A two-port polarization-insensitive coupler module between single-mode fiber and silicon-wire waveguide

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Abstract: A two-port polarization-insensitive single-mode fiber-silicon wire-waveguide coupler module, 5.3 × 3.4 × 0.7 mm³ in size, is realized. The spot-size converter (SSC) involved utilizes a concatenated horizontal up-taper and vertical down-taper. Measured coupling losses between the fiber and the silicon-wire waveguide of the E₁₁ₓ and E₁₁ᵧ modes of the SSC are 2.8 and 2.7 dB/port, respectively. The device platform is planar, robust, and easy to fabricate with conventional lithography.

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1. Introduction

Silicon-based photonic nano-wire waveguide structures may lead to monolithic integration among electronic, optoelectronic and optical devices. Clearly, the resulting integrated optoelectronic circuits together with single-mode fibers (SMFs) will facilitate a variety of applications. However, the great disparity between the mode-field diameters (MFDs) of the SMFs and that of the Si-wire waveguides will result in excessive coupling losses when they are directly butt coupled. Various types of spot-size converters (SSCs) for spot-size matching between the waveguides and the SMFs have been reported [1–13].

In general, horizontal expansion of MFD in the Si-wire waveguide is easily accomplished using an up-taper fabricated with conventional lithography. Grating couplers [1–3], extremely narrow down-tapers in the horizontal direction [4–6], and vertical up-tapers [7–13] were proposed for the vertical expansion. However, vertical expansion of MFD in the waveguides is well-recognized to be much more difficult to accomplish. Furthermore, it is highly desirable for the SSCs be polarization insensitive [3, 6, 13]. Here we report realization of a two-port polarization-insensitive single-mode fiber-silicon wire waveguide coupler module that employs SSCs of new configuration in a silicon-on-insulator (SOI) substrate.

2. Architecture design and calculated performance of SSC

As illustrated in Fig. 1, the SSC consists of horizontal linear up- and vertical down-tapers that adiabatically expand the modal field of the Si-wire waveguide in the Y- and X-directions, respectively. Since control of vertical thickness with accuracy of nm during deposition or etching process is much easier than control of horizontal width with the same accuracy, vertical expansion of the MFD by the vertical down tapering can be easily accomplished. An SOI wafer with 3μm thick buried oxide (BOX) layer was used as the substrate. The design parameters of the Si-wire waveguide core are: width ($W_1$) 0.4μm, thickness ($T_1$) 0.22μm, and refractive-index of 3.5. The core is surrounded with silica of refractive index 1.45. The corresponding MFDs, defined by the full width at 1/e² maximum of the optical intensity in the X- and Y-directions, are $0.41 \times 0.35 \mu m^2$ for the $E_{11}^{yy}$ (TE-like) mode and $0.32 \times 0.46 \mu m^2$ for the $E_{11}^{xy}$ (TM-like) mode, respectively, at the wavelength of 1.55μm, in accordance with the notation of the eigen modes given in reference [14]. The transmission characteristics of the horizontal linear up-taper are well-known. A taper length ($L_h$) of 150μm was chosen in order to ensure an expanded waveguide width ($W_2$) of 5μm along the Y-direction with adiabatic
field transformation. The MFDs of the Si-core waveguide at the output plane of the linear up-taper, \(0.22 \times 5\ \mu\text{m}^2\) in cross section, are expanded to \(0.4 \times 4.6\ \mu\text{m}^2\) and \(0.3 \times 4.4\ \mu\text{m}^2\) for the \(E_{11}^y\) and \(E_{11}^x\) modes, respectively. Finally, in order to expand the MFD vertically with negligible radiation losses a short vertical down-taper length \((L_v)\) of 110\(\mu\text{m}\) was chosen.

Next, the coupling losses between the SSC with a rectangular-core cross section of \(T_2 \times 5\ \mu\text{m}\) and a SMF are calculated in order to determine the optimum core thickness \(T_2\). Figure 2 shows the calculated coupling losses between the eigen modes \((E_{11}^y\) and \(E_{11}^x\)) of the rectangular-core SSC and the fundamental mode of the SMF versus the core thickness \(T_2\). Note that an MFD of 5.2\(\mu\text{m}\) for the fundamental mode of SMFs, which corresponds to that of a typical erbium-doped optical fiber, at the wavelength of 1.55\(\mu\text{m}\) was used in the calculation. The FIMMPROP-3D (by Photon Design), a commercial fully-vectorial eigenmode expansion tool, was used for this purpose. The two coupling loss plots in solid line show decreasing coupling losses as the core thickness \(T_2\) decreases from its initial value of 220nm (0.22\(\mu\text{m}\)), due to expansion of the MFDs. For the much smaller value of \(T_2\), each loss increases due to over expansion of the MFDs, and then each loss has a minimum value at a specific thickness. Since the optimum core thickness that provides the minimum loss depends on the polarization of the modes, the thickness that will facilitate polarization independency is determined by the intersection point of the two solid lines as shown by the empty circle. The corresponding calculated coupling loss is seen to be 2.2dB at the core thickness of 20nm.

As shown by the two plots in dashed line of Fig. 2, simultaneous MFD expansion in the X- and Y-directions can be accomplished by down-tapering the Si-wire waveguide vertically without using a horizontal up-taper. The intersection point of the two dashed lines shown by the filled circle will lead to a higher coupling loss of 4.9dB at the core thickness of 45nm, suggesting that simultaneous utilization of horizontal up-tapering and vertical down-tapering is preferable in construction of the polarization-insensitive SSCs.

It is to be noted that the optimal range of \(W_2\) is 5-7\(\mu\text{m}\). When \(W_2\) decreases from 5 to 3\(\mu\text{m}\), for example, the optimal value of \(T_2\) increases from 20 to 23nm, and the resulting polarization independent loss increases from 2.2 to 2.9dB. On the other hand, when \(W_2\) increases from 5 to
7μm, the optimal value of $T_2$ and the corresponding loss remain the same as those for $W_2 = 5μm$. Characteristics of the proposed SSC are relatively insensitive to the wavelength change. When the wavelength changes from 1.55 to 1.53μm, the corresponding losses of $E_{11}^y$ and $E_{11}^x$ modes change from 2.20 to 2.15dB and from 2.20 to 2.36dB, respectively, showing that there exists a polarization dependent loss of 0.21dB at the wavelength of 1.53μm. On the other hand, when the wavelength increases from 1.55 to 1.57μm, the upper end of the C band, the corresponding losses of $E_{11}^y$ and $E_{11}^x$ modes change from 2.20 to 2.03dB and from 2.20 to 2.50dB, respectively, suggesting a polarization dependence loss of 0.47dB at the wavelength of 1.57μm.

3. Fabrication and measured performance of SSCs

In the construction of SSCs, the horizontal linear up-taper was readily fabricated at the same time as the Si-wire waveguides in the SOI substrate using electron beam lithography. In contrast, the vertical down-taper required a special technique to create a smooth down tapering to the core thickness of 20nm at the output end. Fabrication of the vertical down-taper was carried out utilizing the shadow mask technique during reactive-ion etching (RIE) process as illustrated in Fig. 3. A short vertical taper of 110μm in length was fabricated by employing a 0.79mm-thick silica mask with vertex of 45° at both ends of the mask.

A mixed gas of SF$_6$ and O$_2$ (20%) was used for RIE with a commercial induction-coupled plasma (ICP) system (CE-300I of ULVAC Corp.). In order to attain an etching depth with the best possible precision, the etching rate was set as low as possible by setting the antenna (ionization) rf power at 24W and the bias (extracting) rf power at 10W. Accuracy of the etching was ± 3nm with the aimed etching depth of 200nm. A low etching-rate of 96nm/min for 125sec was carried out to obtain a core thickness $T_2$ of 20 ± 3nm. The smooth profile of the vertical down-taper obtained was found to be arc tangential, much the same as that of the up-taper [9, 11]. The total length of the SSCs at the input- and output-ends of the module was as small as 0.7mm. The fabricated SSC was subsequently coated with a 5μm-thick silica layer by rf sputtering.

Figures 4(a) and 4(b) show, respectively, the fabricated two-port module with SSCs at both ends and the enlarged microphotograph of the output endface of the SSC. A slight amount of reflected light from the 5μm-wide with 20 ± 3nm-thick down-tapered Si core can be seen on the endface. It is to be emphasized that since the Si-core thickness at the output end of the SSC is much smaller than the optical wavelength (1.55μm), the effective refractive index of the SSC at the output end is practically the same as the index of the surrounding silica. Consequently, no anti-reflection coating will be required for the SSCs.
Microphotographs showing nearly identical spot sizes and the corresponding contours of the light intensity distributions for \(E_{11}^y\) and \(E_{11}^x\)-modes are presented in Figs. 5 and 6, respectively. An oil-immersion microscopic objective of \(NA = 1.4\) was employed to facilitate the measurements. The measured MFDs in the \(X\)- and \(Y\)-directions for the \(E_{11}^y\) mode are 3.0 and 5.5\(\mu m\), respectively. The corresponding MFDs for the \(E_{11}^x\) mode in the \(X\)- and \(Y\)-directions are 2.7 and 5.2\(\mu m\), respectively. Thus, these nearly identical MFDs for the two orthogonal modes have clearly demonstrated a high degree of polarization insensitivity of the SSC.

Fig. 5. Measured near-field intensity patterns of the \(E_{11}^y\) mode at the output end of the SSC at the wavelength 1.55\(\mu m\). (a) The microscopic view and (b) the contour of the intensity distribution.

Fig. 6. Measured near-field intensity patterns of the \(E_{11}^x\) mode at the output end of the SSC at the wavelength 1.55\(\mu m\). (a) The microscopic view and (b) the contour of the intensity distribution.
The coupling loss of the two-port coupler module at the wavelength of 1.55 μm was determined using the Si-wire waveguide propagation losses by first measuring fiber-to-fiber total insertion losses of waveguides of nine different lengths in the range of 1.0-2.75mm, and then fitting the data to a straight line. In the measurement, a pair of identical polarization-maintaining SMFs with MFD of 5.2 μm (same as that used in the calculation in Section 2) was coupled to the input and output ports. The measured propagation losses of the Si-wire waveguide for the E_{11y} and E_{11x}-modes are 1.34 and 1.37dB/mm, respectively. The coupling losses of 2.8 and 2.7dB/port for the E_{11y} and E_{11x}-modes, respectively, were then obtained by subtracting the Si-wire propagation losses from the total insertion losses.

The measured total insertion losses of the module with 2.7mm long Si-core waveguide and SSCs on both ends of the module, for example, are 9.3 and 9.1dB for the E_{11y} and E_{11x}-modes, respectively. The total insertion losses include the propagation losses in the 2.7mm long Si-wire waveguide of 3.6 and 3.7dB for the E_{11y} and E_{11x}-modes, respectively. In short, the abovementioned experimental coupling losses of 2.8 and 2.7dB/port for the E_{11y} and E_{11x}-modes, respectively, are in good agreement with the calculated coupling loss of 2.2dB presented in Section 2, again demonstrating the polarization insensitivity of the proposed SSC.

4. Conclusion

A two-port polarization-insensitive single-mode fiber-silicon wire waveguide coupler module, 5.3 × 3.4 × 0.7mm³ in size, has been realized. The experimental performances of the polarization-insensitive SSC that consists of a horizontal up-taper and a vertical down-taper in cascade at the wavelength of 1.55μm are in very good agreement with the calculated results. MFDs of the Si-wire waveguide, 0.41 × 0.35μm² (E_{11y} mode) and 0.32 × 0.46μm² (E_{11x} mode), was expanded to the MFDs of 3 × 5.5μm² and 2.7 × 5.2μm², respectively. The corresponding coupling losses between the SSC and the SMF are 2.8 and 2.7dB/port, respectively. The proposed polarization-insensitive SSC possesses desirable features of planar geometry, robustness, simplicity in design, requiring relatively small number of processing steps in fabrication, and requiring no anti-reflection coating for its endface.

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