Integrated optical microcavities for mass and fluorescence sensing

E. Krioukov, D.J.W. Klunder*, A. Driessen*, J. Greve and C. Otto

Department of Applied Physics, Biophysical Techniques Group,
*Lightwave Devices Group & MESA+ Research Institute,
University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
e-mail: e.y.krioukov@tn.utwente.nl

A novel integrated optical sensor based on a cylindrical microcavity (MC) is proposed. This sensor can be used to monitor the presence of an analyte in the cladding (mass sensing) or to measure the fluorescence emission from the layer of adsorbed species (fluorescence sensing). In both types of applications integrated optical microcavities (MC) have an advantage over conventional linear waveguide sensors due to resonant excitation of high-Q cavity modes. Estimations and experiments performed show that a sub-monolayer sensitivity level is feasible for both fluorescence and mass sensing with the MC.

Introduction

The integrated optical waveguide sensors render a powerful means for analyzing interfacial aspects of (bio)chemical materials. A vast variety of waveguide interferometers for detection of minute amounts of (bio)molecules was elaborated. Some of the devices are based on measurement of a change of light propagation constant in the waveguide due to a change of refractive index in the cladding (mass change). The other class of devices uses the guided or evanescent field of the channel and planar waveguides to excite the spectroscopic (fluorescence or Raman) signal from the molecules. Both types of sensors benefit from high sensitivity, reaching, in most cases, the sub-monolayer level. However, high sensitivity of both mass and fluorescence sensing requires large interaction volume or long sensing lengths, often tens of millimeters. An increase in efficiency of interaction with the sensed molecules can be achieved by introducing a multiple interference device. A promising approach to fulfill all these prerequisites is the use of an integrated optical microcavity (MC). In this work we present the estimations and results on use integrated optics MC's in both mass and fluorescence sensing.

Principle of MC

Field enhancement in a MC originates from excitation of the so-called whispering gallery modes (WGM's) with extremely high Q-factor [1]. WGM's occur as a result of total internal reflection along a circular boundary of refractive index-contrasting materials with a resulted $Q>10^4$, considering all the losses [2,3]. WGM's in an integrated optics MC are excited by tunable laser light coupled to an adjacent waveguide (Fig. 1). The bright "circle" of light intensity is essentially a bright source that can effectively boost Raman/fluorescence response of a molecule put on the top

(Fig. 1). Locally enhanced field results from a multiple constructive interference that takes place in a MC provided

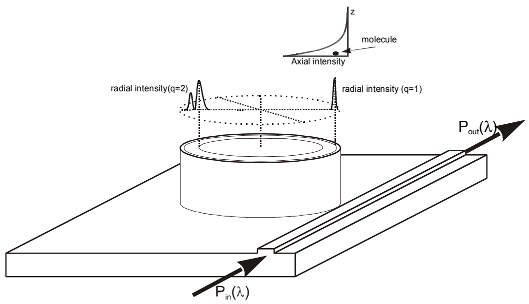

Figure 1. Radial and axial intensity distributions of the WGM's with two lowest radial mode orders.

a number of effective wavelengths in MC fits a roundtrip length [1,2]. At this resonance the intra-cavity power (P_{MC}) is built up so that $P_{MC} >> P_{in}$. Otherwise, the input power remains in the waveguide and P_{MC} is negligible. The value of P_{MC} at resonance can be calculated in terms of the Q-factor of the MC mode:

$$P_{MC} = \frac{Q}{k \cdot 2\pi R} P_{in} = G \cdot P_{in} \qquad (1)$$

where $k \equiv 2\pi/\lambda$ and R is radius of the disk. The power enhancement factor G exceeds unity only at sufficiently high Q. Generally, the limiting factors of Q are radiation and scattering losses. The radiation losses are reduced by enhancing the effective index contrast between the cavity core and its surroundings. In fact, our earlier estimations and measurements show, that using the MC with a radius of 8 μm and reducing substrate leakage losses make $Q > 10^4$ and $G > 20$ feasible [3].

Mass sensing with MC

The sensing of a change in adsorbate mass with the MC is based on the following. The photons stored in the MC on resonance give rise to a wavelength dependent scattering spectrum $P_{scat} = P_{scat}(\lambda)$. A slightest change in the effective index N_{eff} of the propagating mode, for instance, due to sample absorption, will result in a change of power scattered from the MC around its resonance. At FWHM of the resonance this change will relate to the input power P_{in} and a change in the effective index ΔN_{eff} by:

$$\Delta P_{scat}(\Delta N_{eff}) = S \cdot P_{in} \cdot (Q/N_{eff}) \cdot \Delta N_{eff} \qquad (2)$$

where: S is a scattering efficiency, $\Delta N_{eff} = \left(\partial N_{eff}/\partial n_c\right) \cdot \Delta n_c$ is the refractive index change of the MC mode due to the change of the cladding index Δn_c (analyte adsorbtion). As simple estimation from the eq. 2 shows that a refractive index change of 4×10^{-5} in the sample put on top of the MC with Q=5000 should result in a change of detected scattered power by 1%, which can be easily detected with a regular photodiode. Such a level of cladding index sensitivity is already comparable to those of conventional integrated optical interferometers. Further improvement is feasible by proper referencing of laser excitation noise and improving Q-factor of the devices (for instance, by reducing radiation losses). The measurements performed indeed show feasibility of the approach, showing that the refractive index changes down to at least 10^{-4} can be traced [4]. The dependence of scattering signal from the MC as a function of

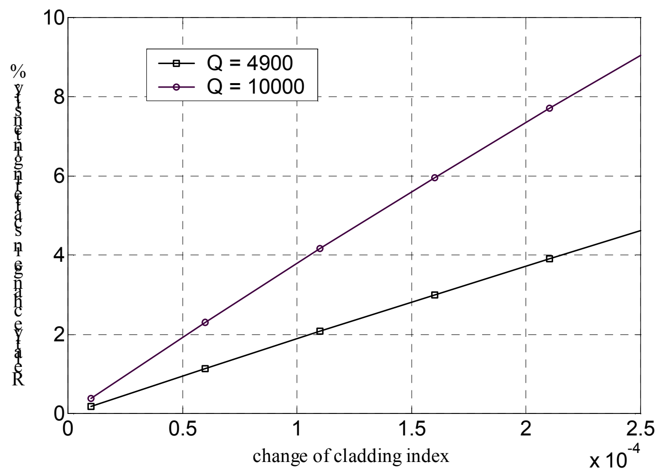

Figure 2. Change of scattering intensity from the MC as a function of cladding index change for the two different Q's of the MC.

cladding index change is shown in fig. 2. As is clearly seen the ultimate resolution in determining cladding index change is defined by the accuracy of intensity measurement. If laser fluctuations are properly handled, one can expect in the shot-noise limited regime of the detector the index sensitivity better than 10^{-9}.

Fluorescence sensing

The transverse mode profile for the disk and evanescent field used for sensing is equivalent to that of a slab waveguide with the same thickness and refractive indices.

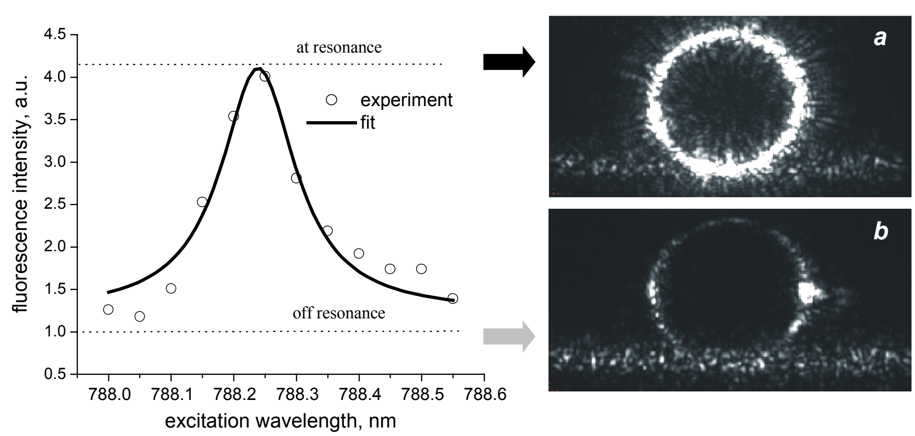

Figure 3. Left: Fluorescence excitation spectrum of the molecules near the MC. Right: Scattering spectra from the MC at (a) and out of (b) resonance.

Therefore, one can take advantage of enhanced power at the surface of the MC, having the same penetration depth and relative cladding power as in the straight waveguide structure. A fluorophore layer placed on top will experience an enhancement of the input optical power by a factor of G given by eq. 1 versus the waveguide of equivalent length. The effect of field enhancement in MC can be interpreted as an increase of absorption efficiency of the fluorophore due to increased interaction length of the incident field with an absorbing molecule. Therefore, an increase in amount of fluorescent photons generated from the molecule at the MC versus the linear waveguide is proportional to G. In terms of signal-to-noise ratio (SNR) that means that an increase by a factor of $\sqrt{G}$ in SNR with the same sample concentration can be realized. Therefore. the advantage of the MC format versus waveguide format for analytical applications is that the amount of molecules needed to obtain the same SNR as in the waveguide can be reduced by a factor of $\sqrt{G}$. Measurement performed (Fig.3) support the estimations made. Indeed, on resonance, the fluorescence signal from the molecules near the MC is increased by a factor of 3 versus off-resonance case.

Conclusions

We have proposed a new sensing device based on a high-Q integrated optics MC capable of accumulating high local optical fields at its surface. Estimations performed undoubtedly show feasibility of the MC for mass and fluorescence sensing. The MC-based sensors have advantage over linear waveguides due to multiple interference and local field enhancement. It allows one a significant decrease of sample needed for sensing with the MC. Estimations and measurements performed show sub-monolayer level of sensitivity feasible in both mass and fluorescence sensing.

Acknowledgements

This work has been supported by the Dutch organization for Fundamental Research on Matter (FOM).

References

[1] "Optical processes in microcavities", R.K. Chang and A.J. Campillo Eds., World scientific, Singapore, 1996

[2] F. C. Blom, D.R. van Dijk, H.J.W.M. Hoekstra, A. Driessen, and Th.J.A. Popma, "Experimental study of integrated-optics microcavity resonators: Toward an all-optical switching device" Appl. Phys. Lett., vol. 71, pp. 747-749, 1997

[3] D.J.W. Klunder, F.S. Tan, T. van der Veen, H.J.W.M. Hoekstra, and A. Driessen, "Design and characterization of waveguide-coupled cylindrical microring resonators in Si_3N_4", Proc. 2000 IEEE LEOS Ann. Meeting **2**, p. 758, 2000

[4] E. Krioukov, D. Klunder, A. Driessen, J. Greve, and C. Otto, "A new type of sensor based on integrated optical microcavity" Opt. Lett., 2001, submitted.