Towards Simultaneous Absorption and Refractive Index Sensing using Integrated Photonics

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Abstract: Photonic integrated sensors traditionally detect changes either in optical amplitude or phase. Here we experimentally demonstrate a sensing architecture which measures both amplitude and phase, enabling simultaneous detection of changes in absorption and refractive index.

1. Introduction

Photonic integrated sensors have emerged as a powerful tool to perform a label-free detection of analytes of interest in applications such as medical diagnosis and environmental monitoring, offering quantitative results in real time. Most evanescent field sensors are used to measure changes either in the real part of the refractive index (n) of the sample, which affects the phase, or in its imaginary part (k), which impacts absorption. This partial information can be used to precisely determine the selective adherence of biomarkers or the presence of molecules with characteristic absorption features [1]. However, having immediate access to both parts of the complex refractive index will provide a further insight of the nature of the sample without performing sophisticated signal processing steps like those required for the computation of Kramers-Kronig relations. Despite its interest, there are, to the best of our knowledge, very few contributions following this approach [2, 3].

Here we present a sensor based on a Mach-Zehnder interferometer, which combines direct amplitude readout with coherent phase retrieval, enabling the determination of the complex refractive index. The sensors have been fabricated on Cornerstone's silicon nitride platform and characterized with preliminary NIR sensing experiments.

2. Sensing architecture

Figure 1 shows a schematic representation of our sensor, which is based on a Mach-Zehnder interferometer. Input light, with a fixed wavelength λ_0, is split into spiraled reference and sensing arms, with length L. The cladding over the sensing arm is removed to enable light-matter interaction. A change in the concentration of analyte induces a proportional change of the real (Δn) and imaginary (Δk) refractive indices of the sample. Via evanescent field sensing this change is transferred into a variation of the complex effective index of the propagating mode $\Delta n_{\mathrm{eff}} = S_{\mathrm{w}}(\Delta n + \mathrm{i}\Delta k)$, where S_{w} is the waveguide sensitivity. The sensing and reference signals are combined by

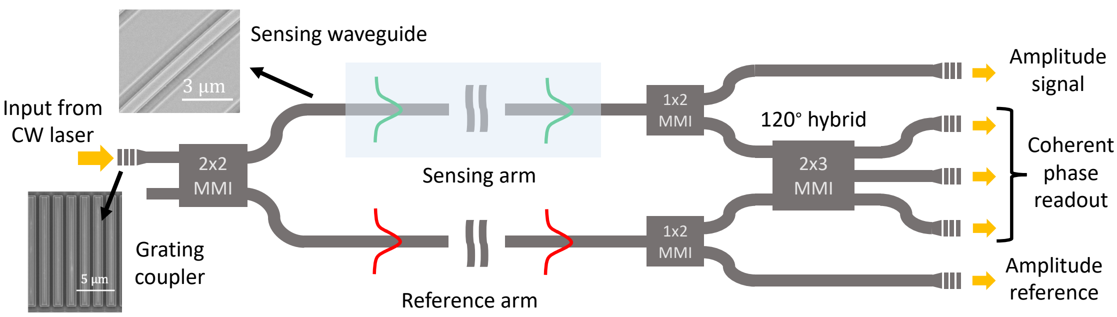

Fig. 1. Schematic representation of the complex refractive index sensor. Its three phase outputs enable a coherent phase retrieval, whereas the sensing and reference intensities can be directly detected.

a 120° hybrid [4] to provide a linear and unambiguous phase signal $\Phi = S_n \Delta n$, where $S_n = S_w(2\pi/\lambda_0)L$ is the system sensitivity to real index changes. The amplitude signal is obtained by computing $\log I/I_0 = S_k \Delta k$, where I is the detected intensity in the sensor output, I_0 is its value in absence of analyte and $S_k = 2\log(e) S_w(2\pi/\lambda_0)L$ is the system sensitivity to imaginary index changes. A reference output can be employed to address problems such as background drift or thermal fluctuations.

3. Experimental results

Our sensors were designed for the NIR wavelength range and fabricated in Cornerstone's silicon nitride platform. Sensors with lengths $L = 6.7\,\text{mm}$ and $L = 16.14\,\text{mm}$ have been validated on a fiber array setup with a laser source operating at 1560 nm. An isopropanol droplet ($n = 1.36$, $k = 6.67 \cdot 10^{-5}$) was carefully deposited over the chip surface. As the sample reaches the sensor, it induces a monotonic change of the complex refractive index of its cladding, which is translated into proportional phase and amplitude changes, as shown in Fig. 2(a) for the longer sensor. The experimental sensitivities represented in Fig. 2(b) are in good agreement with the theoretical predictions. The 16.14 mm sensor shows a better performance, with a sensitivity of $S_n = 8.35 \cdot 10^3\,\text{rad/RIU}$ and $S_k = 6 \cdot 10^3\,\text{au/RIU}$ for the real and imaginary indices respectively. By evaluating the noise over a 1 s fragment of the stable output signal, we computed a 3σ limit of detection below 10^{-6} RIU both for n and k. Compared to [2] this is an order-of-magnitude improvement for the real part of the refractive index while achieving an equivalent limit of detection for the imaginary part.

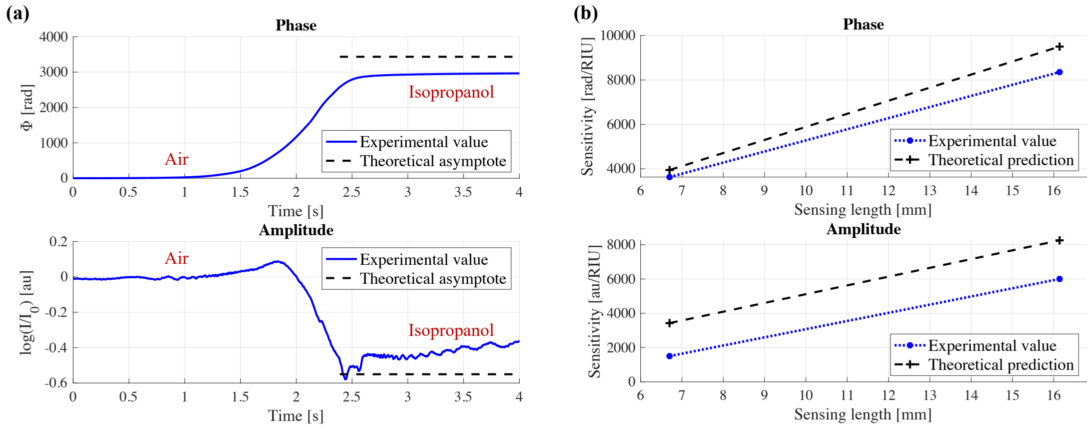

Fig. 2. (a) Phase and amplitude readouts for the 16.14 mm sensor during a basic sensing experiment. (b) Theoretical and experimental sensitivities as a function of the sensing length.

4. Conclusions

We have developed a silicon nitride interferometric sensor which enables simultaneous determination of changes in the real and imaginary parts of the refractive index. Sensors of two different lengths have been experimentally evaluated, yielding results in close agreement with their expected behaviour and competitive with the state-of-the-art. We believe this is a step towards more versatile sensors for a deeper understanding of the analyzed sample.

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