Grated Waveguide Cavity for Label-free Protein and Mechano-Optical Gas Sensing

S. V. Pham,[1] M. Dijkstra,[1] A. J. F. Hollink,[1] R. M. de Ridder,[1] H. A. G. M. van Wolferen,[2] G. J. M. Krijnen,[2] M. Pollnau,[1] and H. J. W. M. Hoekstra[1]

[1]Integrated Optical MicroSystems (IOMS) group, [2]Transducers Science and Technology (TST) group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
Presenting author e-mail address: m.pollnau@ewi.utwente.nl

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.

1. Introduction

A grated waveguide (GWG), which is a waveguide with a finite-length grated section, acts as an optical resonator, exhibiting 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 nanodisplacements of a cantilever suspended above the GWG [3]. Here we present two applications: (1) label-free protein sensing (PepN enzyme - the major Suc-LLVY-AMC-hydrolyzing enzyme in *Escherichia coli*), where the spectral shift of the GWG response is due to the antigen-antibody interaction, leading to growth of an ad-layer on it; and (2) mechano-optical gas sensing, where the GWG detects stress-induced deflections of a doubly-clamped microcantilever (microbridge) with a Pd top layer due to H_2 gas absorption by the Pd receptor layer.

2. Materials and experimental methods

The grating in the Si_3N_4 GWG was 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 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 study the feasibility of the label-free protein sensor (1), we initially tested a homogeneous concentration sensing, based on the bulk index change of the GWG top cladding. We filled a chamber (cuvette) on the surface of the sensor with a phosphate buffered saline solution of 1 wt% (PBS1x - a buffered solution of biomaterials). 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, in this case the PepN enzyme, 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]. The process consists of five steps [5]. The first two steps, 1) surface cleaning and activation and 2) silanization, were carried out in a clean room. Then a polydimethylsiloxane (PDMS) chamber ($5 \times 5 \times 1.5$ mm^3) with removable cap was prepared, cleaned by ethanol, and placed directly on the device surface. This chamber served as a closed environment (to prevent bulk refractive index changes of the liquid owing to evaporation) for liquid-phase reactions in the next steps of the bio-sensing experiment. After each step, the cap of the chamber was opened and the surface of the device was cleaned with a buffer solution, rinsed thoroughly with de-ionized water to remove unbound molecules, then dried with nitrogen gas, and optically characterized. Once the antibody was immobilized on the GWG surface and the blocking/washing/drying steps were applied, the cell-free extracted (CFE) solution, which is the real sample containing the target PepN enzyme and other proteins, was applied and the antigen-antibody interaction was optically monitored through output transmission spectra of the GWG.

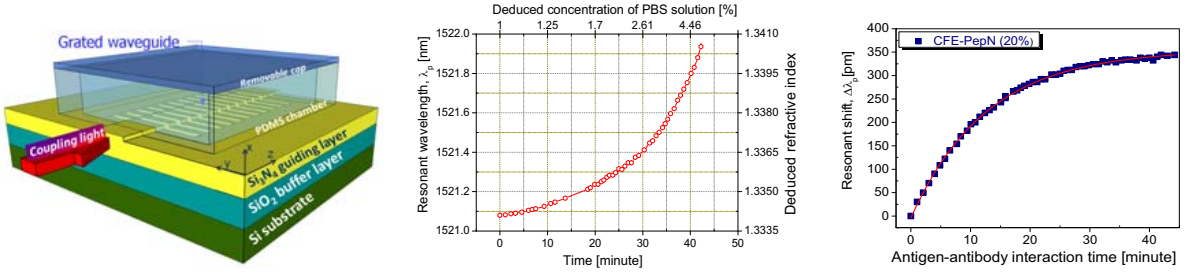
For (2) H_2 gas sensing, instead of singly-clamped cantilevers as mentioned in [3], here we fabricated devices with a doubly-clamped cantilever and with an aimed gap of g = 200 nm. Initial bending of the cantilever was characterized using a white-light interferometer. The PDMS chamber placed on top of 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 (Agilent 8164B) with a resolution of 1 pm and an InGaAs photo detector.

978-0-9775657-7-1 © 2011 AOS

3. Bulk concentration and label-free protein sensing

The measured spectral shift of the bulk concentration sensor with the phosphate buffered saline solution is shown in Fig. 1b. The results show that changes of the refractive index down to 2×10^{-5} RIU (refractive index unit; error in peak position ±1 pm), and concentration changes down to 0.01 wt% can be resolved, which is comparable with the resolution of ultrasonic sensors [6].

When applying the sensor to PepN enzyme detection, small changes on the GWG surface, caused by the antigen-antibody interaction, lead to spectral shifts of the resonant peak, $\Delta\lambda_p$, as shown in Fig. 1c. It was found that the shift of a spectral peak, $\Delta\lambda_p$ in response to the antigen-antibody binding reaction changes exponentially with time t according to $\Delta\lambda_p(t) = C(1 - e^{-t/\tau})$, where C = 342 pm and τ = 770 s. The reaction saturates after ~35 minutes. The total shift was approximately 342 pm, corresponding to the growth of an ad-layer of ~2 nm.



(a) **(b)** **(c)**

Fig. 1. (a) 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. Performance of devices for the measurement of (b) PBS concentration and (c) label-free protein sensing.

4. Mechano-optical hydrogen gas sensing

Figure 2b shows a top-view image of the fabricated device, as recorded with a white-light interferometer, indicating an initial bending (upwards, i.e., away from the GWG structure) of the micro-bridge of approximately 500 nm. 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 Pd receptor film [3].

Prior to supplying H_2 gas to the measurement chamber, N_2 gas was flushed in during 15 min with a flow rate of 0.5 sccm and optical transmission curves were captured repeatedly every minute. The results showed a stable and reproducible resonant peak at λ_p = 1496.631 ± 10^{-3} nm, indicating that such a flow rate did not cause any side effects or mechano-optical vibrations. Noise was removed from the spectrum using low-pass filtering in the Fourier domain, enabling accurate and efficient determination of changes in λ_p, namely $\Delta\lambda_p(t) = \lambda_p(t) - \lambda_p(t_o)$.

Subsequently 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. 2c). The shift $\Delta\lambda_p$ depends almost linearly on time (see Fig. 2d, 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 2d (right-hand side) shows the peak shift during a four-hour period of the desorption process. It can be concluded that the desorption takes place at a much lower rate (~50%) than the adsorption process and full desorption is not achieved during the monitoring period of time.

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.

5. Conclusions

We have demonstrated the great potential of a Si_3N_4 grated waveguide optical cavity as compact integrated optical sensor for label-free protein sensing, as well as mechano-optical gas sensing. Bulk concentration changes ~0.01 wt%, corresponding to refractive index changes of ~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. Due to its simple fabrication and effective operation the sensor is usable 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 read-out scheme is demonstrated as a proof of concept for our proposed and successfully fabricated mechano-optical sensor. This new sensor type can be used as an element of 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.

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

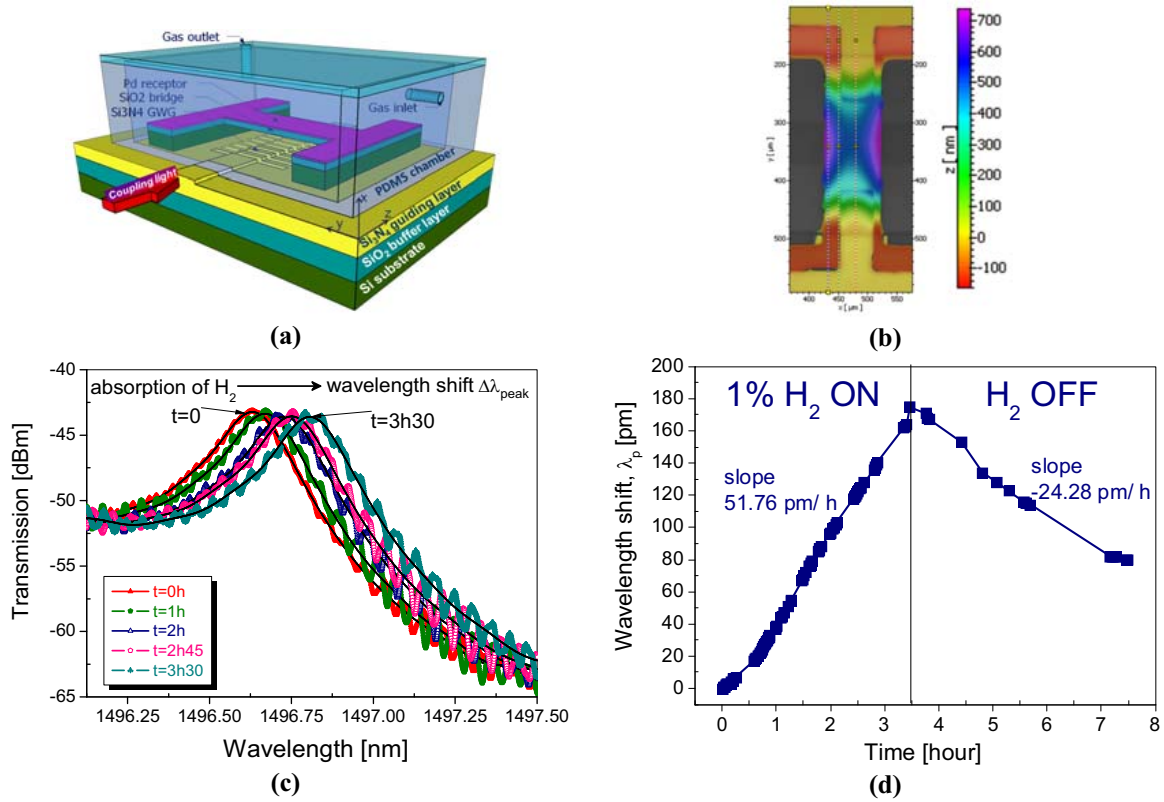


Fig. 2. (a) 3D schematic of the mechano-optical sensor structure with a PDMS chamber serving as a reaction environment for H_2 sensing; (b) top view image of the device attained using a white-light interferometer, showing an initial up-bending of ~500 nm at the center of the micro-bridge; (c) transmission curves of the device in response to the absorption; (d) wavelength shift $\Delta\lambda_p$ versus reaction time.

6. 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 senses," Pure Appl. Opt. **7**, 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**, 1851-1870 (2007).

[3] S. V. Pham, L. J. Kauppinen, M. Dijkstra, H. A. G. M. van Wolferen, R. M. de Ridder, and H. J. W. M. Hoekstra, "Read-out of cantilever bending with a grated waveguide optical cavity," Photon. Technol. Lett. **23**, 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 Symposium of the IEEE Photonics Benelux Chapter, (Brussels, Belgium, 2009), pp. 41-44.

[6] K. Ikeda, "Simple solution-concentration sensor with temperature compensation using ultrasonic waves," Proc. 2000 IEEE/EIA Intern. Conf., 87-90 (2000).