# Mode-Evolution-based Symmetrical Polarization Splitter-Rotator on Monolithic InP Platform

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**Abstract** *Symmetrical polarization splitter-rotator is experimentally demonstrated on monolithic InP platform for the first time. By employing an optimized adiabatic taper and a mode-independent splitter, polarization extinction ratio of 16.3 dB with a polarization-dependent loss below 0.7 dB is obtained at 1550 nm wavelength.*

## Introduction

Integrated polarization splitter-rotator (PSR) is the essential component required for on-chip polarization (de)multiplexing in photonic integrated circuits (PICs). While it is a conventional procedure to use pure TE0 and TM0 modes as the orthogonal bases in realizing PSR, it inevitably requires complicated devices, including asymmetric cross-section waveguides and/or mode-selective couplers[1]-[4].

In many practical applications, such as polarization (de)multiplexing in digital coherent systems, it is not mandatory to split or combine TE0 and TM0 modes. Instead, any orthogonal polarization modes can be used as the bases since the state of polarization (SOP) is scrambled anyway during the fibre transmission and it will be compensated for by the digital signal processing (DSP) at the receiver.

In contrast to the TE0/TM0-based PSRs, ±45° linear SOPs (or any other mutually orthogonal SOPs on the $S_2$-$S_3$ plane of the Poincaré sphere) can be used as the orthogonal bases to enable significantly simpler symmetrical PSR with a wider design space. While such device has been demonstrated on silicon photonics[5], it has not been realized on InP to our knowledge.

In this work, we demonstrate a monolithic InP PSR, which splits two orthogonal SOPs on the $S_2$-$S_3$ plane, rotates them to TE modes, and output to two independent ports. Using the fabricated device, a polarization extinction ratio over 16.3 dB with a polarization-dependent loss (PDL) below 0.7 dB is demonstrated. The entire device consists of a single-etch simple symmetrical ridge structure, which can readily be integrated with InP-based high-speed modulators, photodetectors (PDs), lasers, and semiconductor optical amplifiers (SOAs) to realize monolithic dual-polarization transceivers.

## Device concept and principle

Figure 1 illustrates the schematic of the symmetrical PSR demonstrated in this work. It consists of an adiabatic taper section and a mode-independent splitter section. The entire device has an identical layer profile with 350-nm-thick lattice-matched InGaAsP core layer and 230-nm-thick upper InP cladding layer, which is etched by 210nm to form a ridge waveguide.

When a polarization-multiplexed light is incident to the device, its $x$ and $y$ polarization components, denoted by $E_x$ and $E_y$, respectively, excites the TE0 and TM0 modes of the input ridge waveguide. At the adiabatic taper section, the waveguide width is increased gradually from 2.0

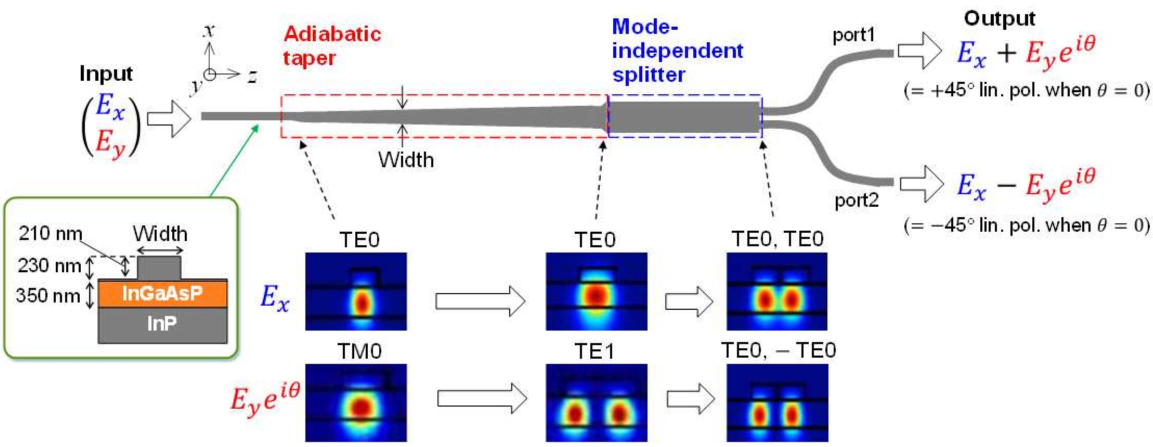


**Fig. 1:** Schematic of the InP symmetrical PSR, which consists of adiabatic taper and mode-independent splitter sections.

μm to 3.2 μm. Due to the adiabatic mode-evolution mechanism[1], the TM0 mode is converted to TE1 mode, while the TE0 mode is kept unchanged. Then, by transmitting through the mode-independent splitter, both TE0 and TE1 mode are split into two TE0 modes at the output ports. Due to the symmetric and anti-symmetric profiles of the TE0 and TE1 modes, the total optical fields at the two output ports would be proportional to $E_x + E_y e^{i\theta}$ and $E_x - E_y e^{i\theta}$, respectively. Note that $e^{i\theta}$ accounts for the birefrigence at the input waveguide. This device, therefore, functions as a PSR, which splits two orthogonal SOPs on the $S_2$-$S_3$ plane of the Poincaré sphere (±45-deg linear polarization modes when $\theta = 0$) into two output ports.

It is noteworthy that the light from both output ports exhibits the fundamental TE0 mode. Therefore, these ports can be connected directly to TE-mode optical hybrids and PDs to realize a compact dual-polarization coherent receiver on InP. Furthermore, this device can also be used in an opposite direction as a polarization-beam combiner. By integrating TE-mode high-speed modulators, lasers, and SOAs, fully integrated monolithic dual-polarization transmitter can be realized.

## Device design and numerical results

In order to minimize the overall device length without degrading the loss and crosstalk properties, each section needs to be optimized judiciously. This is especially challenging for InP devices compared with silicon-photonic devices due to its weaker optical confinement.

First, the thickness of the upper InP cladding is optimized to 230 nm (as shown in Fig. 1 inset) to avoid the use of a pre-converter or a spot-size converter at the input, which was necessary in the previous work[2]-[4] to ensure efficient coupling. This rather thick upper InP cladding of our device, on the other hand, generally increases the required length of the taper section due to the reduced vertical asymmetry. To cope with this issue, we apply a method similar to the fast quasiadiabatic dynamics[6] to design a functional taper instead of a simple linear taper.

Fig. 2 shows the calculated effective indices of the second and the third waveguide modes, $n_2$ and $n_3$, of the ridge InP/InGaAsP structure (shown in Fig. 1 inset) as a function of the waveguide width. The first mode, which is the TE0 mode, is omitted in this plot for clarity. We can see that by gradually increasing the width from 2.0 μm to 3.2 μm, the input TM0 mode can be converted to TE1 mode adiabatically as explained in the previous section. Here, we judiciously change the tapering rate depending

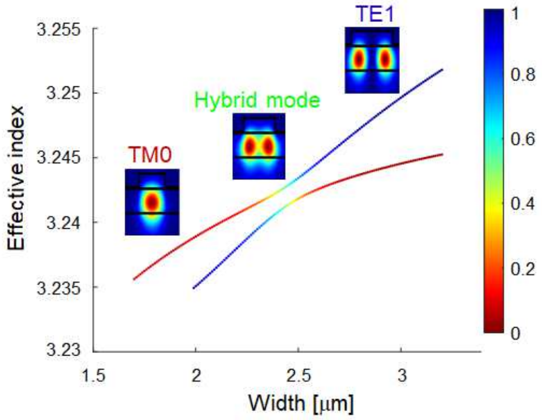


**Fig. 2:** Effective indices of the 2nd and 3rd highest index mode as a function of waveguide width at 1550 nm.

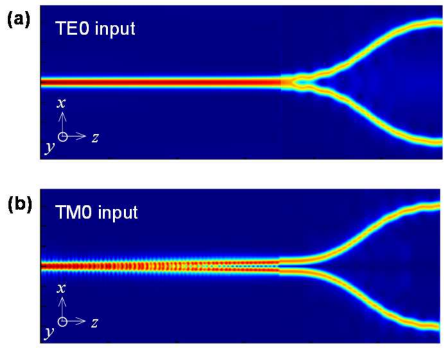


**Fig. 3:** Simulated light propagation of the entire PSR at 1550 nm for TE0 (a) and TM0 (b) inputs.

on $|n_2 - n_3|$. With the optimized taper, having only 700-μm length, we numerically confirm 95% conversion from TM0 to TE1.

Finally, the mode-independent splitter is designed. We employ a 1×2 multimode interference (MMI) coupler with an optimal width, so that only TE0, TE1, and TE2 modes are excited inside the MMI to avoid excess scattering losses. Assuming an MMI coupler with a width of 4.3 μm and a length of 28 μm, we numerically obtain the total transmission of 99.4% and 99.8% for the TE0 and TE1 input, respectively.

Fig. 3 shows the simulated light propagation of the entire device at 1550-nm wavelength when TE0 and TM0 modes are launched at the input. We can confirm that both modes are split equally into two output ports without loss. Due to the symmetry in $x$ direction, the two outputs exhibit in-phase and out-of-phase amplitudes for the TE0 and TM0 inputs, respectively. The entire device, therefore, functions as a PSR with the orthogonal bases on the $S_2$-$S_3$ plane as explained in Fig. 1.

## Device fabrication and characterization

The designed device was fabricated by a simple single-etching process. After patterning by

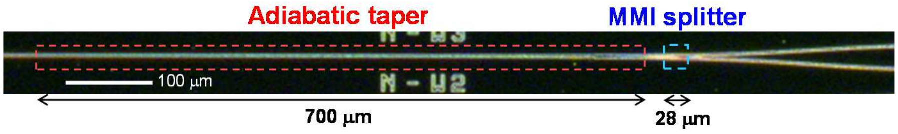


**Fig. 4:** Microscopic image of the fabricated PSR on InP.

electron beam lithography, the ridge waveguides were formed by $CH_4/H_2$-based inductively coupled-plasma reactive-ion etching (ICP-RIE). The microscopic image of the fabricated PRS is shown in Fig. 4. The length of the PSR section is 750 μm, while that of the entire device, including the output fan-out, which was not optimized in this work, is around 1100 μm. This is nearly 1/2 shorter than the previously demonstrated InP-based PSR with a total length of 2000 μm[3].

We used a similar experimental setup as our previous work[7] for characterization. A sequence of a polarizer, a half-wave plate (HWP), and a quarter-wave plate (QWP) was used to align the SOP of the incident light to a state on the $S_2$-$S_3$ plane. The power and SOP of the output light from the device were measured by a polarization analyzer.

Fig. 5 shows the measured output power at 1550 nm as we change the input SOP around the $S_2$-$S_3$ plane by rotating the HWP. We can see that the maximum and the minimum values are obtained at 17.5° and 62.5°, corresponding to a pair of orthogonal SOPs on the $S_2$-$S_3$ plane. The extinction ratios are 18.2 dB and 16.3 dB for the respective ports, with the PDL of less than 0.7 dB.

Fig. 6 shows the wavelength dependence of the measured extinction ratio for both output ports. Due to the birefringence at the input waveguide, $\theta$ is generally nonzero and changes with the wavelength. As a result, the orthogonal bases rotate on the $S_2$-$S_3$ plane as we sweep the wavelength. For each wavelength, therefore, we rotated the HWP to derive the extinction ratio. The extinction ratios of more than 18 dB and 14 dB are obtained for respective ports in a wide wavelength range from 1540 to 1560 nm.

We should note that the change of the orthogonal bases with the wavelength would not be a problem at all when this device is used for polarization (de)multiplexing in dual-polarization coherent transceivers. This is because the SOP would rotate randomly inside the transmission fibre anyway and such rotation is automatically compensated for by the DSP. This device can, therefore, be used for broadband coherent transceivers.

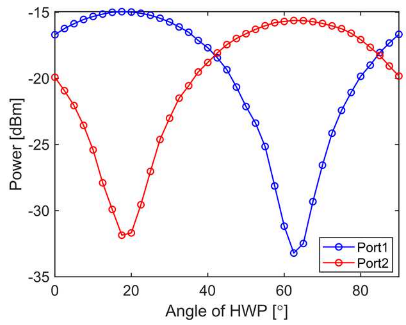


**Fig. 5:** Output power at 1550 nm from each port as the input SOP is rotated on the $S_2$-$S_3$ plane by the HWP.

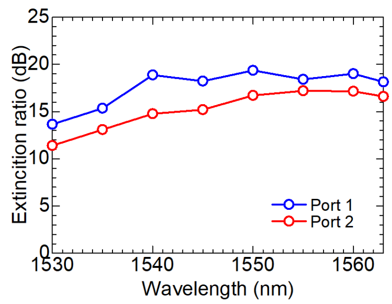


**Fig. 6:** Measured wavelength dependence of extinction ratio for each port.

## Conclusions

We have proposed, designed, and experimentally demonstrated a symmetrical PSR on monolithic InP platform for the first time. By utilizing a functional adiabatic taper and a symmetric MMI splitter, highly efficient PSR with the total length of 750 μm is realized. Using the fabricated device, an extinction ratio of more than 16.3 dB with the PDL below 0.7 is demonstrated.

## References


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