Ultra-Compact Silicon Mode Converter Based on a Zigzag-type Metasurface Structure

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Abstract: An ultra-compact silicon waveguide mode converter is proposed and experimentally demonstrated using an all-dielectric metasurface structure with zigzag-type periodic perturbations. © 2021 The Author(s)

1. Introduction

On-chip silicon mode division multiplexing (MDM) technology is a promising solution for high-capacity integration, which exhibits compact footprint and compatibility with complementary metal oxide semiconductor (CMOS) fabrication [1,2]. A mode converter, which is capable of converting one selected waveguide mode to another, is one of the key components in MDM systems. Recently, many silicon on-chip mode converters were proposed based on phase matching [3], coherent scattering [4], and beam shaping [5]. However, these devices may face the challenges of large footprints, limited operation bandwidths and relatively high insertion losses. Several waveguide-based mode converters were realized based on the phase-gradient metasurfaces [6], periodic perturbed nanoscale waveguides [7] and tilted sub-wavelength periodic perturbation structures [8]. It is highly desired to further shrink the device footprint and realize a high-order waveguide mode converter.

In this paper, we propose and demonstrate an ultra-compact mode converter based on an all-dielectric metasurface structure. By introducing a zigzag-type periodic perturbation, the distribution of the mode coupling coefficients along the propagation direction can be manipulated, thus a high-efficient mode conversion can be achieved with a compact footprint. As a proof-of-concept experiment, two silicon waveguide mode converters are demonstrated, which can convert the TE₀ mode to TE₁ and TE₂ modes, respectively. The device lengths are 3.71 μm and 3.45 μm for the TE₀-to-TE₁ and TE₀-to-TE₂ waveguide mode converters, respectively. The insertion losses are lower than 1 dB and the crosstalk values are below -10 dB in a wavelength range of 30 nm and 20 nm for the TE₀-to-TE₁ and TE₀-to-TE₂ mode converters, respectively. Our proposed mode converter has the potential to be scaled to realize an arbitrary high-order mode conversion. For example, the simulated conversion efficiencies for the TE₀-to-TE₂ and TE₀-to-TE₁₂ mode converters are 74.5% and 73%, respectively.

2. Device design and simulation

The 3D view of the proposed waveguide mode converter is shown in Fig. 1(a). Dielectric metasurface structure is introduced to assist the mode conversion. By adopting a zigzag-type sub-wavelength periodic perturbation, the overlap of the mode profiles between two waveguide modes can be increased, thus a high-efficient mode conversion can be achieved. According to the coupled mode theory, the conversion between two waveguide modes is described by the following equations [9]:

\[ -\frac{\partial A}{\partial z} = j\kappa_{ab}B e^{j(\beta_a - \beta_b)z} , \quad -\frac{\partial B}{\partial z} = j\kappa_{ba}A e^{-j(\beta_a - \beta_b)z} , \tag{1} \]

where A and B are the amplitudes of waveguide modes a and b, respectively. \( \kappa_{ab} \) and \( \kappa_{ba} \), which are related to the periodic perturbation \( \Delta \epsilon(x, y, z) \), represent the exchange coupling coefficients between modes a and b. Based on Eq. (1), the phase matching condition for the mode conversion between mode a and mode b is [9]

\[ \delta = \frac{2\pi}{\sqrt{(\beta_a - \beta_b)^2 + 4\kappa_{ab}^2}} , \tag{2} \]

where \( \delta \) is the period of the \( \Delta \epsilon(x, y, z) \). In this work, a zigzag-type metasurface structure is utilized. Sharp turns are placed by referring to the electric field distributions of the target modes, as shown in Figs. 2(a-d), to maximize the overlapping between the input mode and the target mode. Here, we take the coupling process of the TE₀-to-TE₂ converter as an example. As shown in Fig. 1(b), the TE₀ mode is gradually converted to the TE₂ mode with \( \kappa_{02} \) changing as a sinusoidal function along the propagation direction. After propagating over \( \delta/2 \), the TE₀ mode and the
TE₂ mode will be out of phase. Thus, it is necessary to change \( \kappa_{02} \) from a negative value to a positive value to ensure that the TE₀ mode can always constructively facilitate the conversion to the target mode.

By properly designing the structure of the periodical perturbation, the maximum value of \( \kappa_{0j} \) can be obtained, which leads to an ultra-compact footprint. The coupling length is \( L = \delta + n \cdot \Lambda \) and the angle of the parallelogram can be calculated as \( \theta = \arctan[n/(j + 1)\delta]. \) The number of sharp angles (\( \alpha \)) and the order of the transformed mode (\( j \)) satisfy \( \alpha = j+1. \) For the TE₀-to-TE₁ and TE₀-to-TE₂ mode converters, the theoretical results of \( \theta \) are 17.8° and 18.75° with \( \delta = 2.747 \) μm and \( \delta = 2.838 \) μm, respectively.

Figs. 2(a-d) show the top view of the schematic of the proposed TE₀-to-TE₁, TE₀-to-TE₂, TE₀-to-TE₃ and TE₀-to-TE₁₂ mode converters. Detailed design parameters of mode converters are provided in Table 1. Figs. 2(e-h) show the top view of simulated electric field (\( E_z \)) distribution of the proposed three mode converters. The simulated mode purity of the four mode converters are 76%, 84.2%, 74.5% and 73% at \( \lambda = 1550 \) nm, respectively.

<table>
<thead>
<tr>
<th>Mode converter</th>
<th>Width (μm)</th>
<th>Period (nm)</th>
<th>Duty</th>
<th>( n )</th>
<th>( \theta (°) )</th>
<th>Etching depth</th>
<th>Length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE₀-to-TE₁</td>
<td>1.1</td>
<td>400</td>
<td>75%</td>
<td>5</td>
<td>20</td>
<td>120</td>
<td>3.71</td>
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<tr>
<td>TE₀-to-TE₂</td>
<td>1.8</td>
<td>400</td>
<td>50%</td>
<td>5</td>
<td>20</td>
<td>120</td>
<td>3.45</td>
</tr>
<tr>
<td>TE₀-to-TE₃</td>
<td>5</td>
<td>400</td>
<td>50%</td>
<td>3</td>
<td>16</td>
<td>120</td>
<td>2.98</td>
</tr>
<tr>
<td>TE₀-to-TE₁₂</td>
<td>6.24</td>
<td>400</td>
<td>50%</td>
<td>2</td>
<td>16</td>
<td>120</td>
<td>2.56</td>
</tr>
</tbody>
</table>

3. Device fabrication and measurement results

Multiple devices were fabricated on a SOI platform with a 220-nm thick silicon on top of a 3-μm SiO₂ buried oxide. Grating couplers, silicon waveguides and metasurface structures were patterned using electron beam lithography (Vistec EBPG-5200) and etched by 70nm, 220nm and 120nm, respectively, through inductively coupled plasma (ICP) etching. The scanning electron microscope (SEM) photos and optical microscope photos of the fabricated TE₀-to-TE₁ and TE₀-to-TE₂ mode converters are shown in Figs. 3(a-d), respectively.
Mode de-multiplexers based on asymmetrical directional couplers are cascaded after the mode converters to recover the output high-order mode signals to TE0 modes for the measurements. The measured insertion losses of the fabricated mode de-multiplexers for TE1, TE2, TE3 de-multiplexing are 9.7 dB, 7.4 dB, and 8 dB at $\lambda = 1550$ nm, respectively. The measured transmission responses of the fabricated TE0-to-TE1 and TE0-to-TE2 mode converters are shown in Figs. 3(e) and (f), respectively. The transmission spectra were normalized to that of the grating couplers or mode de-multiplexers fabricated on the same wafer. 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 1525 nm ~ 1555 nm. For the TE0-to-TE2 mode converter, the conversion loss is $<$ 1 dB and the crosstalk value is $<$ -10 dB in the wavelength range of 1535 nm ~ 1555 nm. The dashed curves in Figs. 3(e) and (f) show the simulated responses of the mode converters. The discrepancy between the experimental and simulation results can be mainly attributed to the deviations of the etching depth caused by fabrication imperfections.

4. Conclusion and discussion

We have proposed and experimentally demonstrated a compact silicon waveguide mode converter implemented with all-dielectric metasurface structure. The device lengths are 3.71 $\mu$m and 3.45 $\mu$m for the TE0-to-TE1 and TE0-to-TE2 mode converters, respectively. The conversion losses are lower than 1 dB, and the crosstalk values are below -10 dB in the wavelength range of 1525 nm ~ 1555 nm and 1535 nm ~ 1555 nm, respectively. Our proposed waveguide mode converter can also be scaled to realize higher-order waveguide mode conversions.

5. References


Fig. 3a and 3d show the optical microscope photos of the fabricated TE0-to-TE1 and TE0-to-TE2 mode converters, respectively. Fig. 3b and 3c are the SEM photos of the fabricated TE0-to-TE1 and TE0-to-TE2 mode converters, respectively. Simulated and experimental transmission results of the Fig. 3c: TE0-to-TE1 mode converter and Fig. 3(f): TE0-to-TE1 mode converter.