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An Accurate Characterization Method for Integrated Polarization Converters

Sander F.G. Reniers, Kevin A. Williams, Jos J.G.M. van der Tol, Yuqing Jiao

Abstract—We present a characterization method for polarization converters which improves the accuracy of traditional characterization methods significantly. An experimental demonstration of the method is presented on the InP-membrane-on-silicon (IMOS) platform. The design and fabrication of the polarization converter is discussed, as well as the simulated polarization conversion efficiency. A device of only 4 microns is shown to achieve $97.5\% \pm 0.5\%$ polarization conversion, corresponding to an extinction ratio of -16 ± 0.9 dB. The traditional characterization method is compared to the new 4-port method, and the accuracy is improved from up to 20% to 0.5%.

Index Terms—Photonic integrated circuits, nanophotonics, photonic crystals, polarization, polarization converters.

I. INTRODUCTION

FIBER-OPTIC communication was developed in the 1970s, and has revolutionized the telecommunications industry. The high bandwidth capabilities of optical fibers have made them an alternative to traditional copper cables that could not be overlooked. New technologies, e.g. wavelength division multiplexing, polarization diversity schemes and advanced digital coherent technologies increased the popularity of optical communication even more. Traditionally, optical transceivers were used for long distance communication or for bandwidths exceeding the capabilities of electronics. More recently, optical communications are also used for short distance communication, e.g. rack-to-rack interconnects in data centers. Low power consumption and integratability with electronics is of paramount importance nowadays. Integrated polarization converters enable polarization diversity schemes such as DP-WDM and more complex schemes, e.g. Stokes vector modulation. For these purposes, it is of paramount importance to have precise control over the conversion efficiency. To be able to control the conversion efficiency, one needs to have the tools to characterize the converters as accurately as possible, which are the characterization circuits. Traditionally, on platforms that offer edge-coupling, an arbitrary state of polarization can be coupled in and out of the chip. With proper analysis, the conversion efficiency can be extrapolated from such measurements, when making use of polarizers and waveplates. However, on nanophotonic platforms, edge-coupler is not a conventional method for coupling light, simply due to the mismatch of the mode size of the fundamental

modes in the photonic wires and the optical fiber. Therefore, surface grating couplers, which are operating for either the TE or the TM polarization with high extinction to the orthogonal polarization, are typically used for this purpose. Generally, transmission measurements are dependent on the insertion loss of these surface grating couplers, which can vary based on location on the chip, e.g. due to slight thickness variations in the BCB thickness. Furthermore, one needs to compensate the measurement for those insertion losses by using calibration structures, which introduces uncertainties in the characterization.

We introduce a method for characterization of polarization converters which is independent on the insertion loss of the grating couplers and other components in the characterization circuit, and hence boosts the accuracy of the characterization significantly. This is an adjustment to the method that is used to characterize photonic crystal reflectors [1]. The key difference is that for the characterization of polarization converters, there is only one unknown, the conversion efficiency, instead of two unknowns for the reflectors, the transmission and reflection of a reflector. Therefore, the accuracy for the characterization of polarization converters is even higher.

The InP-membrane-on-silicon (IMOS) platform [2] offers many advantages for demonstration of this characterization method. Firstly, the unique triangular shaped structure is extremely compact [3]. Secondly, the platform offers full active-passive integration, making this method a useful tool for further development. Lastly, the methodology that is reported here can be transferred to any photonic integration platform. The IMOS platform consists of a 300 nm thick membrane of InP, which corresponds to the core thickness in the waveguides, bonded by benzocyclobutene (BCB) to a carrier wafer (typically silicon or CMOS). An example of a cross section of an IMOS waveguide is illustrated in Fig. 1. The core thickness and high index contrast enable tight light confinement and device miniaturization. A description of the fabrication process of IMOS devices, and specifically the polarization converters, is given in Section II-A.

II. POLARIZATION CONVERTER

In this section, the polarization converter that is used for demonstration of the characterization method is presented. Firstly, the design and the fabrication process are discussed. Secondly, the performance of the device in a simulation is shown.

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Fig. 1. Cross section of a typical waveguide on the IMOS platform. Dimensions of the InP waveguide: 400 nm wide, 300 nm thick.

Fig. 2. Design of the polarization converter.

A. Design and fabrication

The design of the polarization converter is shown in Fig. 2. It consists of two triangular sections, which are connected by a short rectangular waveguide. The working principle is based on mode hybridization [3]. To achieve optimal mode coupling between the rectangular and triangular sections, the height of the triangular sections is larger than the standard core thickness of 300 nm. To achieve the slope of the triangular sections, $\text{HCl}:\text{H}_3\text{PO}_4$ (1:4) is used as a wet etchant, which results in a slope of 35 degrees. An additional etch-stop-layer is introduced, such that only in the areas where the triangular sections are present the extra thick membrane exists, whereas on the rest of the wafer the membrane is only 300 nm thick. A separate lithographic step is required to define these areas. To create the slope in only one direction, the vertical sidewall of the polarization converter is etched first, in the same lithographic step as the waveguide definition. The area around the triangular section is then opened in the consecutive lithographic step, and the silicon nitride hardmask is etched directionally, ensuring that the vertical sidewall is still covered by silicon nitride. Since the $\text{HCl}:\text{H}_3\text{PO}_4$ (1:4) wet etch stops on the $\{1\bar{1}2\}$ crystal plane of InP [4], the triangular section is formed. A cartoon view of the key steps in the fabrication process is shown in Fig. 4. Note that the flexibility of the IMOS platform provides the option of processing the InP on

Fig. 3. Scanning electron microscope image of a fabricated polarization converter before bonding.

both sides, before and after the bonding process. In this process flow, the choice is made to perform all the processing before the bonding process, since this enables integration of the component in the twin-guide active-passive integration scheme of IMOS. A scanning electron microscope (SEM) image of a fabricated device, taken before wafer bonding, is shown in Fig. 3.

B. Simulation

To determine the dimensions of the triangular sections, both eigenmode expansion (EME) and finite-difference time-domain (FDTD) simulations are performed. Firstly, the optimal height for the triangular sections is determined, by calculating the best overlap of the hybrid modes in these sections with the modes in the standard IMOS waveguide (400 nm wide by 300 nm high). This height was found to be 460 nm, and thus the thickness for the extra layers shown in Fig. 4 are 20 nm for the etch-stop-layer, and 140 nm for the extra indium phosphide layer.

Secondly, the hybrid modes in the triangular sections need to be analyzed. The two hybrid modes that exist in this 460 nm high triangular section are shown in Fig. 5. The left mode has an effective index of 2.269, the right mode has an effective index of 1.901. From the TE fraction of one of the modes, the tilt angle of the mode is calculated by $\theta = \cos^{-1}(\sqrt{0.78}) \approx 28^\circ$. This result indicates a single section device is not sufficient to achieve full polarization conversion, since the maximum achievable rotation for a single section device is $2 \cdot 28 = 56^\circ$. Therefore, a double section device is chosen, and hence any state of polarization can be achieved. Since we are interested

Fig. 4. Key steps in the fabrication process of a polarization converter on IMOS. (a) Initial layer stack for fabrication of polarization converters. After vertical sidewall definition, coverage by silicon nitride and directionally etching of silicon nitride. (b) After consecutive wet etching with HCl:H₃PO₄ (1:4), H₂SO₄:H₂O₂:H₂O (1:1:10) and again HCl:H₃PO₄ (1:4) and removal of the silicon nitride mask. (c) After bonding and removal of substrate and etch-stop-layer.

in exploring the performance of the converter around full conversion, we can use $L_1 = 2L_\pi - L_2$, where L_n is the length of the n^{th} section and L_π is the half-beat length of the two eigenmodes of the triangular section, as shown in [3]. The half-beat length is given by $L_\pi = \frac{\pi}{(\beta_1 - \beta_2)}$, where β_1 and β_2 are the propagation constants of the two eigenmodes. For this device, the half-beat length is calculated to be 2.1 microns, and hence the length of the full device is 4.2 microns. If one considers the Poincaré sphere, it becomes evident that the lengths of the two sections to achieve full conversion are of unequal length with tilt angles unequal to exactly 22.5°, by considering:

$$L_1 = \frac{L_\pi}{\pi} \cdot \left(\arcsin \left(\frac{1}{(\tan 2\theta)^2} \right) + \frac{\pi}{2} \right) = 2L_\pi - L_2. \quad (1)$$

To determine the optimal lengths of the two sections L_1 and L_2 and improve the accuracy, further 3D-FDTD simulations

Fig. 5. Simulated field profile of the two eigen modes in the triangular section.

Fig. 6. Simulated efficiency and insertion loss for the optimized polarization converter.

are done, showing the optimal lengths for both sections to be $L_1 = 1.7$ microns and $L_2 = 2.3$ microns. We note that the length is slightly shorter than calculated from the mode simulation results. Two reasons which can explain this are the noted inaccuracy in the mode simulation, which was indicated by the TE fractions of the modes not adding up to exactly one, which one would expect. Secondly, a section of 200 nm long rectangular waveguide is introduced between the two rectangular sections, for fabrication reasons. The simulated conversion efficiency and insertion loss are shown in Fig. 6.

III. CHARACTERIZATION

In this section, the methodology for characterization of polarization conversion devices is first introduced. In the second part the results are shown for a polarization converter on the IMOS platform, and the new method is compared to a traditional measurement technique. The polarization conversion efficiency is defined as the fraction of light that has been converted to the orthogonal polarization by the converter. Alternately, one can consider the residual part that is not converted, the extinction ratio.

A. Methodology

1) *Traditional method:* Determining the conversion efficiency of a polarization converter on a platform such as the IMOS platform is often done by measuring both the TE and TM output of a converter, and using $\eta = \frac{P_{\text{TM}}}{P_{\text{TE}} + P_{\text{TM}}}$ (if the input

Fig. 7. Schematic view of a traditional characterization circuit for polarization converters.

was TE). A straightforward way to do this, is to have a TE input grating coupler, a polarization converter, a 1x2 multimode interference coupler for splitting the light 50/50, and a TE and TM grating coupler for the outputs, as shown schematically in Fig. 7. This structure offers the possibility for measuring the TE and TM output in two separate measurements. One has to compensate these measurements for the insertion loss of the MMI and the output grating couplers. The insertion loss of the input grating coupler is automatically compensated when calculating the conversion efficiency. To compensate for the insertion losses, calibration structures are required, which typically give an uncertainty of around 0.5 dB per grating coupler. This has a significant influence on the accuracy of the determined conversion efficiency, since this already adds up to around 20% uncertainty. Furthermore, the MMI behaves differently for the TE and TM mode due to a different effective refractive index for these modes. Due to symmetry, a 1x2 MMI is inherently balanced when used as a splitter, but it can result in a different insertion loss for both polarizations. The latter can be solved by either designing a polarization insensitive MMI, or by using two separate structures without the MMI, one with a TE output coupler and one with a TM output coupler. However, this can create an uncertainty in the measurement by itself, since one is actually measuring two structures in that case, introducing more uncertainties.

2) *4-port method*: The method we introduce to accurately characterize the performance of our polarization converters is a measurement with four ports: two input ports and two output ports. The schematic view of the measurement circuit is shown in Fig. 8, and the design that is fabricated is shown in Fig. 9. For further reference, the input and output ports have been numbered, as shown in Fig. 8. We consider P_{ij} the measured power at output j when input i is used, which, for all combinations of inputs and outputs results in

$$P_{13} = \alpha_1 \alpha_3 \alpha_{\text{MMI}}^2 (1 - \eta) P_{\text{in}}, \quad (2)$$

$$P_{14} = \alpha_1 \alpha_4 \alpha_{\text{MMI}}^2 \eta P_{\text{in}}, \quad (3)$$

$$P_{23} = \alpha_2 \alpha_3 \alpha_{\text{MMI}}^2 \eta P_{\text{in}}, \quad (4)$$

$$P_{24} = \alpha_2 \alpha_4 \alpha_{\text{MMI}}^2 (1 - \eta) P_{\text{in}}, \quad (5)$$

where α_k is the loss in input arm k , α_{MMI} is the insertion loss of the MMI, η is the polarization conversion efficiency and P_{in} is the input power. We then introduce the parameter C as

$$C = \frac{P_{13} P_{24}}{P_{14} P_{23}} = \frac{(1 - \eta)^2}{\eta^2}. \quad (6)$$

The aforementioned losses are polarization dependent, but are compensated in Eq. 6 since all terms appear in both the numerator and denominator. From Eq. 6 it can be seen the parameter C is independent of the insertion losses, propagation losses, and polarization sensitivity of in-circuit components,

Fig. 8. Schematic of 4-port characterization circuit for the characterization of polarization converters.

Fig. 9. Structure for a 4-port measurement. Input TE and TM grating couplers on the left, output TE and TM grating couplers on the right, polarization converter in the center, en two MMIs to connect the grating couplers to the polarization converter.

e.g. the MMIs, and only depends on the polarization conversion efficiency η . Identical MMIs are considered, however, non-identical MMIs will yield the same result, since the insertion losses are canceled out in Eq. 6. Rewriting the equation gives

$$\eta = \frac{1}{1 + \sqrt{C}} = \frac{1}{1 + \sqrt{\frac{P_{13} P_{24}}{P_{14} P_{23}}}}, \quad (7)$$

which provides the polarization conversion efficiency independent of the losses in the grating couplers, the waveguides and the MMIs. An uncertainty in coupling from fiber to grating coupler is minimized by using an automated setup with high-accuracy alignment algorithms. The contribution of the uncertainty of the extinction ratio is therefore less than 0.2 dB.

B. Results

1) *Traditional method*: The polarization conversion efficiency is calculated from measurement that are performed using the traditional method. Two structures with the same design for the polarization converter with both TE inputs and one TE and one TM output are measured. The results are first de-embedded by using calibration structures with TE and TM grating couplers to compensate for the polarization dependent insertion loss. For these results, $L_1 = 1.9$ microns, $L_2 = 2.65$ microns, and the length of the rectangular section S is varied. In this way, the phase relation of the TE and TM polarized light at the input of T_2 will be different depending on the length of this section, and hence result in a different conversion efficiency. The calculated polarization conversion efficiency as a function of the length of section S is shown in Fig. 10, at a wavelength of 1475 nm, which was the peak of the transmission of the grating couplers for these structures. We notice the fit is quite poor, which can be explained by the aforementioned uncertainty in the compensation for the insertion losses of the grating couplers.

2) *4-port method*: For this method, the length of the rectangular section, section S in Fig. 2, between the two sections of the converter was kept constant at 200 nm. Converters with length variations for T_2 have been measured over a

Fig. 10. Polarization conversion efficiency as a function of the length of the rectangular section at a wavelength of 1475 nm. The scatter points represent measured devices and the blue line is a sinusoidal fit.

Fig. 11. Measured polarization conversion efficiency versus wavelength for three lengths L_2 . L_1 is fixed at 1.7 μm .

wavelength range such that both TE and TM surface grating couplers have reasonable coupling efficiency, which is 1540-1580 nm for this fabrication run. In Fig. 11, the measured polarization conversion efficiency (PCE) is shown. No direct comparison to simulated devices was performed, since there are several deviations from the optimal design, e.g. waveguide roughness, sidewall verticality and triangle height. The ripple on the PCE is caused by reflections in the circuit, which introduces 0.5% uncertainty in this method. Reducing these reflections can improve the accuracy of the method further. $97.5 \pm 0.5\%$ PCE or -16 ± 0.9 dB extinction ratio is achieved, which is comparable to the state-of-the-art in silicon photonics [5], [6], [7]. The efficiency is above $96 \pm 0.5\%$ (extinction ratio below -14 ± 0.9 dB) for 1540-1580 nm for a total device length of 4.1 μm . In Fig. 12, the PCE at a wavelength of 1550 nm is shown for five devices with fixed L_1 and various L_2 . A sinusoidal trend is expected, however, there is a

Fig. 12. Measured polarization conversion efficiency at 1550 nm for various lengths of the second triangular section. L_1 is fixed at 1.7 μm .

limited amount of structures available and there is an anomaly for $L_2 = 2.65 \mu\text{m}$. After inspection of the structure, this is expected to be caused by residual InP after the wet etching of the triangular sections. Furthermore, it is likely the peak of the sinusoid is not reached yet, which could mean a higher conversion efficiency can be achieved, as was predicted by the simulations. The reason for the peak being at a shorter device length is that the fabricated triangular sections are lower than designed. This is caused by the directional etch of the silicon nitride, shown in Fig. 4(a). A slight overetch is done to ensure that the horizontally covered sections are opened, etching away some of the silicon nitride on the vertical sidewall of the converter. The result is that the top 25 nm of the indium phosphide is etched away in the subsequent wet etching step, due to the absence of the hard mask in that part. This results in a drop in L_π from around 2.1 microns to 1.85 microns, and hence a shorter device is required to achieve full polarization conversion.

C. Discussion

Although there is no direct comparison between the traditional characterization method and the 4-port method, we can see some differences in accuracy. For the traditional method, for which the results are shown in Fig. 10, it becomes clear that the accuracy is quite low, with some points deviating as much as 40% from the trend-line. If a sufficient amount of points are measured, the conversion efficiency can be obtained from the trend-line. However, if there is a deviation in one of the calibration structures, this will be a systematic error that will also appear in the trend-line. The 4-port method is shown to be independent of this type of errors, however one is still influenced by accurate alignment of the fiber to the grating coupler. However, with an automated setup, consecutive alignments are done with an accuracy much better than 0.1 dB. The ripple on the conversion efficiency is around 0.5%, which can be reduced by suppressing spurious reflections in the circuit, pushing the accuracy of the method even further.

IV. CONCLUSION

We present a new characterization method for polarization conversion devices and experimentally demonstrate the method on the IMOS platform. The accuracy of the traditional method is drastically improved to around 0.5% by introduction of this 4-port characterization method, by removing the uncertainties in insertion losses and polarization dependent losses in in-circuit components, leaving only the influence of spurious reflections in the circuit. The reported polarization conversion efficiency is as high as $97.5\% \pm 0.5\%$ corresponding to an extinction ratio of -16 ± 0.9 dB for a 4.1 microns long device.

REFERENCES

- [1] S. Reniers, Y. Wang, K. Williams, J. Van Der Tol, and Y. Jiao, "Characterization of Waveguide Photonic Crystal Reflectors on Indium Phosphide Membranes," *IEEE Journal of Quantum Electronics*, vol. 55, no. 6, 2019.
- [2] J. Van Der Tol, Y. Jiao, L. Shen, A. Millan-Mejia, V. Pogoretskii, J. Van Engelen, and M. Smit, "Indium Phosphide Integrated Photonics in Membranes," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 24, no. 1, pp. 1–9, 2018.
- [3] J. Pello, "Building up a membrane photonics platform in indium phosphide," Ph.D. dissertation, Department of Electrical Engineering, Technische Universiteit Eindhoven, 2014.
- [4] S. Adachi and H. Kawaguchi, "Chemical Etching Characteristics of (001)InP," *Journal of the Electrochemical Society*, vol. 128, no. 6, pp. 1342–1349, 1981.
- [5] Y. Zhang, Y. He, X. Jiang, B. Liu, C. Qiu, Y. Su, and R. A. Soref, "Ultra-compact and highly efficient silicon polarization splitter and rotator," *APL Photonics*, vol. 1, no. 9, 2016.
- [6] D. Vermeulen, S. Selvaraja, P. Verheyen, W. Bogaerts, D. V. Thourhout, and G. Roelkens, "High Efficiency Broadband Polarization Rotator on Silicon-On-Insulator," *Journal of the Optical Society of America*, pp. 42–44, 2010.
- [7] A. Xie, L. Zhou, J. Chen, and X. Li, "Efficient silicon polarization rotator based on mode-hybridization in a double-stair waveguide," *Optics Express*, vol. 23, no. 4, p. 3960, 2015.

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