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Broadband SOI mode order converter based on topology optimization

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Abstract: Topology optimized SOI mode order converters are proposed to allow mutual conversion between TE_0, TE_1 and TE_2. Broadband conversion efficiency around 85% can be realized on an ultra-compact (~ 4 µm length) footprint.

OCIS codes: (130.3120) Integrated optics devices; (230.1150) All-optical devices

1. Introduction

On-chip mode division multiplexing (MDM) has been heavily researched over decades, which transmits multiple channels in one shared multimode bus waveguide to enhance transmission capacity. A number of MDM devices have been developed, including multiplexers/demultiplexers (MUX/DEMUX), mode order filters and mode order converters. One major challenge of on-chip MDM is the high order mode processing, such as bending and crossing. As a consequence, mode order converters are usually developed to convert high order modes to fundamental mode (TE_0) first before processing.

Silicon-on-insular (SOI) mode order converters have been proposed by a number of researchers already. The most intuitive converter is to evenly split a high order mode into multiple TE_0 pieces, then merged with proper phase relationship. Recently researchers also numerically proved the mode order converter concept with ultra-low loss based on adiabatic taper on a 30 µm-long footprint [1]. In addition, TE_0-to-TE_1 converter with more compact footprint (~ 6 µm length) has also been experimentally demonstrated using inverse design [2]. The reported device is optimized inside a photonic crystal waveguide, giving 70% TE_0-to-TE_1 conversion efficiency over 40 nm bandwidth.

In addition to mode order conversion, photonic inverse design by topology optimization has been widely implemented over several applications, including MDM MUX/DEMUX, polarization beam splitter (PBS), polarization converter and MUX/DEMUX for coarse wavelength division multiplexing (CWDM). For broadband operation, the device should be designed like colorless dielectric meta-material by avoiding the Bragg reflection zone [3]. The reported TE_0-to-TE_1 converter by topology optimization [2] is designed in photonic crystal operation regime with a narrow bandgap, which intrinsically limits the operation bandwidth. Here we present a family of ultra-compact (~ 4 µm length) devices with inverse design for broadband mode order conversion. TE_0, TE_1 and TE_2 can be mutually converted with around 85% efficiency and below 1% crosstalk. Unlike most published converters that can only handle conversion between TE_0 and high order modes [1], our work allows direct conversion between different high order modes. With no more necessity of using TE_0 as a stepping stone, in principle our design technique can be applied to arbitrary mode order conversion. The extreme compactness of optimized converter also allows alternative functionalities (such as bending and crossing) to be realized on a small footprint.

2. Inverse design and performance

First, a TE_0-to-TE_1 converter is optimized on a 3.85 µm × 2.35 µm silicon region, which is discretized into a 15 × 25 pixels (rectangular lattice) binary problem. Each pixel represents a fully etched hole with 50 nm radius at 150 nm lattice constant [3], where "1" means a hole etched and "0" means no hole. 150 nm pitch (Λ) is chosen to ensure Bragg wavelength ($\lambda_{bragg} = 2 \times n_{eff} \times \Lambda$) is far from C band and this can be confirmed by following equation, where neff is the highest effective index of Si waveguide mode (~3).

$$\frac{1550\,nm}{\Lambda} >> 2 \times neff \qquad (1)$$

The device is assumed to be covered by SiO_2 top cladding, which allows us to use a vertical symmetry boundary condition in 3D FDTD calculation. Input mode source launches a TE_0 mode over 100 nm bandwidth centered at 1.55 µm while transmission and reflection into TE_0 and TE_1 are separately measured by eigenmode expansion monitors. Here we follow the neural network (NN) assisted direct binary search (DBS) method [4] to conduct optimization with 2000 random training data, which gives faster initial convergence than conventional DBS. After 800 FDTD runs of NN-DBS, conventional DBS [3] is used to refresh the matrix by 3 times for fine optimization. Figure of merit (FOM) is defined as TE_1 power subtracting TE_0 crosstalk and reflection and we attempt to increase FOM during optimization. Lumerical 3D FDTD is used to calculate 11 spectral points from 1.5 µm to 1.6 µm, and the worst spectral value of FOM (worst case scenario) is being tracked and optimized in order to reduce wavelength dependence. During optimization, coarse mesh (25 nm) is used with vertical symmetry boundary condition to reduce computational time. The finalized structure after optimization is validated under fine mesh (5 nm) with 51 spectral points over 100 nm bandwidth and the perfectly matched layer (PML) condition is used at all boundaries.

Figure 1 shows the finalized geometry after optimization and the major E field component (E_y) distribution plot is also shown. From the field distribution, the input beam is split and then merged at the output with the top beam delayed by π phase shift relative to bottom beam. Distributed holes increase the phase velocity of the beam compared with Si region without holes since the average refractive index is reduced. FDTD spectrum shows ~ 85% efficiency with ~ 0.5% crosstalk and reflection obtained over 100 nm bandwidth. Compared with the reported TE_0-to-TE_1 converter based on photonic crystal, the proposed converter works over a substantially broader bandwidth since the device avoids the Bragg reflection zone. The efficiency of the converter can potentially be improved by using a larger matrix, although larger footprint and higher computational effort will be required.

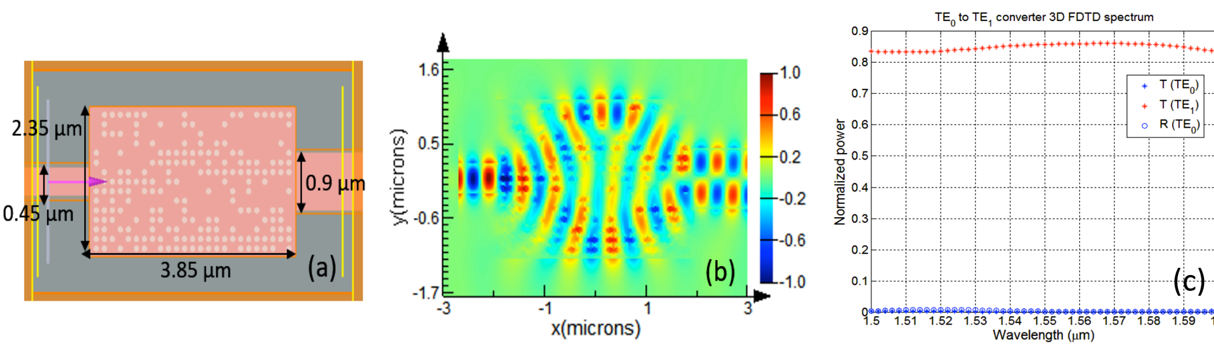

Fig. 1. (a) Optimized geometry, (b) Ey plot, and (c) 3D FDTD spectrum of the finalized TE_0-to-TE_1 converter

A TE_0-to-TE_2 converter is also designed with a similar procedure. In this case, the two outer lobes of TE_2 should be delayed equally and merged with the center lobe. Therefore, a horizontally symmetric structure (20 × 30) is being evaluated on a 4.6 µm × 3.1 µm rectangular silicon region. During inverse design, a 10 × 30 matrix (top half of the geometry) is optimized and mirrored to the bottom half of the Si region. Fig.2 (a) shows the finalized geometry after optimization. Field plot shows most majority of input TE_0 splits equally into two outer routes and some fraction of TE_0 is diffracted and refocused at the output waveguide along the middle route. FDTD spectrum of finalized device shows over 85% efficiency with less than 1% crosstalk and reflection. TE_1 crosstalk power is almost negligible here because TE_0 input cannot excite TE_1 along a horizontally symmetric structure.

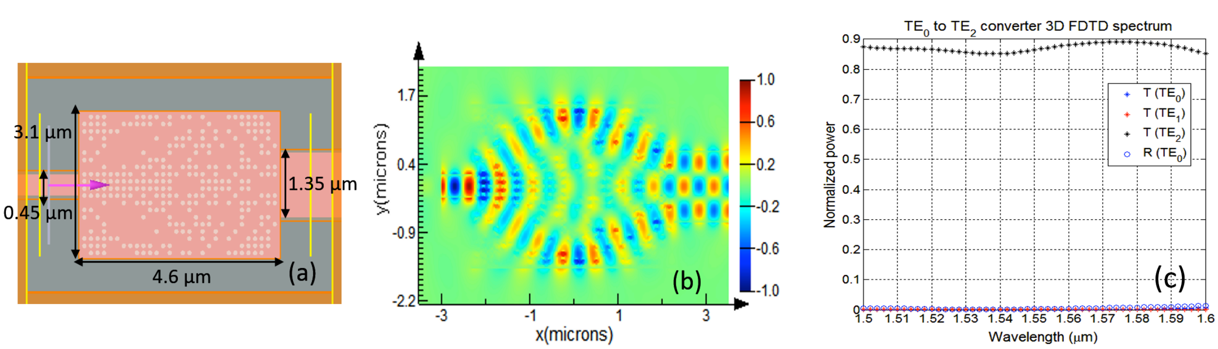

Fig. 2. (a) Optimized geometry, (b) Ey plot, and (c) 3D FDTD spectrum of finalized TE_0-to-TE_2 converter

A TE_1-to-TE_2 converter is also demonstrated (see fig.3) in the same manner as the TE_0-to-TE_1 converter. The optimized device can obtain roughly 87% efficiency with crosstalk/reflection into TE_0 and TE_1 both below 1%. The direct conversion between TE_1 and TE_2 does not demand conversion via TE_0 as a stepping stone. Unlike using a 60 μm-long cascaded TE_0 to high order mode converter based on an adiabatic taper [1], our direct TE_1-to-TE_2 converter can achieve 87% efficiency with device length less than 4 μm.

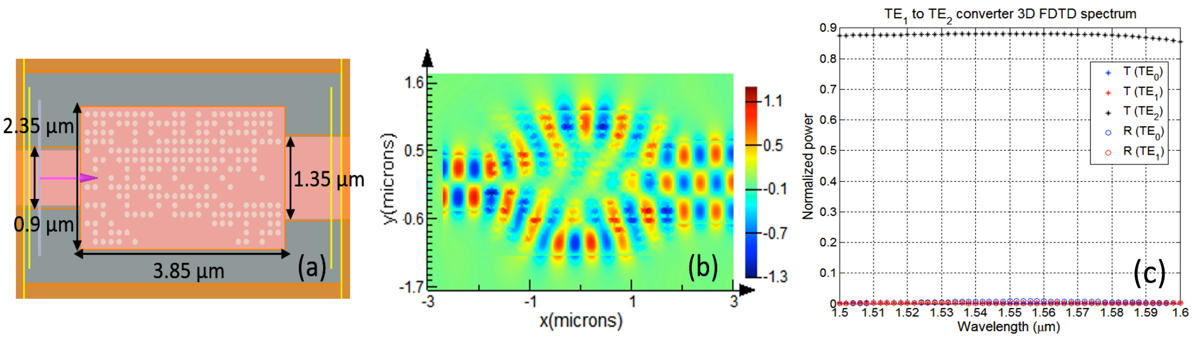

Fig. 3. (a) Optimized geometry, (b) Ey plot, and (c) 3D FDTD spectrum of the finalized TE_1-to-TE_2 converter

Our ultra-compact mode order converter can also be cascaded with other devices to process high order modes. As an example, the TE_2 mode 90-degree cross is demonstrated here, which cascades four TE_0-to-TE_2 converters to a conventional TE_0 90-degree cross [5] at four ports. The total footprint of the TE_2 90-dgree cross is merely 23 μm × 23 μm and less than 1.5 dB insertion loss can be obtained over 100 nm bandwidth. Only -30 dB TE_0 crosstalk will be excited at through port over 80 nm bandwidth and all modes excited at cross port are well below -40 dB.

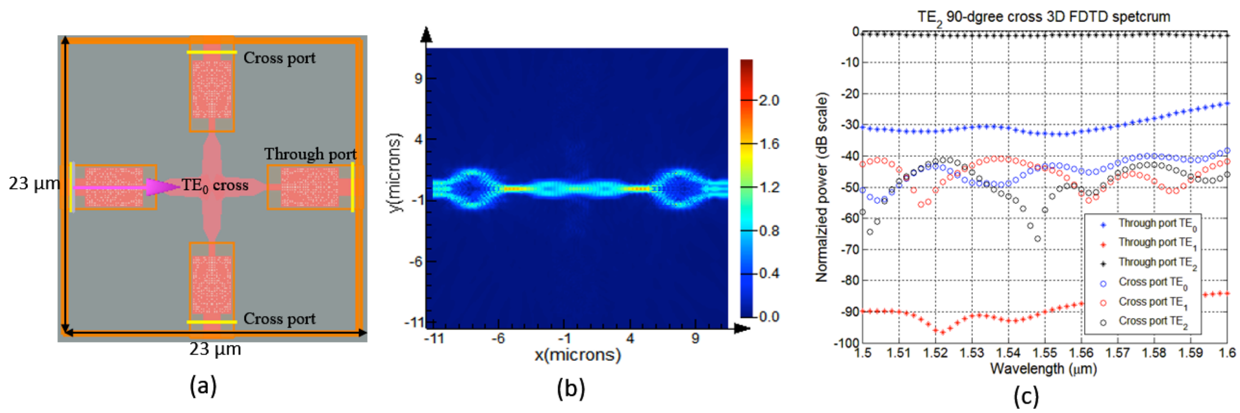

Fig. 4. (a) TE_2 90-degree cross geometry, (b) |E| plot, and (c) 3D FDTD spectrum of the TE_2 90-degree cross

3. Conclusion

We numerically demonstrate a family of ultra-compact (~ 4 μm length) SOI mode order converters based on a machine-learning-assisted optimization method. TE_0, TE_1 and TE_2 can be mutually converted with ~ 85% efficiency over 100 nm bandwidth. In principle, our optimization technique can be used to design arbitrary mode order converters. In addition, topology optimized mode order converter can help establishing alternative functionalities (such as crossing and bending) for high order modes with a compact footprint.

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