Biological sensing with integrated silicon and silicon nitride photonics

Invited Paper

N. Le Thomas, A. Dhakal, F. Peyskens, A. Z. Subramanian, T. Claes, K. De Vos, E. Ryckeboer, R. Bockstaele, P. Bienstman, R. Baets
Photonics Research Group, INTEC-department, Ghent University - imec

Center for Nano- and Biophotonics, Ghent University
Ghent, Belgium
Nicolas.LeThomas@UGent.be

Abstract—**Due to their unique properties to confine and guide light, integrated silicon and silicon nitride photonic chips are currently investigated for biomolecule sensing. We will discuss key integrated photonic structures that have been recently demonstrated for bio analysis.**

I. Introduction

There is a growing interest to implement integrated silicon photonics for biosensing applications, for instance for non-invasive point-of-care disease diagnostics, metabolic status monitoring or drug development. Silicon photonics is envisioned as a solution to the strong need for large-scale sensor arrays able to analyze many biomarkers simultaneously with a high speed, sensitivity and selectivity [1]. It makes use of mature technologies available in an advanced CMOS fab and consists of optical circuits that are defined with nanometer resolution on 200 or 300 mm silicon-on-insulator (SOI) wafers.

A large variety of silicon photonic structures are already available ranging from passive wire waveguides to splitters, arrayed waveguides gratings and optical resonators. Such a variety of structures provides a unique opportunity to control the flow of light and to spectrally analyze the on-chip guided optical signal. As regards sensing, one of the most promising sensing building blocks is the micro-ring resonator. These optical resonators are highly sensitive to any index changes in their surroundings due to both a strong light confinement and a large quality (Q) factor. It makes label-free recognition processes of molecules based on biological receptors possible.

On-chip selective label-free sensing relies on specific surface functionalization, which is not available for all kind of biomolecules. To circumvent specificity issues and broaden the range of detectable biomolecules, on-chip Raman spectroscopy is currently considered, as each Raman spectrum constitutes a fingerprint for a given biomolecule. In addition to be a compact and robust solution, integrated photonics provides crucial signal filtering solutions and signal enhancement opportunities.

In this paper, we review the different implementations of ring resonators that have recently been investigated at Ghent University and we also discuss the potential of silicon photonics for on-chip Raman spectroscopy.

II. Label-free ring resonator sensor

Silicon ring resonators consist of a folded silicon waveguide with typical width of ~400-500 nm and height of ~200 nm. They are generally designed to operate at a wavelength range around 1.5μm. The in-coupling port as well as optional drop ports are made of standard integrated wire waveguides and are designed to minimize the insertion losses and maximize the coupling efficiency. The geometrical forms of the rings can be as diverse as simple circular rings, racetrack rings and long folded-spiral rings [2]. Small bend radii are possible due to the high index contrast between the silicon or silicon nitride and its surroundings, which ensures high compactness with minimal optical losses. Increasing the length of folded-spiral rings for a fixed injection power maximizes the sensing area and hence the amount of biomolecules that are probed, however, it is at the expense of a lower modal electric field, which implies a lower sensitivity per unit area. In addition, the length is limited by the optical losses and the optical power that can be coupled into the ring

The sensing mechanism is based on the determination of the frequency shift of one of the spectral resonance of the ring resonator. Sharper is the resonance, i.e. larger is the Q factor, lower is the detection limit for a given signal to noise ratio. For some applications it is therefore necessary to maximize the Q factor. A critical limiting contribution to the Q factor is the sidewall roughness. It can be counteracted by using shallow etched ridge waveguides as demonstrated in [3]: ring resonators with Q factor up to about 10^6, approaching the intrinsic limit, have been fabricated.

By functionalizing the surface of a SOI ring resonator with a heterobifunctional polyethylene glycol coating, De Vos et al. have shown that non-specific binding was reduced [4]. For a racetrack resonator with radius 5 μm and straight section 2 μm and a Q factor 20000, they were able to measure 10ng/ml with avidin. For the reported Q factor, the surface coating does not deteriorate the detection limit of the sensor.

In the case of standard ring resonators the interaction between the light and the biomolecules takes place at the evanescent part of the confined field, which is not optimal in terms of light/matter interaction. Locating the maximum of the field in the low index material that contains the analytes can maximize the interaction. T. Claes et al. have carried out such

an approach by designing an air slot in the core of the waveguide that forms the ring resonators [5]. They have demonstrated a selective label-free sensing of proteins with an increase of the sensitivity by a factor of 3.5.

The frequency shift of the resonance resulting from a refractive index variation in the surrounding of the ring resonator can be amplified by implementing the Vernier effect. To do this, the probe ring is cascaded with a filter ring resonator whose free spectral range is slightly different. A sensitivity of 2169nm/RIU, that is ~30 times larger than the single ring case, has been demonstrated [6].

A major asset of on-chip sensing is the high flexibility in term of signal management. In particular, it offers the possibility of robust multiplexed detection schemes as reported in [7]: By using an array of three-by-four silicon-on-insulator ring resonators, a simultaneous detection of several antibodies has been achieved with high selectivity. Each basic sensing unit was able to detect 3.4 pg/mm^2 of protein overlay. This proof of principle opens the door for disposable lab-on-chip devices that combine high-throughput analysis with high sensitivity.

III. On-chip spectroscopy

Another route where silicon photonics can play a major role is on-chip absorption, fluorescence and Raman spectroscopy. A key advantage of on-chip Raman spectroscopy as compared to its classical far-field counterpart is the ability to efficiently collect the Raman scattered light into a unique mode, even if the molecules are spatially dispersed.

In the case of a single elementary light source, e.g. a dipole, the aperture of the collecting optics defines the minimal coherence area A_c of the emitted field. For a spectral analysis that relies on an angular dispersion of the signal, the resolution capability of the spectrometer can be infinite even if A_c is diffraction limited. Consider now an ensemble of dipoles having each the same frequency spectrum and spatially distributed on a surface that is larger than the coherence area associated to a single dipole. At a given frequency ω and for a stigmatic optical system, the angular spectrum of each dipole is spatial shifted after the spectrograph if they do not share the same coherence area. As a result of the angular shift of each spectrum, the measured frequency spectrum of the dipole ensemble is subject to an inhomogeneous broadening.

When the dipoles are located at the surface of a wire waveguide, a significant fraction of the emission of each dipole can be coupled into a single mode as shown in [8]. The coherence area A_c is then given by the transverse profile of the field envelope. Due to the strong confinement resulting from the high index contrast, A_c can be larger than in the free space case. It follows that both the spectral resolution and the signal throughput are enhanced by on-chip spectroscopy.

In addition to the collection efficiency, the on-chip excitation is also more favorable. In an optimal coupling scheme a pump beam can address only one single coherence area if the excitation is performed through a classical far-field lens. In the case of an on-chip guided pump all the dipoles dispersed on the waveguide surface are optimally excited provided that the optical waveguide losses can be neglected. In terms of the operating wavelength, silicon is not the most relevant material as it is only transparent above 1.1 µm, whereas shorter wavelengths are more favorable for Raman scattering. But by making use of silicon-nitride (Si_3N_4) waveguide layers instead of silicon, the CMOS technology can be extended to the entire visible and near infrared wavelength range. The silicon-nitride platform is currently under development [9].

The main challenges to implement Raman spectroscopy lie not only in the weakness of the signal from the molecules but also in any background such as the emission (fluorescence or Raman) from the guiding structure itself. A proper on-chip signal filtering can however minimize background issues. A different approach consists also in taking advantage of field enhancement effects by functionalizing integrated dielectric waveguides with a metallic nano-antenna [10].

IV. Conclusion

Several sensing concepts based on silicon photonics have already been demonstrated and are envisioned to evolve into cost effective solution due to high-throughput and reliability intrinsic to CMOS technologies. Besides, the integrated photonics structures have reached a maturity for signal management that makes on-chip Raman spectroscopy achievable.

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References

[1] E. Simon, "Biological and chemical sensors for cancer diagnosis", Meas. Sci. Technol., vol. 21, pp. 112002, 2011.

[2] W. Bogaerts, et al., "Silicon microring resonators," Lasers & Photonics Reviews, vol. 6, p.47-73, 2012.

[3] P. De Heyn, D. Vermeulen, T. Van Vaerenbergh, B. Kuyken, D. Van Thourhout, "Ultra-high Q and finesse all-pass microring resonators on Silicon-on-Insulator using rib waveguides," 16th European Conference on Integrated Optics and technical exhibition, Spain, p.195, 2012.

[4] K. De Vos, J. Girones, S. Popelka, E. Schacht, R. Baets, P. Bienstman, "SOI optical microring resonator with poly(ethylene glycol) polymer brush for label-free biosensor applications," Biosensors and Bioelectronics, vol. 24, pp.2528-2533 2009.

[5] T. Claes, et al., "Label-Free Biosensing With a Slot-Waveguide-Based Ring Resonator in Silicon on Insulator," IEEE Photon. J., vol. 1, pp.197-204, 2009.

[6] T. Claes, W. Bogaerts, P. Bienstman, "Experimental characterization of a silicon photonic biosensor consisting of two cascaded ring resonators based on the Vernier-effect and introduction of a curve fitting method for an improved detection limit," Opt. Express, vol. 18, pp.22747-22761, 2010.

[7] K. De Vos, et al., "Multiplexed antibody detection with an array of silicon-on-insulator microring resonators," IEEE Photonics Journal, vol. 1, p.225-235, 2009.

[8] A. Dhakal, F. Peyskens, A. Z. Subramanian, N. Le Thomas and R. Baets "Enhancement of light absorption, scattering and emission in high index contrast waveguides", unpublished.

[9] A. Subramanian, S. Selvaraja, P. Verheyen, A. Dhakal, K. Komorowska, R. Baets, "Near infrared grating couplers for silicon nitride photonic wires," IEEE Photon. Technol. Lett., vol. 24, pp.1700-1703, 2012.

[10] F. Peyskens A. Subramanian, A. Dhakal, N. Le Thomas, R. Baets, "Enhancement of Raman Scattering Efficiency by a Metallic Nano-antenna on Top of a High Index Contrast Waveguide," CLEO 2013, United States, 2013, in press.

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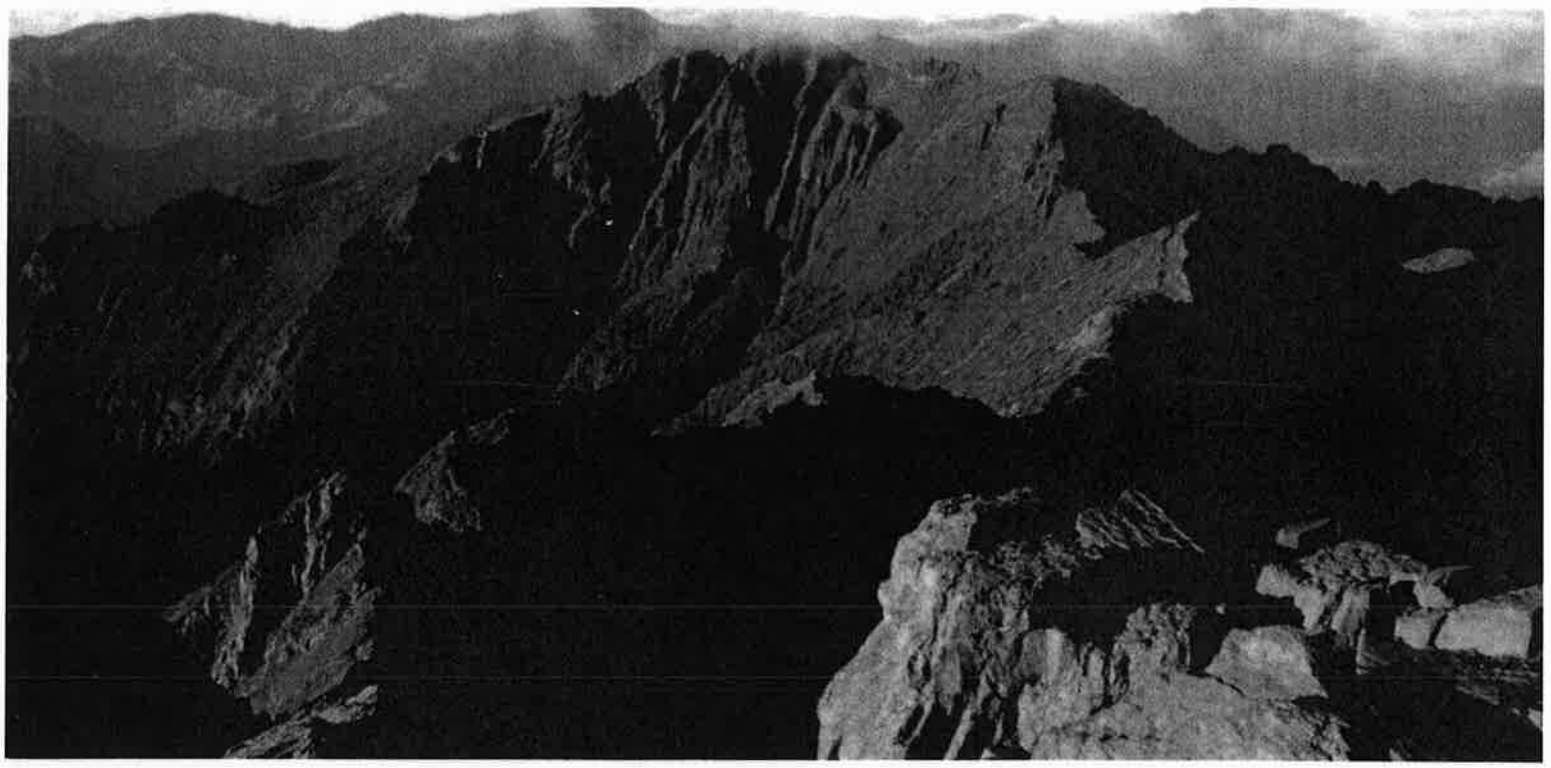

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