Ultra-Compact Silicon TE-Polarized Mode Converters Combining a Directional Coupler and a Phase Shifter

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Abstract: A new concept for ultra-compact and broadband mode-order converters is proposed and several design examples are given and experimentally demonstrated. © 2019 The Author(s)

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1. Introduction

Multimode silicon photonics has attracted more and more attention owing to its potential in the fields of optical information processing, which can increase the channel number for data transmission in mode-division-multiplexed (MDM) systems [1]. The MDM method utilizes the orthogonality of the different eigenmodes in a waveguide to multiplex the information over multimode waveguides. Consequently, a key component in MDM systems is mode converter that can transform a given mode into another desired mode. Recently, several different kinds of silicon on-chip mode converters have been proposed. For examples, mode converters based on Mach–Zehnder interferometer assisted by a phase shifter can strongly control the guided modes with a clear principle but usually require relatively large footprints [2]. Although mode converters implemented with dielectric metasurface structure can achieve small footprints, its operation bandwidth is relatively narrow [3]. Both compact and broadband mode converters based on substrip dielectric waveguides have been proposed lately, but suffer from high insertion loss [4]. While others exploiting e.g., compact tapers [5], Y-splitter [6], high-index-contrast polygonal slot [7], etc. also cannot well address the challenges like the large device footprints, high insertion loss and limited operation bandwidth simultaneously.

In this paper, we propose and experimentally demonstrate a new type of mode converters based on the structure combining a directional coupler (DC) and a tapered phase shifter (PS) as an alternative to solve these problems. These devices have ultra-small footprints, high mode conversion efficiency and low modal crosstalk over broadband bandwidths.

2. Design principle and simulation result

Fig. 1(a)-(d) depict the 3D and top views of the mode converters that convert the TE0 mode to the TE1 and the TE2 mode with all-etched silica slots.

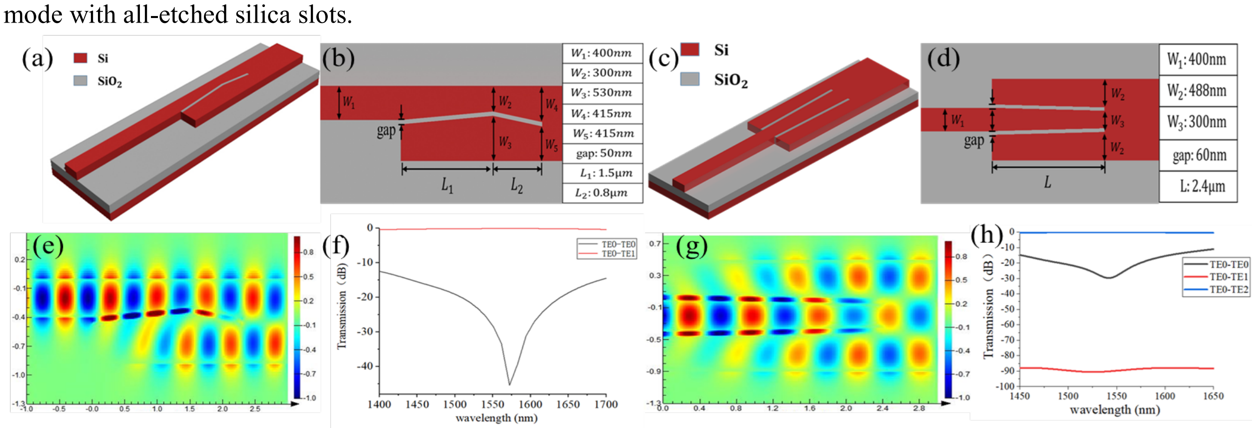

Fig. 1. (a) 3D view (b) top view with detailed parameters of the proposed TE0-to-TE1 mode-order converter. (c) 3D view (d) top view with detailed parameters of the proposed TE0-to-TE2 mode-order converter. (e) simulated Ey distribution (f) simulated transmission curves of the TE0-to-TE1 mode-order converter. (g) simulated Ey distribution (h) simulated transmission curves of the TE0-to-TE2 mode-order converter.

The operation principle with Fig. 1(a) is as follows: Light can be focused into the upper waveguide at the beginning. As the light wave propagates, the mode in the upper waveguide can be coupled into the mode in the bottom waveguide. When the propagation distance is 2.3 μm, around 50% power transfers into the bottom waveguide. Besides, as shown in [8], a tapered structure can serve as a wavelength insensitive PS. When the waveguide width becomes narrower, the effective index gets smaller, which equals providing the bottom waveguide with the delay line. Thus, the phase difference between the lights through the upper and the bottom waveguide can be controlled by adjusting W_2 and W_3 of the PS. By this means, the phase difference of π can be achieved and then the TE1 mode was formed at the end. To verify the scalability of our proposed structure, we also demonstrate the mode converter that converts the TE0 mode to the TE2 mode with Fig.1(c) and (d). The power of light is divided into three equal parts by DC and the phase difference of π between each pair of the neighboring waveguides is also achieved by adjusting the width of the waveguides in order to form the TE2 mode.

The three-dimensional finite-difference time-domain (3D-FDTD) method is implemented to simulate the performance of the devices. Fig. 1(e) and (f) show the simulated electric field distribution and the curves of transmission spectra for the TE0-to-TE1 mode converter, respectively. With a small footprint of 0.88×2.3 μm^2, the TE0-to-TE1 mode converter realizes high mode conversion efficiency of 97% and low modal crosstalk of -28.4dB at 1550 nm. Meanwhile, its insertion loss is below than 0.5 dB and crosstalk lower than -12 dB over a broad bandwidth of 300 nm (1400–1700 nm), which is compatible with wavelength division multiplexing system. Furthermore, Fig. 1(g) and (h) also present the electric field distribution and simulated transmission spectra of the TE0-to-TE2 mode converter with low insertion loss of 0.18dB, broad bandwidth(1450-1650nm) and a small device footprint of 1.396×2.4 μm^2.

3. Fabrication and experiments

The devices were fabricated on an SOI platform with 220 nm top silicon employing e-beam lithography (Vistec EBPG 5200+) and inductively coupled plasma etching (SPTS DRIE-I). To measure the insertion loss and crosstalk of fabricated devices, mode (de)multiplexers based on asymmetrical directional couplers in [9] are cascaded. Fig. 2(a) and (b) show the optical microscope photos of the fabricated structures. The measured transmission responses of the TE0-to-TE1 mode converter and TE0-to-TE2 mode converter are displayed in Fig.2(c) and (d), respectively. The insertion loss is below than 0.5 dB and crosstalk is around 10 dB for both devices. It largely conforms to our simulation results expect for the relatively high crosstalk which may be attributed to the resonances formed by the mode (de)multiplexers introduced to test our devices after analysis. Although our devices manifest large bandwidth in simulation, the limited operation bandwidth (1520-1570 nm) of the mode (de)multiplexers constraints the bandwidth of our measured spectra. Then the next step is to improve our test method for more accurate results.

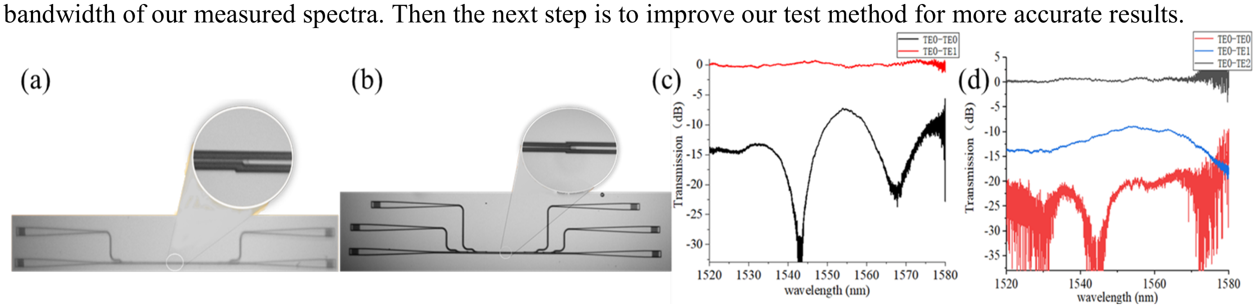

Fig. 2. Optical microscope photo of the fabricated (a) TE0-to-TE1 mode converter (b) TE0-to-TE2 mode converter. Measured transmission spectra of the fabricated (c) TE0-to-TE1 mode converter (d) TE0-to-TE2 mode converter.

4. Discussion

To show the scalability of our model for TE-polarized mode converters, we demonstrate a two-stage TE0-to-TE3 mode converter in Fig. 3.

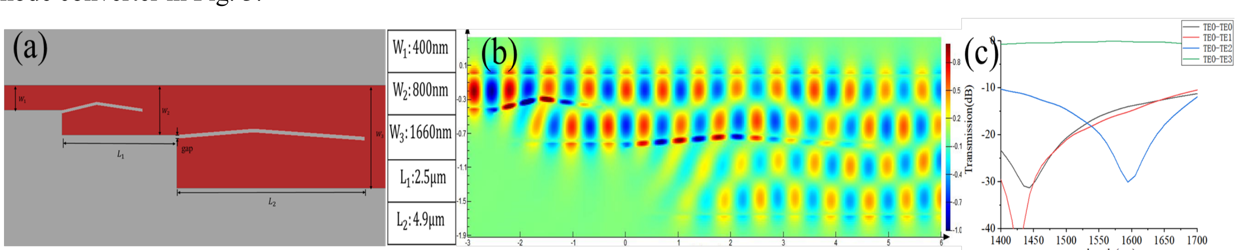

Fig. 3. The TE0-to-TE3 two-stage mode converter's (a) top view (b) simulated Ey distribution. (c) transmission spectra

A similar structure is cascaded after the TE0-to-TE1 mode converter analyzed above to realize the TE0-to-TE3 mode conversion. Fig. 3(b) depicts the simulated electric field distribution. The input TE0 mode is converted to the TE1 mode in the first stage. Subsequently, the TE1 mode is coupled into the bottom waveguide and evolves into the

TE3 mode when the phase difference of π is achieved at the end of second stage. The transmission spectra in Fig. 3(c) present this device has low insertion loss of 0.2 dB and low crosstalk of -16 dB with the length of 7.4 µm. Furthermore, this method can be scaled to realize higher-order mode converters effectively.

5. Conclusion

Table 1. Comparison of several different mode converters and our devices

Structure	Device function	L (µm)	IL (dB)	CT (dB)	BW (nm)
Metasurface[3].	TE0-to-TE1/TE2(E)	5.75/6.736	< -1	< -10	1540-1565
substrip dielectric waveguides [4].	TE0-to-TE1/TE2(E)	2.635/2.27	-2.1/-1.37	-13.4/-12.6	1535-1580
Compact tapers [5].	TE0-to-TE1/TE2(T)	18.6/19.3	-0.1/-0.12	-	1520-1580
Y-junction [6].	TE0-to-TE1(T)	36	-0.84	-20	1400-1700
Polygonal slot [7].	TE0-to-TE1(T)	24	-0.105	-20	1500-1600
Our work in simulation	TE0-to-TE1/TE(T)	2.3/2.4	-0.11/-0.18	-28/-26	1400-1700/1450-1650
Our work in experiment	TE0-to-TE1/TE(E)	2.3/2.4	< -0.5	-10	1520-1580

E, experiment; T, theory; L, length; IL, insertion loss; CT, crosstalk; BW, bandwidth.

Table 1 compares the performance of our devices with several other mode converters. It indicates that our proposed TE0-to-TE1 and TE0-to-TE2 mode converters are competitive candidates in MDM systems. In summary, we demonstrate a new type of silicon mode converters consisting of a DC and a PS. These devices have low insertion loss and crosstalk as well as small footprints over a broad bandwidth. Meanwhile, the experimental results largely agree with the simulation for both TE0-to-TE1 and TE0-to-TE2 mode converters. The relatively high crosstalk and limited bandwidth can be mainly attributed to the mode (de)multiplexers introduced to test our devices, which can be further improved by altering our test method.

6. References

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