Stokes-vector receivers on an indium phosphide membrane

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Initial experimental results of a Stokes-vector receiver on an integrated indium phosphide membrane platform are presented. The ability to detect polarization states with a minimal absolute distance of 34° on the Poincaré sphere is achieved, which can be further improved by optimization of the polarization rotator section lengths.
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INTRODUCTION

Short-reach optical links are still relying on intensity modulation or direct detection formats due to the relatively high cost of coherent modulation format solutions. To add extra dimensions to these single dimensional solutions, the polarization space can be exploited by using Stokes-vector modulation (SVM). These modulation schemes have been demonstrated experimentally in several systems [1]–[3]. We demonstrate a compact (310 µm by 180 µm for the characterization structures) SVM receiver, realized on the InP-membrane-on-silicon (IMOS) platform, which is able to detect 32 polarization states. The realized structures include a fully passive approach to demonstrate the potential of this solution. Integration with high-speed photodiodes can result in a fast fully integrated opto-electronic SVM receiver. In this work we will introduce the SVM receiver design and demonstrate the ability to detect polarization states with these circuits.

DESIGN

A Stokes-vector receiver (SVR) needs to be able to distinguish between polarization states of the incoming signal. The passive circuit consists of input and output grating couplers, multimode interference couplers (MMIs) and polarization converters (PCs). On the IMOS platform, the photodiodes absorb TE polarized light, with high extinction ratio (typically >10 dB) towards the TM polarization. As a result, the S_1 component of the Stokes vector $\boldsymbol{S} = (S_1, S_2, S_3)$ can be directly measured. To measure the other components, polarization rotation is required.

For the polarization converters in the SVRs, optimal tilt angles of the hybrid modes are either 22.5° or 45°, since these would project the S_2 (22.5°) or the S_3 (45°) component onto the S_1 component, which can then be directly measured. An example of the case with a 22.5° tilt angle is shown in Fig. 1. The S_2 component is projected onto the S_1 component with a section length of $L_\pi = \frac{\pi}{\beta_1 - \beta_2}$, where $\beta_{1,2}$ are the propagation constants of the two hybrid modes in the triangular PC-section. The projection of S_3 onto S_1 requires an intermediate step of projecting S_3 onto S_2, which is realized by a $\frac{\pi}{2}$ phase shift between the TE and TM parts of the mode in a rectangular waveguide: $L_r = \frac{\pi}{2(\beta_{1,r} - \beta_{2,r})}$, where $\beta_{1,r}$ and $\beta_{2,r}$ are the propagation constants of the quasi-TE and quasi-TM modes. Then it is projected again onto S_1 with a PC.

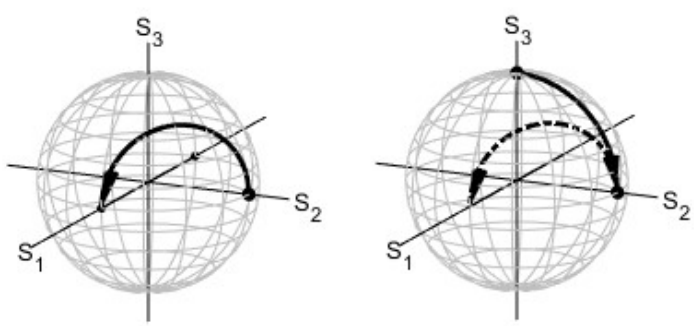

Fig. 1 - Poincaré spheres showing the projection of $\boldsymbol{S_2}$ onto $\boldsymbol{S_1}$ (left) and $\boldsymbol{S_3}$ onto $\boldsymbol{S_1}$ (right).

A schematic of the ideal passive receiver circuit is shown in Fig. 2. Cascaded 1x2 MMIs are used to split the input, since these are inherently symmetric. In the top arm, the S_1 component of the input signal is directly measured. In the second arm, a PC with a length of L_π (introduced above) is included, which will project S_2 onto S_1. This can then be measured with the TE/TM output grating couplers. In the third arm an offset with respect to the PC in the second

arm is included, to first project S_3 onto S_2, after which an identical PC to the one in the second arm is included. In this way, S_3 is projected onto S_1 and can be measured. In the bottom arm, which is redundant, a PC with double the length of the middle arms is included. If the length is chosen correctly, the output measured in this arm should be the same as the top arm, except with the insertion loss and propagation loss of the PC with double length included.

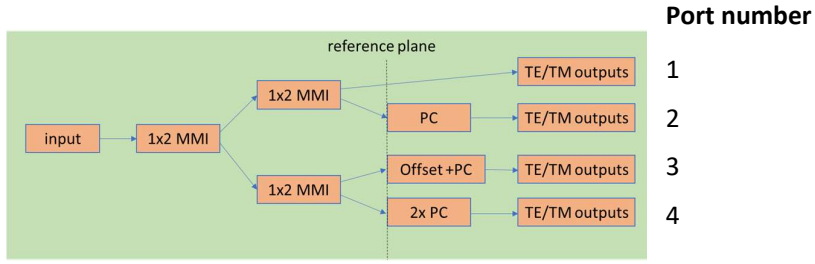

Fig. 2 - Schematic of passive Stokes-vector receiver circuit. The reference plane for determination of the polarization state is chosen just before the PC section in the second and fourth arm.

In our circuits, the PC that is used is shown in Fig. 3 [4]. The waveguides are 300 nm thick and 400 nm wide, and the PC is 460 nm high, with a sloped side with a 35° angle with respect to the wafer. To rotate the polarization from the S_2 and S_3 components to S_1, a single section device will suffice, since the tilt angle of the hybrid modes in the triangular sections is around 26°.

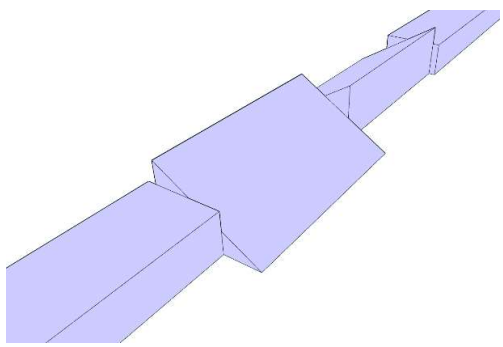

Fig. 3 - 3D mock of a double section polarization converter on IMOS before wafer bonding.

Since the PC on our platform has tilt angles of the hybrid modes that are not exactly 22.5° or 45°, some digital signal processing of the measured values will be required to obtain the original components. In [5], it has been shown that any tilt angle of the hybrid modes between 22.5° and 67.5° is suitable to convert a Stokes-vector on the S_2-S_3 plane to a TE polarization state.

RESULTS

The circuit as depicted in Fig. 2 has been realized on the IMOS-platform [6]. Added to it is an extra polarization rotator in the input, in order to test the detection for various input SOPs. A series of SVRs has been made with the following parameter variations:

- The length of the PC added to the input, varying from 0.6 to 1.4 µm.
- The length of the PCs in the detection branches, running from 0.2 to 0.8 µm.
- Two values for the offset in the 3rd branch: 2.55 and 2.95 µm.

Before the SVR-performance can be analyzed several basic parameters have to be determined from the measurements. This can be done by comparing the TE and TM output for different lengths of input PC on the upper branch (i.e., the "S_1" port). This should reflect the conversion of the input TE-mode for all circuits. The TM/TE ratio from the outputs is shown in Fig. 4. Due to polarization dependent phase and loss variations, related to the long paths between the input PC and the reference plane, only the averaged values can be analyzed. From these three parameters are obtained: the coupling ratio between the TE and TM output gratings (the TM-grating has 1.9 dB higher loss, which agrees with characterization of other structures in the same realization), the conversion length L_π, which is found to be 2.1 µm, and the mode tilting angle of the PC, 26.1°. These values are used in the rest of the analysis. Note however that the conversion length found is much larger than the values used in the circuits. This means that the PCs do not give the intended operation as described in the section "DESIGN". An inverted matrix operation to convert the measured S_1-parameters at the three upper branches to the SOP of the reference plane

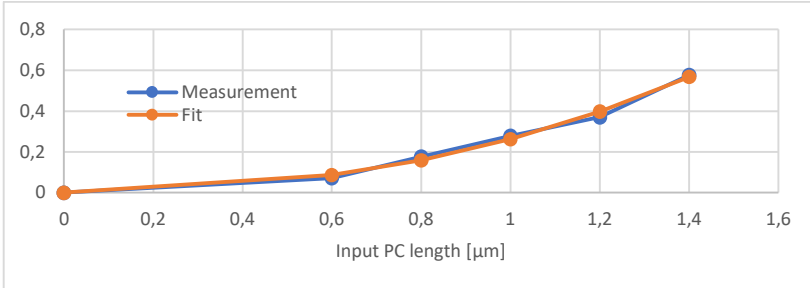

Fig. 4 - Average TM/TE ratio for all circuits (the point at 0 µm length is added for completeness).

can be constructed, but the mathematical problem turns out to be poorly defined (the determinant of the inverted matrix is much smaller than 1, which means the projection is far from ideal). This combined with the observed scattering on the results gives large errors and different points cannot be distinguished. Instead, a different approach was followed, which also considers the fourth branch with the double length PC. For a set of circuits with the same assumed polarization state at the reference plane (i.e., with the same input PC-length) a least square fit is performed to find S_1, S_2 and S_3 at that reference plane. To determine if the SOPs determined in this way are distinguishable from each other we analyze the inner product of every pair of Stokes vectors. If polarization states are identical, this will yield "1", if they are orthogonal, it will be "-1". If a statistically significant difference between two pairs can be detected by the SVR-circuits, the polarization states are distinguishable, and can be used in a polarization modulation scheme. Fig. 5 shows the inner product of the SOP resulting from the shortest input PC (with 0.6 µm length; there are two sets of these, with different offsets in the third branch) with those from all the other lengths.

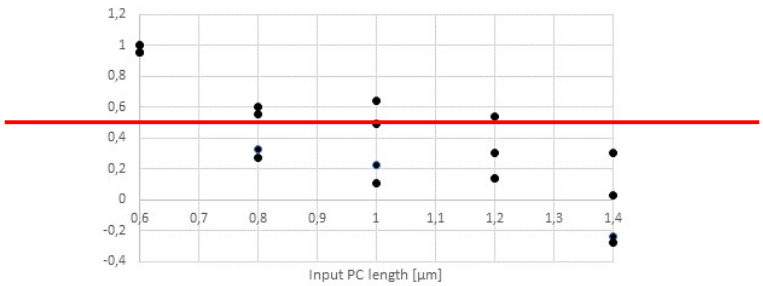

Fig. 5 - Stokes vector inner products for SOPs from different input PC lengths. The red line indicates a decision threshold between two points.

It can be seen that the only unambiguous difference is found between the SOPs from the shortest and the longest input PCs. For the other lengths the scatter on the data is too much to distinguish the states. The length difference of 0.8 µm implies a rotation over the Poincaré sphere of about 34°. With this separation of polarization states at least 32 of them can be positioned on the sphere, allowing 5 bits of information in one symbol, and thus a 5-fold increase of transmission capacity. However, if the length of the PCs in the branches is adjusted to 2.1 µm, and if the variation in transmission is reduced with shorter waveguide paths, even more distinguishable states will become possible.

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