Scalable Metasurface Building Blocks for Arbitrary On-chip High-order Mode Manipulation

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Abstract *We propose a novel metasurface building block concept to implement arbitrary on-chip high-order mode manipulation with uniform performance. The fabricated TE_0-TE_2 mode operator shows a compact footprint (2.7x1.23 μm^2), low insertion loss (< 1.5 dB), low modal crosstalk (< –15 dB) and broad bandwidth (1520-1580 nm), and can be parallelized to extend for high-order modes.*

Introduction

By leveraging the extra degree of freedom of orthogonal guided-modes in multimode waveguides, mode-division-multiplexing (MDM) technology[1] has attracted extensive attention to further increase the transmission capacity with a single-wavelength carrier. Among plenty of integrated MDM devices, mode converters and mode exchangers are key components for flexible on-chip mode manipulation. A mode converter can transform a given mode into a desired mode, thus laying the foundation to build a practical MDM system. While a mode exchanger can enable the data exchange between two different mode channels, thus utilizing network resources more efficiently and improving the network performance.

Previously, considerable efforts have been made for on-chip mode conversion and mode exchange [2]. The working principles can be generally classified into four categories: phase matching method[3-5], constructive interference of coherent scattering[6, 7], beam shaping technique[8, 9] and metasurface [10, 11]. Mode exchangers are typically implemented with the combination of mode converters, thus making the design complicated[4, 5]. Metasurface has recently emerged as a promising alternative to realize the functionalities of both mode conversion and mode exchange[11]. However, the reported device is intended for a specific mode. As a result, time-consuming optimization iterations have to be done for different target modes. So far, a simple practical scheme for arbitrary high-order (>3) mode manipulation hasn't been demonstrated.

In this paper, we propose a universal methodology to enable efficient on-chip high-order mode manipulation, utilizing the novel concept of metasurface building blocks (BBs). The metasurface BB, i.e., the TE_0-TE_2 mode operator can realize the TE_0-TE_2 and TE_2-TE_0 mode conversion/exchange simultaneously. The fabricated BBs show measured insertion losses (ILs) less than 1.5 dB and modal crosstalk lower than –15 dB from 1520 nm to 1580 nm with compact footprints (2.7x1.23 μm^2). More importantly, arbitrary high-order mode operators with uniform performance as the basic BBs can be easily obtained by parallelizing multiple BBs, which will open the door for various dynamic multimode photonic applications.

Design methodology and building block

We have proved that a dielectric perturbation slot on a silicon waveguide implementing the straightforward beam shaping method can efficiently serve as a mode converter[10]. Now we further extend this concept with metasurface BBs to realize arbitrary on-chip high-order mode manipulation including both conversion and exchange. Actually, we can reasonably consider the n_{th} ($n \geq 1$) order TE mode as a combination of n+1 antiphase adjacent TE_0-like modes. To realize the n_{th}-order mode manipulation, the TE_0 (TE_n) input mode should be split into $n+1$ equal

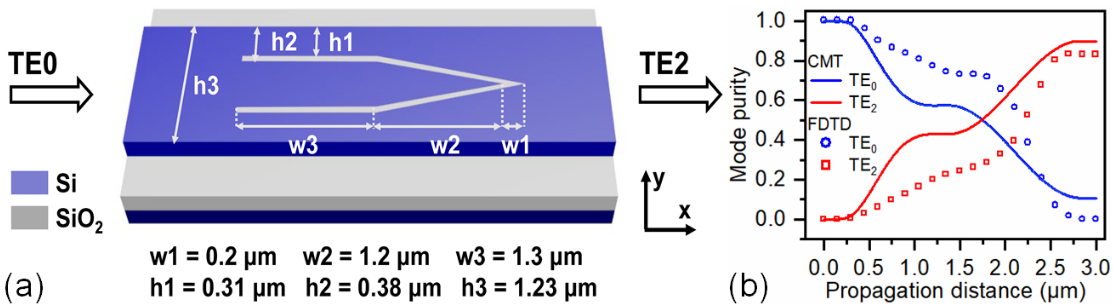

Fig. 1: (a) Schematic of the TE_0-TE_2 mode converter. (b) Theoretical mode conversion calculated by CMT and FDTD.

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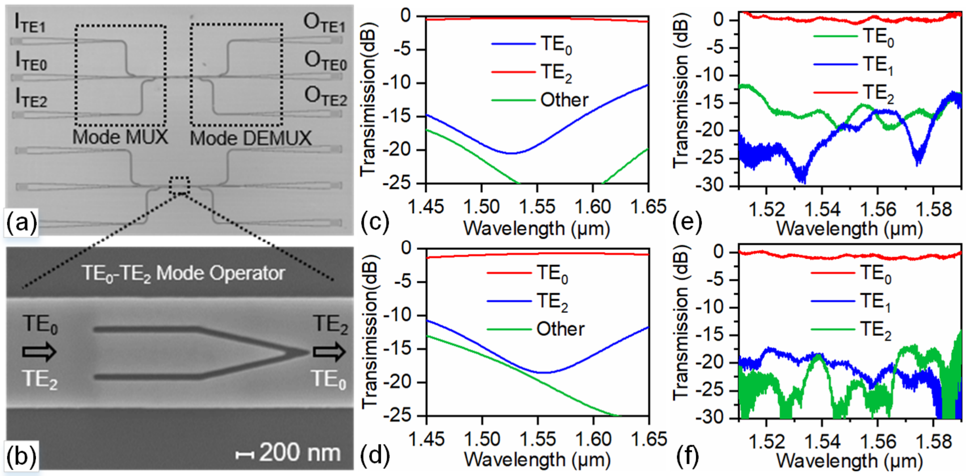

Fig. 2: (a) Microscope photo for the fabricated BBs devices consisting of an ADC mode multiplexer, a TE_0-TE_2 mode operator and an ADC mode demultiplexer. (b) SEM image of the TE_0-TE_2 mode operator. The simulated (c-d) and measured (e-f) transmission spectra of the TE_0-TE_2 mode operator.

parts, which then travel through different effective lengths in the conversion region and achieve the antiphase (in-phase) condition between adjacent components, thus forming the desired TE_n (TE_0) output mode.

The geometry structure of the TE_0-TE_2 mode operator is schematically shown in Fig. 1(a). Dielectric perturbations with a symmetric polygon shape are exploited, which divide the multimode waveguide into three single-mode channels with two straight arms. The input mode will be split into three TE_0-like modes and a π phase difference will be introduced between two adjacent components in this optimized structure, thus efficiently realizing the desired TE_0-TE_2 and TE_2-TE_0 mode conversion at the same time.

3D finite-difference-time-domain (3D-FDTD) simulations are performed to optimize the structure parameters by injecting the TE_0 mode and TE_2 mode, respectively. We try to find the best results in both scenarios, and the final results are presented at the bottom of Fig. 1(a). The evolution of optical field in perturbed silicon waveguides can be described by the coupled mode theory (CMT)[12]. As shown in Fig. 1(b), the mode purity calculated with the CMT model agrees well with the FDTD simulation results. It's clear that the TE_0 mode is gradually converted to TE_2 mode within a short length less than 3 μm.

The simulated transmission spectra are given in Fig. 2(c) and (d). The ILs are below 1.3 dB with the modal crosstalk lower than –10 dB across the broad bandwidth from 1450 nm to 1650 nm accordingly. It's worth noting that the curves 'other' stand for the total crosstalk from all other modes that are not interested as they account for a very low portion. We use this term in the following context.

We fabricate the proposed BBs on a SOI wafer with a 220 nm-thick top-silicon layer and a 3 μm-thick buried dioxide layer. The devices are first patterned using E-beam lithography and fully etched by inductively coupled plasma (ICP, SPTS) etching. A 1-μm-thick SiO_2 cladding layer is then deposited on top of the devices by plasma-enhanced chemical vapor deposition (PECVD). Fig. 2(a) shows the microscope photos of the fabricated BBs devices. Fig. 2(b) is the SEM image of the TE_0-TE_2 mode operator. We use asymmetry directional couplers (ADCs) to characterize the BBs. The transmission spectra are normalized with references of a pair of ADC mode (de)multiplexers on the same chip.

The TE_0-TE_2 and TE_2-TE_0 mode conversion efficiencies are presented in Fig. 2(e) and Fig. 2(f), respectively. When injecting the TE_0 mode, the ILs are below 1.5 dB and the modal crosstalk is lower than –10 dB from 1510 nm to 1590 nm. Besides, modal crosstalk less than -15 dB can be even obtained from 1520 nm to 1580 nm. When injecting the TE_2 mode, the measured ILs are lower than 1.2 dB with the modal crosstalk less than -15 dB in the wavelength range of 1510-1590 nm. Considering the wavelength limitation of the grating couplers, the operation bandwidth can be further improved with edge couplers. This excellent performance of the TE_0-TE_2 BB lays a solid foundation for arbitrary high-order mode manipulation of both conversion and exchange.

Scalability to high-order modes

Following the proposed design methodology, we can further implement arbitrary high-order mode operators by parallelizing a set of TE_0-TE_2 BBs inside waveguides with proper width. Here, we take typical design cases, i.e., the TE_0-TE_4 and the TE_0-TE_3 mode operators as examples to illustrate the generality of the proposed concept.

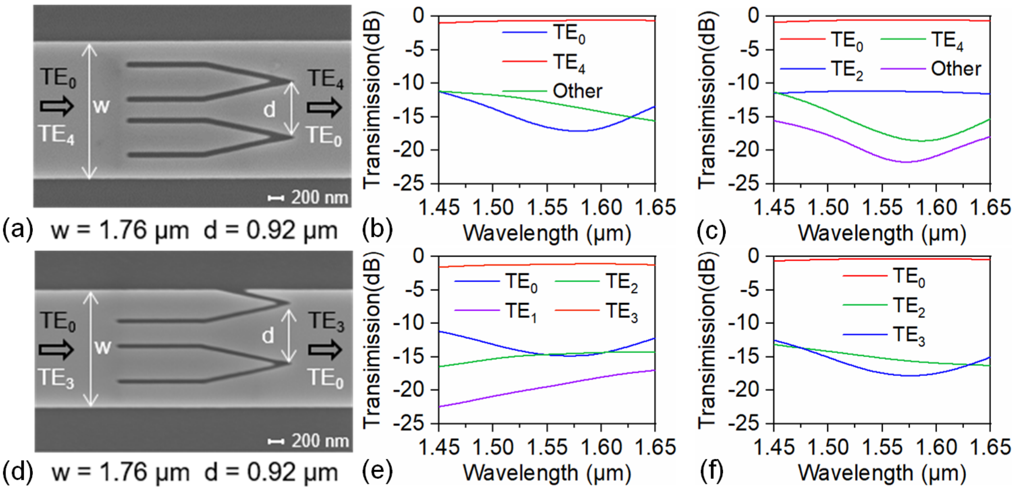

Fig. 3: Geometry structure of (a) the TE_0-TE_4 mode operator and (d) the TE_0-TE_3 mode operator. The simulated mode conversion efficiency of (b-c) the TE_0-TE_4 mode operator and (e-f) the TE_0-TE_3 mode operator.

As presented in Fig. 3(a), two BBs are arranged parallelly to obtain a TE_0-TE_4 mode operator. Due to the fact that the two TE_0-like components on both sides of a single BB have the same phase, we adjust the gap width between two neighboring BBs to form only one waveguide channel, thus maintaining the antiphase relationship between adjacent TE_0-like modes. Consequently, the desired modes can be successfully formed at the end of the conversion region. The optimized waveguide width and central distance between two BBs are 2.22 μm and 0.92 μm, respectively. Figure 3 (b) and (c) show the simulated transmission spectra of TE_0-TE_4 and TE_4-TE_0 mode conversion. The ILs are less than 1 dB and the modal crosstalk is lower than –10 dB in the wavelength range of 1450-1650 nm in both situations.

As shown in Fig. 3(d), we can also obtain the TE_0-TE_3 mode operator on the basis of the TE_0-TE_4 mode operator. To be exact, we directly cut off one waveguide channel by chopping part of the structure on one side of the TE_0-TE_4 mode operator. In this way, the input optical field can evolve into the target mode profile after travelling through the remaining four channels. The optimized width of the truncated part is 0.46 μm, which means the final waveguide width is 1.76 μm. The simulated transmission spectra of TE_0-TE_3 and TE_3-TE_0 mode conversion are depicted in Fig. 3(e) and (f). The performance maintains good with the ILs below 1.6 dB and the modal crosstalk lower than -10 dB from 1450 nm to 1650 nm on both occasions, which is comparable to the TE_0-TE_4 mode operator.

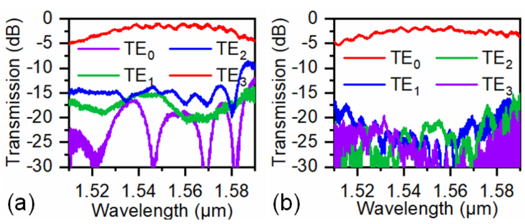

Fig. 4: The measured transmission spectra of the (a) TE_0-TE_3 and (b) TE_3-TE_0 mode conversion

We fabricate and characterize the TE_0-TE_4 and TE_0-TE_3 mode operators with the same process mentioned above. Due to the fabrication imperfections, the performance of the TE_0-TE_4 reference ADC mode (de)multiplexers is quite poor. Here, we only provide the experimental results of the TE_0-TE_3 mode operator. As shown in Fig. 4, for the TE_0-TE_3 mode conversion, the ILs are below 2.5 dB with the modal crosstalk lower than –12 dB in the wavelength range of 1530-1570 nm. While for the TE_3-TE_0 mode conversion, the ILs are less than 3 dB and the modal crosstalk is lower than –16.5 dB from 1530 nm to 1570 nm. One might notice that the ILs and modal crosstalk degrade greatly when the wavelength becomes longer than 1580 nm and shorter than 1530 nm, which is mainly due to the imperfect ADC mode (de)multiplexers. The results verify the scalability of the BB concept.

Conclusions

In this paper, we report a novel technique to implement arbitrary on-chip high-order mode conversion/exchange with the metasurface building block concept. The fabricated TE_0-TE_2 BBs have compact footprints (2.7x1.23 μm^2), low ILs (< 1.5 dB), low modal crosstalk (< –15 dB) and broad bandwidth (1520-1580 nm). More importantly, arbitrary high-order mode operators without performance degradation can be simply realized by parallelizing multiple BBs, owing to the similarities in field distribution of all eigenmodes. The proposed methodology may boost applications in dynamic multimode photonics and on-chip MDM systems.

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