Chemical and biological detection using ultrahigh-Q toroidal microresonators

Andrea Armani and Kerry Vahala

The high circulating intensities in ultrahigh-Q optical microresonator sensors improve their sensitivity enough to detect a part per million of heavy water in water.

High-Q and ultrahigh-Q (quality factor > 100 million) silica optical microcavities can perform as highly sensitive detectors; their excellent transduction properties result from the long photon lifetime within their whispering gallery. This signal amplification is an inherent property of resonant devices. For example, in a waveguide sensor, a photon interacts with the functionalized surface only once. However, in a microcavity with a Q-factor > 10^6, cavity recirculation allows photons to interact with the surface over 100,000 times, thus amplifying a single detection event. Additionally, the surface of silica-based microcavities is easily functionalized using a variety of techniques. Since the sensitivity increases as the cavity Q-factor increases, maximizing this parameter then becomes crucial.

Several loss mechanisms can lower Q-factors. We have recently shown that, in toroidal microcavities (see Figure 1), the dominant loss mechanisms in water were radiation loss at small cavity diameters and material loss (induced by the ambient liquid) at large diameters.

This is illustrated in Figure 2 which plots the measured intrinsic Q-factors for microtoroids immersed in water (H_2O) and heavy water (D_2O) at different toroid diameters in the 1300nm band. Both the radiation-loss-limited regimes and the material-loss-limited regimes are clearly visible. At this wavelength, D_2O has a lower optical absorption and hence exhibits a material-limited Q plateau that is higher than that of H_2O (approximately 10^5 for H_2O compared to more than 10^7 for D_2O). The origin of this limit is the vibration overtone of water.

But what about microtoroid detection abilities? They were recently elegantly demonstrated when applied to heavy water detection. At 1300nm, there is a large difference in the optical absorption of heavy water and normal water which leads to a large change in the cavity Q-factor. Therefore, by monitoring the Q-factor, it was possible to determine how much heavy water was present in water.

To demonstrate this effect, a simple test procedure was designed. The microtoroid was first immersed in 100% D_2O, and the concentration of H_2O in D_2O was gradually increased to 100% H_2O, followed by returning the concentration of D_2O to 100%. The difference between the Q-factor in H_2O and D_2O is liquid-limited; therefore, it can be described by: Q_{\text{liquid}} = 2\pi n/\alpha \lambda, where n=effective refractive index, \lambda=wave, and \alpha is the absorption loss due to the liquid. The refractive index of H_2O and D_2O are similar and the resonant wavelength is constant.

During the initial series of measurements, the solutions were prepared in 10% increments (10% H_2O in D_2O, 20% H_2O in D_2O, etc). As shown in Figure 3(a), when the concentration of D_2O was reduced, the Q-factor decreased and the decrease was reversible. The theoretical values for each concentration are indicated by a dashed line.

To determine the lower detection limit, larger dilutions of D_2O in H_2O were prepared, ranging from .01% to 1 × 10^{-13}%. Figure 3(b) shows that there is a strong signal at .001% D_2O

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Figure 2. A graph plots the measured and predicted Q-factors in the 1300nm band vs. toroid diameter. The measured material-loss limits are $5 \times 10^5$ (H$_2$O) and $1.6 \times 10^7$ (D$_2$O).

Figure 3. (a) The Q-factor is decreased (circles) and recovered (triangles) during repeated D$_2$O and H$_2$O exchanges. (b) Using solutions with low concentration of D$_2$O ranging from $1 \times 10^{-9}$% to .01%, the minimum detectable change in Q-factor occurs at .0001% (1ppmv) with a small, yet detectable, shift occurring with the .0001% D$_2$O solution. These values do not reflect the fundamental detection limit of this device since no attempt was made to reduce operational noise sources.

Based on the different optical absorption of H$_2$O and D$_2$O, the ultrahigh-Q microcavity was able to detect 0.0001% (1ppmv) of D$_2$O in H$_2$O. This result lays the groundwork for further chemical and biological detection developments. In biological detection experiments, both specificity and sensitivity are important. While the ultrahigh-Q optical resonator is inherently sensitive, specificity could be achieved by functionalizing the surface of the microtoroid, for which several different techniques are currently available.

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Author Information

Andrea Armani and Kerry Vahala
Department of Applied Physics
California Institute of Technology
Pasadena, California
http://www.armani.caltech.edu

Andrea Armani is a Clare Boothe Luce Postdoctoral Fellow at the California Institute of Technology. She received her PhD in Applied Physics from the California Institute of Technology with a minor in Biology (2006) and her BA in Physics from the University of Chicago (2001).

Kerry Vahala is the Jenkins Professor of Information Science and Technology at the California Institute of Technology. He received his BS (1980) and PhD (1985) in Applied Physics from Caltech, where he helped to develop the modern theory of phase noise in semiconductor lasers.

References