Improved Phase Detection in On-Chip Refractometers

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***Abstract*—An improved phase detection scheme for Mach-Zehnder and bimodal interferometers is presented. By using a 90° hybrid, always two outputs operate at a highly sensitive point and the phase-shift-unambiguousness is extended to a range of 2π. The phase detection is independent of mode attenuations and input power fluctuations.**

I. Introduction

Mach-Zehnder interferometers (MZIs) [1] and bimodal interferometers (BMIs) [2] are established devices for the detection of refractive index changes, e.g. in sensors for bioanalysis [3,4]. Two common architectures with differential outputs are shown in Fig. 1(a). A signal entering an MZI is split into two fundamental modes that are guided locally separated. One of the waveguides is surrounded by a substance-under-test (SUT). The refractive index of the SUT affects the phase velocity of the corresponding optical signal. Thus, a phase shift $\Delta\phi$ between both modes appears. In a subsequent multimode interferometer (MMI) both signals interfere. The detected output power contains the phase shift information and thus the change of refractive index (see Fig. 1(b)). In the BMI the input signal excites two different modes that are guided in a single, bimodal waveguide. This waveguide has such a geometry, that both mode propagation velocities are affected differently by the surroundings. The resulting phase shift between both modes appears as interference pattern at the output. In common BMIs a mode converter is used to discriminate the phase shift by the output power of one or two single-mode waveguides. Such mode converters can exhibit an excess loss (EL) of only 0.25 dB with one and 0.5 dB with two differential outputs for balanced mode excitations [5]. Generally, the MZI and BMI have to operate in a range with high sensitivity, defined as the derivative of the transmission over the phase shift $\Delta\phi$ or the refractive index change, respectively. Considering the periodic characteristic of the output powers, two challenges are illustrated in Fig. 1(b). In the flat region of the extrema, marked by rectangles, the sensitivity is poor. There are also points, where the transmission is ambiguous in terms of corresponding phase shift (see e.g. circles in Fig. 1(b)). This ambiguity can be resolved by another measurement at a different wavelength, but this requires additional effort and time.

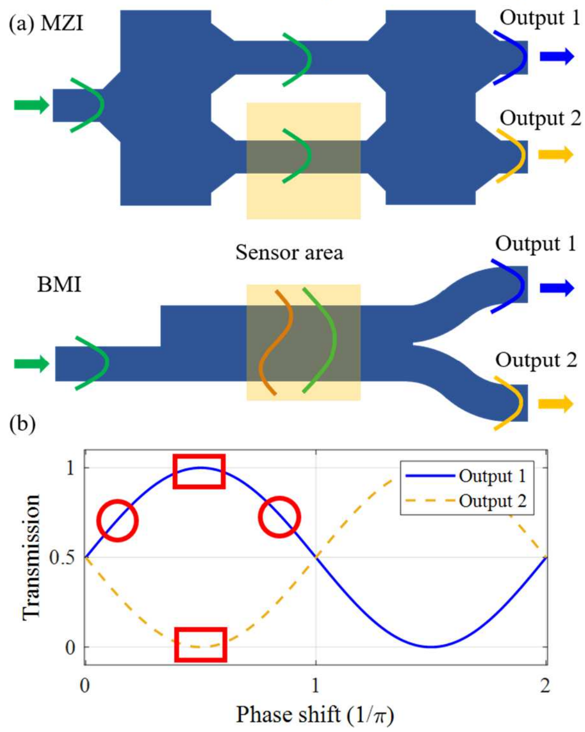

Fig. 1. (a) Common setups of Mach-Zehnder and bimodal interferometers and (b) corresponding transmissions.

This work presents phase detectors on a 220 nm silicon-on-insulator material platform that improve these issues. The simulations were performed with the method of eigenmode expansion at a wavelength of 1550 nm using the FIMMWAVE and FIMMPROP software from Photon Design.

II. Designs and Results

The architecture of the proposed phase detector for an MZI is shown in Fig. 2. The input signal is split by a 1x2 MMI. The induced phase shift is read out by a subsequent 90° hybrid consisting of a 4x4 MMI with a simulated EL of 0.08 dB. The corresponding transmission is also depicted in Fig. 2.

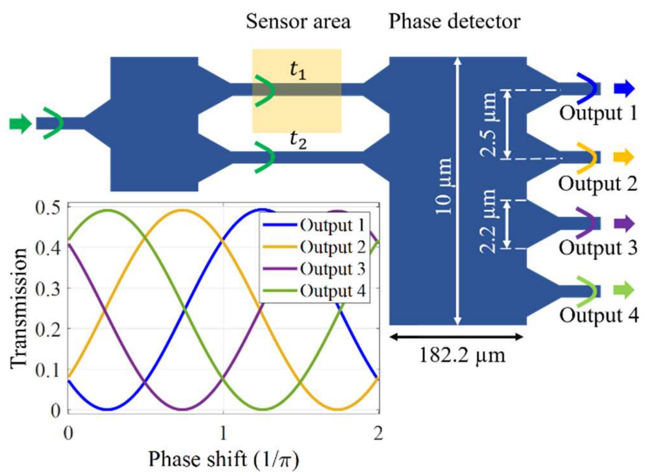

Fig. 2. The setup of a sensor based on an MZI with an integrated 90° hybrid and its corresponding transmission curves.

The power P_i of the corresponding output i follows the formula

$$\frac{P_1}{P_1+P_2+P_3+P_4} = \frac{1}{4} - \frac{1}{2\sqrt{2}}\frac{t_1 t_2}{t_1^2+t_2^2}(\sin(\Delta\phi) + \cos(\Delta\phi)) \quad (1)$$

$$\frac{P_2}{P_1+P_2+P_3+P_4} = \frac{1}{4} + \frac{1}{2\sqrt{2}}\frac{t_1 t_2}{t_1^2+t_2^2}(\sin(\Delta\phi) - \cos(\Delta\phi)) \quad (2)$$

$$\frac{P_3}{P_1+P_2+P_3+P_4} = \frac{1}{4} + \frac{1}{2\sqrt{2}}\frac{t_1 t_2}{t_1^2+t_2^2}(-\sin(\Delta\phi) + \cos(\Delta\phi)) \quad (3)$$

$$\frac{P_4}{P_1+P_2+P_3+P_4} = \frac{1}{4} + \frac{1}{2\sqrt{2}}\frac{t_1 t_2}{t_1^2+t_2^2}(\sin(\Delta\phi) + \cos(\Delta\phi)) \quad (4)$$

where t_1 and t_2 represent the amplitude transmission coefficients of the corresponding guided modes. For the shown curves they are assumed lossless ($t_{1,2} = 1$). For extracting the induced phase shift, the following formula applies:

$$\Delta\phi = \tan^{-1}\left(\frac{P_1+P_3-P_2-P_4}{2(P_1-P_3)}\right) + \left\{\begin{matrix} \pi & \text{for } P_1 > P_3 \\ \pi & \text{for } P_1 = P_3 \wedge P_1 > P_2 \\ 0 & \text{else} \end{matrix}\right\}. \quad (5)$$

This expression is unambiguously over the range of 2π and depends on the output powers only. As a consequence, input power fluctuations and mode losses do not affect the result. By contrast, for the determination of $\Delta\phi$ in common interferometers the input power and the extinction ratio have to be known. Hence, a spectral window has to be observed. The presented detection scheme enables a phase extraction without this information, which makes it suitable for single wavelength operation.

Due to the 90° hybrid, there is always the situation, where two outputs operate in a highly sensitive range. The lowest sensitivity of this configuration occurs at $\Delta\phi = \pi/2 + m\pi/2$ with $m \in \mathbb{Z}$ (see Fig. 2). However, it's still 70.07% of the maximal sensitivity instead of 0%, as in common MZIs.

The same measurement principle can be adapted on a BMI (see Fig. 3). However, a special mode converter is required to deal with the anti-symmetric transverse electric first order mode (TE1) in the bimodal section. The mode converter is a 1x3 MMI with one bimodal input and three single-mode outputs. With appropriate length, the first self-image of the input signal appears at the output. Due to the symmetric interference, the transverse electric fundamental mode (TE0) is reproduced with an EL of 0.09 dB. The anti-symmetric TE1 mode is split into two parts. Each of these parts transmit with an EL of 0.22 dB and their mutual phase difference is 180°. Thus, the output of the BMI is converted into three guided TE0 modes. To extract the phase shift induced in the sensing region, the signals pass a 90° hybrid build up of three identical 2x2 MMIs with 0.07 dB simulated EL each. The first 2x2 MMI splits the reproduced TE0 mode signal. These resulting 90° phase-shifted outputs enter the corresponding MMIs and are brought into interference with the signals that contain the phase information of the TE1 mode. The resulting transmission of the whole phase discriminator with balanced bimodal input is shown in Fig. 3. The presented architecture has a total simulated EL of 0.26 dB. Compared to Fig. 2, the outputs 2 and 4 are switched. Nevertheless, (5) still holds, except an additional constant phase offset. This additional offset is caused by the mode converter and different lengths of the optical paths between the dark green and brown marked signals (see Fig. 3). With a reference measurement, that is also required in common MZIs and BMIs, the total constant phase offset can be determined to calibrate the sensing data.

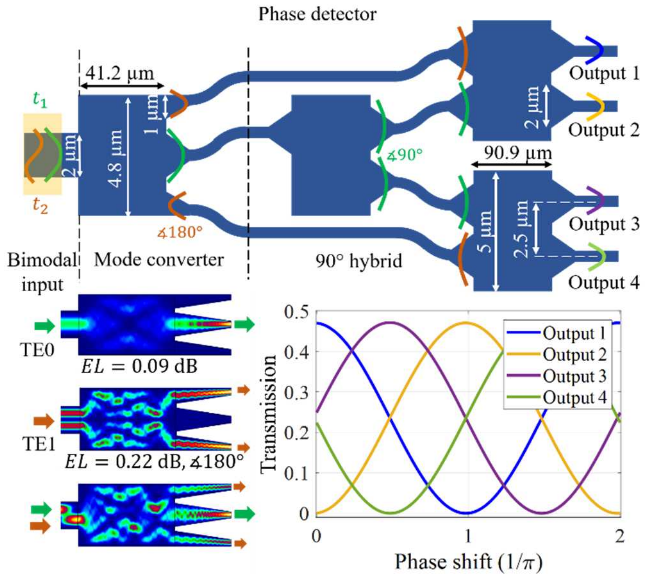

Fig. 3. The setup of a phase detector consisting of a mode converter and a 90° hybrid. The simulated EL of the converter and the transmissions of the whole setup is shown. The EL of the phase detector is 0.26 dB for a balanced bimodal input.

III. Conclusion and Outlook

BMIs and MZIs are established on-chip devices for refractive index measurements. Performance limitations are set by an operation point dependent sensitivity, by the ambiguity of the transmission versus phase relation and by the unknown influence of mode losses. This work presents a phase detection scheme for MZIs and BMIs, that improves these drawbacks. In contrast to common systems, this setup enables a single wavelength operation without the knowledge of mode losses or input power fluctuations. The phase detectors show a simulated EL of 0.08 dB for MZIs and 0.26 dB for BMIs with balanced bimodal input.

Acknowledgement

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