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Design of a broadband reciprocal optical diode in multimode silicon waveguide by partial depth etching

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ABSTRACT

We propose a design of reciprocal optical diode based on asymmetric spatial mode conversion in multimode silicon waveguide on the silicon-on-insulator platform. The design possesses large bandwidth, high contrast ratio and high fabrication tolerance. The forward even-to-odd mode conversion and backward blockade of even mode are achieved by partial depth etching in the functional region. Simulated by three-dimension finite-difference time-domain method, the forward transmission efficiency is about −2.05 dB while the backward transmission efficiency is only −22.68 dB, reaching a highest contrast ratio of 0.983 at the wavelength of 1550 nm. The operational bandwidth is up to 200 nm (from 1450 nm to 1650 nm) with contrast ratio higher than 0.911. The numerical analysis also demonstrates that the proposed optical diode possesses high tolerance for geometry parameter errors which may be introduced in fabrication. The design based on partial depth etching is compatible with CMOS process and is expected to contribute to the silicon-based all-optical circuits.

1. Introduction

The optical diode [1], in which light asymmetrically propagates, is one of fundamental components for information processing in optical communication systems [2]. It has attracted great interest due to its significant applications in integrated optical circuits [3–6]. The non-reciprocal optical diode, as the primary choice for optical isolator, allows light to propagate in one direction but block all light in the other direction. The conventional non-reciprocal designs mainly focus on breaking the reciprocity of the Lorentz theorem by utilizing indirect inter-band photonic transition [7–10], angular-momentum biasing [11], magneto-optic effect [12–17], third-order optical nonlinearity [18–21], and asymmetric silicon ring resonators [22]. However, some non-reciprocal optical diodes based on positive devices have relatively large footprint and require high power input, which hinder the fabrication on chip scale. Recently, reciprocal optical diode has been shown as another promising candidate. Unlike non-reciprocal optical diodes, reciprocity of the Lorentz theorem and time-reversl symmetry will be held [23]. A reciprocal optical diode usually exploits two mechanisms, spatial symmetry breaking and polarization symmetry breaking. Its passive and linear characteristic offer the device with small size and ease of fabrication.

In the last several years, several schemes have been reported on reciprocal optical diodes via breaking the polarization symmetry or the spatial symmetry. Menzel proposed a three-dimensional chiral optical metamaterial that exhibited the diode effect for the linearly polarized light at wavelength ranging from 0.5 μm to 2.5 μm [24]. Grady designed metamaterial-based terahertz polarization converters and metamaterial structures which are capable of realizing near-perfect anomalous refraction. The maximum output power reached 61% and the anomalous refraction intensity dropped to zero at 1.4 THz [25]. Based on the concept of abrupt phase change and birefringence effect, Liang demonstrated two kinds of integratable quarter-wave plates enabling one-way angular momentum conversion [26]. Zhang proposed a hybrid plasmonic structure that performs optical diode behavior in single mode waveguides based on the combination of polarization rotation and polarization selection. The extinction ratios of forward and backward propagation are 19.43 dB and 11.8 dB, respectively [27]. As for the mechanism of spatial symmetry breaking, the reciprocal optical diode only operates for certain modes due to the spatial asymmetric mode conversion in linear structures [2]. Ye [28,29] presented compact broadband optical diode designs in linear rod-type and air-hole photonic crystal (PhC) waveguide within the operational bandwidth of about 40 nm. In air-hole PhC design which connected two standard silicon waveguide, the maximum asymmetric propagation reached approximately 19.6 dB in 3D model with only one deformed air hole in the functional region. Based on Mach–Zehnder interferometer Y-shaped model [30], the optical diode effect was observed due to two different width SOI channel waveguides.

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About 90% forward transmission and 3% backward transmission were obtained with at least 17.28 μm conversion length [30]. In order to make the device compact, Shen [31] proposed optical diodes for TE mode and TM mode based on 3 μm × 3 μm-size integrated digital metamaterials in silicon. The forward and backward transmission efficiencies in 3D simulations were, respectively, 71.1% and 1.8% for TE mode, and 91.1% and 3.2% for TM mode at the wavelength of 1550 nm. In addition, a ratio of 94 (17% forward transmission and 0.18% backward transmission) was obtained in Callewaert's work [32] with 60 × 120 pixels determined by the objective-first inverse optimization algorithm. More recently, assisted by plasmonic splitter [33], an optical diode in multimode silicon waveguide working in 100 nm operational bandwidth was presented. Still, schemes for ideal optical diode with high contrast ratio, low insertion loss, large operational bandwidth, ultra-small size and perfect compatibility with mature semiconductor CMOS process is pursued.

Moreover, several designs of mode converter based on interference principle in multimode silicon waveguide have been proposed, but few targeted for optical diode effect except Oner's work [30]. Recently, Ohana [34] proposed a novel mode converter in multimode waveguide based on a graded index co-directional grating coupler, in which several different nano-size cuboids were etched partially in the depth direction. The functional regions were at least 18.5 μm long. In addition, the experiments of Ohana's work [35] and Tseng's work [36] have demonstrated that the partial depth etching (PE) method is perfectly compatible with CMOS processing and easy to be realized. Therefore, in order to reduce the footprint of the device, combining interference principle and the PE method, we propose a compact design for broadband reciprocal optical diode in multimode silicon waveguide. The device is designed on SOI platform and works in the optical telecommunication band from 1450 nm to 1650 nm.

2. Device designs

Firstly, we start from the simple structure of mode converter as shown in Fig. 1(a). The performances of the proposed device are simulated with three-dimension finite-difference time-domain (3D FDTD) method. The device is surrounded by air and perfectly matched layers are employed as the absorbing boundary. Only TE polarization (magnetic field perpendicular to the slab) is considered. When the air cuboid by PE is not introduced, an incomplete spatial mode conversion effect (even-to-odd mode) is observed in Fig. 1(b). In order to make the mode conversion effect more satisfactory, an air cuboid by PE is introduced to the structure. Then an asymmetric spatial mode converter is obtained in a silicon waveguide with asymmetrical ports on the SOI platform. The functional region of this mode converter is as compact as 1 μm × 2.4 μm. However, the asymmetric propagation of the converter is not high (−0.83 dB for forward transmission and −11.67 dB for backward transmission at 1550 nm).

As for a reasonable optical diode, the insertion loss of functional region in forward direction is expected lower than 3 dB while the value in backward direction should be higher than 20 dB. Working as a building block, the device should be designed with symmetrical input and output ports. In order to fulfill the symmetric requirement, two identical 2 μm long strip silicon multimode waveguides are located at both ends of the functional region. To keep the backward transmission lower than −20 dB, the width of the middle narrow waveguide should be reduced. The proposed optical diode is depicted in Fig. 2. From left to right, the functional region comprises a tapered coupler, a narrow waveguide, a triangular prism and a partial depth etched cuboid. The refractive indices of silica and silicon are set as 1.44 and $\sqrt{12}$ in the simulation, respectively. The permittivity can be safely assumed as constant for 200 nm wavelength range [32]. All geometry parameters of the proposed device are marked in Fig. 2.

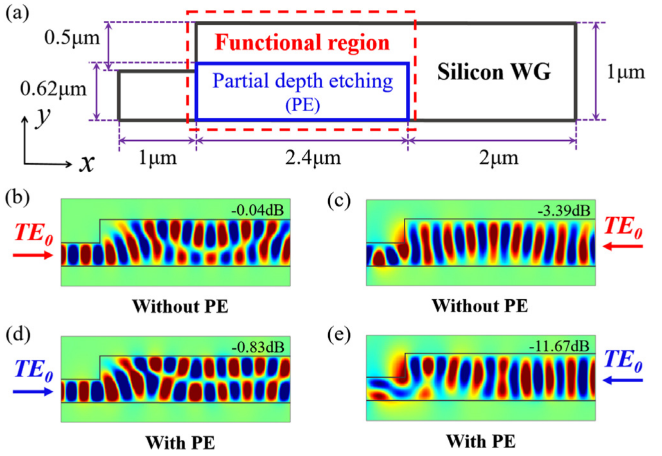

Fig. 1. Design of a mode converter. (a) Top view of the mode converter. The height of silicon waveguide and etched cuboid are 340 nm and 150 nm, respectively. (b) Field profiles of even mode in forward direction without the etched cuboid. (c) Field profiles of even mode in backward direction without the etched cuboid. (d) Field profiles of even mode in forward direction. (e) Field profiles of even mode in backward direction. In (b) and (c), the XY flat monitor is placed at the middle of the silicon waveguide in z direction.

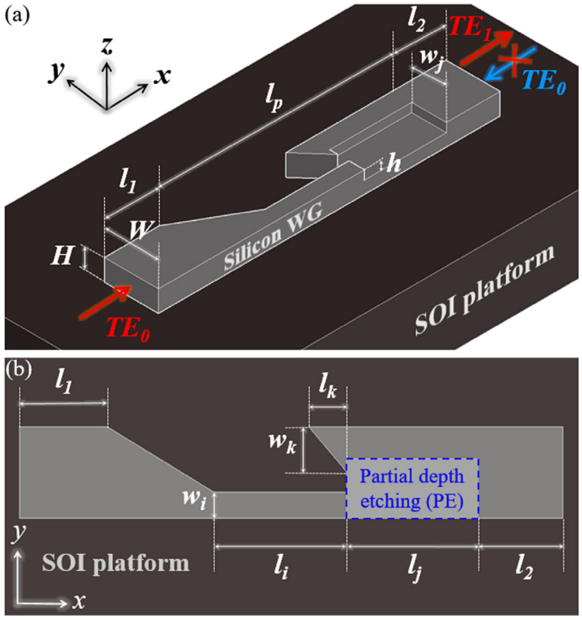

Fig. 2. Schematics of the proposed optical diode. (a) Perspective view of the device. H = 340 nm, W = 1 μm, $l_1 = l_2$ = 2 μm, l_p = 7 μm, h = 0.15 μm, w_j = 0.62 μm. (b) Top view of the device. w_i = 0.29 μm, $w_k = l_k$ = 0.5 μm, l_i = 2.6 μm, l_j = 2.4 μm. The light gray area surrounded by blue dotted lines is the air cuboid by PE.

3. Results and discussion

After exciting the even mode into the device from the left port of standard multimode waveguide, the spot is compressed in the tapered coupler and enters the narrow waveguide. Then the light enters the region where the cuboid is etched partially. Because of the air cuboid by PE, the effective refractive index of the waveguide is modified and the mutation in y direction also contributes to the modification of the wavevector. Due to the collective modification, the wavevector gets close to that of the odd mode in the waveguide. Consequently, the even-to-odd mode conversion in forward direction is realized. Without