Optical fiber probe sensor based on Silicon-on-Insulator ring resonator.

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In this paper we propose a fiber probe refractive index sensor based on Silicon-On-Insulator (SOI) ring resonator as transducer. The ring resonator is transferred from a SOI chip to the tip of an optical fiber without any degradation of the sensor performance. The proposed device combines the high quality of SOI ring resonator sensors with the portability of optical fibers.

Introduction

Optical fiber technology has undergone tremendous growth and advancement over the last years. The application of this technology for sensing is developed at a rate that could barely have been predicted few years ago [1]. Its use as a medical device for imaging hard-to-reach locations and its property to conduct light to a remote convenient location make it a suitable tool for in vivo sensing applications. The most common and known is the endoscope.

Here, we propose an optical fiber probe sensor for label-free biosensing based on an SOI ring resonator as transducer.

In [2], we described an SOI ring resonator, which has 70 nm/RIU sensitivity for bulk changes of the refractive index and showed a 625 pm saturation shift of the resonance wavelength for label-free sensing of proteins with the well-known strong affinity couple biotin/avidin.

In this paper, we present a fabrication method to transfer this ring resonator to a fiber facet. The device was experimentally tested for bulk refractive index sensing, and did not show any performance degradation compared to the original chip-based sensor.

Biosensing with microring resonators

Microring resonators are considered a promising technique for label-free biosensing thanks to its high sensitivity and high Q factor [3]. We designed a microring cavity in an add-drop filter configuration. The ring supports modes that resonate at a wavelength λ_{res} for which:

$$\lambda_{res} = \frac{L}{m} n_{eff} \qquad (1)$$

L is the round trip length, m is the cavity mode order (=1,2...) and n_{eff} is the effective refractive index of the resonator waveguide. The resonance results in a sharp dip in the transmission or a peak in the drop port.

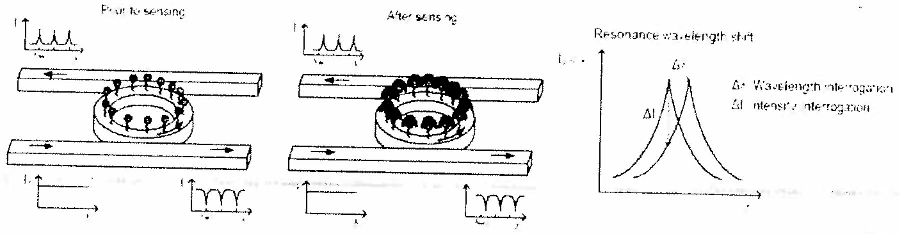

Figure 1. Basic principle of a ring resonator as biosensor.

The resonance wavelength shift resulting from a changing local refractive index when biomolecular interaction takes place in the vicinity of the cavity is a quantitative measure for the number of binding events. Taking into account first order dispersion, this shift can be determined by means the following formula:

$$\Delta\lambda = \frac{\Delta_{env} n_{eff} \cdot \lambda_{res}}{n_g} \tag{2}$$

where $\lambda_{env} n_{eff}$ is the effective index shift caused by an environmental change and n_g is the group index.

Design

The silicon waveguides in our design are 220nm high and 450nm wide, on top of 2 µm of silicon oxide and 750 µm silicone substrate. The microring resonator used in this experiment is a racetrack with 4 µm radius and 4 µm straight sections.

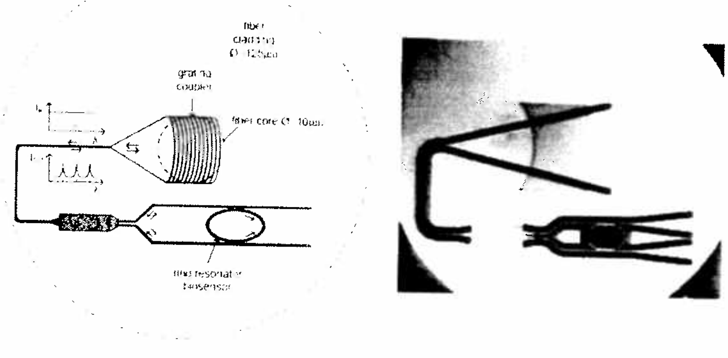

Figure 2. Top view of the optical fiber probe: photonic integrated circuit for biosensing aligned to the core of the optical fiber.

The chip is designed to be 'retroreflective'[4]: using a dedicated light coupling scheme, light will couple into and out of the integrated circuit via the same grating coupler and under the same angle. The fiber core is aligned to a grating coupler. The cladding of the fiber carries the rest of the integrated circuit comprising a 3dB MMI splitter/combiner and a ring resonator biosensor. A curved grating focuses the light onto the SOI waveguide, which circumvents the need for space consuming waveguide tapers. A top view of the design is shown in Figure 2.

Fabrication

The aim of the fabrication is to transfer the sensing circuit, previously described, from the SOI chip to the fiber facet.
First, the sample is bonded upside down to a silicon wafer that will be used as carrier by means of wax.

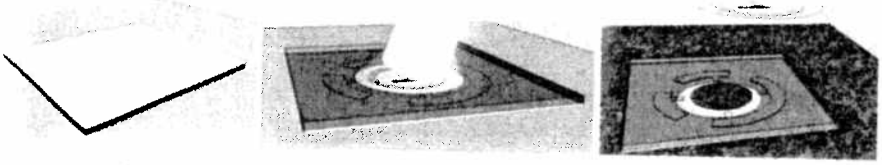
(a) (b) (c)

Figure 3. Fabrication process. (a) Sample fixed up-side down by means of wax to a Si wafer. (b) Alignment of the fiber after the complete removal of the substrate. (c) Fiber pulled up with the sensing circuit attached to the tip.

Next step is the removal of the silicon substrate. This step consists of three parts: First mechanical grinding of the substrate reducing its thickness up to 100 μm. Second, dry etching to thin down the silicon down to 50 μm and finally, wet etching for the rest of the silicon. For this wet etching a mixture of acetic, nitric and hydrofluoric acid is used. At this moment in the process, the whole Si substrate has been completely removed. Only the Si waveguides and the 2μm thick SiO_2 layer are left on the sample.
The alignment of the optical fiber to the grating couplers can then be carried out. A drop of UV curable glue is used during the alignment, which is cured when the resonance detection is optimal. The sensing structure is now attached to the fiber.
Subsequently, the hot plate where the sample is held is set at 120°C. The melting of the wax that joined the sample with the Si wafer allows the fiber to be pulled up breaking the thin layer of SiO_2 and transferring onto the tip of the fiber the previously glued sensing circuit.
Finally, the immersion of the fiber in boiling acetone cleans the residues of wax at the sensing surface.

Bulk sensing

The sensing device has been characterized by bulk sensing experiments. The sensor was introduced in watery NaCl-solutions with different concentrations. No surface chemistry was applied to the sensor surface for this experiment.
The change of the refractive index in those concentrations leads to a shift in the resonance wavelength. Figure. 4 shows a linear shift of the resonance wavelength with increasing salt concentration. Lorentzian fitting has been used to determine these shifts. The sensitivity of this device is 70 nm/RIU (Refractive Index Unit). It is the expected sensitivity for the same ring resonator that was simulated and measured on a SOI sample and demonstrated in [5].
Surface functionalization will be the next step to achieve the biomolecular detection using this fiber probe.

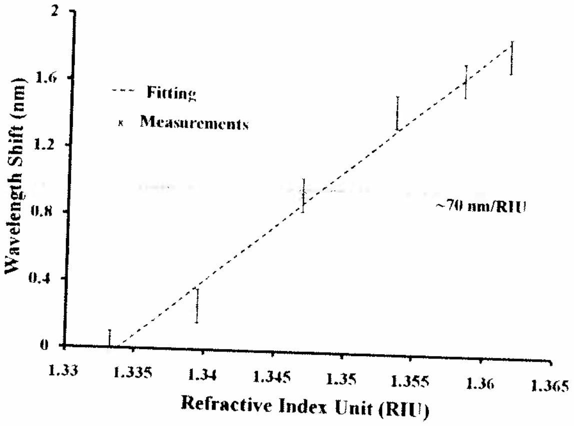

Figure 4. Measured resonance wavelength shift versus bulk refractive index unit. The figure shows a sensitivity of 70nm/RIU.

Conclusions

This work deals with a novel implementation: an integrated SOI circuit is transferred to the facet of a single mode optical fiber. This can lead to a robust and portable device for in-vivo label-free biosensing. Its sensitivity is 70nm/RIU. The results for bulk sensing experiments achieve the same results of the same sensor on SOI chip. The characterization of the device for biomolecular sensing is the next challenge for this work.

References

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References

[1] A. Leung, P. M. Shankar, and R. Mutharasan. "A review of fiber-optic biosensors" Sensors and Actuators B-Chemical, vol. 125(2), pp. 688–703, Aug. 2007.

[2] K. De Vos, I. Bartolozzi, E. Schacht, P. Bienstman, R. Baets, "Silicon-on-Insulator microring resonator for sensitive and label-free biosensing",Optics Express, vol. 15(12), pp. 7610-7615, Jun. 2007

[3] D.X. Xu, M. Vachon, A. Densmore. " Label-free biosensor array based on silicon-on-insulator ring resonators addressed using a WDM approach" Optics letters, vol. 35(16), Aug. 2010.

[4] M. Verbist, W. Bogaerts, J. Schrauwen, R. Baets. "Silicon-on-Insulator-Based Retroreflective Optical Marker Chips for Simultaneous Identification and Localization." IEEE Journal of Selected Topics in Quantum Electronics, 15(5), p.1427-1431 (2009)

[5] De Vos, K. Bartolozzi, I. Schacht, E. Bienstman, E. Baets, R "Silicon-on-Insulator microring resonator for sensitive and label-free biosensing",Optics Express, 15(12), p.7610-7615 (2007).