Efficient Fiber-to-Slot-Waveguide Grating Couplers Based on a Double-Strip Waveguide

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***Abstract*— We propose and experimentally demonstrate a fiber-to-slot-waveguide grating coupler based on a double-strip waveguide, together with a double-strip-to-slot waveguide mode converter. By employing the double-strip waveguide, we improve the coupling efficiency from a fiber to the slot waveguide by ∼1.2 dB, compared with previous grating-based two-stage schemes. In addition, the double-strip-to-slot waveguide mode converter, consisting of two S bends and a taper pair, occupies a short conversion length of only 4 μm. Parameters, including taper length and S-bend length are numerically optimized. Bandwidth and fabrication error tolerance are also analyzed. Experimental results verify the feasibility of the proposed scheme.**

***Index Terms*— Slot waveguide, strip waveguide, grating coupler, mode converter.**

I. Introduction

SLOT waveguides, which consist of a low-index slot embedded between two high-index slabs, have attracted tremendous attention during the last decade due to their unique capability in confining light inside the nano-scale slot [1]. Functional passive devices using slot waveguides such as directional couplers [2] and polarization splitters [3] have been reported. Moreover, by combining with compatible materials, this strong enhancement property allows highly efficient interaction between light fields and active materials, leading to applications such as all-optical switching [4] and ultrafast electro-optic modulation [5].

However, direct excitation of the eigen-mode of the slot waveguide through coupling light from a single-mode fiber poses some challenges. The field profile and mode size of the fundamental mode of the slot waveguide are different from those of the Gaussion-like mode of a single-mode fiber, setting a potential barrier for coupling light in and out of the slot waveguide. Haishan *et al*. employed two inverted lateral tapers to couple light from a fiber to the slot waveguide [6]. However, butt coupling schemes cause resonance effects and are sensitive to the roughness of waveguide end-facets. Grating structures were proposed to alleviate this problem and there is no need to cleave the devices, which enables wafer-scale testing of integrated circuits [7]. To date, there has been no direct fiber-to-slot-waveguide grating coupler. An efficient strip-to-slot waveguide mode converter is usually utilized to achieve coupling light to the slot waveguide after the fiber-to-single-strip-waveguide grating coupler [8], [9]. These mode converters suffer from a long conversion length of several or even tens of micrometers, resulting in increased structure dimension, transmission loss, and coupling loss.

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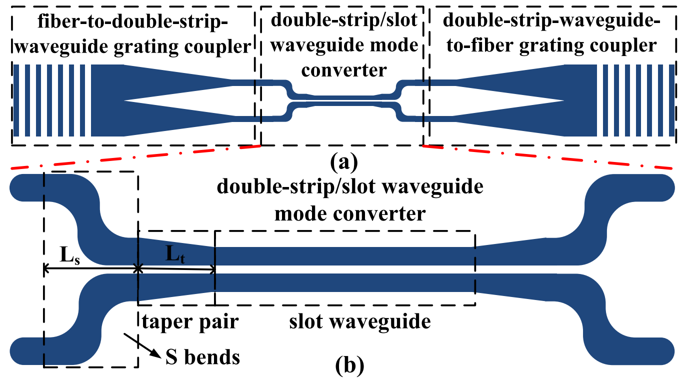

Fig. 1. (a) Schematic diagram of the proposed fiber/slot-waveguide grating coupler (top view). (b) The detailed double-strip/slot waveguide mode converter (top view).

Here, we propose and demonstrate a fiber-to-slot-waveguide grating coupler based on a double-strip waveguide which can couple more light from a fiber than the single-strip waveguide in previous schemes, and a double-strip-to-slot waveguide mode converter with comparable conversion efficiency, to improve the overall fiber-to-slot-waveguide coupling efficiency. Measurement results show that the coupling efficiency from a fiber to the slot waveguide is improved by about 1.2 dB compared to previous grating-based two-stage schemes. The proposed mode converter, which is composed of two S bends and a taper pair, occupies a short conversion length of only 4 μm. This coupler configuration is also tolerant to the mismatch of the upper and lower S bends.

II. Device Structures

Fig. 1(a) shows the schematic diagram of the proposed fiber/slot-waveguide grating coupler from top view, which consists of a fiber/double-strip-waveguide grating coupler and a double-strip/slot waveguide mode converter. The detailed structure of the mode converter is depicted in Fig. 1(b), composed of two S bends with a length of L_S and a pair of taper structure with a length of L_t. The vertical grating coupler couples light from an external fiber into the double-strip waveguide. Then the subsequent mode converter converts the Gaussion-like mode of the strip waveguide to the mode of the slot waveguide through the S bends and the taper pair.

III. Simulation Results and Discussions

In this section, we simulate the performance of the proposed fiber-to-slot-waveguide grating coupler using commercial software Lumerical FDTD solutions 7.5.3. Silicon-on-insulator (SOI) structure is assumed. One can also apply this coupling scheme to other platforms. The refractive indices for SiO_2 and Si around 1550-nm wavelength are set to be 1.45 and 3.48, respectively. Due to the limited computing capability of our server, we divide the simulations into two steps including the fiber-to-double-strip-waveguide grating coupler and the double-strip-to-slot waveguide mode converter.

A. Fiber-to-Double-Strip-Waveguide Grating Couplers

In previous two-stage fiber-to-slot-waveguide grating couplers [8], [9], coupling light into the slot waveguide from a fiber is achieved by firstly utilizing a fiber-to-single-strip-waveguide grating coupler and then a following strip-to-slot waveguide mode converter. In this letter, we employ a double-strip waveguide to improve the coupling efficiency of the fiber/strip-waveguide grating coupler, and then design a double-strip-to-slot waveguide mode converter with comparable conversion efficiency (CE). Thus, the overall coupling efficiency of the fiber-to-slot-waveguide grating coupler is improved. To verify the improvement, we perform simulations of fiber-to-double-strip-waveguide and fiber-to-single-strip-waveguide grating couplers, as depicted in Figs. 2(a) and 2(b), respectively. Since gratings can excite fundamental and also high-order modes [10] in the case of misalignment between the fiber and the grating center that usually occurs in practice, we treat the gratings with a single-mode fiber source as a 10-μm-wide slab waveguide with fundamental and high-order mode sources, as shown in Figs. 2(c) and 2(d), to simplify the simulation. The cross sections of the slab waveguide, the double-strip waveguide, and the single-strip waveguide along the A-a, B-b, and C-c cut lines are illustrated in Figs. 2(e), 2(f), and 2(g), respectively. The widths of the double-strip and single-strip waveguides are both set to be 450 nm such that only the fundamental modes in the waveguides can be excited. The distance of the two 450-nm-wide silicon strips of the double-strip waveguide is about 5 μm, which means the double-strip waveguide is actually consisted of two independent single-strip waveguides with nearly no intermode interference. The slab waveguide is utilized as the access waveguide. The heights of all the waveguides are 220 nm. The entire structure is covered by silica.

We numerically calculate the field evolutions of the slab-to-single-strip and slab-to-double-strip waveguide mode converters for the sources of first-order, second-order, third-order, and fourth-order modes with transverse electric (TE) polarization at 1550 nm (see Fig. 3(a)), as shown in Fig. 3(b). In Fig. 3(b), the electric field intensities are plotted along the central XY

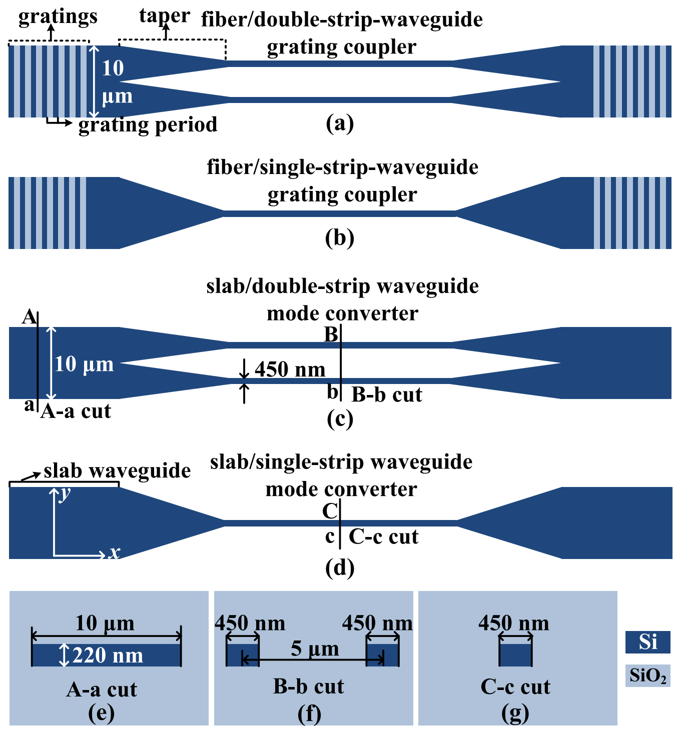

Fig. 2. (a-b) Schematic diagrams of the fiber/double-strip-waveguide (a), and fiber/single-strip-waveguide (b) grating couplers (top view). (c-d) Schematic diagrams of the slab/double-strip (c), and slab/single-strip (d) waveguide mode converters (top view). (e-g) The cross sections of the slab waveguide (e), double-strip waveguide (f), and single-strip waveguide (g) at A-a, B-b, and C-c cut lines, respectively.

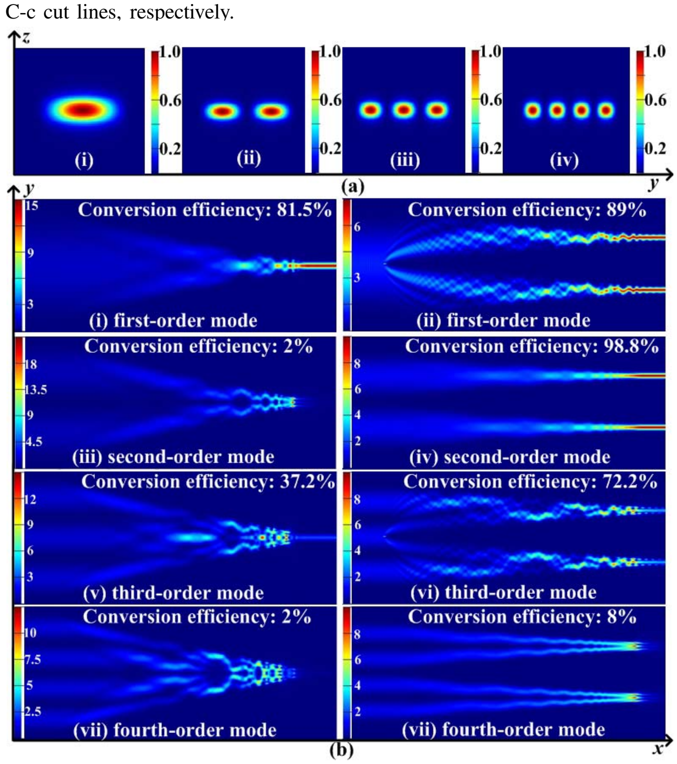

Fig. 3. (a) The electric field distributions of the first-order (i), second-order (ii), third-order (iii), and fourth-order (iv) TE modes of the slab waveguide at 1550 nm. (b) Simulated field evolutions of the slab-to-single-strip waveguide (left four insets) and slab-to-double-strip waveguide (right four insets) mode converters for the four sources.

plane of the converter structures. We also perform the simulations of coupling for higher-order modes (up to eight), which

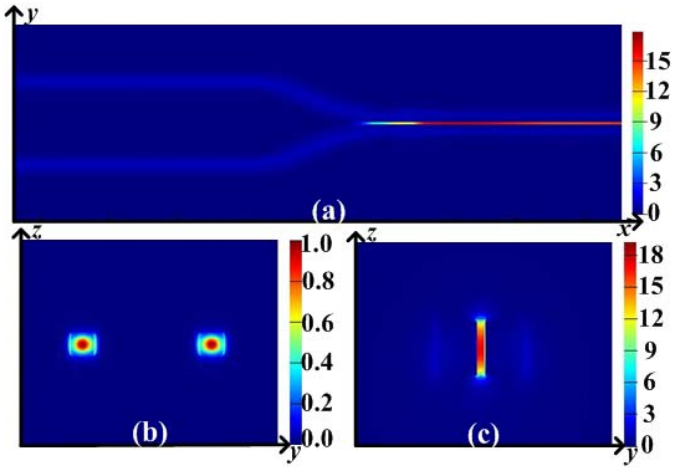

Fig. 4. (a) The field evolution of the double-strip-to-slot waveguide mode converter. (b) The fundamental TE mode of the double-strip waveguide at 1550 nm. (c) The excited fundamental TE mode of the slot waveguide. In all these figures, the electric field intensities are plotted.

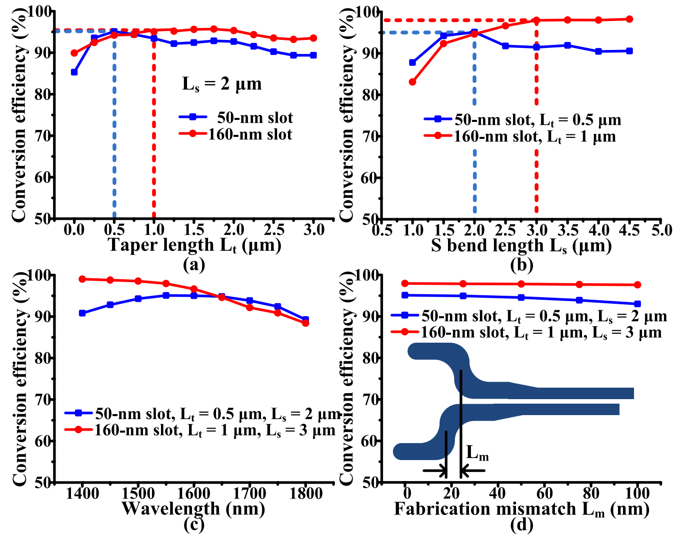

Fig. 5. Conversion efficiencies as functions of taper length L_t (a), S bend length L_s (b), wavelength (c), and fabrication error (d) for waveguides with 50-nm and 160-nm slots, respectively.

are not shown in the figures. In the simulations, the lengths of the tapers are set to be 100 μm due to the limited computing capability of the server. Simulation results show that the slab-to-single-strip waveguide mode converter couples the odd modes but reflects the even modes. In contrast, the slab-to-double-strip waveguide mode converter only reflects the fourth-order and eighth-order modes. In addition, the conversion efficiencies improve for all the eight modes by employing the slab-to-double-strip waveguide mode converter, as shown in Fig. 3(b), since the taper in the double-strip waveguide has a smaller tapering slope than that in the single-strip waveguide. Thus, the fiber-to-double-strip-waveguide grating coupler can couple more light to the double-strip waveguide, and hence the slot waveguide.

B. Double-Strip-to-Slot Waveguide Mode Converters

We perform simulations of coupling light from the double-strip waveguide to the slot waveguide in this sub-section. The silicon slab width and the slot width of the slot waveguide are chosen as 220 nm and 50 nm, respectively. To efficiently couple light into the nano-scale slot, two S bends and a taper pair are designed (see Fig. 1(b)). The fundamental TE mode of the double-strip waveguide at 1550 nm is used as the launch field, as shown in Fig. 4(b). Here, the lengths of the S bend and the taper pair, L_s and L_t, are set to be 2 μm and 1 μm, respectively, as examples. The conversion process can be clearly observed in the field evolution pattern illustrated in Fig. 4(a). Fig. 4(c) depicts the excited fundamental TE mode of the slot waveguide.

Figs. 5(a) and 5(b) show the influences of two structural parameters, taper length L_t and S bend length L_s, on the conversion efficiency at 1550-nm wavelength. In order to keep consistent with experimental results in Section IV, simulations for the waveguides with a slot width of 160 nm and a strip width of 300 nm are also presented. One can find that these four curves both have slight resonance effects, which are possibly induced by the reflections in the converter structures. When $L_s = 2$ μm and $L_t = 0.5$ μm for the waveguide with a 50-nm slot, the mode converter achieves the maximum efficiency of 95.5%, while the conversion length, defined as $L_s + L_t$, is only 2.5 μm. Thus, our proposed double-strip-to-slot waveguide mode converter occupies a much shorter conversion length than previous single-strip-to-slot waveguide mode converters, with a comparable efficiency, making the converter very compact. For the waveguide with a 160-nm slot, L_s and L_t are chosen as 3 μm and 1 μm to make a trade-off between CE and device compactness, and a CE of as high as 97.9% can be achieved. The conversion efficiencies over a wavelength span of 400 nm are plotted in Fig. 5(c). The CE reaches the maximum value of 95.5% at 1550 nm for the waveguide with a 50-nm slot and varies less than 3% over a wavelength span as wide as 360 nm. The CE increases with the decrease of wavelength for the waveguide with a 160-nm slot, as more power is distributed in the two 300-nm silic on slabs. Since the double-strip-to-slot waveguide mode converter is based on two symmetric S bends and a taper pair, it is essential to consider the performance tolerance to fabrication mismatch L_m, as shown in Fig. 5(d). L_m is defined as the difference between the cores of the upper and lower S bends, as illustrated in the inset of Fig. 5(d). The wavelength is set to be 1550 nm. When the mismatch changes within a small range, e.g., 20 nm, the CE keeps almost the same. As the mismatch continues to increase, the CE starts to decrease slowly, indicating a high tolerance of the proposed mode converter to fabrication mismatch.

IV. Experimental Results and Discussions

In order to verify the feasibility of the proposed fiber-to-slot-waveguide grating coupler, samples including fiber/single-strip-waveguide, fiber/double-strip-waveguide, and fiber/slot-waveguide grating couplers were fabricated on an 8-inch SOI wafer with a 220-nm-thick top silicon layer and a 2-μm-thick buried dioxide layer. The micrographs of the fabricated devices are shown in the insets of Fig. 6. The silicon layer was first patterned by 248-nm deep ultraviolet photolitho-

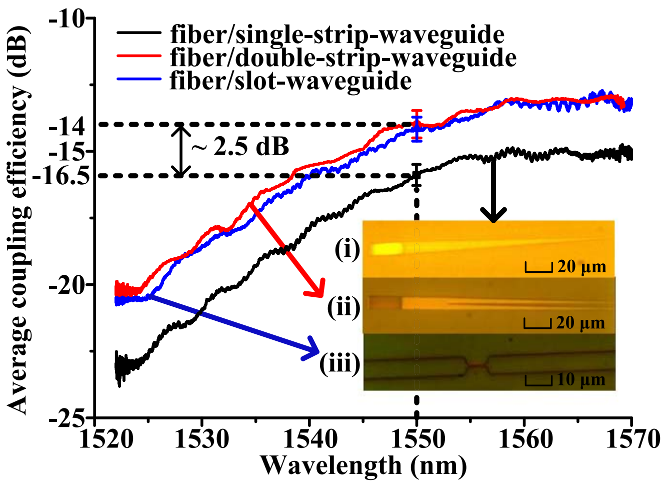

Fig. 6. Measured average coupling efficiencies and micrographs of the fabricated grating couplers with fiber-to-single-strip-waveguide-to-fiber (i), fiber-to-double-strip-waveguide-to-fiber (ii), and fiber-to-slot-waveguide-to-fiber configurations (iii).

graphy (DUV) followed by inductively coupled plasma (ICP) etching. A 1.5-μm-thick silica layer was deposited by plasma enhanced chemical vapor deposition (PECVD) to fill the slot and cover the whole device. The gratings of these samples all have 25 periods with a period of 630 nm, a duty cycle of 50%, a width of 13 μm, and a length of about 15 μm. The etch depth is 70 nm. This dimension matches well with the mode size of a standard single-mode fiber. The lengths of the adiabatic tapers connecting the gratings and the single- or double-strip waveguide are designed to be the same, and so are the lengths of the single- and double-strip waveguides. Thus, the comparison between the coupling efficiencies of the fiber/single-strip-waveguide and fiber/double-strip-waveguide grating couplers can be conducted under the same condition. The width of the strip waveguide is 450 nm. Due to the resolution of the DUV, the slot width is chosen as 160 nm. The width of the two silicon slabs of the slot waveguide is designed to be 300 nm. L_s and L_t, are chosen as 3 μm and 1 μm, respectively. The bending radius of the S bend in the mode converter is about 1.5 μm, which will cause a bending loss of less than 0.08 dB. The length of the slot waveguide is 3 μm.

We then measure the coupling efficiencies of the grating couplers with fiber-to-single-strip-waveguide-to-fiber, fiber-to-double-strip-waveguide-to-fiber, and fiber-to-slot-waveguide-to-fiber configurations, respectively. Each type of the three configurations has ten samples with the same structural dimensions. The averaged efficiencies for the three structures versus wavelength are plotted in Fig. 6. Measurement results show that at 1550 nm, the coupling efficiency of the fiber-to-double-strip-waveguide-to-fiber grating coupler ranges from -13.5 dB to -14.6 dB with an average value of -14.2 dB, while that of the fiber-to-single-strip-waveguide-to-fiber grating coupler is in the range of -16 dB to -17.2 dB and the average value is -16.6 dB. The values are lower than the expected values since we use the broadband un-polarized erbium-doped fiber amplifier (EDFA) source instead of a tunable laser as the launch field to measure the spectra, while these grating couplers are polarization selective and only TE-polarized modes can be propagated through the grating couplers. The taper length is also a little shorter compared to other designs, causing additional loss. At 1550 nm, the measured coupling efficiencies of the fiber-to-double-strip-waveguide-to-fiber and fiber-to-slot-waveguide-to-fiber grating couplers are almost the same, leading to a negligible conversion loss of the double-strip/slot waveguide mode converter. Thus, the double-strip waveguide improves the fiber-to-fiber coupling efficiency by an average value of about 2.4 dB, i.e., 1.2 dB/facet, while the conversion losses of the proposed double-strip/slot and previous single-strip/slot waveguide [8], [9] mode converters are comparable. The 3-dB bandwidth of the proposed grating coupler is about 40 nm, mainly limited by the bandwidths of the gratings. The coupling efficiency can be further improved by employing more efficient vertical grating coupler designs.

V. Conclusion

In this letter, we have proposed, numerically analyzed, and experimentally demonstrated an efficient fiber-to-slot-waveguide grating coupler based on a double-strip waveguide and a double-strip/slot waveguide mode converter. Measurement results show that the proposed coupler can effectively improve the coupling efficiency by approximately 1.2 dB. The double-strip/slot waveguide mode converter occupies a short conversion length of only 4 μm, which could be further reduced to 2.5 μm predicted by the simulation results, making this configuration very compact. In addition, the proposed coupler is highly tolerant to the fabrication mismatch. This work provides a practical and efficient solution for coupling light into and out of slot waveguide-based devices.

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