Strip-slot waveguide mode converter based on symmetric multimode interference

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Optical mode mismatch makes coupling between strip and slot waveguides a tough issue in integrated photonics. This Letter presents both numerical and experimental results of a strip-slot mode converter based on symmetric multimode interference (MMI). Distinct from previous reported converters which gradually convert the mode through sharp tips, the proposed solution makes full use of the symmetry of the two-fold image of MMI, and its field distribution similarity with a slot waveguide to convert the mode. A converter based on this mechanism is able to convert light from a TE-polarized fundamental mode of a strip waveguide to that of a slot waveguide, and vice versa. Strip-slot waveguide coupling though this mode converter has a measured efficiency of 97% (−0.13 dB), and the dimensions are as small as 1.24×6 μm. Further analysis shows that the proposed converter is highly tolerant to fabrication imperfections, and is wavelength-insensitive.

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Due to its excellent ability of enhancing and confining light in a nanometer-wide low-index material, slot waveguides, formed by a narrow low-index slot embedded between two high-index regions, have attracted a great amount of interest since they were proposed [1,2]. Various functional devices based on slot waveguides have been reported, such as an athermal microring resonator [3], a polarization beam splitter [4], an optical amplifier [5], nonlinear optical devices [6], and a high performance electro-optic modulator [7]. On the other hand, a slot waveguide has relatively higher loss (~10 dB/cm [8]) than a strip waveguide (~2 dB/cm [9]). Therefore, it is only used in the functional region, while a strip waveguide is needed for guiding light from and to the integrated optical systems. Because of the optical mode mismatch between slot (non-Gaussian-like mode) and strip (Gaussian-like mode) waveguides, the coupling efficiency between these two different waveguides is low with direct butt-joint coupling. A great deal of effort has been made to eliminate the mode mismatch, which can be classified into two different approaches based on their structures [10–15], shown in Figs. 1(a) and 1(b). The approach in Fig. 1(a), proposed in [10], uses a taper structure to gradually push the field out from the upper high-index region to the lower high-index region, so that the strip waveguide mode can be converted to the slot waveguide mode. The approach in Fig. 1(b), proposed in [11], tapers the strip waveguide and inserts it into the slot waveguide to convert the optical field distribution adiabatically. Both of these two approaches can achieve highly efficient coupling between strip and slot waveguides, and have been widely applied in the previously mentioned slot waveguide based applications. However, fabrication is a big problem for both schemes since there are extremely sharp tips which must be well-shaped, or the coupling efficiency will degrade significantly [10,11]. On the other hand, a relaxed fabrication requirement is one of the main advantages of multimode interference (MMI) devices [16]. Furthermore, MMI effects have been demonstrated to be efficient for mode coupling between a strip waveguide and a slot photonic crystal waveguide [17]. In this Letter, we propose and experimentally demonstrate a compact strip-slot mode converter based on symmetric MMI for efficient coupling between strip and slot waveguides, which allows large fabrication imperfections while maintaining the advantages of high efficiency, wavelength insensitivity, and compactness of the device.

The schematic of the proposed converter is shown in Fig. 1(c). The whole structure is based on a material platform of silicon-on-insulator (SOI) with SiO_2 cladding. The strip and slot waveguides have the following dimensions: the thickness of top silicon is 250 nm; the widths of the strip and slot waveguide are 400 and 620 nm, respectively; and the 100 nm slot is located at the center of the slot waveguide. The converter consists of two parts, the symmetric 1×2 MMI and the taper regions. The length and width of the MMI region are $L_{mmi} = 1.38$ μm and $W_{mmi} = 1.24$ μm, whereas L represents the total length of the converter. To illustrate the working principle, the optical energy flux density (P_z) distribution of symmetric MMI with TE-polarized fundamental mode incidence is plotted in Fig. 2(a). According to self-imaging principles [16], the incident optical energy is rebuilt into a two-fold image periodically along the propagation direction. The first two-fold image [A-A′ cut in Fig. 2(a)] is selected as the MMI output to minimize the converter

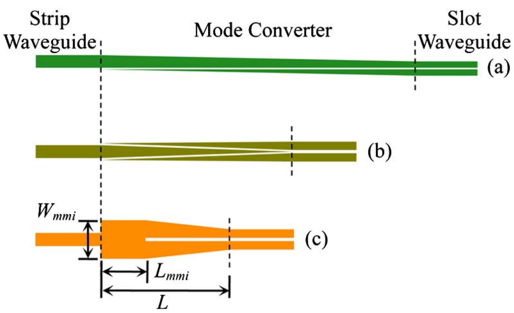

Fig. 1. Schematics (plotted to scale): (a), (b) previously reported mode converter; (c) proposed strip-slot mode converter.

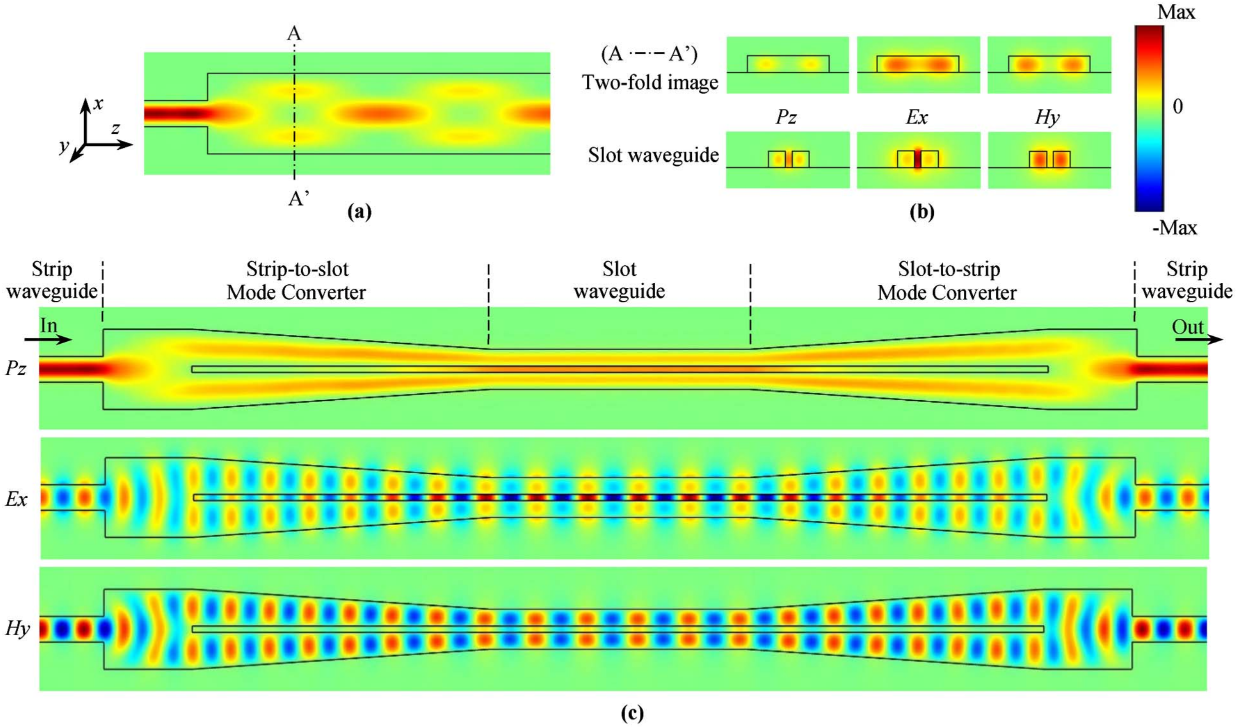

Fig. 2. (a) Optical energy flux density (P_z) distribution of symmetric MMI; (b) comparison of optical field distributions between the first two-fold image of symmetric MMI [A-A′ cut in Fig. 2(a)] and the slot waveguide; (c) optical field evolution between strip and slot waveguides. All simulations in this Letter are performed with 3D full vector finite element method (FEM), while the refractive indices of Si and SiO_2 are set to 3.48 and 1.45, respectively.

length. The similarity of optical field distributions between the two-fold image and slot waveguide [Fig. 2(b)], two quasi-Gaussian-like peaks symmetrically distributed in the waveguides, makes efficient coupling between them possible. For better coupling, a slot taper is optimized to connect the multimode region and slot waveguide. Benefiting from little field distribution in between of the two images, the slot in the middle of the taper does not introduce much additional loss, while the width shrinks to the width of the slot waveguide, and the field is pushed into the slot smoothly. As shown in Fig. 2(c), this converter can convert a strip TE-polarized fundamental mode to a slot TE-polarized fundamental mode and vice versa, with negligible loss.

It is easy to fabricate the proposed converters since there are no sharp tips. The designed converter was fabricated on a SOI wafer, of 250 nm thick top silicon and 2 μm thick buried oxide, by electron-beam lithography, followed by inductively coupled plasma etching. Then, 1 μm thick SiO_2 cladding was deposited as the upper cladding by plasma enhanced chemical vapor deposition. Converters with different length (L) were fabricated to analyze the effects of L on strip-slot waveguide coupling efficiency. One pair of fabricated converters with $L = 6$ μm is shown in the top-view scanning electron microscope (SEM) picture of Fig. 3, captured before the SiO_2 cladding was deposited. Ten pairs of such converters [20 converters, Fig. 3(b)] are cascaded to reduce the influence of measurement error (Err). The loss per strip-slot waveguides coupling is calculated as $Loss$ (dB) $= (P_{\text{out}} - P_{\text{in}} + Err)/20$. To characterize these devices, a tunable CW laser of TE polarization is butt-coupled into the chip, and then butt-coupled out to an optical spectrum analyzer through tapered lens fibers. Five identical testing devices are fabricated for each converter length (L), and the mean values of their measured results are recognized as the final results to ensure the accuracy of the measurement.

The measured and simulated strip-slot waveguide coupling efficiencies, coupling through the proposed converter, are plotted in Fig. 4. The measurements agree well with the simulations. Both measurements and simulations indicate that (i) the coupling efficiency is low for a 2-μm-length converter, (ii) the efficiency increases dramatically with a longer converter ($L = 2 \sim 4$ μm), and (iii) the converter maintains a very high efficiency (simulated, ~98%; measured, >96%) as long as the converter is longer than 4 μm. The measured efficiency is as high as $97\% \pm 2\%$ while the converter length is 6 μm, which is more compact than the ones reported in [10,11].

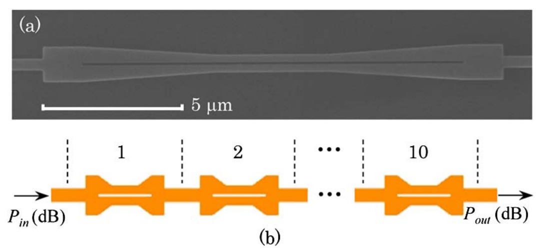

Fig. 3. (a) Top-view SEM picture of the fabricated converters (one pair) with $L = 6$ μm; (b) schematics of 10 pairs of mode converters cascaded for measurement (not to scale).

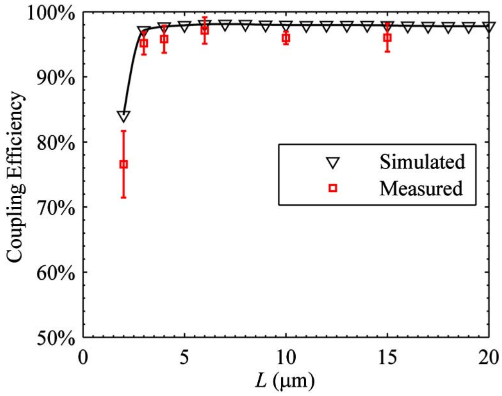

Fig. 4. Simulated (triangles) and measured (squares) coupling efficiency with different converter lengths at 1550 nm (wavelength in free space). Error bar, standard deviation of the measured results.

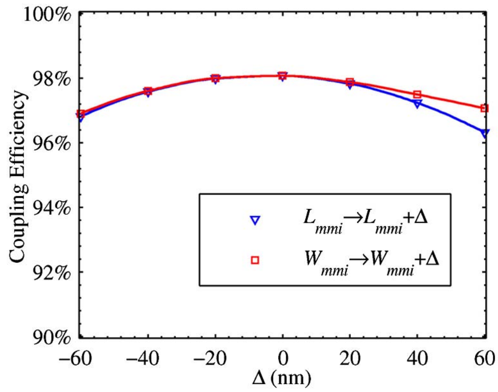

Fig. 6. Simulated relations of coupling efficiency versus the length (triangles) and width (squares) variation of the multimode region at 1550 nm wavelength.

Further measured results on wavelength dependence of the proposed converter are shown in Fig. 5. There is no significant degradation in coupling efficiency (~97%, −0.13 dB) for a wavelength range of 130 nm (1450–1580 nm). To the best of our knowledge, this is the widest operation bandwidth ever measured from a strip-slot mode converter.

Finally, we numerically analyzed the fabrication tolerance. As indicated in Fig. 1(c), three characteristic parameters (W_{mmi}, L_{mmi}, and L) are used to determine the proposed converter's structure when the dimensions of the strip and slot waveguides are fixed. The converter length (L) will not affect the coupling efficiency if it is longer than 4 μm, as analyzed in Fig. 4. Therefore, the length (L_{mmi}) or width (W_{mmi}) of the MMI region is changed by Δ to analyze the fabrication tolerance, while the other dimensions are fixed. The analysis results (Fig. 6) indicate that the degradations of coupling efficiency are less than 2%, while L_{mmi} (or W_{mmi}) deviates ±60 nm from the optimized size. All the characteristic parameters have been demonstrated to be insensitive to dimension variations. It can be concluded that the proposed strip-slot mode converter has a large fabrication tolerance.

In summary, we numerically and experimentally demonstrated a novel strip-slot mode converter based on symmetric MMI. Distinct from the previously reported converters which gradually convert the mode with sharp tips, the proposed converter, which makes full use of the symmetry of the two-fold image and the similarity of the field distributions between the two fold image and the slot waveguide, tapers the two images into the two high-index regions of the slot waveguide. A converter based on this scheme keeps all the advantages of the previous reported strip-slot mode converters, such as high coupling efficiency, wavelength insensitivity, and compactness. Moreover, the proposed converter is fabrication-friendly with a large tolerance for fabrication imperfections, while no previous reported scheme can offer this advantage due to the existence of sharp tips. It is worthwhile to mention that even though all the results presented in this Letter are based on a TE-polarized fundamental mode, the proposed scheme is also applicable for TM-polarized fundamental mode conversion between strip and slot waveguides, since the MMI two-fold image and slot waveguide have similar mode profiles. If the multimode region is optimized to be polarization-insensitive [18], this scheme can achieve a polarization-insensitive mode converter. The proposed mode converter is an ideal solution for coupling light between strip and slot waveguides.

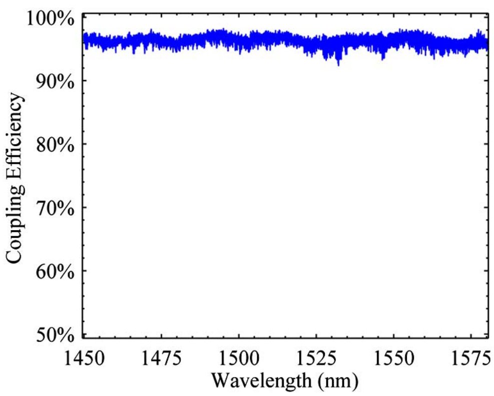

Fig. 5. Measured wavelength dependence of coupling efficiency with $L = 6$ μm.

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