

# TOWARD HYBRID POLYMER-POROUS SILICON WAVEGUIDES FOR VERNIER EFFECT OPTICAL BIOSENSORS

P. AZUELOS<sup>1\*</sup>, N. LORRAIN<sup>1</sup>, M. GUENDOUZ<sup>1</sup>, P. PIRASTEH<sup>1</sup>,  
J. LEMAITRE<sup>1</sup>, I. HARDY<sup>2</sup>, J. CHARRIER<sup>1</sup> AND M. THUAL<sup>1</sup>

<sup>1</sup> Univ Rennes, CNRS Institut FOTON - UMR 6082, F-22305 Lannion, France

<sup>2</sup> IMT Atlantique, CNRS, Institut FOTON, UMR 6082, F29238, Brest, France

\*Corresponding author e-mail address: paul.azuelos@enssat.fr

## SUMMARY

An optical and hybrid integrated sensor based on the Vernier effect principle and implemented with porous silicon and polymer waveguides is studied to detect low concentrations of biomarkers such as Bovine Serum Albumin (BSA).

The principle of the Vernier effect integrated sensor adopted consists of a reference micro-resonator (MR) cascaded to another MR, the sensing MR, which is sensitive to analyte concentration. Waveguides based on porous silicon material are used to constitute this sensing MR transducer in the part of the sensor where BSA molecules are grafted to benefit from its large specific surface and its high surface sensitivity. The other parts of the sensor including the reference MR are constituted by low loss polymer waveguides.

The presentation will focus on the theoretical study and the design of the sensor, particularly on the evanescent coupling between porous silicon and polymer waveguides. Then, the fabrication of the sensor, using standard photolithography will be detailed. Moreover, characterization on optical bench and comparison to theoretical results will be presented.

This hybrid Vernier effect based sensor demonstrates a theoretical Limit Of Detection (LOD) of 0.019 pg.mm<sup>-2</sup> and a sensitivity of 12.5 nm/(pg.mm<sup>-2</sup>). To our knowledge, these values are 8 times lower for the LOD and 200 times higher for the sensitivity compared to the state of the art of Vernier effect biosensors implemented with bulk materials.

## 1. INTRODUCTION

Thanks to its porosity, porous silicon (PSi) material is particularly interesting for sensing applications as it allows to reach high homogeneous sensitivities based on refractive index variations of analytes not only localized in the micro resonator (MR) environment but also in the core of the porous material optical waveguide. A first and recent publication with PSi MR gave homogeneous sensitivities up to 560 nm/RIU for a sensor based on refractive index variation.<sup>1</sup>

PSi is also biocompatible as its surface can be functionalized for grafting biomolecules.<sup>2</sup> Surface detection is different from homogeneous detection as the interaction between EM-field and grafted biomolecules is enhanced when the waveguide specific surface increases. PSi is interesting for surface detection, as its high specific surface up to 800 m<sup>2</sup>/cm<sup>3</sup> dramatically increases the waveguide surface sensitivity to molecules grafted in its pores.<sup>3</sup>

If the sensitivity and the LOD are respectively presented in nm/RIU and RIU for homogeneous sensing, different units are used in the literature for surface detection. In this presentation, we will use respectively nm/(pg.mm<sup>-2</sup>) and pg/mm<sup>2</sup> for surface sensing sensitivity and LOD. A theoretical PSi MR surface sensitivity to Bovine Serum Albumin (BSA) has been calculated up to 0.02 nm/(pg.mm<sup>-2</sup>).<sup>4</sup>

One way to highly increase the sensitivity of the sensor is to take benefit from the Vernier effect with the use of interferences between several interferometers. The evanescent surface sensitivity has already been experimentally tested with two cascaded Mach Zehnder (MZ) with silicon nitride (SiN) waveguides with a sensitivity of 0.06 nm/(pg.mm<sup>-2</sup>) and a LOD of 0.155 pg.mm<sup>-2</sup>.<sup>5</sup>

The novelty of our present work consists on the choice of hybrid polymer and PSi waveguides in a Vernier effect integrated optical structure based on two cascaded MRs in order to obtain the best contrast, sensitivity and LOD for surface detection application.<sup>6</sup>

## 2. RESULTS AND DISCUSSIONS

The spectrum optical response of a MR represented in Figure.1.(a)(top), can be measured with a spectrum analyzer and shows maxima of transmission at resonant wavelengths. These resonant wavelengths depend on the effective index of the waveguide and shift with the grafting of analytes on the waveguide surface. The sensitivity of the MR is proportional to the shift of the resonant wavelength called  $\Delta\lambda_{res,MR}$  in Figure.1.(a) (middle). The interest of the Vernier effect in increasing the shift,  $\Delta\lambda_{res,Vernier}$ , thanks to the combined interferences of the two cascaded MRs is illustrated in Figure.1.(a) (bottom).

PSi waveguides based MRs have been demonstrated recently for biological analyte detection with high sensitivity thanks to its high specific surface which increases the quantity of analytes grafted in the waveguide.<sup>2</sup>

However, the main drawback of the PSi waveguides are the high optical losses which limit the practical application of a sensor whose entire structure is only based on this material.

So, in order to increase the sensitivity and reduce the propagation losses, a hybrid Vernier effect integrated optical transducer presented in Figure 1.(b) is proposed in this presentation. In this structure, low losses SU8 polymer waveguides are used for the reference part of the transducer and PSi waveguides are used for the part of the transducer, sensitive to the analytes. The coupling between the waveguides is eased by adiabatic tapers presented in Figure 1.(c) which relax successive photolithographic alignment constraints necessary for the fabrication of the transducer.

The theoretical study of hybrid Vernier effect transducer has been performed by optimizing the Free Spectral Range of the reference MR ( $FSR_{ref}$ ) and the MR sensitive to analytes ( $FSR_{sens}$ ). This study leads to the calculation of high sensitivity up to  $12.5 \text{ nm}/(\text{pg}\cdot\text{mm}^2)$  and a very low limit of detection of  $0.019 \text{ pg}\cdot\text{mm}^{-2}$  for BSA sensing applications.<sup>6</sup> The preliminary experimental results of the implementation of this device will then be presented.

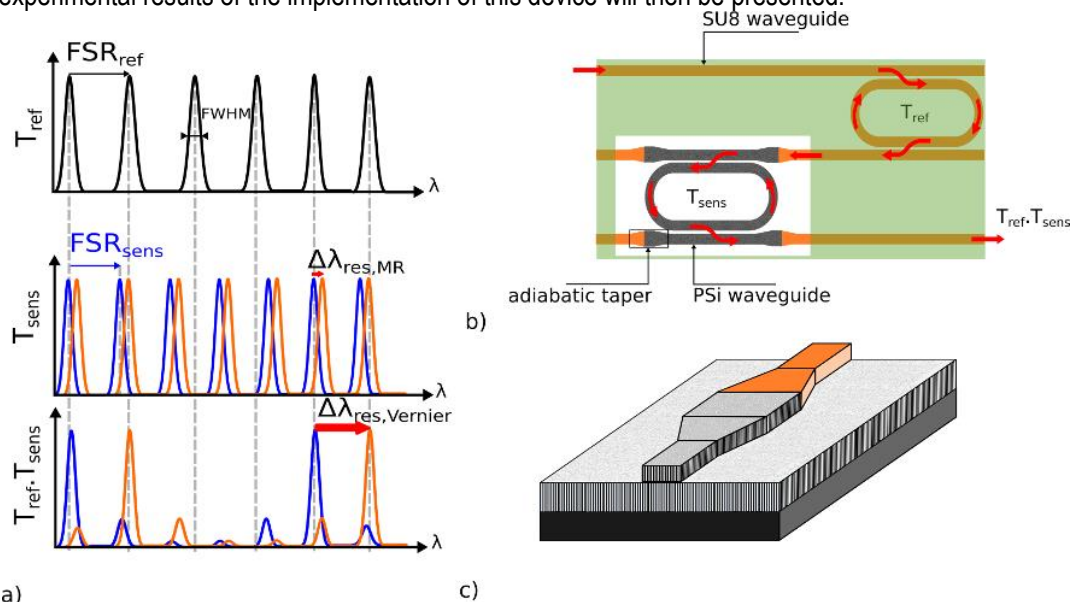


Figure 1: (a) Transmittance function of the reference MR (top) MR sensitive to analytes (middle) and Vernier effect of the two cascaded MRs (bottom) (b) Top view of the hybrid Vernier effect sensor constituted by a reference MR and a MR sensitive to analytes (the transducer) (c) Perspective view of the adiabatic taper for polymer to porous silicon waveguide coupling.

### 3. CONCLUSIONS

In this presentation, an integrated Vernier effect sensor based on hybrid polymer/PSi cascaded MRs is investigated. The combination of polymer and PSi waveguides reduces the total optical propagation losses and the Vernier effect structure enhances the sensitivity compared to a single PSi MR. With this structure, we demonstrate a theoretical calculation results of  $0.019 \text{ pg}\cdot\text{mm}^{-2}$  for surface LOD and  $12.5 \text{ nm}/(\text{pg}\cdot\text{mm}^2)$  for sensitivity. These results are respectively 8 times lower and 200 times higher than state of the art Vernier effect biosensors.<sup>5,6</sup> Experimental implementation of this structure is currently under development and preliminary experimental results will be presented.

### ACKNOWLEDGMENT

This work was funded by Lannion Trégor Communauté, Région Bretagne and the French government.

### REFERENCES

- [1] P. Girault, P. Azuelos, N. Lorrain, L. Poffo, J. Lemaitre, P. Pirasteh, I. Hardy, M. Thual, M. Guendouz, J. Charrier, *Opt. Mat.* **2017** 72 596-601.
- [2] G.A. Rodriguez, S. Hu, M. Weiss, *OSA.* **2015.** 23(6), 7111-7119.
- [3] N. Lorrain, M. Hiraoui, M. Guendouz, L.Haji, *Materials Science and Engineering: B.* **2011,** 14(176), 1047-1053.
- [4] P. Girault, J. Lemaitre, M. Guendouz, N. Lorrain, L.Poffo, *SPIE Photonics Europe.* **2014,** Brussels, Belgium.
- [5] X. Tu, J. Song, T-Y. Liow, M. K. Park, J.Q. Yiyang, J. S. Kee, M. Yu, G-Q. Lo, *Opt. Express.* **2012,** 20(3).
- [6] P.Azuelos, P.Girault, N.Lorrain, L.Poffo, I.Hardy, M.Guendouz, M.Thual, *JAP.* **2017,** 121(14) 144501.