Compact Silicon Waveguide Mode Converter Employing Dielectric Metasurface Structure

Hongwei Wang, Yong Zhang,* Yu He, Qingming Zhu, Lu Sun, and Yikai Su*

Mode converters are key components in on-chip mode-division-multiplexing systems. A compact silicon waveguide mode converter is proposed and demonstrated using all-dielectric metasurface structure with a tilted subwavelength periodic perturbation. The proposed waveguide mode converter can be scaled to realize arbitrary waveguide mode conversion. As examples, two waveguide mode converters are experimentally demonstrated on a silicon-on-insulator wafer, which can convert the TE0 mode to the TE1 mode and the TE2 mode with coupling lengths of 5.75 and 6.736 μm, respectively. The conversion losses of <1 dB and crosstalk values of <-10 dB are achieved for both the TE0-to-TE1 and the TE0-to-TE2 mode converters.

Advanced multiplexing technologies have been explored to increase data carrying capacity for optical communications and optical information processing.[1–4] On-chip mode-division-multiplexing (MDM) technology, which leverages the spatial modes of multimode waveguides,[5–10] allows significant scaling of transmission capacity. Benefitting from its compact footprint and compatibility with the complementary metal-oxide-semiconductor (CMOS) fabrication process, silicon on-chip MDM has attracted much attention. Various MDM devices have been demonstrated on a silicon-on-insulator (SOI) platform, such as mode (de) multiplexers,[9,10] mode converters,[11,12] multimode waveguide bends,[13] and mode-selective switches.[14–17] Among them, mode converters are key components in MDM systems. Many silicon on-chip mode converters have been proposed based on phase matching,[9–11] coherent scattering,[12–14] and beam shaping.[15–17] However, these structures may face the challenges of large footprints, limited operation bandwidth, and relatively large insertion losses. Metasurfaces are 2D artificial materials with subwavelength feature, allowing complete control of the phase, amplitude, and polarization of light beams.[18–24] Integrated optical waveguides with metasurface structures can help address these challenges. Recently, waveguide mode converters were realized based on gradient metasurface structures consisting of arrays of plasmonic or dielectric nanoantennas.[20] Mode conversions between the trans-electric (TE) modes TE0, TE1, and TE2 were achieved with a length of ~30 μm at 1550 nm using silicon nanoantennas on LiNbO3 or Si3N4 waveguides by simulations.[20] A nanoscale mode converter was theoretically proposed[11] and experimentally demonstrated[21] by introducing a periodic perturbation in its effective index along the propagation direction and a graded effective index profile along its transverse direction. Mode conversion between TE0 and TE1 modes was successfully achieved with a length of 23 μm at 1550 nm. However, no experimental results on the crosstalk of the TE mode conversion were provided in the previous reports.[20,21] It is highly desired to miniaturize the device footprint and realize a compact waveguide mode converter.

In this article, we propose and demonstrate a compact silicon waveguide mode converter based on all-dielectric metasurface structure with a tilted subwavelength periodic perturbation. The mode coupling coefficient changes along the propagation direction, which can help the mode conversion process. Our proposed waveguide mode converter can be scaled to realize arbitrary waveguide mode conversion. As examples, we experimentally demonstrate two silicon waveguide mode converters employing all-dielectric metasurface structures that can convert TE0 mode to TE1 mode and TE0 mode to TE2 mode, respectively. The mode conversion lengths are 5.75 and 6.736 μm for the TE0-to-TE1 and TE0-to-TE2 waveguide mode converters, respectively, which are shorter than previously reported results.[20,21] Mode multiplexers are cascaded after the metasurface mode converter to measure the crosstalk values and conversion losses. The insertion losses are lower than 1 dB and the crosstalk values are below −10 dB in a wavelength range of 20 nm for the TE0-to-TE1 and TE0-to-TE2 waveguide mode conversions.

Figure 1a depicts the 3D view of the proposed waveguide mode converter based on dielectric metasurface structure with a tilted subwavelength periodic perturbation. Propagation of optical field in a perturbed dielectric structure can be described by the coupled mode theory. Associated to the perturbation on the silicon waveguide, one waveguide mode can be coupled into another mode, and the amplitude of each waveguide mode along the propagation direction is determined by a set of differential equations[11,25]

$$\frac{\partial A}{\partial z} = jk_{0} E_{x} e^{-j(\beta_{x} z)}$$

$$\frac{\partial B}{\partial z} = jk_{0} E_{y} e^{-j(\beta_{y} z)}$$

(1)
where $A$ and $B$ are the amplitudes of waveguide modes $a$ and $b$, respectively, $\beta_a$ and $\beta_b$ are the propagation constants of waveguide modes $a$ and $b$, $\kappa_{ab}$ and $\kappa_{ba}$ represent the exchange coupling coefficients between waveguide modes $a$ and $b$. The mode coupling coefficient can be defined asef{11,25}

$$
\kappa_{ab}(x) = \frac{\alpha}{4} \int S(x,y,z) \Delta \varepsilon \Delta \delta (x,y,z) dxdy
$$

(2)

where $E_a(x,y)$ and $E_b(x,y)$ are the electric field profiles of waveguide modes $a$ and $b$, respectively, $S$ is the cross section of the silicon waveguide, $\Delta \varepsilon(x,y,z)$ is the periodic perturbation in the dielectric waveguide.

Based on Equations (1) and (2), the phase matching condition for the mode coupling between the TE$_0$ and TE$_j$ mode along the propagation direction $z$ isef{11}

$$
\delta = \frac{2\pi}{\beta_a - \beta_b}
$$

(3)

where $\delta$ is the period of the periodic perturbation $\Delta \varepsilon(x,y,z)$. According to Equation (2), the value of $\kappa_{ab}$ is related to $\Delta \varepsilon(x,y,z)$, which depends on the cross section of the waveguide. As shown in the insets of Figure 1a, the cross section of the waveguide changes along the propagation direction in the proposed parallelogram metasurface structure. Figure 1b shows the calculated mode coupling coefficient and mode purity of the TE$_0$ and TE$_1$ modes along the propagation direction $z$. The TE$_0$ mode is gradually converted to the TE$_1$ mode with $\kappa_{01}$ changing as a sinusoidal-like function along the propagation direction. According to the phase matching condition, the TE$_0$ mode and the TE$_1$ mode will be out of phase after propagation over $\delta/2$. Therefore, changing $\kappa_{01}$ from positive to negative value is required after $\delta/2$ to ensure that the TE$_0$ mode always contributes constructively to the conversion to the TE$_1$ mode. Multiple periods of $\kappa_{ab}$ are needed for mode conversion in the parallelogram metasurface structure. For mode coupling between the TE$_0$ and TE$_j$ modes, the period number of $\kappa_{0j}$ should be $(j+1)/2$, which is related to the field distribution $E_j(x,y)$ of the TE$_j$ mode. So the coupling length is

**Figure 1.** a) Schematic configuration for the proposed waveguide mode converter. Insets show the cross sections at point I, II, and III, respectively. b) Calculated $\kappa_{01}$ between waveguide modes TE$_0$ and TE$_1$ (black thick curve) and the mode purity of TE$_0$ mode (red dash-dotted curve) and TE$_1$ mode (blue thin curve) along the propagation direction $z$. The design parameters of the structure are: period $\Lambda = 400$ nm, period number $n = 5$, the length of the metasurface structure $L = 5.75$ $\mu$m, and the width of waveguide $w = 1100$ nm.

**Figure 2.** a) Top view of schematic configuration and b) simulated $E_y$ distribution for the proposed TE$_0$-to-TE$_1$ mode converter. c) Top view of schematic configuration and d) simulated $E_y$ distribution for the proposed TE$_0$-to-TE$_2$ mode converter.

**Table 1.** Detailed design parameters for the proposed mode converters.

<table>
<thead>
<tr>
<th>Mode converter</th>
<th>Width ($w$) [nm]</th>
<th>Period ($\Lambda$) [nm]</th>
<th>Length ($L$) [$\mu$m]</th>
<th>Angle ($\theta$) [degree]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE$_0$-to-TE$_1$</td>
<td>1100</td>
<td>400</td>
<td>5.75</td>
<td>15.5</td>
</tr>
<tr>
<td>TE$_0$-to-TE$_2$</td>
<td>1400</td>
<td>400</td>
<td>6.736</td>
<td>15.85</td>
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$(j + 1)\delta/2$ and the angle of the parallelogram can be calculated as $\theta = \arctan[2w/((j + 1)\delta)]$. For the TE$_0$-to-TE$_1$ and TE$_0$-to-TE$_2$ mode converters, the theoretical results of $\theta$ are 11.3$^\circ$ and 17.3$^\circ$ with $\delta = 5.535 \, \mu$m and $\delta = 3.229 \, \mu$m, respectively. The period of the metasurface structure is 400 nm. The feature size ($w$), as shown in Figure 2a, is smaller than 50 nm if $\theta$ is 11.3$^\circ$, which is difficult to fabricate in our lab. So $\theta$ is selected to be larger than 14.5$^\circ$ in our experiment to relax the fabrication process. Fortunately, the devices show large tolerance to $\theta$ variation. Based on such a design specification, we provided design parameters and simulation results of TE$_0$-to-TE$_j$ ($j = 3, 4$) mode converters in Table S1 and Figure S1 in the Supporting Information, respectively.

Figure 2a shows the top view of the proposed TE$_0$-to-TE$_1$ mode converter. Tilted subwavelength periodic perturbations with parallelogram shapes are etched on a silicon waveguide to

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<tbody>
<tr>
<td>TE$_1$</td>
<td>1100</td>
<td>540</td>
<td>100</td>
<td>57</td>
</tr>
<tr>
<td>TE$_2$</td>
<td>1400</td>
<td>468</td>
<td>110</td>
<td>40</td>
</tr>
<tr>
<td>TE$_3$</td>
<td>1900</td>
<td>463</td>
<td>100</td>
<td>29</td>
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Figure 3. a) Optical microscope photo and b) SEM image of the fabricated TE$_0$-to-TE$_1$ mode converter. c) Optical microscope photo and d) SEM image of the fabricated TE$_0$-to-TE$_2$ mode converter. e) Magnified SEM image of the metasurface structure.

Figure 4. Measured transmission spectra of a) a fabricated TE$_0$-to-TE$_1$ mode converter, b) a fabricated TE$_0$-to-TE$_2$ mode converter.
form dielectric metasurface structures. The width of the silicon waveguide is 1100 nm. The period, duty cycle, etch depth, and angle of the perturbations are 400 nm, 50%, 95 nm, and 15.5°, respectively. The length of the metasurface structure is 5.75 µm. 3D finite-difference time-domain (3D FDTD) method is used to simulate the electric field ($E_y$) distribution, as shown in Figure 2b. If the TE0-mode light is launched into the input port, the light is coupled and converted to the TE1 mode.

To verify the scalability of our proposed metasurface structure, we also demonstrate a TE0–TE2 mode converter. Figure 2c,d shows the top view and simulated $E_y$ distribution of the proposed TE0-to-TE2 mode converter. Tilted subwavelength

Figure 5. Simulation results to study the fabrication tolerance. a–d) The transmission loss and crosstalk by changing the angle, period, etch depth, and duty cycle for TE0-to-TE1 mode converter. e–h) The transmission loss and crosstalk by changing the angle, period, etch depth, and duty cycle for TE0-to-TE2 mode converter. The solid curves represent the simulation results, the red circles represent parameters we used in the experiment.

Table 3. Comparison of various mode converters.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Device length [µm]</th>
<th>Device function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodically structured</td>
<td>22.5</td>
<td>TE₂-to-TE₁ (Experiment)</td>
</tr>
<tr>
<td>waveguide[21]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase-gradient</td>
<td>5.4/8.4</td>
<td>TE₂-to-TE₁/TE₂ (Theory)</td>
</tr>
<tr>
<td>metasurface[22]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microring resonator[7]</td>
<td>25</td>
<td>TE₂-to-TE₁ (Experiment)</td>
</tr>
<tr>
<td>Directional coupler[23]</td>
<td>30</td>
<td>TE₂-to-TE₁ (Experiment)</td>
</tr>
<tr>
<td>Mach–Zehnder</td>
<td>18</td>
<td>TE₂-to-TE₁ (Experiment)</td>
</tr>
<tr>
<td>interferometer[24]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compact waveguide taper[25]</td>
<td>20</td>
<td>TE₁/TE₂-to-TE₃ (Theory)</td>
</tr>
<tr>
<td>Our work</td>
<td>5.75/6.74</td>
<td>TE₂-to-TE₁/TE₂ (Experiment)</td>
</tr>
</tbody>
</table>

periodic perturbations are etched on a silicon waveguide. The period, duty cycle, etch depth, and angle of the perturbations are 400 nm, 50%, 90 nm, and 15.85°, respectively. The detailed design parameters are provided in Table 1. If the TE₀-mode light is injected into the input port, the light is converted to the TE₂ mode over a conversion length of 6.736 µm.

In the experiment, the proposed metasurface mode converters were fabricated on a SOI wafer (220 nm thick silicon on 3000 nm thick silica). Grating couplers, silicon waveguides, and tilted periodic structures were patterned and etched by e-beam lithography (Vistec EBPG 5200) and inductively coupled plasma etching (SPTS DRIE-I). A tunable continuous wave laser (Keysight B1960A) and an optical power meter (Keysight N7744A) were used to characterize the mode converter devices. The grating couplers were used to couple the light into/out of the chip. The period and duty cycle of the grating coupler are 630 nm and 50%, respectively. The etching depth is 70 nm. The coupling loss was 7.7 dB/port at the central wavelengths of the grating coupler.

Figure 3a,c shows the optical microscope photos of the fabricated TE₀-to-TE₁ and TE₀-to-TE₂ mode converters, respectively. To characterize the conversion losses and crosstalk values of the fabricated mode converters, modes (de)multiplexers based on asymmetrical directional couplers[10,20] are cascaded after the mode converters to recover the output higher-order mode signals to TE₀ modes for the measurements. The detailed parameters for the mode (de)multiplexers are shown in Table 2. The measured insertion losses of the fabricated mode (de)multiplexers for TE₁, TE₂, TE₃ (de)multiplexing are 4, 9.7, and 8 dB at λ = 1550 nm, respectively. The mode demultiplexers exhibit low intermodal crosstalk and significant mode dependence. The scanning electron microscope (SEM, ZEISS) photos of the fabricated TE₀-to-TE₁ and TE₀-to-TE₂ mode converters are shown in Figure 3b,d,e, respectively.

The measured transmission responses of the fabricated TE₀-to-TE₁ and TE₀-to-TE₂ mode converters are shown in Figure 4a and 4b, respectively. The transmission spectra were normalized to that of the identical grating couplers or the mode (de)multiplexers fabricated on the same wafer. For the TE₀-to-TE₁ mode converter, the TE₀-to-TE₁ mode conversion loss is lower than 1 dB and the crosstalk value is below −10 dB in the wavelength range of 1542–1563 nm. For the TE₀-to-TE₂ mode converter, the TE₀-to-TE₂ mode conversion loss is <0.5 dB and the crosstalk value is <−10 dB in the wavelength range of 1545–1565 nm. The dashed curves in Figure 4 represent the simulated responses of the mode converters using 3D FDTD methods. The discrepancy between the experimental and simulation results may be mainly attributed to the variation of etching depth caused by fabrication errors.

As shown in Figure 5, to investigate the fabrication tolerance, we simulated the transmission responses of the devices with different periods, duty cycles, etch depths, and angles by 3D FDTD methods, respectively. For the TE₀-to-TE₁ mode converter, in the range of 11° < θ < 16°, 300 nm < Λ < 800 nm, etch depth varying from 90 to 110 nm and the duty cycle larger than 45%, the insertion losses are <1 dB and the crosstalk values are below −10 dB at λ = 1550 nm. For the TE₀-to-TE₂ mode converter, the insertion losses are less than 1.5 dB and the crosstalk values are below −10 dB at λ = 1550 nm with 15° < θ < 17.6°, Λ < 450 nm, etch depth varying from 90 to 100 nm, and the duty cycle larger than 40%. The simulation results indicate that the devices are tolerant to the variation of period, duty cycle, etch depth, and angle.

Table 3 compares our device with various mode converters with dielectric materials. It indicates that the length of the mode converter is shorter than the previously reported experimental results.

We have proposed and experimentally demonstrated a compact silicon waveguide mode converter implemented with all-dielectric metasurface structure. Attributed to the tilted subwavelength perturbation on the silicon waveguide, the mode coupling coefficient changes along the propagation direction, which can help the mode conversion process. Our proposed waveguide mode converter can be scaled to realize higher-order waveguide mode conversions. Two silicon waveguide mode converters employing all-dielectric metasurface structures are experimentally demonstrated, which can convert TE₀ mode to TE₁ mode and to TE₂ mode, respectively. The mode conversion lengths are 5.75 and 6.736 µm for the TE₀-to-TE₁ and TE₀-to-TE₂ waveguide mode converters, respectively. For the TE₀-to-TE₁ mode converter, the conversion loss is lower than 1 dB, and the crosstalk value is below −10 dB in the wavelength range of 1542–1563 nm. For the TE₀-to-TE₂ mode converter, the conversion loss of <0.5 dB and crosstalk value of <−10 dB are achieved in the wavelength range of 1545–1565 nm. The demonstrated coupling and conversion of waveguide modes provide a general method to manipulate on-chip optical modes, and may find applications in integrated mode-division communication and optical signal processing systems.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords
dielectric metasurface, integrated devices, mode converters, silicon

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