Grated Waveguide Optical Cavity for Sensing

S.V. Pham, M. Dijkstra, A.J.F. Hollink, R.M. de Ridder, G.J.M. Krijnen, P.V. Lambeck, M. Pollnau, and H.J.W.M. Hoekstra

Integrated Optical MicroSystems (IOMS) Group, MESA[+] Institute for Nanotechnology, University of Twente
P.O. Box 217, 7500 AE Enschede, The Netherlands

***Abstract*—We demonstrate the versatility of a silicon nitride grated waveguide optical cavity as compact integrated optical sensors for (bulk) concentration detection, label-free protein sensing, and – with an integrated cantilever suspended above it – gas sensing.**

Keywords-integrated optics, sensing, waveguide, grating

I. INTRODUCTION

A grated waveguide (GWG), which is a waveguide with a finite-length grated section, acts as an optical resonator, showing sharp fringes in the transmission spectrum near the stop-band edges of the grating. These oscillations are due to Fabry-Perot resonances of Bloch modes propagating in the cavity defined by the grated section [1]. Any small structural changes in the environment of the GWG, which disturb the evanescent field of the GWG resonant modes, will lead to a shift of its transmission spectrum. Such an effect can be exploited for sensing applications, such as the detection of a bulk refractive index change [2] or nano-displacements of a cantilever suspended above the GWG [3]. Here we present 3 applications: (1) a concentration sensor, based on the bulk index change of the GWG top cladding; (2) label-free protein sensing (PepN enzyme), where the spectral shift of the GWG response is due to the antibody-antigen interaction, leading to growth of an ad-layer on it; and (3) gas sensing, where the GWG detects stress-induced deflections of a doubly-clamped micro-cantilever (micro-bridge) with a 50 nm thick Pd top layer due to H_2 gas absorption by the Pd receptor layer.

II. FABRICATION AND EXPERIMENTS

The Si_3N_4 grated waveguides were fabricated using laser interference lithography. The integrated GWG-cantilever devices have been fabricated successfully using MEMS techniques. Details of the fabrication process were described in [3]. The GWG setup for the (bulk) concentration and label-free protein sensing experiments is shown in Fig. 1a, while the 3D schematic structure of the GWG-cantilever device for gas sensing is shown in Fig. 2a.

To demonstrate (1) concentration sensing, we filled a chamber (cuvette) on the surface of the sensor with a phosphate buffered saline solution of 1 wt% (PBS1x). The evaporation of water from the open cuvette leads to a continuous change of concentration, and hence of the bulk index, which can be deduced from the measured spectral shift of the sensor.

To detect a target biomaterial (2), such as PepN enzyme in this case, its antibody needs to be immobilized on the surface of the GWG device. We followed the standard immobilization process developed by Imenz b.v. [4]. Once the antibody was immobilized on the GWG surface, the cell-free extracted solution, containing the target PepN enzyme and other proteins, was applied and the antibody-antigen interaction was optically monitored through the GWG transmission spectra.

For H_2 gas sensing (3), instead of singly-clamped cantilevers as mentioned in [3], we fabricated devices with a doubly-clamped cantilever and with an aimed gap of g = 200 nm. Initial bending of the cantilever was characterized using a white-light interferometer. The PDMS chamber placed on top of the device was connected with gas bottles (i.e., N_2 and 1% H_2-N_2 mixture) through mass flow controllers. The optical performance of the integrated device was monitored using a tunable laser source with a repeatability of 0.3 pm.

III. RESULTS AND DISCUSSION

A. Bulk concentration sensing

The measured spectral shift of the concentration sensor is shown in Fig. 1b. The results show that changes of the refractive index down to 2×10^{-5} RIU (refractive index unit), and concentration changes down to 0.01 wt% can be resolved.

B. Label-free protein sensing

Small changes on the GWG surface, caused by the antibody-enzyme interaction, lead to spectral shifts of the resonant peak, as shown in Fig. 1c. The reaction saturates after ~35 minutes. The total shift was approximately 342 pm, corresponding to the growth of an ad-layer of ~2 nm; the limit of detection for ad-layer growth is around 4 pm.

C. Mechano-optical hydrogen gas sensing

Using a white-light interferometer, an initial bending (upwards, i.e., away from the GWG structure) of the micro-bridge of approximately 500 nm was found. This initial bending, which leads to a lower sensitivity at low H_2 concentrations (owing to the relatively large gap of g ~ 700 nm), is due to the difference between residual stresses in the SiO_2 base layer and the Pd receptor film [3].

Prior to supplying H_2 gas to the chamber, N_2 gas was flushed in during 15 min with a flow rate of 0.5 sccm and optical transmission curves were captured every minute. The results showed a stable and reproducible resonant peak at

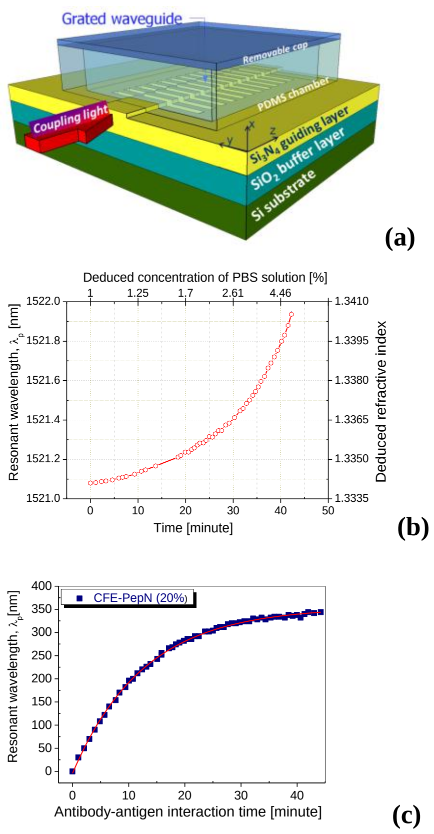

Figure 1. 3D schematic of the Si_3N_4 grated waveguide (GWG) device with a PDMS chamber serving as an open cuvette for bulk concentration sensing and a closed environment for accurate monitoring of the antibody-enzyme interaction **(a)** and performance of devices for **(b)** measurement of PBS concentration, **(c)** label-free protein sensing

$\lambda_p = 1496.631 \pm 10^{-3}$ nm, indicating that such a flow rate did not cause any side effects or mechano-optical vibrations.

Next we supplied the H_2(1%)-N_2 mixture (flow rate 0.5 sccm) for a longer period of time, during which the transmission spectrum was monitored (see Fig. 2b). The shift $\Delta\lambda_p$ depends almost linearly on time (see Fig. 2c left-hand side), which can be explained partly by noting that the effect of the initially rapid change of the gap size, g, is compensated by lower values of $\partial\lambda_p/\partial g$ at larger gap size. After 3.5 hours the flow of the H_2 (1%)-N_2 mixture was switched off and replaced again by a pure N_2 inflow, leading to desorption. Figure 2c (right-hand side) shows the peak shifts during a four-hour long period of the desorption process.
The result provides a proof of concept of a novel and compact integrated mechano-optical sensor. This result gives us a strong confidence in the feasibility of this type of sensor.

IV. CONCLUSIONS

We have demonstrated the great potential of a Si_3N_4 grated waveguide optical cavity as compact integrated optical sensors for concentration detection, label-free protein sensing, and gas sensing. Concentration changes ~0.01 wt%, corresponding to 2×10^{-5} RIU, can be resolved. The enzyme is selectively recognized by its corresponding antibody immobilized on the surface of the sensor, and monitored in real-time. Owing to its simple fabrication and effective operation the sensor has potential as an element of a sensitive, on-chip multi-sensing system for label-free detection of a variety of bio-molecules. Hydrogen sensing with a novel and compact integrated optical

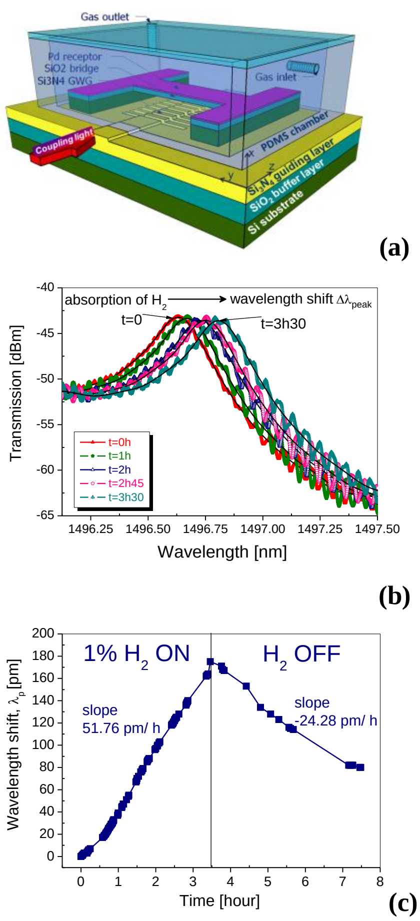

Figure 2. 3D schematic of the structure with a PDMS chamber as a reaction environment for H_2 sensing **(a)**, transmission curves of the device in response to the absorption **(b)**, and the wavelength shift versus the reaction time **(c)**.

read-out scheme is demonstrated as a proof of concept for our proposed and successfully fabricated mechano-optical sensor. This new sensor type possesses a great potential as an element for a sensitive and on-chip multi-sensing system, provided that the gap between the GWG and the micro-bridge can be well controlled during fabrication.

ACKNOWLEDGMENTS

This research is supported by MEMSland, a project funded by the Dutch Ministry of Economic Affairs and the STW Technology Foundation through project TOE. 6596. We thank the company Imenz b.v. for supplying bio-materials.

REFERENCES

[1] G.J. Veldhuis, J.H. Berends, R.G. Heideman and P.V. Lambeck, "An integrated optical Bragg-reflector used as a chemo-optical sensor," Pure and Applied Optics, vol. 7: pp. L23-L26, 1998.
[2] W.C.L. Hopman, H.J.W.M. Hoekstra, R. Dekker, L. Zhuang, and R.M. de Ridder, "Far-field scattering microscopy applied to analysis of slow light, power enhancement, and delay times in uniform Bragg waveguide gratings," Opt. Express, **15**(4): pp. 1851-1870, 2007.
[3] S.V. Pham *et al.*, "Read-out of cantilever bending with a grated waveguide optical cavity," Photon. Technol. Lett., IEEE , vol.23, no.4, pp.215-217, 2011
[4] IMEnz Bioengineering BV, LJ Zielstraweg 1 9713 GX Groningen The Netherlands, (http://www.imenz.com/).
[5] L.J. Kauppinen, M. Dijkstra, H.J.W.M. Hoekstra, and R.M. de Ridder, "Label-free Enzyme Sensing with Grated Silicon Photonic Wire," in Proc. Annual Symp. IEEE Photon. Benelux Chapter, (Brussels, 2009), pp. 41-44.