# Compact highly-efficient polarization splitter and rotator based on 90° bends

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**Abstract:** We propose a compact highly-efficient CMOS-compatible polarization splitter and rotator (PSR) with a wide bandwidth covering the whole O-band. It benefits from the different confinement capability of TE and TM modes in bend structure. This bend structure helps shorten the PSR and maintain high efficiency, achieving the bending, polarization splitting, rotating of light beam at the same time. Numerical simulations utilizing Lumerical 3-D FDTD solutions demonstrate that the present PSR has a high TM-TE conversion efficiency of -0.11 dB and high TE-TE conversion efficiency of -0.09 dB at 1310 nm, while the extinction ratio is 27.36 dB and 30.61 dB respectively.

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#### 1. Introduction

As essential building blocks, polarization beam splitter and rotator (PSR) plays a significant role in most photonic integrated circuits where polarization handling is needed, including telecom, datacom, quantum circuits, etc [1, 2]. Compact and highly efficient PSR is desired for manipulating polarization-entangled photons [3] as well as coherent transceivers in large-scale high-density photonic integrated chips. Different types of PSRs have been reported with various structures, such as Mach-Zehnder interferometer [4, 5], asymmetric Y-junction [6,7], directional coupler [3,8–13], slot waveguides [14], and photonic crystals [15].

Those structures commonly use straight waveguides for achieving PSRs as their design rules are relatively easy [6–13]. Liu Liu and Yunhong Ding et al have demonstrated an efficient PSR by using two parallel straight strip waveguides with air top cladding [11]. Although this PSR is compact with a length of ~ $30\mu$ m at 1550nm, it uses 100-nm gap for efficient coupling, which is not applicable for current standard foundry service [16]. The lack of solid upper cladding breaks the vertical symmetry of strip waveguide, making polarization rotation achieved more easily. However, that also induces incompatibility and greatly complicates its integration with other building blocks based on most metal back-end-of-line processes. PSRs using SiO<sub>2</sub> layer as cladding have recently been reported in [3, 12, 13] on an SOI platform. However, these designs are relatively long with a device length of several tens or hundreds of microns.

In this work we exploit two 90° bends with a radius of 10  $\mu$ m to build an O-band compact PSR, since photonic integrated devices operating at O-band have recently attracted more and more attention, especially in the areas of datacom [5], and quantum communication [17, 18]. As known, the bend structure creates different confinement capability for TE and TM modes, which is undesirable in most devices reported previously [19]. However, here we take advantage of it to help shorten the PSR and maintain high efficiency, achieving the bending, polarization splitting, rotating of input light beam at the same time. Numerical simulations utilizing Lumerical 3-D FDTD solutions demonstrate that this compact PSR has a high TM-TE conversion efficiency of -0.11 dB and high TE-TE conversion efficiency of -0.09 dB at 1310nm, while the extinction ratio is 27.36 dB and 30.61 dB respectively. Moreover, the 3-dB bandwidth of proposed PSR covers all the O-band range. Furthermore, this design uses SiO<sub>2</sub> as top-cladding, making it compatible with current multi-layer CMOS foundry services [16].

## 2. Principle and design

As shown in Fig. 1, the inner bend of proposed PSR is set as the through waveguide so that this design is able to exploit the different confinement of TE and TM in bend structure, i.e., the TE is naturally better confined in the inner bend while TM is relatively easier leaking into the outer bend.

For TE mode, the light beam keeps propagating along the inner bend and then exits at the output port of inner bend. This can be realized by setting a sufficient difference of effective refractive indices between TE mode in the inner bend and all possible modes in the outer bend, making phase-matching condition unsatisfied for mode coupling. At the same time, TM mode launched in the inner bend needs to be converted to TE mode supported by the outer bend. This can be achieved by optimizing the cross section of two 90° bends for better satisfying the phase-matching condition of TM mode coupling. Moreover, due to the unique double-bend structure, the TM mode is easier leaking into the outer bend, indicating the coupling coefficient of TM mode increases by utilizing bend structure. In order to use SiO<sub>2</sub> as top-cladding and also break the vertical symmetry for achieving TM-TE conversion at the same time, the outer bend is partially etched.



Fig. 1. (a) Top view and (b) three-dimensional view of the PSR based on the  $90^{\circ}$  bends. For clarity, the SiO<sub>2</sub> cladding is not shown.

Here we design a sample operating at O-band based on SOI platform with top silicon thickness  $H_1 = 220$ nm. In order to take advantage of the better confinement for TE mode than TM mode in bend structure, the width and radius of inner bend are chosen as 400 nm and 10  $\mu$ m respectively, which keeps low loss for fundamental modes in the bend structure. Although smaller gap can increase the coupling efficiency and thus shorten the device length, the gap between two parallel waveguides cannot be too small as it would make the fabrication difficult. Since the 248-nm optical lithography technology normally uses 200-nm gap, here the gap  $W_g$  is 0.2  $\mu$ m [16]. In order to have a complete coupling of TM mode supported by the inner bend and TE mode supported by the outer bend, theoretically these two bends need proper cross sections for satisfying the phase-matching conditions, i.e. their optical path lengths (OPLs) should be the same [20, 21], which means,

$$OPL = N_1 k_0 R_1 \theta = N_2 k_0 R_2 \theta \tag{1}$$

where  $\theta$  is the angle for the bend,  $k_0$  is the wavenumber,  $N_1$  and  $N_2$  are the effective refractive indices of the TM and TE mode supported by the inner and outer bend respectively,  $R_1$  and  $R_2$  are the corresponding bend radii. By using Lumerical MODE solutions, the refractive index of different cross section of double bends can be calculated, and thus the

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cross sections are able to be optimized for high coupling efficiency. Here the height of etched slab  $H_2$  is 110nm. We choose the width of the fully-etched layer  $W_2$  to be 0.21µm and the width of partial-etched one  $W_3$  to be 0.285µm, which makes the OPLs in these two bends match with each other. In order to convert the partial etched outer bend into a stripe waveguide, a taper is exploited at the end of the outer bend with a length of 5µm.



Fig. 2. OPLs of the TE and TM mode supported by the inner and outer bend.

Figure 2 shows the numerically calculated optical path lengths OPL ( $\theta = \pi/2$ ) for TE and TM mode supported in designed cross section as the wavelength varies from 1.26 µm to 1.36 µm. The OPL of TE mode in the inner bend is much larger than that of the modes in the outer bend, which prevents any mode coupling when TE mode is injected into the inner bend. At the same time, the OPL of TM mode supported by inner bend is almost the same as that of TE mode supported by outer bend within 100-nm wavelength range, which makes possible the high efficient coupling from TM mode supported by inner bend to TE mode supported by outer bend.



### **3. Simulation results**

Fig. 3. (a) The light propagation when TE mode is stimulated in the inner bend. (b) The light propagation when TM mode is stimulated in the inner bend. The light wavelength is 1310 nm.

By exploiting three-dimensional finite-difference-time-domain (3-D FDTD) method, the simulation result of light propagation is depicted in Fig. 3 (a) and (b), when TE and TM

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#260701 © 2016 OSA modes at 1310-nm wavelength are stimulated in the inner bend. As predicted in the design principles, when the TE mode is injected into the inner bend, the light beam is well confined and maintains its propagation in the inner bend. When TM mode is stimulated in the inner bend, light is efficiently coupled to TE mode in the outer bend and then exits from the cross output port.



Fig. 4. (a) The TM mode at the input port of inner bend. (b) The hybrid mode at the middle of the bend, where the energy carried by TM mode is converting into TE-like mode in the outer bend. (c) Most energy is coupled into TE-like mode in the outer bend. (d) Converted TE mode at the cross output of the outer bend. The light wavelength is set to be 1310 nm.

The TM mode splitting and rotating process is further demonstrated in Fig. 4. At cross section (I), TM mode is stimulated at the input of inner bend, as depicted in Fig. 4(a). At cross section (II), the TM mode is partially converted to TE-like mode in the outer bend, as depicted in Fig. 4(b). At cross section (III), almost all the power carried by TM mode in the inner bend are coupled to TE mode supported by outer bend, as demonstrated in Fig. 4(c). At cross section (IV), the cross waveguide is separated enough far away from the through waveguide so that no light could be coupled back, while the partial-etched outer bend is tapered into a strip waveguide at the cross output.



Fig. 5. The mode conversion efficiency as a function of the wavelength in the cross output port (a) and through output port (b). The conversion efficiency below -40 dB is not shown.

The proposed PSR is evaluated by conversion efficiency (CE), extinction ratio (ER), and crosstalk (CT) [5, 12, 13]. The CE for the input TM and TE mode is defined as  $CE_{TM-TE}^{Cross} = 10 \log_{10} \left( P_{TM-TE}^{Cross} / P_{TM}^{Input} \right)$  and  $CE_{TE-TE}^{Through} = 10 \log_{10} \left( P_{TE-TE}^{Input} / P_{TE}^{Input} \right)$  respectively. The ER for the input TM and TE mode is defined as  $ER_{TM-TE}^{Cross} = 10 \log_{10} \left( P_{TM-TE}^{Cross} / P_{TM}^{Input} \right)$  and respectively.

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#260701 © 2016 OSA  $ER_{TE-TE}^{Through} = 10 \log_{10} \left( P_{TE-TE}^{Through} / P_{TE-TE}^{Cross} \right) \text{ respectively. There are two possible types of CT for each input mode: one is to evaluate the influnce of the TM mode at cross port, which is defined by <math display="block">CT_{TM-TM}^{Cross} = 10 \log_{10} \left( P_{TM-TM}^{Cross} / P_{TM-TE}^{Cross} \right) \text{ and } CT_{TE-TM}^{Cross} = 10 \log_{10} \left( P_{TE-TM}^{Cross} / P_{TE-TE}^{Through} \right) \text{ for TM and TE input mode respectively; the other is to evaluate the influnce of the TM mode at through port, which is defined by <math display="block">CT_{TM-TM}^{Through} = 10 \log_{10} \left( P_{TM-TM}^{Through} / P_{TE-TE}^{Through} \right) \text{ for TM and TE input mode respectively; the other is to evaluate the influnce of the TM mode at through port, which is defined by <math display="block">CT_{TM-TM}^{Through} = 10 \log_{10} \left( P_{TM-TM}^{Through} / P_{TE-TE}^{Through} \right) \text{ for TM and TE input mode respectively. } P_{Model1-Model2}^{Port} \text{ is defined as the detected power of the mode2 in the port when mode1 is the input.}$ 

The CE and ER of TM-TE mode conversion at 1310 nm is -0.11 dB and 27.36 dB, while the CE and ER of TE-TE mode conversion at 1310 nm is -0.09 dB and 30.61dB. The CT of cross port for TM and TE input mode at 1310 nm is -17.92 dB and -38.79 dB respectively, while the CT of through port for TM and TE input mode at 1310 nm is -18.97dB and -19.77dB respectively. Figure 5 demonstrates the optical spectrum transmission of different mode conversion at both cross output port and through output port, indicating that the 3-dB bandwidth of proposed PSR covers the whole O-band. As shown in Fig. 5(a), the polarization conversion loss of the short wavelength is higher than that of the long wavelength. This is because the light at short wavelength is better confined in the inner bend compared to that at long wavelength, which makes the light harder be coupled from TM mode in the inner bend into TE mode in the outer bend.

#### 4. Fabrication tolerance analysis



Fig. 6. The CE as a function of (a) through waveguide width  $W_1$ , (b) rib width  $W_2$ , (c) slab width  $W_3$ , (d) height of slab  $H_2$ , and (e) gap width  $W_g$ . The wavelength is set to be 1310 nm.

We further investigate the fabrication tolerance by varying five key geometry parameters within  $\pm 10$  nm, including the width of through waveguide  $W_1$ , rib  $W_2$ , slab  $W_3$ , the height of the slab  $H_2$ , and gap  $W_g$ . Figure 6(a) and 6(e) demonstrates that, the CE of mode conversion at cross port does not change obviously when  $W_1$  or  $W_g$  varies, indicating that the PSR has a good fabrication tolerance towards both  $W_1$  and  $W_g$ . The other figures in Fig. 6 show that this PSR is relatively sensitive to  $W_2$ ,  $W_3$ , and  $H_2$ , though excess losses remain relatively modest even for 10 nm. It would be a challenge to control these fabrication dimensions to achieve the low loss below 0.2 dB. However, we can also modify the structure for improving the fabrication tolerance, such as applying the tapered structures [10]. Additionally, the CE of TE-TE mode has a good fabrication tolerance towards all these five geometry parameters.

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# 5. Conclusion

In summary, we have proposed an O-band compact PSR by exploiting  $90^{\circ}$  bends. We take advantage of bend structure with a radius of only 10 µm to help shorten the PSR and maintain high efficiency, achieving the bending, polarization splitting, rotating of input light beam at the same time. Smaller radius might be possible to be used for even shorter PSR design. Numerical simulations show that the present PSR has a high TM-TE polarization conversion efficiency of -0.11 dB and high TE-TE conversion efficiency of -0.09 dB at 1310nm, while the extinction ratio is 27.36 dB and 30.61 dB respectively. Moreover, the 3-dB bandwidth of proposed PSR covers all the O-band range. Due to its general principle, similar design with different geometry parameters can be applied for operating in other wavelength ranges, including C-band, L-band, and mid-IR. Furthermore, this design uses SiO<sub>2</sub> as top-cladding, making it compatible with most advanced CMOS technology. Thus it's ready for fabrication and testing by using standard foundry services [16]. This design provides a potential solution for polarization handing in future large-scale high-density photonic integrated chips.

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