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2008 Annual Symposium of the IEEE/LEOS Benelux Chapter

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Editors
K. Wörhoff, L. Agazzi,
N. Ismail, X. Leijtens

November 27-28, 2008
University of Twente
The Netherlands

PROCEEDINGS 2008

Thirteenth Annual Symposium of the IEEE/LEOS Benelux Chapter

Thursday/Friday, November 27-28, 2008
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Organized by
Integrated Optical MicroSystem Group, University of Twente
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Label-free biosensing with silicon-on-insulator slotted racetrack resonator

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We present a label-free biosensor based on a racetrack resonator comprised of slot waveguides that are fabricated with deep-UV lithography in silicon-on-insulator. Experiments with biotin/strept-avidin binding indicate that this sensor is 4.8 times more sensitive than sensors based on normal racetrack resonators.
Slot waveguides are numerically optimized for biosensing, and our sensor is experimentally characterized for both bulk refractive index sensing and surface sensing.

Introduction

Analysis of biological samples is important for many applications, such as medical diagnostics, food quality control, drug development and environmental monitoring. Nowadays this is typically done in a large-scale laboratory, where skilled personnel needs to perform time-consuming experiments with expensive equipment. By miniaturizing the functionality of these laboratories in a so called *lab-on-a-chip*, the cost and duration of analysis would be reduced significantly. A lab-on-a-chip would be able to measure the concentration of hundreds or even thousands of different biomolecules, such as proteins, anti-bodies and DNA, in parallel on a very small sample volume. A very compact, fast and accurate detection method for biomolecules is thus essential for a lab-on-a-chip.
Previous results [1] showed a label-free biosensor based on a racetrack cavity in silicon-on-insulator (SOI) with a $10x10\mu m^2$ footprint. By covering the racetrack resonator waveguide with a chemical layer with receptor molecules that selectively bind with the biomolecules one wants to detect (proteins, anti-bodies, DNA, ...), the resonance wavelength of the racetrack can be made to change proportionally with the concentration of the analyte biomolecules. The sensor in [1] showed an experimental bulk refractive index sensitivity of 68nm per refractive index unit (RIU) and surface sensing with the biotin/strept-avidin strong affinity couple proved to saturate at a 0.8nm resonance wavelength shift, resulting in a concentration detection limit of 10ng/ml for strept-avidin.

Towards a higher sensitivity

An important route towards an improvement of the sensitivity, and hence the detection limit, of this sensor, is to increase the interaction between light in the resonator waveguide and biomolecules attaching to the waveguide surface. When using a normal photonic wire, only the evanescent tail of the wire mode will interact with biomolecules. By etching a narrow slot in the middle of the waveguide, a vast fraction of the quasi-TE mode will

be concentrated in that slot [2], so that more light is concentrated along the bio-activated surface of the slot waveguide. This will cause attached molecules to have a larger impact on the propagating light, so that the resonance wavelength shift of a racetrack resonator consisting of slot waveguides will be larger than that of a normal racetrack resonator. In [3] this concept already proved to be promising for biosensing.

Waveguide design

Using an eigenmode expansion tool, the dimensions S and W (top of Figure 1) of a silicon slot waveguide were optimized for biosensing. The height of the waveguide was kept constant at 220nm, as this was already fixed by our fabrication process. Surface sensing was simulated by a layer with refractive index 1.45 covering the whole waveguide. As a function of S and W, the effective index of the waveguide was simulated once for $1nm$ biolayer thickness (model for initial surface chemistry) and once for $6nm$ biolayer thickness (model for saturated surface). Taking first order dispersion into account, the difference in effective index was used to calculated the expected resonance wavelength shift of the racetrack resonator. The bottom of Figure 1 shows the calculated resonance wavelength shift as a function of S and W. The smaller the slot width S, the higher the sensitivity, and for each value of S, the optimal value for W van be read from the graph.

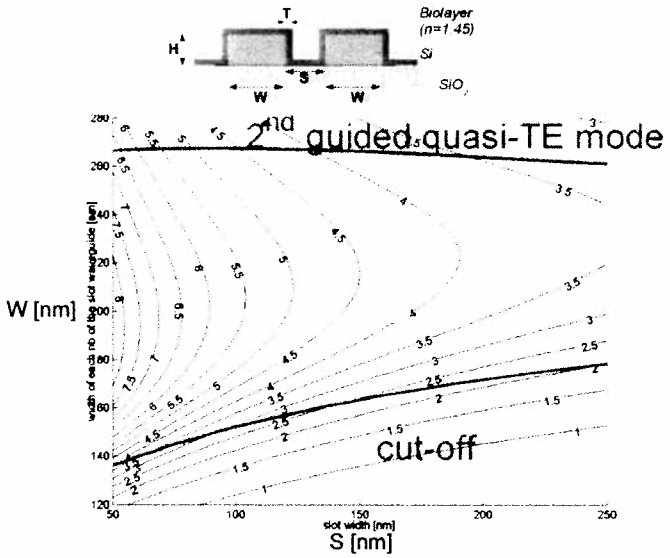

Figure 1: Slot waveguide optimization for biosensing

Fabrication

Slotted racetrack resonators with $5\mu m$ radius and $3\mu m$ straight coupling sections were fabricated with deep-UV lithography [4]. Figure 2 shows scanning electron microscope images of our slotted racetrack resonator with 100nm slot width.

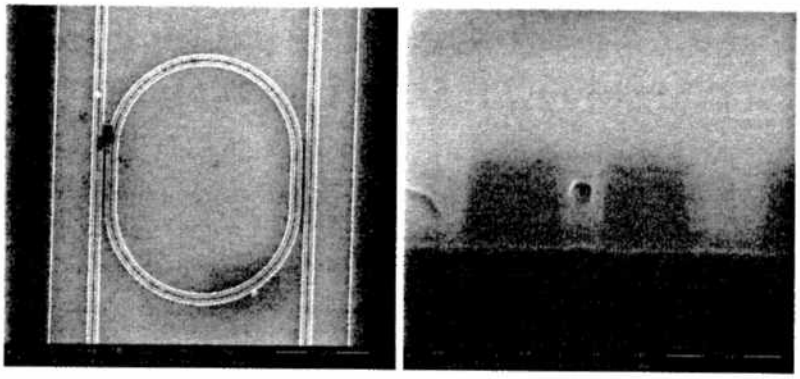

Figure 2: Left: top view SEM image of our slotted racetrack resonator, right: SEM image of the cross section of the racetrack resonator slot waveguide with 100nm slot region, measured at half height

Bulk sensing

The bulk sensitivity of this slotted racetrack resonator was measured by flowing watery NaCl-solutions with different concentrations over the sensor. A flow cell with closed channel was used to avoid evaporation and no surface chemistry was applied to the sensor surface for this experiment. The refractive index of the solutions was determined at a wavelength of 1550nm [5]. The left graph in Figure 3 shows the linear shift of the resonance wavelength as a function of the top cladding index. The bulk sensitivity of the slotted racetrack resonator with 100nm slot region is $298nm/RIU$ as compared to $68nm/RIU$ for normal racetracks.
Using an eigenmode expansion tool, the effective index change of a slot waveguide with the same dimensions as in Figure 2 was simulated for changing top cladding index. Based on this, a theoretical bulk sensitivity of $384nm/RIU$ was calculated, taking first order dispersion into account.

Surface sensing

The biotin/strept-avidin strong affinity couple was used to verify the increased sensitivity of our sensor for surface sensing. The sensor surface was functionalized with GOPTS and biotin. Using a flow cell and a syringe pump, HBS-buffer fluid was flow over the sensor at a constant rate to determine the reference resonance wavelength. Then a known concentration of avidin in HBS-buffer was flown over the sensor, while the resonance wavelength of the sensor was continuously tracked. When the change of the resonance wavelength over time became negligible, HBS-buffer fluid was flown over the sensor again to remove all non-covalently bound molecules. The right graph in Figure 3 compares the respons of our slotted racetrack with the respons of a normal racetrack. For the high concentrations of avidin we used here, the sensors will be saturated (all biotin binding sides will be occupied). The resonance wavelength shift of our slotted racetrack resonator at saturation is 4.8x larger then the one of a normal racetrack, indicating a 4.8x higher sensitivity. The comparison between the slotted racetrack and normal racetrack is indicative, because there were differences in flow rate and surface chemistry between the experiments.

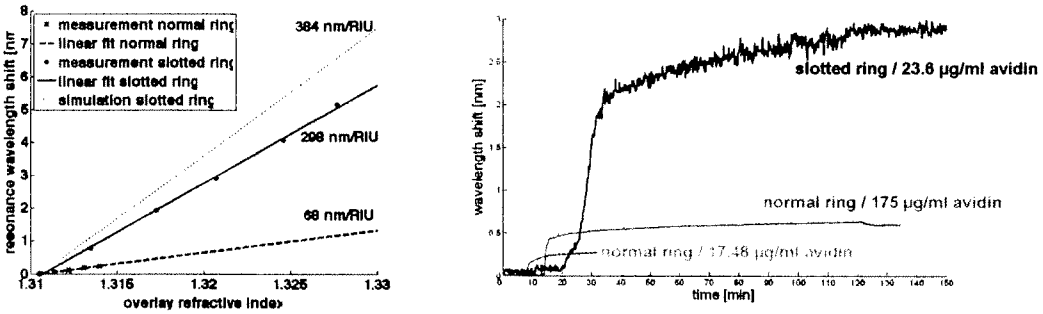

Figure 3: Left: comparison of the bulk sensitivity of a slotted racetrack resonator (both theory and experiment) and the experimental bulk sensitivity of a normal racetrack resonator [1]. The slotted racetrack resonator has the same dimensions as the one shown in Figure 2. Right: comparison between the respons of our slotted racetrack biosensor and that of a normal racetrack biosensor, when a certain avidin concentration in HBS-buffer fluid is flown over the sensor chip

Conclusions

We presented a label-free biosensor based on a slotted SOI racetrack resonator fabricated with deep-UV lithography. Experiments with biotin/strept-avidin binding indicated that this sensor is 4.8 times more sensitive than sensors based on normal racetrack resonators. Slot waveguides were numerically optimized for biosensing, and our sensor was experimentally characterized for both bulk refractive index sensing and surface sensing.

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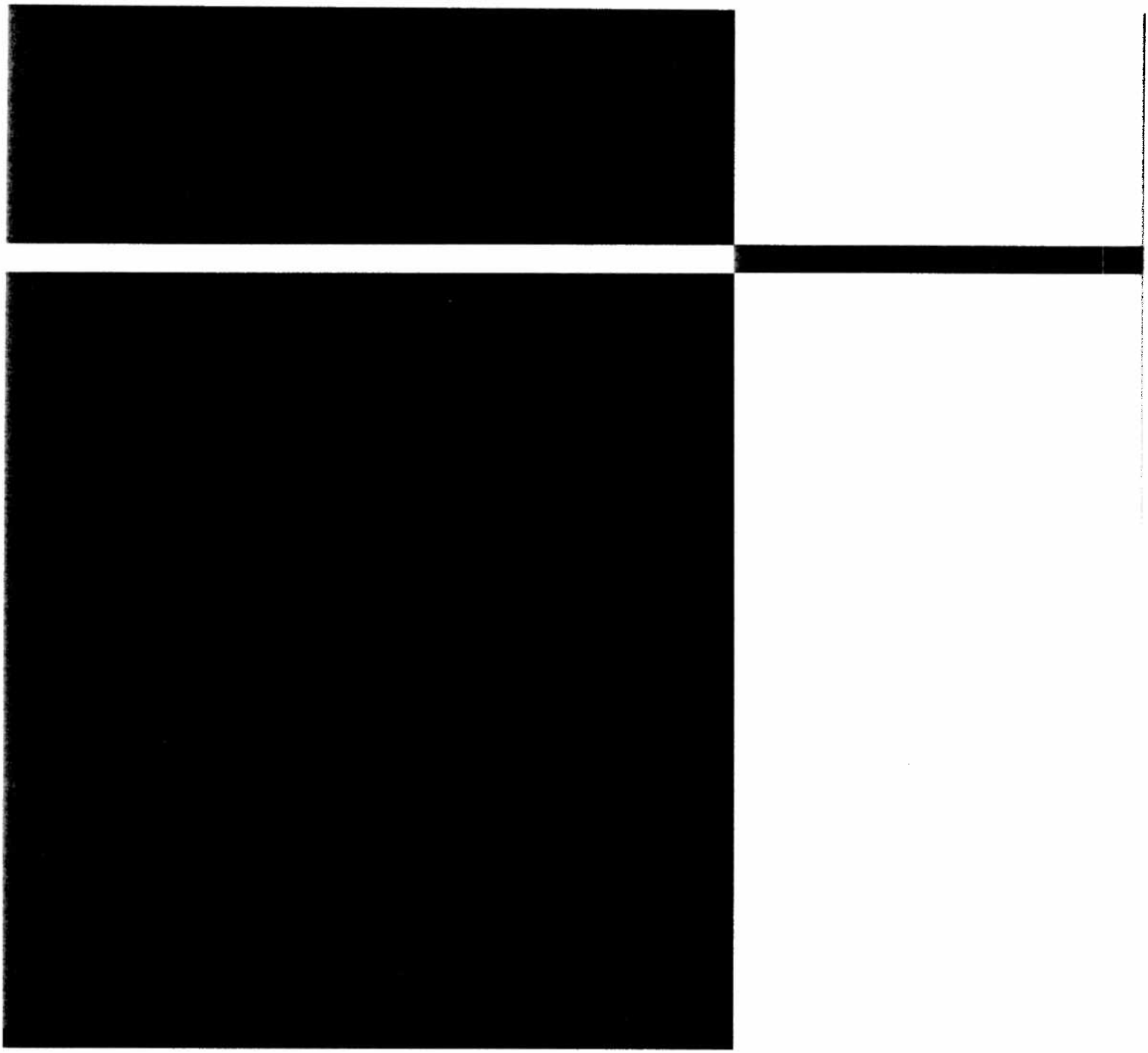

ISBN: 978-90-365-2768-2
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