Compact Polarization Rotator for Silicon-Based Cross-Slot Waveguides Using Subwavelength Gratings

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***Abstract*—A compact subwavelength grating (SWG) based polarization rotator (PR) for silicon-based cross-slot waveguides is proposed and analyzed. By replacing the diagonal regular Si wires with the SWGs, the rotation region is constructed. Numerical results show that a PR of 12.6 μm in length at the wavelength of 1.55 μm is achieved and the polarization conversion efficiency and insertion loss are, respectively, 97.2% and 0.71 dB for TE to TM mode.**

I. Introduction

There have been great advances in silicon-based photonic integrated circuits (PICs) over the last decades, most prominently in silicon-on-insulator (SOI) platforms due to their high-index contrast and complementary metal-oxide -semiconductor (CMOS)-compatible processing, where ultra-dense monolithic integration of various kinds of photonic devices can be achieved [1]. Recently, SOI based slot waveguides show great potential in PICs, for their dramatic confinement of light in the nano-scaled slot region with low index. However, the high-index contrast usually introduces large birefringence to the devices, which causes polarization-dependent losses or other polarization-dependent optical effects. Therefore, polarization diversity schemes are proposed to achieve a single polarization state in PICs [1], [2], where polarization rotators (PRs) are basic components to rotate the polarization. To realize compact PRs with excellent performance, additional material, such as metal, liquid crystal and magneto-optic materials are usually needed [1], [3], [4]. However, this will increase the complexity and manufacturing difficulty of the PRs. More recently, subwavelength gratings (SWGs) that can effectively suppress diffraction effects and behave as homogenous media offer a new degree of freedom for the design of novel photonic devices, since the effective index of the waveguide core can be easily engineered by changing the duty cycle [5], [6]. Here, we present a compact PR for the SOI based cross-slot waveguides, where two Si strips in one of the crossing symmetry port of the cross-slot waveguide are replaced by SWGs. The proposed PR has the advantages of compact size and simple structure since the SWGs can be easily fabricated by fully etching the Si wires. Numerical results show that the conversion length is 12.6μm at the wavelength of 1.55μm with the polarization conversion efficiency and insertion loss of 97.2% and 0.71 dB, respectively, for TE to TM mode.

II. Device Structure and Operating Principles

Figure 1 shows the three-dimensional (3D) schematic layout of the proposed PR, together with cross-sectional views of the input cross-slot waveguide, the polarization rotation region, and an enlarged view of the SWG. The input and output regions of the PR are the same type of cross-slot waveguides, which are directly coupled with the rotation region for fabrication convenience, while in the rotation region, two regular Si wires in one of the diagonal of the cross-slot waveguide are replaced by full etching SWGs, forming a SWG-based cross-slot waveguide. Therefore, the symmetry of this structure is broken significantly by introducing these SWGs. If a TM/TE polarization mode is injected into the PR, two hybrid modes will be excited in the conversion region and they beat with each other with a π-phase difference. Finally, at the output port, a TE/TM polarization mode is obtained. To minimize the size of the PR, the conversion length L_C should be equal to the half beat length $L_\pi = \lambda/[2(n_1 - n_2)]$, where n_1 and n_2 represent the effective indexes of the two lowest-order modes of this PR [3], [4]. The SWGs, which can effectively suppress diffraction effects and behave as homogenous media, is used to enlarge the effective index difference between the two lowest-order modes, thus L_π is reduced, resulting more compact device.

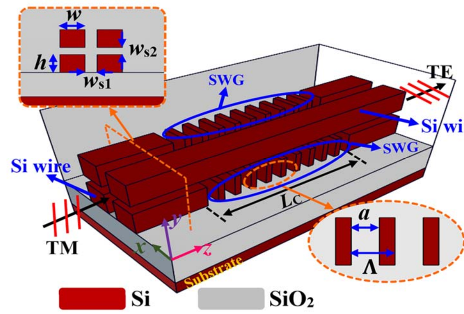

Fig. 1. Schematic of the proposed PR using SWGs.

For the PR, the most important parameter is polarization conversion efficiency (PCE), defined as $PCE = P_{TE}/(P_{TE}+P_{TM})$ for TM-to-TE conversion, where P_{TE} and P_{TM} are the output power of TE and TM modes, respectively. For the presented mode interference scheme, PCE can also be represented as follows [3], [4]

$$PCE = \sin^2(2\theta)\sin^2\left(\frac{\pi L_C}{2L_\pi}\right)\times 100\% \tag{1}$$

where θ is the rotation angle. Therefore, to get a ~100% PCE, $\theta = 45°$ is needed.

III. Results and Discussion

To analyze the modal characteristics of the designed PR and choose the suitable waveguide dimensions, a full-vectorial mode solver based on the finite-difference frequency-domain (FDFD) method [7] is utilized. As is previously demonstrated, the optical axis angle can be adjusted by changing the

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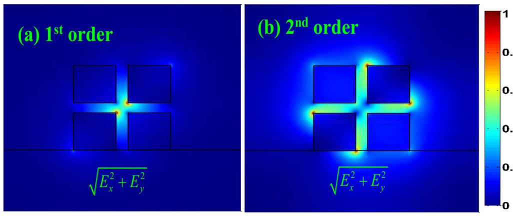

Fig. 2. Field distributions of the first (a) and second (b) order normal mode of the PR.

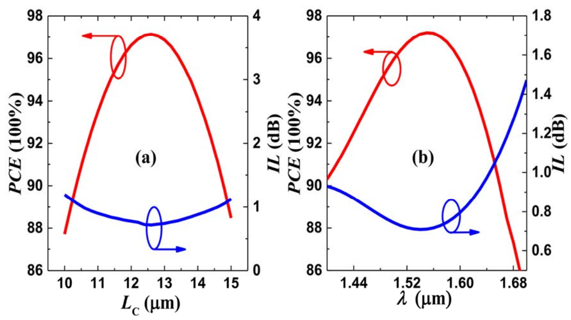

Fig. 3. *PCE* and *IL* as functions of L_C (a) and (b).

waveguide parameters [3], [4]. Here, for the convenience of design, the height and the width of the Si strips are set to be h=w=180nm, and the thickness of the horizontal (vertical) slot is w_{s1}=50nm (=w_{s2}). The refractive index of the Si and SiO_2 are, respectively, taken as 3.476 and 1.444, and the wavelength λ is assumed to be 1.55μm. To rotate the optical axis angle of the mode, SWGs are utilized by fully etching the Si strips. The pitch width and duty cycle of the SWGs are Λ =200nm and a/Λ = 50%, and the effective modal index of the SWG can be estimated using the formulas provided in [5]. Figs. 2(a) and 2(b) illustrate the electric field distributions of the two lowest-order normal modes ($\sqrt{E_x^2+E_y^2}$) of the polarization rotation region. As is clearly seen, the optical axes of the two lowest-order modes are rotated by 45°, indicating that PCE~100% can be ensured.

Then, a three-dimensional finite-difference time-domain (3D-FDTD) [8] method is employed to assess performance of this PR, where *PCE* and insertion loss (*IL*) are calculated. Fig. 3 (a) shows the *PCE* and *IL* as a function of the conversion length L_C. For the *PCE*, it is seen that the optimal conversion length is 12.6μm for the maximum value of PCE (~97.2%), and the corresponding value of *IL* is ~0.71dB. Moreover, if *PCE* >96% is required, the conversion length must be controlled within the range of [11.7, 13.5]μm, which is very beneficial for fabrication. For the *IL*, its value is always less than 1 dB when L_C is ranged from 10.6 to 14.6μm. Figure 5(b) shows the wavelength dependence of *PCE* and *IL* for the designed PR. It can be obviously found that the *PCE* is always higher than 90% when ranges from 1.4 to 1.66μm, which ensures the PR operates in a wide bandwidth (~260 nm), and the *IL* maintains a relatively low value (below 1 dB) within this range.

The field evolution of E_x and E_y components along the propagation distance are, respectively, illustrated in Fig. 4 (a) and (b), taking fundamental TE mode of the cross-slot waveguide as input mode, where L_C =12.6μm. Apparently, the component E_x gradually fades away, while the component E_y is excited and gradually becomes dominant at the output port.

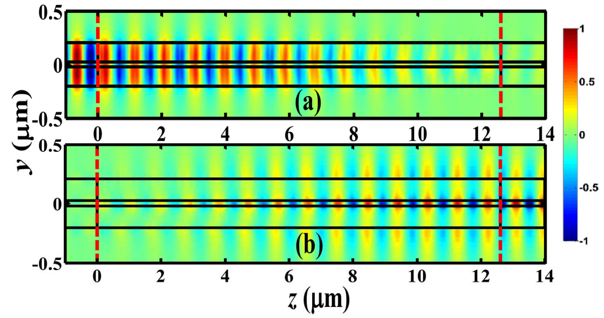

Fig. 4. Field evolution of E_x and E_y components along the propagation distance.

Therefore, the input TE mode is rotated efficiently to the output TM mode through this PR.

IV. Conclusion

A compact PR based on SWG for cross-slot waveguides is designed and analyzed by utilizing the combination of FDFD and FDTD methods. The rotation region is constructed by imposing SWGs on the diagonal regular Si wires of the cross-slot waveguide. By optimizing the structural parameters, effective polarization rotation is achieved for both input polarizations with the conversion length of only 12.6μm **at the wavelength of 1.55μm**. Numerical results show that **the *PCE* and *IL* of the PR are, respectively, 97.2% and 0.71 dB for TE to TM**. The PR can operate in a bandwidth of ~260 nm for keeping the PCE higher than 90%, and the IL of the device is less than 1 dB within the range.

Acknowledgment

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