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Ultrashort polarization rotator based on cross-symmetry waveguide

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ABSTRACT

An ultrashort polarization rotator (PR) based on cross-symmetry waveguide is proposed and discussed. At the operating wavelength of 1. 55 μm, the presented PR has a small conversion length of 3. 3 μm. The polarization conversion efficiency (PCE) is 99. 8% (TE–TM) and 99. 97% (TM–TE). The PR can achieve rather high conversion efficiency (>97%) over a broad bandwidth (1450 – 1700 nm). The cross-symmetry structure can significantly improve the extinction ratio. The extinction ratio is 27. 7 dB (TE–TM) and 35. 9 dB (TM–TE) with the insertion loss of 0. 28 dB. The fabrication tolerances for the waveguide for both transverse and horizontal directions are also studied.

1. Introduction

Large-scale photonic integrated circuits (LS-PICs) are becoming very promising for many applications, including next-generation optical networks, optical interconnects, wavelength division multiplexed systems, coherent transceivers and lab-on-chip [1]. In such a photonic integrated circuits (PICs), an ultra-compact and high efficient polarization rotator (PR), which is one of the most important elements, is especially imperative [2].

There are several approaches to realize PR based on LS-PICs. Some works are based on asymmetrical waveguide, such as the scheme based on Si nanowires with asymmetrical cross-section [3]. In this scheme, the one-step etched PR had a small conversion length of 22.1 μm and a broad bandwidth (~120 nm). By combining with the polarization diversity circuits in Ref. [4], a polarization splitter and rotator (PRS) was proposed and had a short length of 27 μm [5]. Furthermore, the two-step etched PR, which is optimized based on the one-step one, had better performance at bandwidth (290 nm) and size (4.2 μm) [6]. A TE–TM mode converter fabricated in a single trench SiON waveguide was demonstrated, which had the advantage that only single masking and etching process is needed to fabricate it [7]. However, the extinction ratio (ER) is only 15 dB at the wavelength of 1.27 μm, which is not enough high, and the conversion length is too long. A PR with double paralleled nonlinear geometry slot crossings achieved high ER (22 dB) and low loss (0.12 dB), however the structure was too complex to implement [8]. Meanwhile, plasmonic is emerging and promising for compact polarization-selective devices. An ultra-compact and low-loss PR based on mode interference was realized by asymmetric hybrid plasmonic waveguide, which achieved high PCE (99. 5%) with a short conversion length (3.2 μm) [9]. However, the total device insertion loss of 1.38 dB was much larger than the schemes without plasmonic. Besides, mode evolution principle was usually used in plasmonic PRs [10–12]. The challenge for plasmonics is that it is hard to reduce its significant loss due to the metal existence. Moreover, the tapered submicron silicon ridge optical waveguides could achieve nearly 100% conversion efficiency from TM0 mode to TE1 mode theoretically and experimentally [13]. And this principle was used to design polarization splitter-rotator with excellent performance [14,15]. However, the device length was relatively long. In summary, the proposal of a PR which can have a well balance of PCE, ER, Loss, bandwidth and the device length is still a question.

2. Operation principle

In this letter, we propose an ultrashort PR based on the cross-symmetry waveguide. As shown in Fig. 1, the proposed PR structure is built on a SOI substrate. The input and output sections are made of silicon wire waveguides. The rotation section between the input and output sections is a cross-symmetry waveguide which is made of Si and SiN. Due to the difference of relative refractive index between the SiN (n_{SiN}=2. 36) and Si (n_{Si}=3. 455), the proposed PR structure is asymmetry both in horizontal and vertical directions. In the rotation section, the width and height of the four rectangular parts are all equal to w and h respectively. Hence the dimensions of the whole waveguide are always $2w \times 2h$. However, it is symmetry along the two diagonals. Therefore, it could support two hybrid modes whose optical axes are rotated 45° with respect

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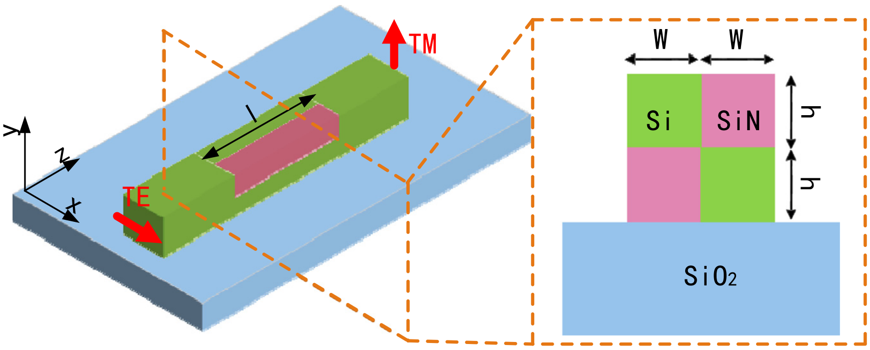

Fig. 1. Three-dimension schematic of the proposed device. Inset, the cross-section of the polarization rotation section.

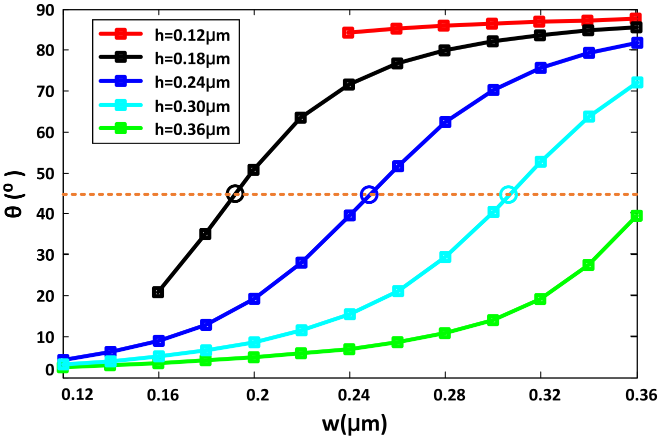

Fig. 2. Optical axis rotation angle as a function of the *w* and *h*. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

to the *z* axis. If we input a vertical or horizontal polarized light, the two hybrid modes will have a phase difference of π or odd times of π after transmitting for a certain length in the rotation section. That is to say, the presented PR can realize mode conversion of TE–TM or TM–TE.

For the PR, the most important parameter is PCE. When we consider the case where the polarization conversion is from TE polarization to TM polarization (two fundamental modes of the input Si nanowire), the PCE is defined by $\mathrm{PCE}=\frac{P_{TM}}{(P_{TE}+P_{TM})}*100\%$, where P_{TM} and P_{TE} are the power of the two output polarized modes, respectively [3]. For the presented mode interference scheme, PCE can be described by [3]

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

where θ is the rotation angle of the optical axis, L is the length of the rotation section, $L_C=\pi/k_0(n_{effTE}-n_{effTM})$ is the half interference length. If we need to realize the 100% PCE, we must make sure that $\theta=45°$ and $L=L_C$. Here the rotation angle (θ) is defined as [3]

$$\tan\theta=\frac{\iint n^2(x,y)e_x^2(x,y)dxdy}{\iint n^2(x,y)e_y^2(x,y)dxdy} \tag{2}$$

Here $n(x,y)$ is the refractive index distribution in the cross-section, $e_x(x,y)$ and $e_y(x,y)$ are the transverse and horizontal electrical components of eigenmode, respectively. We can calculate the rotation angle θ by Eq. (2). The optical rotation angle θ is closely associated with the width (w) and the height (h) of the cross-symmetry waveguide apparently. So we can find the conditions, which make θ equal 45°, by scanning the parameters w and h.

In order to calculate θ, we firstly use the COMSOL software to simulate the mode distribution of the cross-section. As shown in Fig. 2, the different color lines represent the different height, and we can see the θ increases with the width. In addition, some point are missing in the red line and the black line, it is because that there are no corresponding modes due to the small dimensions. For a constant waveguide width, θ will increase when the waveguide height decreases. According to Fig. 2, we can find some proper w and h to make θ equal 45°. Due to the limitation of the choice of parameters, there are 3 pairs of w and h which we can use to satisfy the above conditions. The circle on the black line is corresponding to h=0.18 μm and w=0.19 μm. While θ changes rapidly around $\theta=45°$, it will lead to small fabrication tolerance. However, the Δn_{eff} is bigger than others which can make L_C=2.2 μm to achieve a shorter structure. The circle on the cyan-blue line is corresponding to h=0.3 μm and w=0.31 μm. In this case, the conversion length will be as long as 6.6 μm, and the high order modes are emerged due to the large dimension and the ER will become worse. Synthesizing the above factors, we choose the circle on the blue line with w=250 nm and h=240 nm as the proper

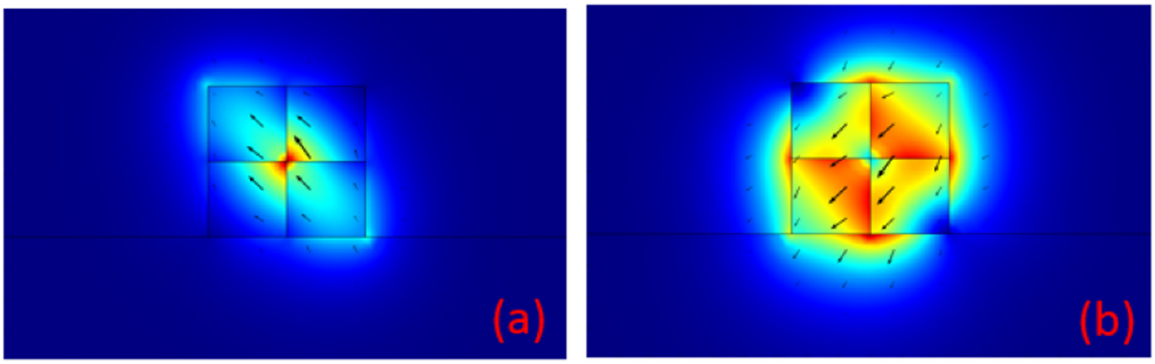

Fig. 3. (a) Quasi-TE$_0$ mode and (b) quasi-TM$_0$ mode. Here w = 250 nm and h = 240 nm.