Dual-polarization photonic integrated biosensor in a Mach-Zehnder interferometer with coherent phase readout

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Abstract. Photonic integrated biosensors have garnered considerable attention due to their promising applications in various fields such as healthcare. Differentiating specific targets from interfering background effects is a challenging task. In this work, a dual-polarization Mach-Zehnder interferometer (MZI) with coherent phase readout is proposed to identify refractive index changes from different layers above the waveguide surface, thus improving sensor specificity. All the system building blocks have been designed for a 300 nm-thick silicon nitride platform, fabricated and characterized. The first experimental results show a bulk waveguide sensitivity of 0.17 RIU/RIU for TE polarization and 0.25 RIU/RIU for TM, confirming the correct functioning of the sensors when operating for each polarization separately. Future work will focus on simultaneous sensing with both polarizations and experiments with layered variation of refractive indices.

1 Introduction

Photonic integrated biosensors have experienced a great rise, potentially allowing reliable molecule detection via low-cost devices. Making use of the evanescent field sensing principle, these devices detect changes in refractive index induced by the binding of analytes to bioreceptors on the waveguide surface [1]. One of the necessary properties of biosensors is specificity, achieved by functionalizing the sensor surface with a substance that shows high bioaffinity for the analyte of interest [2].

In this work, we present advancements towards an integrated photonic biosensor which can be simultaneously operated with TE and TM polarization to differentiate changes occurring in two distinct layers within the evanescent zone. This approach combines the robustness of Mach-Zehnder interferometric systems with coherent detection schemes, enhancing practical implementation and complementing chemical techniques to improve sensor specificity. The system has been implemented on a 300 nm-thick silicon nitride platform, operating at the 1310 nm wavelength to reduce water losses.

This paper is organized as follows: Section 2 presents a theoretical approach, while Sections 3 and 4 detail the biosensor configuration, experimental setup and measured results. Conclusions are outlined in Section 5.

2 Theoretical approach

In this work, we aim to distinguish refractive index variations occurring in the 10 nm closest to a waveguide surface (Δn_{p}) due to protein binding to bioreceptors and variations in the remaining cover (Δn_{c}), due to interfering background effects. To calculate these two variations we propose performing two measurements (one for TE polarization and another for TM) in a MZI interferometer, thereby obtaining Δn_{p} and Δn_{c} as:

$$\underbrace{\begin{bmatrix}\Delta\varphi_{\mathrm{TE}}\\ \Delta\varphi_{TM}\end{bmatrix}}_{\boldsymbol{\Delta\varphi}} = \frac{2\pi}{\lambda} L \underbrace{\begin{bmatrix}\left.\frac{dn_{\mathrm{eff}}}{dn_{\mathrm{p}}}\right|_{\mathrm{TE}} & \left.\frac{dn_{\mathrm{eff}}}{dn_{\mathrm{c}}}\right|_{\mathrm{TE}}\\ \left.\frac{dn_{\mathrm{eff}}}{dn_{\mathrm{p}}}\right|_{\mathrm{TM}} & \left.\frac{dn_{\mathrm{eff}}}{dn_{\mathrm{c}}}\right|_{\mathrm{TM}}\end{bmatrix}}_{\boldsymbol{S_{\mathrm{wg}}}} \underbrace{\begin{bmatrix}\Delta n_{\mathrm{p}}\\ \Delta n_{\mathrm{c}}\end{bmatrix}}_{\boldsymbol{\Delta n}}, \tag{1}$$

where L is the sensor length, λ is the operation wavelength, $\boldsymbol{\Delta n}$ contains refractive index variations in each layer, $\boldsymbol{\Delta\varphi}$ is composed of phase shift experienced by each polarization and $\boldsymbol{S_{\mathrm{wg}}}$ is the waveguide sensitivity matrix, obtained using the perturbational analysis in each layer.

The condition number of the sensitivity matrix quantifies the layer discrimination accuracy. A condition number close to one implies a high interaction of each polarization with one of the layers, i.e., an accurate layer discrimination. In the proposed system, the condition number is around 60 and the theoretical achievable limits

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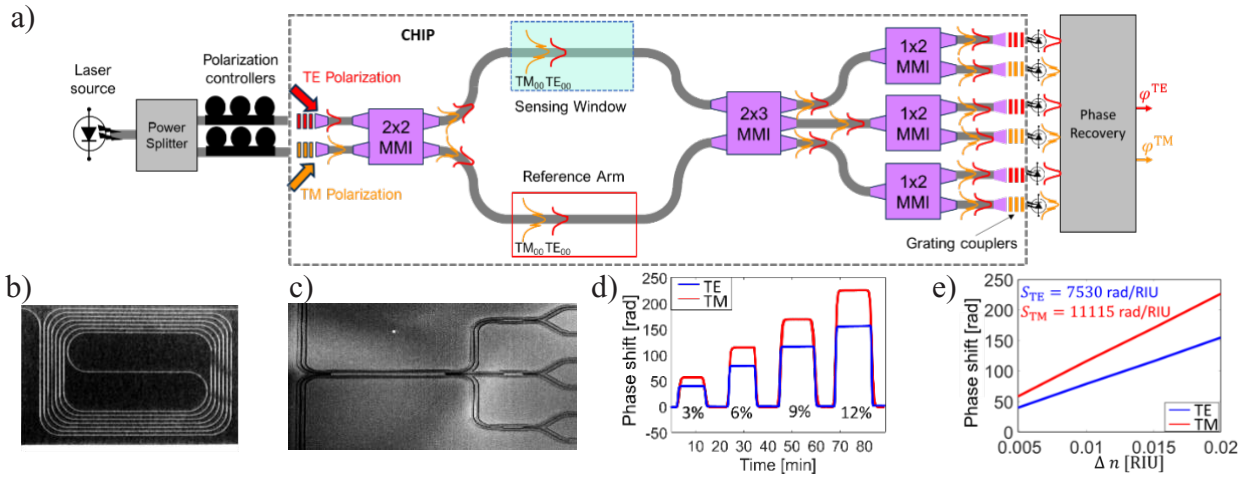

Fig. 1. Dual-polarization biosensor with coherent readout: a) Schematic of the system; b) SEM picture of the spiral used in the sensing and reference arms; c) SEM picture of MMIs that compose coherent readout system; d) Sensor calibration with different NaCl solutions and e) Experimental sensitivity for TE and TM polarizations measured consecutively but not at the same time.

of detection (LOD) are $8.5 \cdot 10^{-9}$ RIU and $8 \cdot 10^{-10}$ RIU in the 10 nm- layer and within the rest of the cover, respectively. These values are comparable to conventional sensing systems, thus making biosensors with layer discrimination capability a great alternative to other existing biosensors.

3 Dual-polarization MZI biosensor

A general schematic of the proposed sensing system is shown in Fig. 1.a). It employs two different grating couplers with a 2x2 MMI to couple and combine light of both polarizations into the chip. The gratings couplers are designed to selectively operate for TE and TM polarization at the same angle. Due to variations in penetration depth into the water-based upper cladding, each polarization provides unique sensing information when interacting with the sample along the same physical paths (Fig. 1.b). Unlike bimodal sensors [3, 4], this system offers a separated physical path for the sensing and reference arms, thus enabling non-differential sensing. Each interferometric signal is combined via a single 2x3 MMI (Fig.1.c.). Then, each MMI output is split by a 1x2 MMI before being coupled to a fiber array through grating couplers. Figure 1.a) shows how design considerations must ensure polarization insensitivity in MMIs and high selectivity in grating couplers, reducing the number of components and crosstalk. After detection, phase shifts experimented by each mode are obtained and processed for layer discrimination.

4 Experimental setup and results

The experimental setup consists of a laser source, a power splitter, two polarization controllers to generate input signals for the chip, and a fiber array. A polydimethylsiloxane (PDMS) fluidic channel on top of the chip and a connected pump allows the flow of different samples over the sensor with a controlled flow rate. Each output signal is detected by an individual photodetector and digitalized by a consecutive data acquisition board.

To assess the sensor's performance we calibrated the system using different sodium chloride (NaCl) solutions (3%, 6%, 9%, 12%), as shown in Fig.1.d). This experiment allows us to determine the sensor's bulk sensitivity for both polarizations (Fig. 1.e.) when are working consecutively but not at the same time. For 9 mm-length spirals, an experimental sensitivity of 7530 rad/RIU is obtained for TE mode and 11115 rad/RIU for TM mode. These values correspond to a waveguide sensitivity of 0.17 RIU/RIU for TE and 0.25 RIU/RIU for TM, being in good agreement with simulated results (0.168 RIU/RIU for TE and 0.285 RIU/RIU for TM).

5 Conclusions

This work proposes a dual-polarization photonic integrated biosensor to detect refractive index variations in different layers of the cover. Embedded into a coherent phase read-out MZI architecture, a first prototype has been fabricated on a silicon nitride platform. Early experimental results show promising results. In this work, sensitivities of 0.17 RIU/RIU and 0.25 RIU/RIU were demonstrated for TE and TM polarization, respectively, closely matching the simulated sensitivities. This initial validation of the system sets a strong precedent for future experiments targeting specific layers, opening new avenues for research.

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