On-chip Silicon Three-mode (De)Multiplexer Employing Subwavelength Grating Structure

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Abstract *We propose and experimentally demonstrate a silicon three-mode (de)multiplexer using subwavelength grating structure. The three channels show < -16.3 dB crosstalk values and <3.8 dB insertion losses at 1550 nm.*

Introduction

Mode-division multiplexing (MDM) is a promising option to scale optical bandwidth by employing the spatial modes of waveguides[1]. Mode (de)multiplexers are key components in the MDM systems. Various types of mode (de)multiplexers have been demonstrated based on multimode interference (MMI) couplers[2], adiabatic mode-evolution couplers[3], asymmetric Y-junctions[4], and asymmetric directional couplers[5]. Subwavelength grating (SWG) is a periodic structure functioning as a homogenous medium[6], which provides a new approach to effectively tailor the refractive index by modifying the pitch, width and duty cycle of the grating structure. In addition, with properly designed parameters, the phase-matching condition can be maintained if the SWG waveguide width changes with that of a strip waveguide, thus resulting in tolerance to fabrication errors in coupling devices. The SWGs have been used as efficient fiber-chip coupler[7], crossing[8], MMI coupler[9], polarization splitter and rotator[10]. However, to date, no SWG-based mode multiplexer has been demonstrated.

In this paper, to the best of our knowledge, we propose and experimentally demonstrate the first silicon three-mode (de)multiplexer using cascaded SWG-based directional couplers (DCs). The DC consists of a strip waveguide and a SWG waveguide. The coupling length and the widths of the two waveguides of the DCs are optimized to achieve highly efficient selective mode coupling through 3D finite-difference time-domain (3D-FDTD) simulations. The signal carried by the fundamental mode of a SWG waveguide can be coupled to a higher-order mode in the multimode bus waveguide. Adiabatic tapers are used to connect the bus waveguides with different widths. The overall insertion losses for the three channels are lower than 3.8 dB, and the crosstalk values are below -16.3 dB at 1550 nm.

Device structure and operation principle

The 3D view of the proposed SWG-based three-

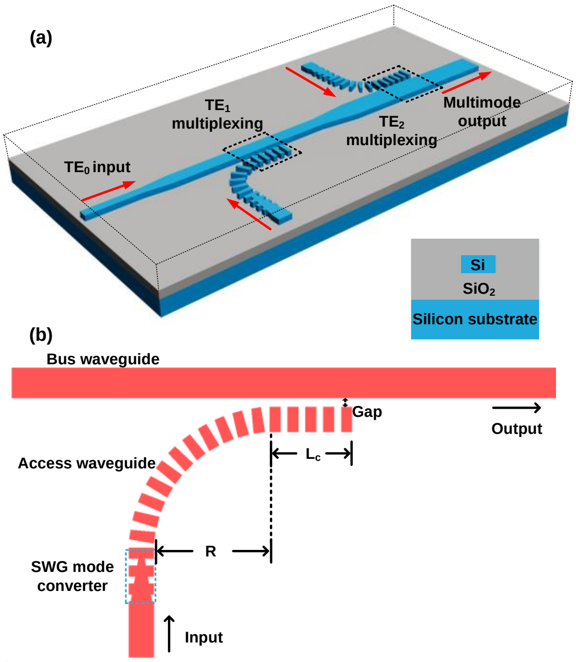

Fig. 1: Schematic configuration of the proposed silicon SWG-based mode multiplexer, (a) 3D view, (b) top view of the SWG based DC.

mode (de)multiplexer is sketched in Fig. 1(a). It consists of a bus waveguide and two SWG access waveguides. The fundamental transverse electric mode (TE_0 mode) is injected from the input port of the bus waveguide. The multiplexing of the higher-order modes (TE_1, TE_2 modes) are realized by using the SWG-based DCs, as depicted in Fig. 1(b). The equivalent material refractive index of the SWG waveguide can be calculated by a simplified model[11]:

$$\Delta n_{eq} = \delta \times \Delta n, \tag{1}$$

where Δn_{eq} represents the refractive index difference between the equivalent material and the SiO_2 cladding, δ is the duty cycle, and Δn is the refractive index difference between the silicon core and the SiO_2 cladding. Here we choose $\delta = 65\%$ and the SWG structure can be considered as a homogenous medium with an equivalent material refractive index of 2.776. The period of the SWGs is 330 nm.

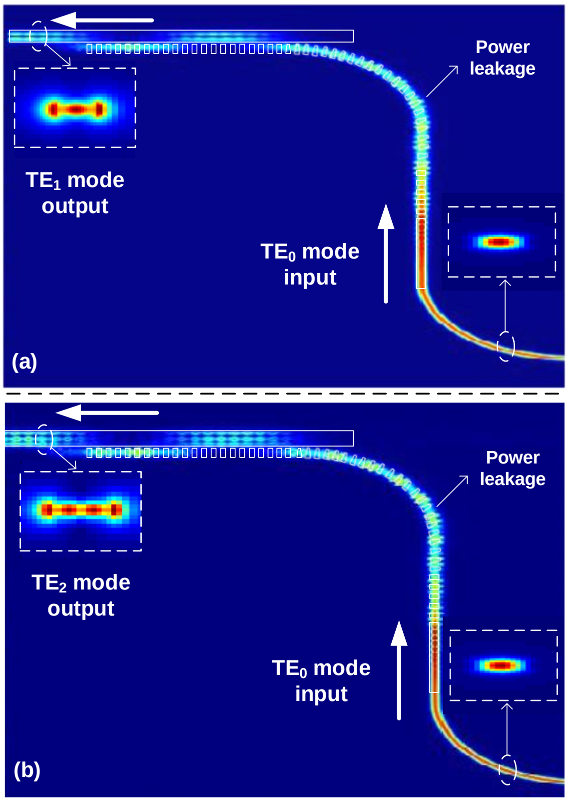

Fig. 2: Simulated power distributions of the SWG-based DCs for the (a) TE_1 and (b) TE_2 modes multiplexing, respectively.

To achieve highly efficient mode coupling, the phase matching between the waveguides should be satisfied, i.e. the effective refractive index of the TE_0 mode in the SWG access waveguide should be equal to that of the TE_1 or TE_2 mode in the bus waveguide. In this case, if a TE_0 signal is injected into the SWG waveguide, a high efficiency TE_1 or TE_2 signal can be obtained at the output port of the bus waveguide. We use 3D-FDTD method to optimize the phase matching conditions of TE_0-TE_1 and TE_0-TE_2 mode selective couplings.

The thickness of the top silicon layer of a silicon-on-insulator (SOI) wafer is 220 nm. The widths of the SWG access waveguides are 500 nm, and the widths of the bus waveguides are 615 nm and 946 nm for the TE_1 and TE_2 modes coupling, respectively. Adiabatic tapers are used to connect the bus waveguides with different widths. The gap between the two waveguides is 100 nm. The bend SWG waveguides built with trapezoidal silicon pillars[12] are used to decrease the bending losses, the bend radius is set to be 10 μm.

The simulated power distributions in the proposed SWG-based DCs are illustrated in Fig. 2. The insets show the mode distributions at the input and output ports. When the fundamental TE_0 modes are injected from the input ports of the SWG access waveguides, high efficient TE_1 or TE_2 modes are obtained at the output ports of the bus waveguides with different widths. Note that there is some power leakage in the SWG bend, where the mode moves towards the outer edge of the bend, which could increase the scattering losses[13].

Device fabrication

The SWG-based mode (de)multiplexer devices were fabricated on a SOI wafer (220-nm-thick silicon on 3000-nm-thick silica) by E-beam lithography (Vistec EBPG 5200) and inductively coupled plasma (ICP) etching. A 1-μm-thick SiO_2 cladding was deposited on the chip using plasma enhanced chemical vapor deposition (PECVD).

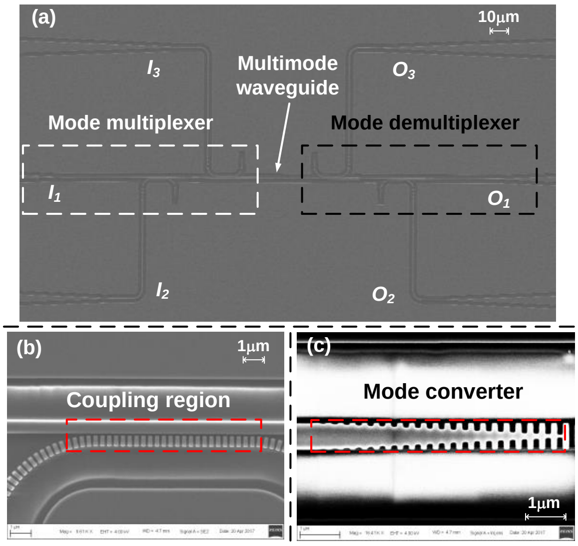

Fig. 3: (a) SEM image of the fabricated SWG-based three-mode (de)multiplexer; zoom-in images of the (b) coupling region, (c) mode converter region.

In order to couple the fundamental TE_0-polarized light into and out of the chip using grating couplers, a mode de-multiplexer is added to the output port of the multimode bus waveguide of the mode multiplexer. Scanning electron microscope (SEM) images of a fabricated device including a mode multiplexer, a multimode waveguide and a mode de-multiplexer are shown in Fig. 3(a). Fig. 3(b) and 3(c) show the magnified photos of the coupling region and a mode converter between a silicon strip waveguide and a SWG waveguide. The footprint of the three-mode multiplexer is less than 88 × 20 μm^2. A tunable continuous wave (CW) laser (Keysight 81960A) and an optical power meter were used to characterize the devices. The transmission spectra of the mode (de)multiplexers were measured and normalized to that of identical grating couplers fabricated on the same wafer.

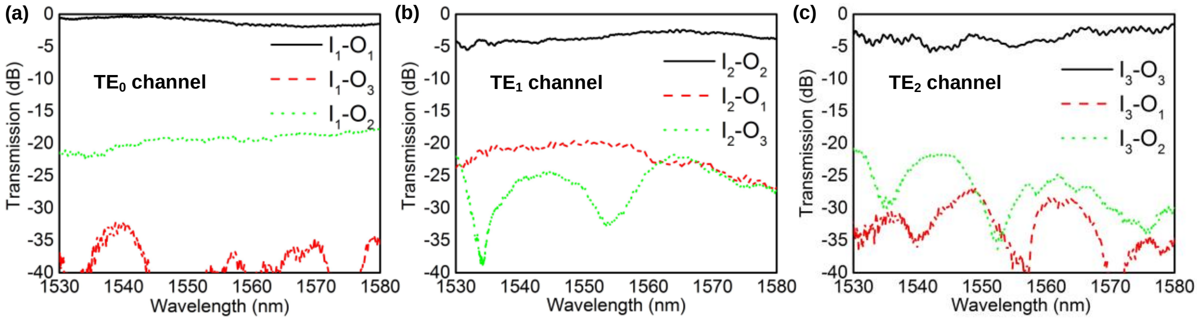

Fig. 4: Measured transmission responses at output ports O_i (i=1, 2, 3) with the light input from port: (a) I_1, (b) I_2, (c) I_3, respectively.

Experimental results

Figure 4 shows the measured transmission responses and modal crosstalk values of the fabricated mode (de)multiplexers. It can be seen that the signal outputs from the corresponding output port. For example, when the light is input to port I_1 of the multiplexer, the signal outputs from the port O_1. The insertion loss is about 0.8 dB and the crosstalk values are lower than -18.6 dB at 1550 nm. For the TE_1 and TE_2 channels, the insertion losses are relatively high. This is mainly caused by introducing the bend SWG waveguides. We measured the performance of the SWG bend structure, the average bend loss is about 1.25 dB per 90°, while the coupling losses between the SWG access waveguides and the multimode bus waveguide are lower than 1 dB. For all the three channels, the overall insertion losses are lower than 3.8 dB, and the crosstalk values are below -16.3 dB at 1550 nm. In the wavelength range of 1530 nm to 1580 nm, the overall insertion losses are lower than 5.4 dB, and the crosstalk values are below -15.7 dB. The losses can be further reduced by optimizing the SWG parameters to minimize the scattering.

Conclusion

We have experimentally demonstrated a silicon three-mode (de)multiplexer based on the SWG structure. The proposed mode (de)multiplexer consists of two cascaded SWG-based DCs, it can (de)multiplex three mode channels of TE_0 - TE_2. For all the three channels, the insertion losses are lower than 3.8 dB, and the crosstalk values are below -16.3 dB at 1550 nm. The losses are mainly attributed to the bend SWGs, which can be further optimized to reduce the scattering.

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