The Integration of Polarization Splitter-Rotator and Photodetector in Optical Receiver

Xiaojuan She\textsuperscript{1,2}, Han Liao\textsuperscript{1,2}, Yingxuan Zhao\textsuperscript{1*}, Junbo Zhu\textsuperscript{1,2}, Yang Li\textsuperscript{1,2}, Lue Tao\textsuperscript{1,2}, Zijian Zhu\textsuperscript{1,2}, Rui Huang\textsuperscript{1,2}, Xiang Liu\textsuperscript{1,2}, Chao Qiu\textsuperscript{1}, Haiyang Huang\textsuperscript{1}, Zhen Sheng\textsuperscript{1*}, Fuwan Gan\textsuperscript{1,2*}

\textsuperscript{1}State Key Laboratory of Functional Materials for Informatics, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China
\textsuperscript{2}Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{*}zhaoyx@mail.sim.ac.cn, *zsheng@mail.sim.ac.cn, *fuwan@mail.sim.ac.cn

Abstract: Because of high-index contrast Si/SiO$_2$ system, polarization sensitivity is a severe problem in photonic integration devices. In this paper, we design a integration devices comprised of polarization splitter-rotator (PSR) and germanium photo detectors (PDs) on chip. The integration of PSR and PD can realize the integrated layout which can realize the measurement of PSR polarization properties. After calculation, the on-chip loss of the polarization beam splitter is 1.19dB, and the polarization isolation of the system is 14.59dB/5.141dB in TE0/TM0 mode.

1. Introduction

In the past decades, silicon photonics on a silicon-on-insulator (SOI) platform are greatly put forward for its compact footprint accompanied with high integration level \cite{1}, \cite{2}, low power consumption, and compatibility with the complementary metal oxide semiconductor (CMOS) process with the ever-increasing demand for higher system interconnect \cite{3} bandwidth and smaller footprint. There is a large of research in integration device for on-chip optical networks. Due to high refractive index contrast between Si and SiO$_2$, polarization sensitivity is a serious problem in photonic device \cite{4}. PSR is one of the most critical components for both on-chip and off-chip optical networks, which can convert TM mode to TE mode on chip. Optical signals carried by different polarization states are transmitted in the same fibre or waveguide, and the test system composed of PSR and PD can convert TM mode to TE mode, which can be transferred along waveguide in subsequent process.

2. Device principle

We designed a broadband PSR based on mode hybridization principle and integrate it with PD to obtain high bandwidth and polarization isolation \cite{5}, \cite{6}. Based on the mechanism of mode hybridization, the phase-matching condition, i.e., the approximately equal in the effective indices of guided modes with two polarization state is satisfied in PSR. Mode hybridization principle can be written as formula (1)

\[ n_{eff}(TM0) - n_{eff}(TE1) < n_{eff}(TE0) \]  

(formula 1)
Where $n_{\text{eff}}(\text{TE1})$, $n_{\text{eff}}(\text{TM0})$ and $n_{\text{eff}}(\text{TE0})$ are effective refractive indices of different mode in coupling field. When the TM0 mode is launched in the waveguide, it is completely coupled to TE1 mode due to the equation of $n_{\text{eff}}(\text{TE1}) \approx n_{\text{eff}}(\text{TM0})$. For $n_{\text{eff}}(\text{TE0}) > n_{\text{eff}}(\text{TE1})$, TE1 mode is easily converted to TE0 mode in coupling field. As showed in Figure 1, the device is composed of a broadband PSR, left PD and right PD. TM0 mode can be converted to TE0 mode in right-taper, and then be detected by right PD. Similarity, TE0 mode can go through the coupling region and received by left PD. The schematic structure of the device is shown in Figure 1.

![Figure 1. (a) Layout of device (b) Microscope picture of the device](image)

3. **Experimental results**

The proposed device is fabricated on a SOI wafer with a top silicon layer of 220nm. The waveguide pattern is fabricated with inductively coupled plasma reactive ion etching (ICP-RIE) with photo resist, which acts as a mask layer for the subsequent Si etching. To obtain high coupling efficiency between the chip and fibre, we use two-step etching process to fabricate a grating coupler. A thick silicon dioxide layer is deposited on the surface to protect the device.

Light is incident from the grating coupler and then pass through the waveguide. The loss of different length waveguide is showed in Figure 2 with the wavelength range from 1.5 to 1.6 um, where No.1, 2 and 3 indicated different length waveguide. The parameters of three groups are list in Table 1. It can be clearly seen that the mean coupler loss of three groups is 3.8183 dB in 1.55 um.

![Figure 2. The loss of three group grating with different length waveguide in the waveband from 1.5 um -1.6 um.](image)

| No. | Loss(dB) (@1.55 um) | Coupler Loss(dB) (@1.55 um) |
|-----|---------------------|-----------------------------|
| No.1| 7.98                | 3.865                       |
| No.2| 7.89                | 3.82                        |
| No.3| 7.79                | 3.77                        |

Table 1. Parameters of three groups
Figure 3. Experimental setup for testing the bandwidth of device

By integrating the silicon PSR with two germanium photo detectors (PDs) as described in Figure 1 (a), the on-chip loss of the polarization beam splitter is 1.19 dB and 4.08 dB in TE0 and TM0 mode. Meanwhile the polarization isolation is 14.59 dB and 5.141 dB in TE0 and TM0 mode, respectively, compared to the PD after being calculated. As referred in formula (2), the calculation method of the responsivity is interpreted clearly.

\[
\text{Responsivity of } \frac{\text{TE0}}{\text{TM0}} = \frac{\text{PC}_{\text{TE0}}}{\text{PC}_{\text{TM0}}} \frac{\text{Power}_{\text{in}} - \text{Loss}_c}{\text{Power}_{\text{in}}}, \quad \text{(formula 2)}
\]

Where \(\text{PC}_{\text{TE0}}\) and \(\text{PC}_{\text{TM0}}\) are the photocurrent of TE0 and TM0 mode, respectively. \(\text{Power}_{\text{in}}\) indicates the incident light power, the value of which is -0.2909 dBm. \(\text{Loss}_c\) is the coupling loss of the system, which is measured as 2.6975 dB.

The bandwidth is an important property in the system, which expresses the system interconnect bandwidth. The experimental setup system of testing bandwidth is showed in Figure 3 to obtain properties of device. In the photocurrent and bandwidth testing experiment, the input wavelength is set to 1.55 μm. The photocurrent of 0.23 mA and 8 μA is obtained at -2 V for TE0 polarization in left and right PD, respectively.

\[
\text{PI} = \frac{\text{RV}_{\text{mm}}}{\text{RV}_{\text{sm}}} \quad \text{for formula (3)}
\]

Where PI is the polarization isolation, \(\text{RV}_{\text{mm}}\) and \(\text{RV}_{\text{sm}}\) are responsivity value of main mode and secondary mode in two PDs. The polarization isolation is 14.59 dB and 5.141 dB under TE0 and TM0 mode. As shown in Figure 4 (a), I-V curve of the typical PD illuminates the property of PD. Dark current of PSR with two PDs is about 0.221 nA at -2 V bias. In Figure 4(b), under the reverse bias of 2 V, the 3dB OE bandwidth of device in TE0 polarization state is 20 GHz.

Figure 4. (a) Photocurrent and (b) Loss of PSR integrated with PD
4. Conclusions
In this paper, the system of PD combing with PSR, which is comprised of a bi-level taper and a counter-taper coupler, is proposed to realize the measurement of PSR polarization properties. After experimental test, the loss of the polarization beam splitter is 1.19dB, the polarization isolation is 14.59dB/5.141dB in TE0/TM0 mode and the 3dB bandwidth is 20GHz.

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