92 dB with a 2.3  $\mu\text{m}$  gap and 130 nm tip width. The meta-taper and SWG strip lengths are set as 50 and 9  $\mu\text{m}$ , respectively. The total length of this SWG metamaterial edge coupler is set as 90  $\mu\text{m}$ . Notably, the loss fluctuation is only 0.18 dB with the variation of the tip width from 50 to 150 nm, indicating a relaxed fabrication tolerance.

The situation of the light transmission from the SOI waveguide to SMF is also analyzed. As shown in Figure 5, in the simulation settings, the  $\text{TE}_0/\text{TM}_0$  light sources are put in the waveguide. The monitors are set in the SMF, with different distances from the chip facet, to collect the light from the SOI chip. During the transmission, the light will go through the metamaterial coupler and then transformation from chip to fiber, a portion of the fundamental TE/TM modes transform

into other mode lights, which are also collected by the monitor. Thereby, the loss of the total mode is smaller than the pure  $\text{TE}_0/\text{TM}_0$  mode. Moreover, the loss with the source of  $\text{TM}_0$  mode is higher than that with the  $\text{TE}_0$  source.

## ■ SUBSTRATE LEAKAGE AND CLADDING

One of the superiorities of our proposed metamaterial coupler is the simplified fabrication process, especially avoiding the



**Figure 6.** Influence of the substrate Si on the light leakage. (a) The simulated coupling loss of the TE/TM mode with and without the undercut. The mode field at the chip facet (b) without and (c) with an undercut.

complex waveguide suspension process. Many other structures need an air trench or undercut etching to prevent light from leaking into the substrate.<sup>9,18,19</sup> The more complicated fabrication process will be caused by these extra steps. In addition, the cost increase and yield reduction increase obstructs the pursuits of industrial application of high-volume and low-cost production. The undesired loss of the metamaterial-based edge coupler induced from the leakage into the substrate is investigated and quantified by the FDTD simulations.

The simulated results are shown in Figure 6. For the TE mode, compared with the structure with an undercut, the loss of the metamaterial coupler without undercut is only 0.2 dB higher. For the TM mode, this enlargement is about 0.46 dB. Importantly, this increased loss is not originating from the leakage. As observed in Figure 6b, when the undercut is removed, the light is mainly confined in the BOX, top Si, and cladding layers, with a relatively weak field leaking into the substrate. When adding the undercut, the BOX layer is replaced by air; the mode field at the chip facet is more similar to that in the SMF, which cause the reduced coupling loss.

The thickness of the cladding  $\text{SiO}_2$  layer has influence on the coupling performance and fabrication cost. Figure 7 depicts the influence of the cladding layer on coupling losses. The light will leak into air partially with a thin cladding  $\text{SiO}_2$ , causing the relatively high coupling loss. When the thickness is higher than 3.5  $\mu\text{m}$ , a comparatively perfect confinement of light is achieved, and the loss is nearly stable. Thus, considering both the performance and the fabrication, a 3.5  $\mu\text{m}$  thick cladding layer is chosen.

## ■ RESULTS AND DISCUSSION

We fabricate the device at the Center for Advanced Electronic Materials and Devices of Shanghai Jiao Tong University. Figure 8 shows the diced single chip and SEM pictures of the fabricated metamaterial edge coupler (see Supporting Information for the edge facet pictures).

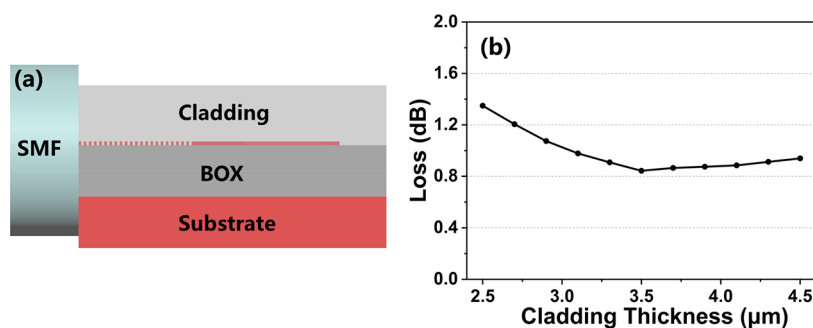


Figure 7. Influence of the cladding layer thickness on the loss of the SWG metamaterial coupler.

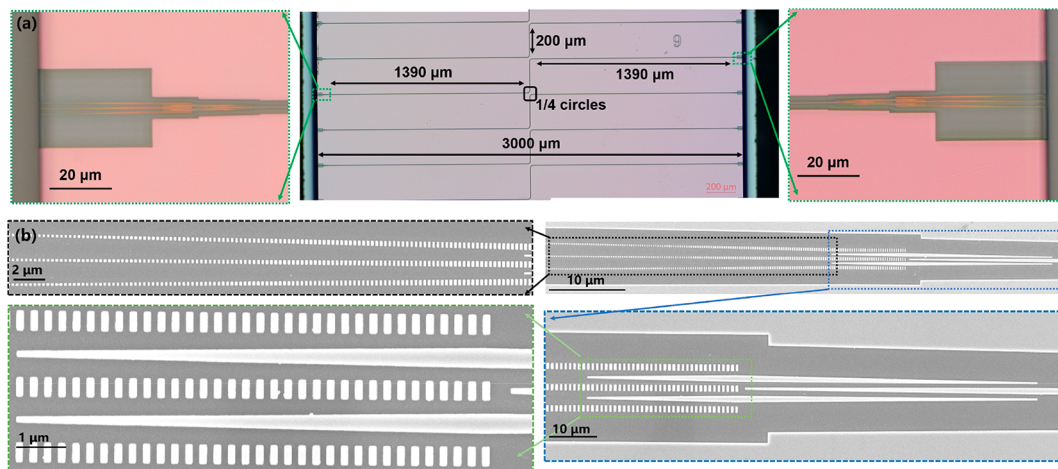


Figure 8. (a) Optical microscope photographs of the diced single chip and (b) the scanning electron microscope photographs of the fabricated SWG metamaterial edge coupler.

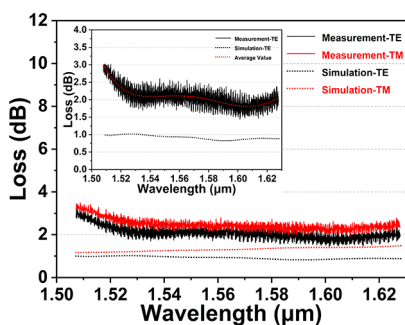


Figure 9. Transmission spectra of the SWG metamaterial edge coupler in simulation and measurement; the inset indicates the spectra of the TE<sub>0</sub> mode.

Table 1. Measured Losses of the Metamaterial Edge Couplers with Different Tip Widths at 1550 nm

tip width $w_1$ (nm)	107	116	126	136
loss (dB)	3.38	2.80	2.22	2.98

The coupling losses in simulation and measurement are shown in Figure 9. The slight ripples in the spectra are caused by the reflection at the interface between fiber and chip and the oscillation of measurement stage. These ripples can be minimized dramatically by the Chemical Mechanical Polishing (CMP) at the chip facet and coating antireflection film on the facet.<sup>20,29–31</sup> Unfortunately, our laboratory is not equipped with CMP equipment, the surface of the edge facet cannot be

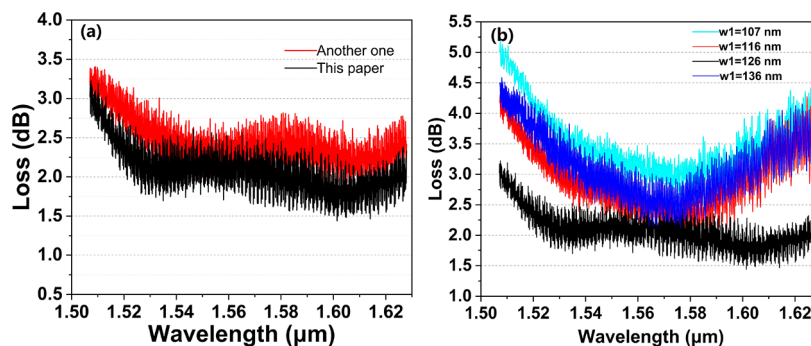


Figure 10. Measured results of the fabrication tolerance. (a) Measured spectra of two couplers with identical structure parameters. (b) Measured spectra of couplers with different tip width.

**Table 2. Comparison of the SWG-Metamaterial Edge Coupler and Other Reported Couplers<sup>a</sup>**

structure	loss (TE/TM; dB)	3 dB bandwidth (nm)	length ( $\mu\text{m}$ )	fabrication
SWG metamaterial single taper <sup>9</sup>	2.22/2.53	120 <sup>b</sup>	90	SOI; planar
taper <sup>11</sup>	2/NA	60	130	parabolic taper; trench
SWG metamaterial <sup>17</sup>	1/1.5	230	500	multiple layer Si <sub>3</sub> N <sub>4</sub> tapers; with matching oil
SWG metamaterial <sup>17</sup>	1.3/1.5	60	NA	metamaterial; undercut; V-groove; with matching oil
multitaper <sup>10</sup>	NA/1.7	64	1200	10 $\mu\text{m}$ thick SU-8 cladding; slot width 30–40 nm
taper <sup>6</sup>	2.9/2.1	NA	>300	SiN on Si; with matching oil

<sup>a</sup>The coupling loss, bandwidth, length of the coupler, and the fabrication complexity are listed. The first line represents the metamaterial coupler in this paper. <sup>b</sup>This bandwidth is limited by the laser source.

improved further. The measured loss is 2.22 dB for TE<sub>0</sub> mode and 2.53 dB for TM<sub>0</sub> mode at 1550 nm, which is polarization independent. As the inset shows, the loss is no more than 3 dB from 1508 to 1628 nm, meaning the 3 dB bandwidth is as wide as 120 nm, covering the whole C and L bands. It should be noted that this bandwidth is limited by the wavelength range of the laser source. The red dot line in the inset represents the average value of the measured coupling loss; the minimum average loss is 1.81 dB at around 1605 nm for the TE<sub>0</sub> mode. The results in simulation and measurement show a difference that may be induced from the fabrication roughness and test errors.

In order to verify the relaxed tolerance in fabrication, two couplers with identical structure parameters are fabricated. The measured results are shown in Figure 10a. For another coupler, the loss at 1550 nm is 2.42 dB, only 0.2 dB higher than the coupler presented in the manuscript. Moreover, Figure 10b presents the measured spectra of couplers with different tip

width, the black line ( $w_1 = 126$  nm) represents the result in Figure 9. The specific loss values at 1550 nm are shown in Table 1. The loss fluctuation is below 0.76 dB with the variation of the tip width being less than  $\pm 10$  nm. It is worth noting that the fabrication accuracy of EBL far exceeds 10 nm. In general, the metamaterial-based edge coupler possesses a high tolerability to the fabrication deviation.

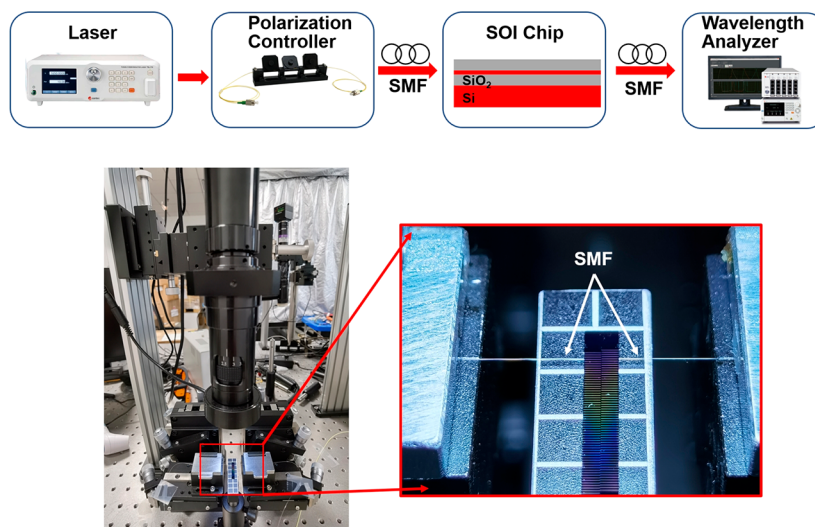
Table 2 gives the main performance and fabrication complexity of the metamaterial-based edge coupler and other reported edge couplers for SMF. The conspicuous superiority of our proposed SWG-metamaterial coupler is the eased fabrication process. Additionally, the coupler is a planar structure and fabricated based on a pure SOI platform without introducing heterogeneous material system. Despite the fabrication process being tremendously evolved, the coupling performance is not sacrificed. Moreover, the compact footprint, 90  $\mu\text{m}$  long, is realized by using the metamaterial structure, remaining a reasonably large bandwidth of 120 nm.

## CONCLUSION

An ultracompact metamaterial edge coupler for SMF with an eased fabrication process is experimentally demonstrated. The edge coupler shows low coupling loss and a large bandwidth simultaneously. At 1550 nm, the coupling loss is 2.22 dB for the TE<sub>0</sub> mode and 2.53 dB for the TM<sub>0</sub> mode, respectively. The minimum average loss is approximately 1.81 dB with a large 3 dB bandwidth of 120 nm, covering the entire C/L band. In addition, the total length of the coupler is only 90  $\mu\text{m}$ , which is an extra extraordinary excellence in the exorbitant PICs. This metamaterial edge coupler veritably evinces superior performance to their counterparts, especially the simplified fabrication, which is an essential step forward toward efficient coupling between the SMF and SOI chips in a large scale. We believe this low-loss and large-bandwidth edge coupler with simplified fabrication is strongly requisite in integrated Si photonics, not just for fiber-to-chip coupling, but also potentially effective for chip-to-chip butt coupling.

## EXPERIMENTAL SECTION

To validate our design method in an experiment, the proposed edge coupler is manufactured on a SOI wafer with a 220 nm



**Figure 11.** Test process and test platform of the edge coupling.

thick top Si layer and a 3  $\mu\text{m}$  thick buried  $\text{SiO}_2$  layer. We fabricate the device at the Center for Advanced Electronic Materials and Devices of Shanghai Jiao Tong University. The coupler and interconnecting waveguide are defined through a single EBL process. A total length of 3043  $\mu\text{m}$  propagation waveguide is designed to connect the input and output couplers. The resist pattern was fully etched using the ICP-RIE process. Subsequently, a 3.5  $\mu\text{m}$  thick  $\text{SiO}_2$  cladding layer is deposited by plasma-enhanced chemical vapor deposition (PECVD) after removing the e-beam photoresist. Then the integral chip is deep etched and finally diced into several separate chips for measurement (Figure S2). Because only one EBL and ICP-RIE process is needed, the fabrication is tremendously simplified, possessing great feasibility and repeatability.

As shown in Figure 11, the performance of the SWG metamaterial edge coupler is characterized by a CW laser (Keysight 81960A), the wavelength range is from 1507 to 1628 nm, which limits the measured bandwidth. The transmission spectra are recorded by the optical power meter (Keysight 81636B). A polarization controller is connected with the laser to control the polarization of input light. Two identical couplers, at the input port and output port, are implemented to realize the light coupling in and out of the chip. The MFDs of the input and output SMFs are 10  $\mu\text{m}$ . The waveguide transmission losses are measured with the cutback method by varying the length of the waveguide, the average transmission loss is estimated as 7.602 dB/cm (Supporting Information, Figure S1 and Table S1). It is worth noting that all of the measurements are performed without the assistance of a refractive index matching oil.

## ■ ASSOCIATED CONTENT

### SI Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsphotonics.1c00993>.

Waveguide transmission loss (Figure S1 and Table S1); Deep etching and dicing of the chip (Figure S2); Pictures of the chip edge facet (Figure S3 and S4); Fabrication tolerance of the etching and dicing (Figure S5) (PDF)

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## Author Contributions

X.G. initiated and directed the work. A.H. conducted the design, fabrication, and measurement. X.G. and T.W. analyzed the experimental data. Y.S. supervised the project. The manuscript was discussed and corrected by all authors.

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## Notes

The authors declare no competing financial interest.

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