Design of Polarization Splitter Rotator on AlGaAs-on-insulator

Xiangchen Zhang
State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University
Shanghai, China
xiangchenzhang@sjtu.edu.cn

Weiqiang Xie*
State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University
Shanghai, China
weiqiang.xie@sjtu.edu.cn

Yikai Su
State Key Lab of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University
Shanghai, China
yikaisu@sjtu.edu.cn

***Abstract*—A polarization splitter rotator (PSR) is a highly promising solution for polarization management in photonic integrated circuits (PICs). This paper proposes a PSR structure design based on AlGaAs-on-insulator (AlGaAsOI) platform. The device is capable of achieving TM_0-TE_0 conversion on AlGaAsOI, as demonstrated by simulation results.**

***Index Terms*—Polarization splitter rotator, AlGaAs-on-insulator, Ridge waveguide**

I. Introduction

Silicon photonics has been the subject of extensive research due to its compatibility with the complementary metal-oxide-semiconductor (CMOS) process [1]. However, it is increasingly challenging for silicon to meet the demands for higher performance in photonic devices, especially in the field of nonlinear optics, due to the lack of second-order nonlinear effects and two-photon absorption in silicon.

AlGaAs, a widely used III-V semiconductor material, has gained significant attention in nonlinear photonics because of several advantages. First, AlGaAs has a large refractive index, similar to that of silicon ($n_{Al_{0.2}Ga_{0.8}As}$=3.27 at $1550nm$) [2], potentially enabling strong light confinement and compact integration. Second, AlGaAs exhibits strong second-order and third-order nonlinear optical effects, which are crucial for nonlinear photonics. Furthermore, the material composition in AlGaAs can be adjusted ($Al_xGa_{1-x}As$) to tune its band gap, which can effectively avoid the issue of two-photon absorption. Hence, AlGaAs is often considered as " the silicon of nonlinear optical materials " [3]. In particular, in recent years, the emerging AlGaAs-on-insulator (AlGaAsOI) platform allows the full exploitation of the said advantages of AlGaAs in nonlinear PICs.

AlGaAsOI nanowaveguides have strong mode confinement due to high index contrast, which also causes birefringence. The propagation constants of light differ for transverse electric and transverse magnetic polarization states, leading to varying dispersions for different polarizations. The role of dispersions is essential in nonlinear optics, and the flexibility in managing the polarization of light is significant in advancing research in this field. For example, AlGaAsOI devices can use varying polarizations to achieve different optical frequency comb states [4] [5]. This is highly significant for the further development of nonlinear integrated optics. Therefore, the ability of polarization management in AlGaAsOI devices becomes a crucial requirement, while those building blocks are still missing.

Polarization management can be achieved in AlGaAsOI devices by polarization split rotators (PSRs), which relies on a vertical cross-section asymmetric structure. However, the complex structures required for PSRs, such as bi-level tapers or subwavelength gratings, are difficult to fabricate, potentially resulting in increased surface roughness and light scattering losses. Previous work has introduced an adiabatic taper-based polarization split rotator that presents a new design based on silicon-on-insulator, providing a fabrication-friendly solution [6].

In this paper, we design a PSR, utilizing adiabatic tapers and asymmetric directional couplers (ADC) based on AlGaAsOI ridge waveguides. The simulation shows that the proposed structure is effective in converting the transverse magnetic fundamental mode (TM_0) to the transverse electric fundamental mode (TE_0).

II. Design

In the design, we utilize a ridge waveguide structure instead of a fully-etched nanowire waveguide because the latter cannot provide vertical asymmetry in the presence of a SiO2 cladding layer and the absence of vertical asymmetry leads to negligible mode hybridization, which means that the propagating modes do not hybridize with each other as the waveguide width changes. The total thickness of the AlGaAs layer is chosen to be 400nm, a typical waveguide height for nonlinear photonics [4]. The slab height is set as $200nm$ and the ridge height is $200nm$ as well. The thickness of the buried oxide layer is $3\mu m$ and the thickness of the top oxide layer is $1.5\mu m$. In fabrication, the ridge waveguide can be obtained by a shallow etching process in AlGaAsOI platform with a total height of $400nm$. At a wavelength of $1550nm$, the refractive index of the material used in the structure is 3.27 for AlGaAs and 1.445 for silicon dioxide. Fig. 1 shows the three-dimensional configuration of the PSR, while Fig. 2 displays its planar projection from a top-down perspective.

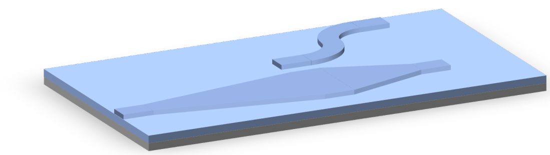

Fig. 1. Three-dimensional schematic of the PSR.

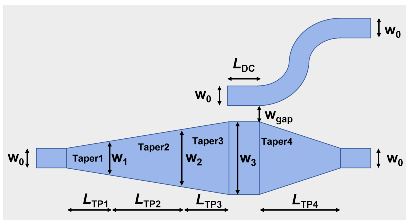

Fig. 2. The planar projection of the PSR viewed from a top-down perspective.

To keep proper interfacing with other devices on the chip, the PSR was designed with a ridge width of $600nm$ at the input and output ends, corresponding to an effective index of 2.813 for the TE_0 mode. To satisfy the phase matching condition, a waveguide width of $w_3 = 1.4\mu m$ is chosen in the coupling region. This width enables the efficient coupling between the TE_1 and TE_0 modes in the wide waveguide and the narrow waveguide with a width of $w_0 = 600nm$, as both waveguides have an effective refractive index of 2.81 as shown in Fig. 3. To ensure compatibility with the fabrication process, we have selected a gap of $150nm$ for the ADC. By utilizing the eigenmode expansion (EME) method, the optimal coupling length L_{DC} for this configuration is determined to be $21\mu m$ as shown in Fig. 4. So far, we have designed an ADC that allows the TE_1 mode in the wide waveguide to couple to the TE_0 mode in the narrow waveguide, while the TE_0 mode on the wide waveguide will pass through directly.

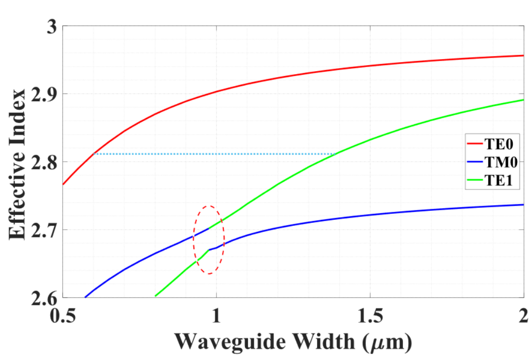

Fig. 3. The relationship between the effective refractive index and the ridge waveguide core width. Mode hybridization occurs within the region enclosed by the dashed line. The points on the two curves with an effective refractive index of 2.81 are specifically marked.

Next, a taper structure is used for conversion between TM_0 mode in the input waveguide with a width of w_0 and TE_1

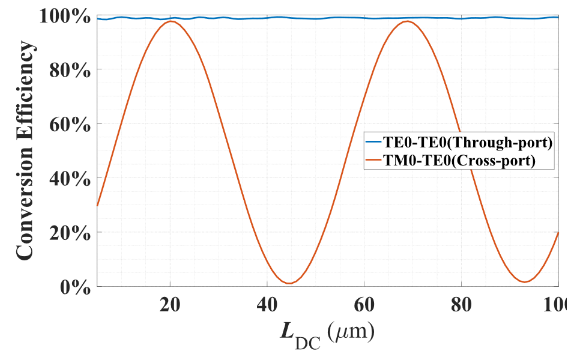

Fig. 4. The relationship between the conversion efficiency and the length of the asymmetric directional coupler (L_{DC}).

mode in the waveguide with a width of w_3. We divide the taper into four sections to fulfill the requirements of mode conversion with a small footprint. The principle of mode conversion is that when an asymmetric waveguide undergoes a width variation, the modes will hybridize and convert with each other. This is reflected in the relationship between the effective index of mode and the waveguide width, as shown in Fig. 3. In fact, the TE_1 and TM_0 modes in the mode conversion region are not purely polarized, yet denoted as TE_1 and TM_0 for convenience. To facilitate the conversion of the TM_0 mode to the TE_1 mode during the propagation of light in Taper2, it is necessary to ensure that the widths of both ends of Taper2 meet the conditions $w_1 < 1\mu m$ and $w_2 > 1\mu m$, as shown in Fig. 2 where mode conversion occurs at $w_c = 1\mu m$. Furthermore, it is crucial to ensure that w_1 and w_2 are sufficiently separated away from w_c, as any proximity may result in mode hybridization at the edge of Taper2. Moreover, w_2 should not be excessively wide, as it may introduce undesired higher-order modes. Therefore, we choose $w_1 = 0.8\mu m$ and $w_2 = 1.2\mu m$ to guarantee the conversion of the TM_0 in Taper2. The length of Taper2, denoted as L_{TP2}, is a critical parameter, and the mode conversion can only be achieved when it is sufficiently long. The relationship between the conversion efficiency of the TM_0 and the length of Taper2 can be obtained through the eigenmode expansion method, as shown in Fig. 5. To ensure a larger fabrication tolerance without sacrificing the device footprint, a length of $120\mu m$ is used.

The lengths of Taper1, Taper3 and Taper4 (denoted as L_{TP1}, L_{TP3} and L_{TP4}, respectively.) should be optimized to achieve high performance while minimizing the footprint. To ensure the outputs of the cross port and the through port are aligned horizontally, L_{TP4} is designed to be the same as the length of the S-bend. Through simulation, it was found that L_{TP1} and L_{TP3} have little effect on the conversion efficiency near $5\mu m$, and only introduce acceptable ripples. Fig. 6 shows the impact of L_{TP4} on the overall mode conversion of the device. We have selected $L_{\mathrm{TP1}} = 4\mu$m, $L_{\mathrm{TP3}} = 4\mu$m and $L_{\mathrm{TP4}} = 30\mu$m as the design parameters.

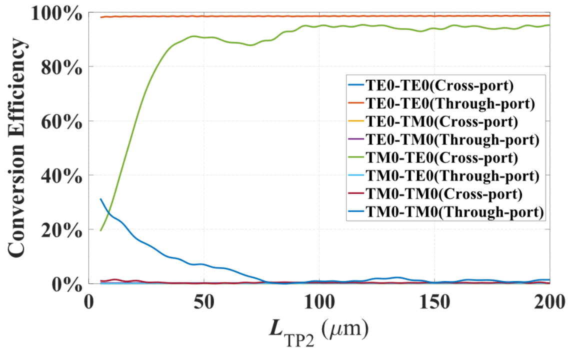

Fig. 5. The relationship between the conversion efficiency and the length of Taper2 (L_{TP2}).

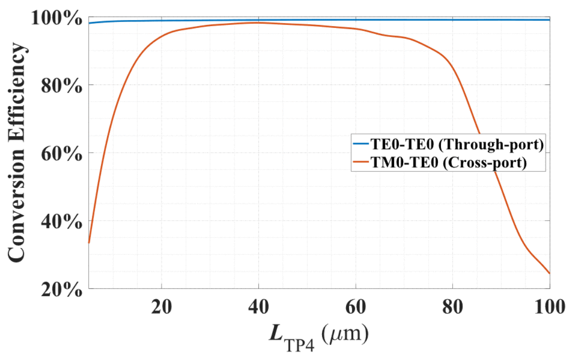

Fig. 6. The relationship between the conversion efficiency and the length of Taper4 (L_{TP4}).

Based on the above optimization, we have successfully designed a PSR on the AlGaAsOI platform with a total length of $180\mu m$ approximately. This design can achieve a high mode conversion efficiency exceeding 97% and also allow high feasibility in fabrication.

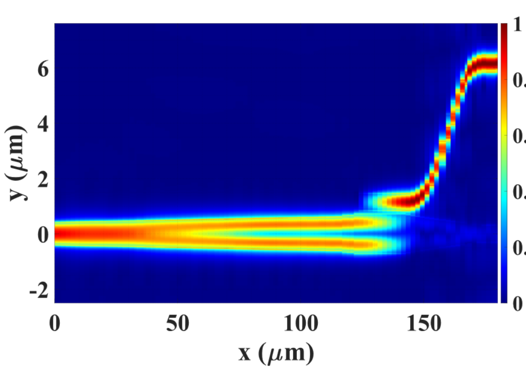

Fig. 7. The light field evolution in the designed PSR under TM_0 input.

III. Result

We have simulated the light propagation in our designed structure. Fig. 7 and Fig. 8 show the light propagation in this

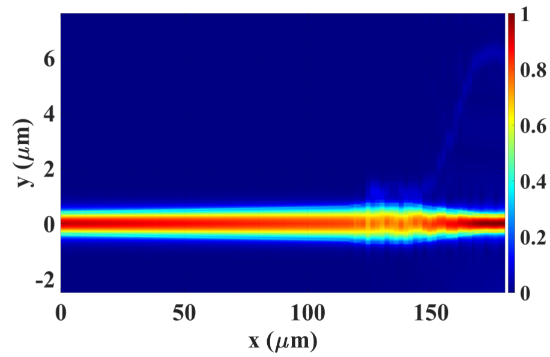

Fig. 8. The light field evolution in the designed PSR under TE_0 input.

structure when the input is TM_0 and TE_0, respectively. It can be seen that the conversion of TM_0 to TE_1 occurs in the taper when the input is TM_0. In the coupling region, TE_1 mode is not transmitted through the Taper4 to the through port but is coupled to the TE_0 mode of the narrow waveguide through the asymmetric directional coupler, and then is output at the cross port. When the input is TE_0, the mode neither has mode conversion in the taper nor is coupled to the narrow waveguide in the coupling region. Therefore, the device can function as a PSR component.

IV. Conclusion

In this paper, we present a structure for PSR utilizing an adiabatic taper and an asymmetrical directional coupler based on AlGaAsOI ridge waveguides. Simulation results indicate that this device can effectively convert the mode between TM_0 and TE_0. Additionally, the proposed structure is simple and easy for fabrication. In our future work, we plan to fabricate the device and conduct performance test. Finally, we believe the device performance can be further improved and the footprint can be reduced by utilizing optimization algorithms.

References

[1] S. Y. Siew, B. Li, F. Gao, H. Y. Zheng, W. Zhang, P. Guo, S. W. Xie, A. Song, B. Dong, L. W. Luo, *et al.*, "Review of silicon photonics technology and platform development," *Journal of Lightwave Technology*, vol. 39, no. 13, pp. 4374–4389, 2021.

[2] A. A. Martin, "Refractive index of ga1- xalxas," *Solid State Communications*, vol. 15, no. 1, pp. 59–63, 1974.

[3] G. Stegeman, A. Villeneuve, J. Kang, J. Aitchison, C. Ironside, K. Al-Hemyari, C. Yang, C.-H. Lin, H.-H. Lin, G. Kennedy, *et al.*, "Algaas below half bandgap: the silicon of nonlinear optical materials," *International Journal of Nonlinear Optical Physics*, vol. 3, no. 03, pp. 347–371, 1994.

[4] W. Xie, L. Chang, H. Shu, J. C. Norman, J. D. Peters, X. Wang, and J. E. Bowers, "Ultrahigh-q algaas-on-insulator microresonators for integrated nonlinear photonics," *Optics Express*, vol. 28, no. 22, pp. 32894–32906, 2020.

[5] W. Xie, C. Xiang, L. Chang, W. Jin, J. Peters, and J. E. Bowers, "Silicon-integrated nonlinear iii-v photonics," *Photonics Research*, vol. 10, no. 2, pp. 535–541, 2022.

[6] D. Dai and J. E. Bowers, "Novel concept for ultracompact polarization splitter-rotator based on silicon nanowires," *Optics express*, vol. 19, no. 11, p. 10940, 2011.