Demonstration of an ultra-compact bend for four modes based on pixelated meta-structure

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Abstract: A multimode bend for TE_0, TE_1, TE_2 and TE_3 modes with a radius of 3.9 µm is demonstrated. The insertion loss is measured to be < 1.8 dB, and the crosstalk is below -17 dB.

OCIS codes: (130.0130) Integrated optics; (230.0230) Optical device

1. Introduction

Over the past decade, the mode division multiplexing (MDM) technology has attracted intensive research interests owing to its great potential for increasing the data capacity in optical communication system [1]. Growing efforts have also been directed to implementing MDM technique for on-chip applications [2]. Towards this goal, the radiation leakage and inter-mode crosstalk for waveguide bending is the primary challenge for on-chip MDM circuits. This places an ultimate limit on the integration density of the photonic chip. There have been many demonstrations of multimode bend using different techniques. Transformation optics [3] and metamaterial structure [4] have been applied to design MDM bend, but the bending radius is still large. More recently, pixelated meta-structure has been reported to achieve extremely compact MDM bend [5, 6], which enable dense integration of the MDM circuits. However, such compact bending device has not been proved to support four-mode multiplexed signal routing yet.

In this letter, we have proposed and experimentally demonstrated an ultra-compact multimode bend with the radius of only 3.6 µm which is much smaller than the previous demonstrations. It supports simultaneous transmission of four modes (TE_0, TE_1, TE_2 and TE_3). The bend is designed based on pixelated meta-structure which is optimized by an inverse design algorithm. The measured insertion loss (IL) is less than 1.8 dB, and the crosstalk (CT) is below -17 dB over the wavelength range from 1530-1570 nm.

2. Device Design

The proposed multimode bend is designed on the standard silicon-on-insulator (SOI) platform with 220 nm top silicon layer and 2 µm buried oxide. The width of the bend is chosen to be 2.3 µm which can support at least four modes (TE_0, TE_1, TE_2 and TE_3). The simulated optical field profiles are shown by the insets of Fig. 1. The bending radius R is chosen to be 3.9 µm. Initially, the silicon bend structure is discretized into 560 pixels. Each pixel is a nanohole which has a binary material property: silicon or air. In this work, the diameter of these nanoholes are set to be 120 nm and the gap between two adjacent nanoholes is 30 nm, which can be easily fabricated using electron-beam lithography (EBL). In the design process, a direct binary search (DBS) algorithm is utilized to optimize the distribution of these air holes which are considered as diffraction element. The light waves with different order modes are launched into the input waveguide and then diffracted by a group of etched nanoholes. The diffracted waves are superimposed at the output port with specific target distribution eventually.

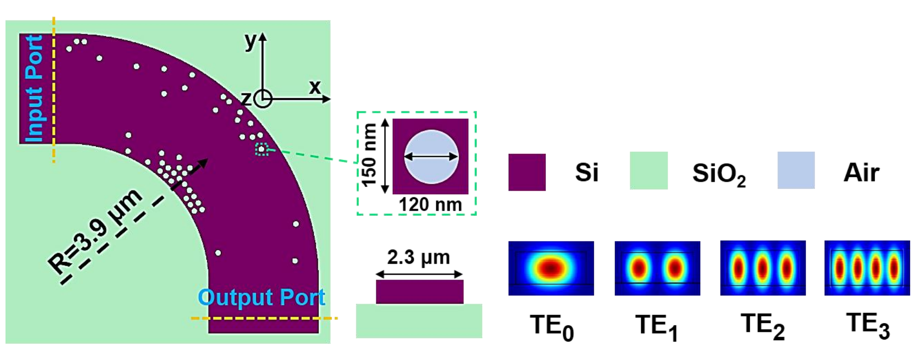

Fig. 1. The schematic diagram of the designed four-mode bend structure and its parameters. Inset: simulated optical field profiles.

For the inverse design process, a figure of merit (FOM) is defined as the summation of transmission efficiency for all the four modes. The FOM is calculated via the three-dimensional finite difference time domain (3-D FDTD) method. In each iteration, the simulation results will be treated as effective data and saved only if the FOM gets improved compared with the last iteration. The detailed information of DBS-based optimization can be found in Ref [7, 8]. A normal 4-core desktop computer operating at 3.4 GHz is utilized to perform the optimization. The total computation time is around 40 hours, and the finalized structure pattern is illustrated in Fig. 1.

Fig. 2 (a), (b), (c) and (d) are the numerically simulated magnetic field (H_z) distributions at the wavelength of 1550 nm for TE_0, TE_1, TE_2 and TE_3 modes, respectively. It can be found that the etched nanoholes near the outer sidewall play an important role to bent the light with TE_0 and TE_1 mode profile. These nanoholes function like a mirror which reflects the wave into the orthogonal direction. For TE_2 and TE_3, the optical wave bending is realized by an overall effect of the nanoholes. It is also worth noting that the optical waves are well confined in the bending region without significant leakage for all the modes. At the output port, very high mode purity is observed. The simulated ILs and CTs are calculated to be less than 1.1 dB and below -20 dB for the four modes over the wavelength band of 1530-1570 nm.

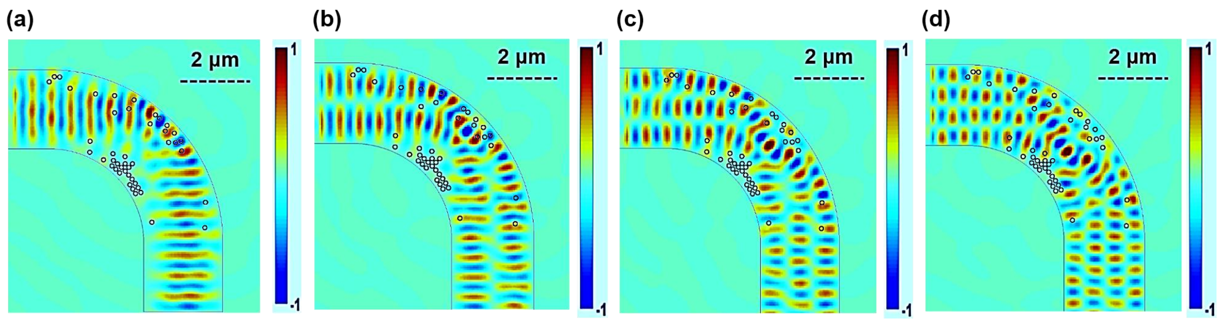

Fig. 2. The simulated magnetic field (H_z) distributions across the whole bend structure at the wavelength of 1550 nm for (a) TE_0 mode (b) TE_1 mode (c) TE_2 mode (d) TE_3 mode.

3. Fabrication and Characterization

To validate the simulation results, we have fabricated and characterized the multimode bend on a commercial SOI wafer from SOITEC. The EBL operating at 30 kV and reactive ion etching (RIE) are utilized to pattern the designed layout on the silicon. Here, in order to generate TE_0, TE_1, TE_2 and TE_3 modes, a compact four-mode multiplexer based on meta-structure is also fabricated and characterized. Fig. 3 (a) is the optical microscope image of the reference MDM circuit consisting of a pair of back-to-back mode multiplexers. Fig. 3 (b) is the optical microscope image of the fabricated MDM bending circuit, including a pair of bends, two mode multiplexers and grating couplers. The grating coupler operating for transverse electric polarization is used to couple the light into the waveguide, and the coupling efficiency is measured to be around 6 dB per facet. Fig. 3 (c) and (d) are the zoom-in scanning electron microscope (SEM) images to show detailed structure of the fabricated bend.

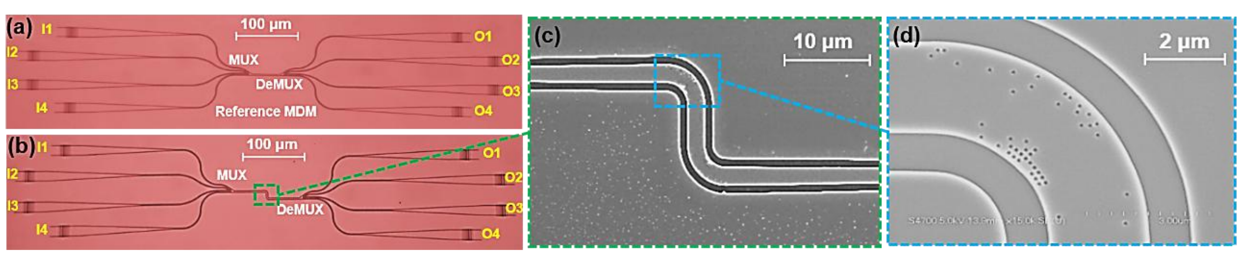

Fig. 3. The optical microscope image of (a) the fabricated reference MDM system and (b) the fabricated four-mode bending circuit. (c)-(d) The scanning electron microscope (SEM) images to show the detailed structure of the bend.

A continuous wave sweep laser, a polarization controller, a coupling stage and an optical power meter are utilized to setup the characterization system. Fig. 4 (a), (b), (c) and (d) show the measured transmission spectra of the reference MDM circuit in order to normalize the transmission data of the bending device. For the multiplexer, the measured minimum ILs are less than 1.5 dB and the CTs are lower than -20 dB. The loss mainly comes from the scattering. Similarly, the transmission spectra of the bending circuit (two back-to-back bends) is characterized, and the results are presented in Fig. 4 (e), (f), (g) and (h) for TE_0, TE_1, TE_2 and TE_3 modes, respectively. After normalization to the reference MDM device, the measured minimum ILs and CTs of the bend are less than 1.8 dB and -17 dB for all four modes across the entire wavelength band of 1530-1570 nm. Both the bend and the multiplexer have quite flat spectral response, which show negligible wavelength dependence.

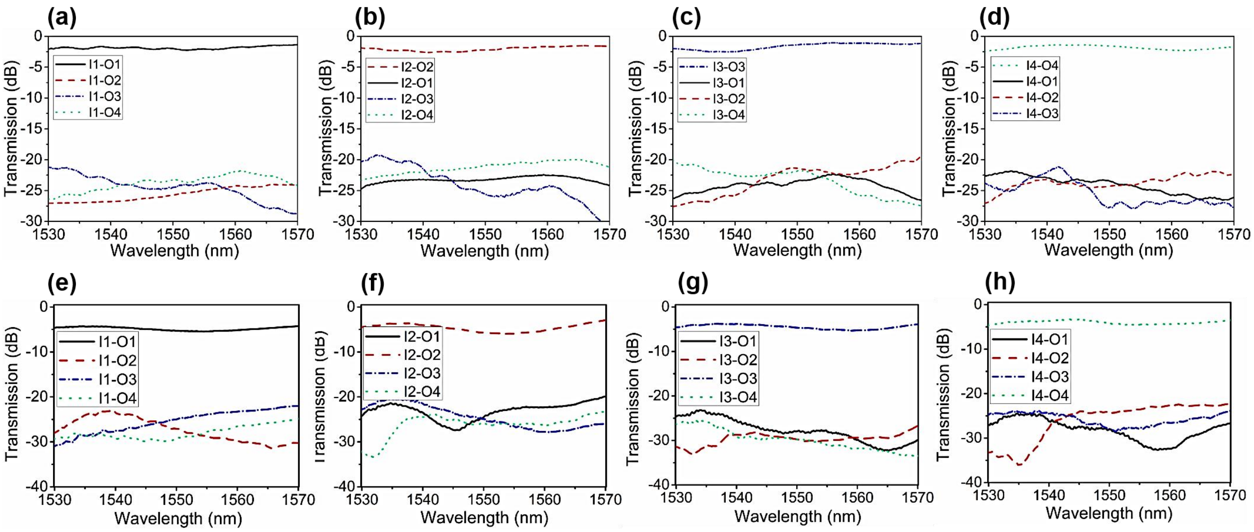

Fig. 4. (a)-(d) The measured transmission curves of the reference MDM system for TE_0, TE_1, TE_2 and TE_3 modes, respectively. (e)-(h) The measured spectral responses of the MDM bending circuit for TE_0, TE_1, TE_2 and TE_3 modes, respectively.

3. Conclusion

In conclusion, we have proposed, fabricated and characterized an ultra-compact bend operating for TE_0, TE_1, TE_2 and TE_3 modes with a small bending radius of only 3.9 μm. The multimode bend is designed based on pixelated meta-structure and an inverse design method. The experimental results exhibit high transmission efficiency and low inter-mode crosstalk over the wavelength range of 1530-1570 nm. The demonstrated four-mode bend is promising to greatly improve the integration density of on-chip MDM circuits.

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