Sensor based on an integrated optical microcavity

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A novel integrated optical sensor based on a cylindrical microcavity (MC) is proposed. A MC sustains so-called whispering-gallery modes (WGMs), in which the energy of the optical field can be efficiently stored. By monitoring the scattering intensity from the MC, one can detect minute changes in the refractive index of the WGM, for instance, as a result of analyte adsorption. Measurement of a change in refractive index of as little as $10^{-4}$ is demonstrated experimentally. The MC-based integrated optical sensor may have a size of approximately $8 \mu m$, and it is rugged and inexpensive. © 2002 Optical Society of America

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During recent years integrated optical sensors have been used extensively in sensitive (bio)chemical analysis. A number of such sensors, e.g., uniform grating couplers and difference, Mach–Zehnder, and Young interferometers, have been proposed and successfully implemented. The principle of these sensors is based on highly accurate measurement of the effective refractive-index change ($N_{eff}$) that occurs as a result of the adsorption of an analyte in the sensing area of a waveguide. The Mach–Zehnder interferometer is a highly sensitive device. With the Mach–Zehnder interferometer a cladding index change of $10^{-4}$ to $10^{-8}$ can be identified, depending on the experimental configuration used. These double interference devices usually require large sampling areas (analyte volumes) and advanced detection electronics. These disadvantages can be overcome by the introduction of multiple interference detectors. In this Letter we propose, to our knowledge for the first time, a high-order optical interference sensor based on an integrated optical microcavity (MC).

Figure 1 is a schematic drawing of an integrated optical MC. The MC consists of a microwdisc with a radius $R$ of few micrometers. It is excited by being coupled to a monomodal waveguide. The sensing principle of the MC is as follows: A small fraction ($\kappa$) of the waveguide mode is evanescently coupled to a MC mode with a propagation constant $\beta = \beta_0 + i\alpha$, where $\alpha$ is an attenuation coefficient of the mode that arises from all intrinsic losses. If the phase of the MC mode after a round trip is a multiple of $2\pi$, the so-called whispering-gallery mode is resonantly excited. At this resonance the intracavity power ($P_{MC}$) is built up such that $P_{MC} >> P_m$. Otherwise, the input power remains in the waveguide and $P_{MC}$ is negligible. The photons stored in the MC on resonance are ultimately

Fig. 1. Cross section and view of an integrated optical MC sensor. Light from a tunable laser is coupled into the excitation waveguide, and the scattering is measured from the top of the MC as a function of the wavelength with various solutions in the sensing area. Dotted line, localization of a high-Q whispering-gallery mode; its propagation direction is shown by an arrow around the circumference. Device parameters: $R = 15 \mu m$, $h_c = 255 nm$, $h_s = 150 nm$. © 2002 Optical Society of America
scattered out, giving rise to a wavelength-dependent spectrum $P_{\text{scat}} = P_{\text{scat}}(\lambda)$ that is related to $P_{\text{in}}$ by

$$
P_{\text{scat}} = \frac{P_{\text{in}}}{1 + (4F/\pi)^2 \sin^2[0.5(2\pi/\lambda)N_{\text{eff}} L]},$$

where $S$ is a factor that describes the scattering intensity at resonance; $L = 2\pi R_{\text{eff}}$ is the effective round-trip length; $N_{\text{eff}}$ is an effective index of the propagating mode in the MC; and $F$ is the finesse of the MC related to $Q$: $F = (\lambda/\pi N_{\text{eff}})Q$. At resonance, $\beta L = 2\pi m$, where $m$ is an integer mode number. According to Eq. (1), the spectrum of $P_{\text{scat}}$ consists of number of repeating resonance peaks. Near some resonance wavelength $\lambda_{\text{eff}} = \lambda_{\text{eff}}/N_{\text{eff}}$, it will change as a function of the change in the effective index $\Delta N_{\text{eff}}$:

$$
P_{\text{scat}}(\Delta N_{\text{eff}}) = \frac{SP_{\text{in}}}{1 + 4Q^2(\Delta N_{\text{eff}}/N_{\text{eff}})^2} + BP_{\text{in}},$$

where $\Delta N_{\text{eff}} = (\partial N_{\text{eff}}/\partial n_c)\Delta n_c$ is the refractive-index change of the MC mode that is due to the change in cladding index $\Delta n_c$ (analyte adsorption); $B$ is a nonresonant background contribution from the light that is coupled to the MC (slab modes, other low-Q modes, etc.). As is clear from Eq. (2), minute changes in the effective index of a cavity mode, caused, e.g., by analyte adsorption, will result in a change in the detected amount of scattering, $P_{\text{scat}}$. The maximum sensitivity of the MC sensor will be observed at FWHM of the resonance: $\lambda_{\text{FWM}} = \lambda_{\text{FWM}}/N_{\text{eff}}$. At these wavelengths $\partial P_{\text{scat}}/\partial (\Delta n_c)$ grows linearly with $Q$. The magnitude of $Q$ is determined by intrinsic losses (bending and material—scattering losses) and coupling strength to the adjacent waveguide. With the vertical coupling scheme of the MC used in this study (Fig. 1) the $Q$ of the MC may exceed $0.5 \times 10^7$. A simple estimation from Eq. (2) shows that a change of $4 \times 10^{-8}$ in the cladding index must result in a change of 1% in the scattered power.

The MC sensor fabricated with the layout shown in Fig. 1 was fabricated with silicon oxynitride technology by conventional optical lithography and was first characterized by scattering measurements made with various claddings. Figure 2 shows a typical scattering spectrum collected from the MC with water cladding. Clearly, at least three radial mode orders, designated A, B, and C, are excited in the MC. Each mode has a different $Q$ factor; that of the largest (mode B) is $\sim 4900$. When the cladding is changed from water ($n = 1.3330$) to alcohol ($n = 1.3614$), a significant resonance upshift of $\sim 0.65$ nm occurs (Fig. 3). To detect the change in the refractive index that results from dissolving glucose in water we chose the mode B with highest $Q$ (water spectrum, Fig. 2). A series of measurements with different cladding concentrations of glucose in the cladding was performed (Fig. 4). A comparison of the spectra obtained shows a prominent and progressive upshift of the maximum as the concentration of glucose (and the cladding refractive index) is increased. The results of all cladding measurements together with theoretical values of wavelength shifts are summarized in Fig. 5. Even for the limited number of experimental points available, good agreement with the theory is manifest (see the caption to Fig. 5).

Compared with linear waveguide sensors with a sensing length of few centimeters, a MC sensor benefits from its extremely small size. Indeed, a MC of $R = 8 \mu m$ occupies less than $2 \times 10^{-6}$ cm$^2$ of wafer space, thousands of times less than does a low-order interference sensor. The active volume of the sample used in the MC is less than 10 fL. This means that...
the number of molecules required for the MC sensor is several orders of magnitude less than for the linear waveguide sensor. An estimate of the MC sensor in terms of monolayer sensitivity is also informative. Assuming that a single layer of protein molecules ($n_p = 1.45$) assembles in the sensing region of the MC, the resonance wavelength will shift by 0.07 nm. This shift is easily detectable with the present setup.

It should be emphasized that performance of the MC sensor depends on the setup used. Accuracy in determining the refractive index is limited by both the rms noise of the laser source and the detector noise. In our present experimental configuration, laser noise was the limiting factor. However, with proper referencing the laser fluctuations can be canceled, and detection may occur in the shot-noise-limited regime. Then, if the scattering intensity is measured at $\lambda_{\text{FWHM}}$, we estimate that the progression of the change in refractive index of the cladding to $10^{-8}$ can be followed. This level of sensitivity may already exceed that of conventional integrated optical interferometry.\(^8\)

In conclusion, a novel, integrated optical sensor based on a cylindrical microcavity has been proposed and characterized. The measurements performed have shown that a refractive-index difference of as little as $10^{-4}$ can be unambiguously identified. With optimization of the detection scheme and of the MC sensor, detection of refractive-index changes of the order of $10^{-9}$ seems technologically possible. A MC sensor must be highly competitive with conventional integrated optical interferometers. It is a miniature, robust device that yields a number of advantages in terms of operation. A MC sensor overcomes the problem of an extended interaction length in low-order integrated optical interferometers and permits sufficient reduction of analyte volume. In general, this micrometer-sized integrated optical sensor can become a versatile tool for lab-on-a-chip systems.

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