Solving the interferometric readout in sensor devices by an all-optical phase modulation technique

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Abstract—A novel phase modulation system based on an all-optical approach for integrated interferometric devices is presented. This method provides real-time linear phase read-out for highly sensitive, label-free and user-friendly biosensing applications oriented to a Lab-on-Chip final implementation.

Keywords — Mach-Zehnder interferometer, Bimodal interferometer, biosensor, integrated optics, phase modulation.

I. INTRODUCTION

Current needs for highly sensitive, real-time and fast detections of biological/chemical targets in extremely reduced amount of samples, have motivated the seek for Lab-on-Chip (LOC) sensing platforms. These compact devices include a highly sensitive transducer, properly functionalized for the application of interest, a microfluidic network for sample preparation and delivery and electronics for signal acquisition and processing. The transducer is one of the key elements for suitable LOC operation: it must be enough sensitive, reliable and stable in time. Integrated optical sensors, based on evanescent wave interaction, are the most suitable candidates as they have demonstrated their capability for real-time and label-free applications. In particular interferometric transducers are one of the most sensitive configurations [1], allowing limits of detection (LOD) in the range of $10^{-7}$ refractive index units (RIU), which corresponds to pM analyte concentrations. Different configurations have been suggested in the last decades, as Mach-Zehnder (MZI), Young (YI), Hartman (HI) or Back-scattering (BSI) Interferometers. More recently a simpler configuration, the so-called Bimodal Waveguide Interferometer (BiMW), based on a two-mode interference scheme, has been demonstrated [2] as a valid alternative to more complex MZI or YI devices. In the BiMW device an interference pattern is created at the output of a single channel waveguide supporting two transversal modes: the fundamental and the first order ones of a same polarization. In this configuration, beams separation and recombination through Y junctions is unnecessary, reducing fabrication tolerances influence and consequently increasing device performance. The detection limit obtained with BiMW device is comparable with the one from MZI sensor.

But despite their high sensitivity, interferometric devices suffer an important limitation due to their intrinsic periodic nature. Since output intensity is a periodic function of the phase change to be detected, clear output interpretation is prevented by signal ambiguity and sensitivity fading. Furthermore input fluctuations can give rise to false positive responses, inadmissible for real clinical practice. For these reasons, commercial interferometric biosensors are scarce.

All the drawbacks arising from the periodic interferometric output can be solved with a phase modulation system able to provide a linear signal read-out. Moreover it is immune to sensitivity variations and input fluctuations. Common methods for phase tuning in integrated optical devices rely on electro-optic, acousto-optic, thermo-optic or magneto-optic working principles. Their validity has been demonstrated, but they are not suitable for a complete LOC integration, since they require further and not conventional fabrication processes/materials, often incompatible with microfluidics, and they need expensive and bulky electronic equipment, unserviceable for LOC implementation.

We present here the implementation of an all-optical phase modulation system for MZI and BiMW devices, requiring only a standard Fabry-Perot commercial laser diode as light source to induce the phase modulation. Interferometric devices are fabricated using standard CMOS compatible processes at clean-room facilities. The sensors are constituted by Si/SiO$_2$/Si$_3$N$_4$ rib waveguides, optimized for visible light operation.

II. PHASE MODULATION WORKING PRINCIPLE

In standard interferometric measurements, output signal is described by $I(t) \propto \cos(\Delta \phi(t))$, where $\Delta \phi(t)$ is the phase change induced by a biological interaction, which depends on the difference of effective refractive index between the two interfering modes.

In our approach, a phase variation between the modes propagating in the device (MZI or BiMW) is induced by changing the wavelength of the input light beam (a few nms). In both devices, a change of propagating wavelength will differently modify the effective refractive indexes of the two propagating modes, resulting in a variation of their phase difference. According to our previous numerical simulations, the wavelength change necessary to induce a $2\pi$ phase variation between the two modes is less than 2 nm for both MZI and BiMW devices. This value depends on geometric...
parameters, materials (i.e. refractive index) and central operating wavelength (in our case \( \lambda_0 = 660 \) nm). Such wavelength variation can be obtained by taking advantage of a drawback of common semiconductor laser diodes: the power dependence of their wavelength emission. The use of a sinusoidally varying driving current for the laser source allows an output analysis by Fourier Transform method.

When introducing a phase modulation function, the interferometer output is transformed in:

\[
I(t) \propto \cos[\Delta \phi(t) + \mu \sin(\omega_M t)]
\]

being \( \mu_M \) and \( \omega_M \) the modulation amplitude and frequency respectively. By choosing the proper modulation amplitude, \( \mu_M \), it can be demonstrated that the phase change induced by a biological reaction occurring in the device sensing area can be directly and real-time evaluated from the inverse tangent of two consecutive signal harmonics [3]. Fig.1 summarizes this detection technique: a laser beam with varying wavelength is used to excite mode propagation in the interferometer and its output is deconvoluted with Fourier analysis in order to get a linear response. A Labview application gives the real-time phase extraction and its unwrapping: the signal obtained in this way is linear and shows a theoretically infinite working range.

![Scheme of the all-optical phase modulation approach for integrated interferometric devices (MZI or BiMW).](image)

### III. EXPERIMENTAL

For our experiments, a laser diode ML101J27 (Thorlabs) with nominal wavelength of 660 nm has been employed as light source. Light propagation inside the interferometer is obtained by end-fire method, by focusing the input beam with a 40x objective at the entrance of a polished waveguide. In the case of MZI the single mode output light is collected by a Si photodiode (Thorlabs, DET36A), while in the case of BiMW the bimodal output is measured with a two sections photodiode (Hamamatsu, S4349). Temperature stabilization is required for both the laser diode mount and the BiMW holder, as in the BiMW device there is no reference arm to compensate for temperature variations.

Fig. 2 shows the comparison between the standard interferometric pattern (i.e. DC component in this modulation scheme, in Fig.2a)) and the linear phase signal (Fig.2b)) corresponding to the detection of an index change of \( \Delta n = 1.8 \times 10^{-3} \) RIU. Measurements have been done in TE polarization, with a BiMW device operated with a driving current of \((143 + 36) \) mA and a modulation frequency of \( f_M = 215 \) Hz. The index change is induced in the device sensing area by injecting a solution of HCl while milli-Q grade water is used as buffer. Refractive index of the solution is measured prior to injection with a commercial Abbe refractometer. A calibration curve obtained in these conditions shown a detection limit for index changes of \( \Delta n_{\text{limit}} = 4 \times 10^{-3} \) RIU, comparable with standard interferometric schemes.

![Detection of an index change \( \Delta n = 1.8 \times 10^{-3} \) RIU, for TE polarization on a BiMW device. a) standard intensity interferometric pattern and b) linear phase read-out.](image)

With this simple and cost-effective modulation approach, phase information is not deduced anymore from the variations of the intensity interference pattern (as shown in Fig.2a), but is directly evaluated (Fig.2b). All the issues arising from the periodic nature of interferometric signals are therefore solved. Furthermore the sensitivity to index changes is the same as reported with the standard configuration employing a bulky He-Ne laser, but an easily integrated laser diode is employed in this case, allowing portable sensing platforms implementation.

Biosensing evaluations are currently being performed in order to study the device sensitivity for immuno sensing detections.

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### REFERENCES

