Low Limit of Detection Silicon Photonic Sensor with Extremely-Low-Cost Laser Source

1st Jonas Leuermann
Bionand Center for Nanomedicine and Biotechnology
Málaga, Spain
jonas.leuermann@uma.es

2nd Adrián Fernández-Gavela
Dep. de Física
Universidad de Oviedo
Oviedo, Spain
fernandezadrian@uniovi.es

3rd Laura M. Lechuga
Catalan Institute of Nanoscience and Nanotechnology
Universitat Autònoma de Barcelona
Barcelona, Spain
laura.lechuga@icn2.cat

4th Alejandro Sánchez-Postigo
Dep. de Ingeniería de Comunicaciones
Universidad de Málaga
Málaga, Spain
asp@ic.uma.es

5th Robert Halir
Dep. de Ingeniería de Comunicaciones
Universidad de Málaga
Málaga, Spain
rhalir@uma.es

6th Íñigo Molina-Fernández
Dep. de Ingeniería de Comunicaciones
Universidad de Málaga
Málaga, Spain
imf@ic.uma.es

***Abstract*—Integrated photonic biosensors have demonstrated low bulk detection limits down to 10^{-7} refractive index units. Nevertheless, most rely on expensive optical sources, such as DFB lasers. Here, we experimentally demonstrate that with adequate sensor design comparable detection limits are achievable with a low-cost Fabry-Perot laser.**

***Index Terms*—Photonics, Biosensing, Coherent Detection, Low-Cost**

I. Introduction

Photonic integrated biosensor technologies have become a major candidate for point-of-care (POC) devices in the recent decades as they exhibit low limits of detections (LOD), in a label-free and real-time process [1]–[3]. Silicon based sensors furthermore benefit from high integration density, i.e. small footprints and parallel detection of several target analytes, in addition to large-scale low-cost fabrication [4].

However, while sensor chips can be cheap, the overall cost of the POC system depends heavily on the read-out device, which usually incorporates a high quality, narrow linewidth laser ($\Delta\upsilon$). Ring resonator based sensors achieve LODs of the order of 10^{-6} to 10^{-7} RIU but usually rely on tunable telecom laser sources, with sub-MHz linewidths [1] [5] [6]. Mach-Zehnder interferometer based sensors have reported LODs of the order of 10^{-7} to 10^{-8} RIU and while they operate with fixed laser sources, their typical linewidth is still in the sub MHz range [5] [7] [8]. These linewidths preclude the use of cheaper, Fabry-Perot type lasers.

However, from a conceptual perspective, narrow linewidth laser sources are only required for some of these sensing systems. For ring-resonators, especially those with high Q-factors, even reduced spectral noise imposes a significant LOD floor: for typical silicon nitride configurations, this floor is of the order of 10^{-8} refractive index units (RIU) for a $0.8\,\mathrm{fm}$ ($1\,\mathrm{MHz}$) linewidth, scaling to 10^{-5} RIU for $1\,\mathrm{pm}$ ($1\,\mathrm{GHz}$) [11]. For Mach-Zehnder interferometer based configurations (see Fig. 1(a)), the impact of laser linewidth depends on the optical length difference between the sensor arms [9], meaning that for well-balanced configurations the LOD floor imposed is still below 10^{-8} RIU even for a $1\,\mathrm{nm}$ broad source. While the sensors overall LOD depends on several additional factors, including mechanical, thermal, chemical, relative intensity and electronic noise [7] [9], using a balanced MZI based sensor it should thus be possible to attain good LOD values even

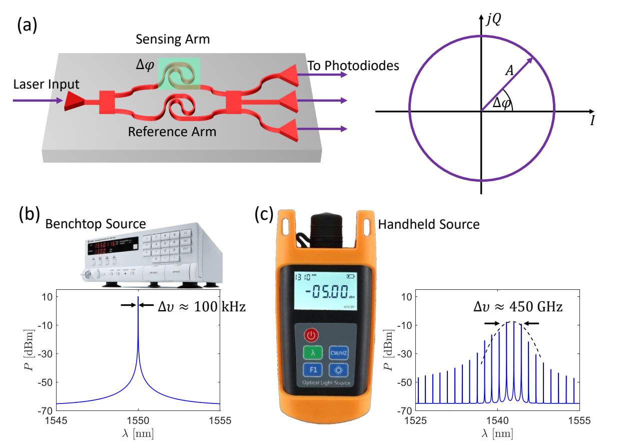

Fig. 1. (a) Schematic of the a balanced MZI sensor and the corresponding complex signal obtained with coherent detection. (b) High-performance benchtop DFB laser and its ideal spectrum [12]. (c) Handheld Fabry-Perot fiber test laser and its spectrum [13].

European Union's Horizon 2020, Marie Skłodowska-Curie grant agreement No 713721; Ministerio de Economía y Competitividad (FEDER), Proyecto TEC2016-80718-R; Programa Operativo FEDER Andalucía 2014-2020 (UMA18-FEDERJA-219); Severo Ochoa program from Spanish MINECO, Grant No. SEV-2017-0706.

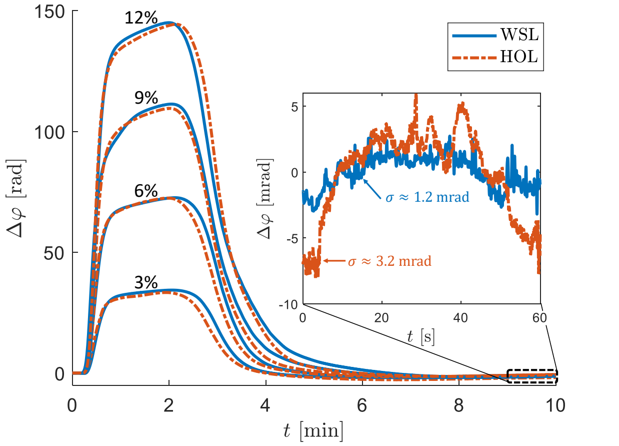

Fig. 2. Phase shift $\Delta\varphi$ for different mass percentage solutions of sodium chloride while using the DFB (solid blue) and the Fabry-Perot (dashed orange) laser on low power. The inset shows their corresponding noise signal.

with broad linewidth sources. As an extreme example, here we demonstrate, for the first time to our knowledge, the use of a remarkably low-cost, handheld Fabry-Perot laser source for sensing applications achieving a LOD of approximately $3 \times 10^{-7}\,\mathrm{RIU}$. Under the same experimental conditions, a high-performance bench-top, distributed feedback laser source achieves a limit of detection of ca. $9 \times 10^{-8}\,\mathrm{RIU}$.

II. Experiment

Two different optical light sources were used for the following experiment: the benchtop WSL-100 from SANTEC [12], referred to as WSL from now on, and a handheld optical fiber test laser (HOL) [13]. The first, shown in Fig. 1(b) has an approximated linewidth of $100\,\mathrm{kHz}$ and costs several thousand Euros, whereas the second (Fig. 1(c)) costs around 30€ [13] with an approximated bandwidth of $450\,\mathrm{GHz}$. Light from one of those is directed to the photonic chip via fiber array. The balanced sensing Mach-Zehnder interferometer, shown in Fig. 1(a), couples the three output signals back to the fiber array and is finally detected by photodiodes [7]. A microfluidic channel is placed on top of the sensing structure, enabling the flow of solutions with different homogeneous refractive indices (HRI) over the sensors surface, inducing a phase shift $\Delta\varphi$. From the three output powers a complex signal $C = A \cdot e^{-j\Delta\varphi} = I + jQ$ is calculated, j being the imaginary unit, from which the applied phase shift $\Delta\varphi$ can be extracted without sensitivity fading or phase ambiguity. A detailed description and optimization of the entire setup can be found in [7].

With each laser two experiments were performed: a first experiment with low laser power and a second experiment with high laser power, i.e. $\approx -30\,\mathrm{dBm}$ and $\approx -10\,\mathrm{dBm}$ received optical power by the photodiodes (PD). All signals were filtered by a digital low-pass filter with an integration time of $0.25\,\mathrm{s}$. For every experiment, four sodium chloride solutions with 3%, 6%, 9%, 12% mass percentage (HRI changes $\approx [0.5, 1.0, 1.5, 2.0] \times 10^{-2}\,\mathrm{RIU}$ [7] in comparison to the Milli-Q purified water running buffer) were injected while recording the extracted phase $\Delta\varphi$.

III. Results

The measured phase change $\Delta\varphi$ for the low power experiments is shown in Fig. 2. As expected, both experiments produce very similar results in terms of sensitivity: $7160\,\mathrm{rad/RIU}$ and $7200\,\mathrm{rad/RIU}$ using the HOL and WSL, respectively. Those values are close to the theoretical calculated sensitivity of $7800\,\mathrm{rad/RIU}$. While running the buffer over the sensor, the noise level of the system was obtained, as shown in the inset of Fig. 2, achieving detection limits of $1 \times 10^{-6}\,\mathrm{RIU}$ and $5 \times 10^{-7}\,\mathrm{RIU}$, for the HOL and WSL lasers. Increasing the input power so that $-10\,\mathrm{dBm}$ optical power is received at the PDs, the LODs drop to $5 \times 10^{-7}\,\mathrm{RIU}$ and $9 \times 10^{-8}\,\mathrm{RIU}$, for the HOL and WSL laser.

IV. Conclusion

We have experimentally demonstrated that low-cost optical sources, such as the Fabry-Perot handheld optical fiber test laser, can be successfully applied for refractive index sensing with coherently detected balanced MZIs without significantly increasing the noise level of the system. We believe that this can be an important step towards cheap future point-of-care biosensing systems.

References

[1] M. Iqbal et al., "Label-free biosensor arrays based on silicon ring resonators and high-speed optical scanning instrumentation," IEEE J. Sel. Top. Quantum Electron., vol. 16, 3, pp. 654–661, March 2010.

[2] A. F. Gavela, D. G. García, J. C. Ramirez, and L. M. Lechuga, "Last advances in silicon-based optical biosensors," Sensors, vol. 16, 3, pp. 1–15, February 2016

[3] E. Luan, H. Shoman, D. Ratner, K. Cheung, and L. Chrostowski,"Silicon Photonic Biosensors Using Label-Free Detection," Sensors, vol. 18, 10, 3519, October 2018

[4] R. Baets, et al., "Silicon photonics: silicon nitride versus silicon-on-insulator," Optical Fiber Communications Conference and Exhibition (OFC), Anaheim, CA, 2016, pp. 1-3, March 2016

[5] R. J. J. van Gulik, B. M. de Boer, and P. J. Harmsma, "Refractive Index Sensing Using a Three-Port Interferometer and Comparison With Ring Resonators," IEEE J. Sel. Top. Quant., vol. 23, 2, pp. 433-439, March 2017

[6] L. Gounaridis, et al., "High performance refractive index sensor based on low Q-factor ring resonators and FFT processing of wavelength scanning data," Opt. Express, vol. 25, 7, pp. 7483-7495, March 2019

[7] J. Leuermann, et al., "Optimizing the Limit of Detection of Waveguide-Based Interferometric Biosensor Devices," Sensors, vol. 19, 17, 3671, August 2019

[8] M. Knoerzer, et al., "Optical frequency comb based system for photonic refractive index sensor interrogation," Opt. Express, vol. 27, 15, pp. 21532-21545, July 2019

[9] Í. Molina-Fernández, J. Leuermann, A. Ortega-Moñux, J. G. Wangüemert-Pérez, R. Halir, "Fundamental limit of detection of photonic biosensors with coherent phase read-out," Opt. Express, vol. 27, 9, 12616, April 2019

[10] R. Halir, L. Vivien, X. Le Roux, D.-X Xu, and P. Cheben, "Direct and Sensitive Phase Readout for Integrated Waveguide Sensors," IEEE Photonics J., vol. 5, 4, 6800906, August 2013

[11] X. Zhou, L. Zhang, and W. Pang, "Performance and noise analysis of optical microresonator-based biochemical sensors using intensity detection," Opt. Express, vol. 24, 16, pp. 18197-18208, July 2016

[12] SANTEC. Available online: https://www.santec.com/en/products/instruments/tunablelaser/wsl-110 (accessed on 13 April 2020).

[13] Amazon. Available online: https://www.amazon.es/ (accessed on 13 April 2020).