Ultrasensitive real time measurement of dissipation and dispersion in a whispering-gallery mode microresonator.

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We present the first characterisation of the recently developed CEAMLAS technique to measure dissipation within the evanescent field of a whispering-gallery mode resonator, and demonstrate the parallel use of CEAMLAS and the Pound-Drever-Hall measurement techniques to provide both dissipation and dispersive real time microresonator measurements. Using an atomic force microscope tip, we introduce a controlled perturbation to the evanescent field of the resonator. In this case, dissipative sensing allows up to 16.8 dB sensitivity improvement over dispersive measurements, providing the possibility for enhanced sensitivity in application such as biomolecule detection. © 2013 Optical Society of America

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Whispering gallery mode microtoroid resonators (WGM) are increasingly being applied to cavity enhanced optical sensing [1–5]. Typically, the evanescent field, guided just outside the boundary of the microresonator medium senses the presence of a particle by changes in cavity loss, or cavity detuning. Due to the small modal volume of these resonators, a single molecule or nano-particle can have a large relative effect on both the cavity loss and detuning, which can be measured very precisely due to their high optical Q . However, most WGM based nanoparticle sensors have measured only the cavity detuning, and neglected the information available through the cavity loss. Moreover, all such sensors have been sensitive to laser noise, which degrades the achievable sensitivity [6]. Recently Cheema et al [7] measured both loss and detuning of a microcavity through use of phase shift ring down spectroscopy. While that scheme allowed parallel dispersion and dissipation measurement, it lacked the sensitivity typically achieved with purely dispersive measurement [2] and was limited to measurement of sub-Hz dynamics.

In this paper we use two highly sensitive and complementary, real time measurement techniques to determine both dispersion and dissipation of a microtoroid WGM resonator. For detecting optical path length changes within the resonator, we use the well established Pound-Drever-Hall (PDH) technique [8]. For the measurement of cavity losses we use the recently developed Cavity Enhanced Amplitude Modulation Laser Absorption Spectroscopy (CEAMLAS) technique [9]. CEAMLAS uses radio frequency amplitude modulation (AM) of the optical field incident on the resonator to sense the resonator coupling condition. The optical field reflected off the resonator is detected and demodulated at the AM frequency to produce a zero crossing error signal that is linearly proportional to the impedance mismatch of the resonator around the critical coupling point. A change

in resonator loss causes a first order change in the coupling condition of the resonator. The CEAMLAS error signal can therefore be used as a sensitive and dynamic measure of optical resonator loss. In addition to cavity loss measurements, we also use CEAMLAS to lock the WGM resonator to the critical coupling point by actuating the WGM to fiber taper distance [10]. PDH and CEAMLAS are readily used in parallel, producing real time measurements of both amplitude and phase of the WGM intra-cavity electric field as first suggested in [10]. This yields the complete complex response of the WGM resonator to dynamic changes in dispersion and dissipation.

Fig. 1. A microscope photograph of the experiment showing the microtoroid side on, the atomic force microscope tip on the left side of the toroid and the fiber taper behind. The haziness of the image was due to scattering from the cantilever.

Figure 1 shows a microscope photograph of our experiment. A microtoroid resonator sits on a pedestal with the coupling fiber taper visible behind the microtoroid. Immediately to the left of the microtoroid is an atomic force microscope (AFM) cantilever with a tip close to the edge of the microtoroid. Figure 2 shows the corresponding schematic of our experiment. Both the PDH

and CEAMLAS error signals are used in closed loop configuration where the PDH system holds the laser on the WGM resonance whilst the CEAMLAS system actuates the WGM-taper gap to ensure that the WGM is held at the critical coupling point. The signal at point “A” in figure 2 therefore yields the dynamic detuning information as it represents the signal required to maintain WGM resonance, whilst point “B” provides the open loop PDH error signal for frequencies above the unity gain bandwidth of the laser frequency servo. Point “C” of figure 2 yields the gap actuation signal necessary to maintain WGM critical coupling and therefore the dynamic loss perturbations of the WGM resonator. Point “D” provides the CEAMLAS open loop error signal at frequencies above the unity gain bandwidth of this servo. Figure 2 also includes the AFM tip mounted on a calibrated PZT actuator that is used to introduce a perturbation into the evanescent field of the WGM resonator. This tip is used to simulate the WGM resonator response to nano-particles in a highly controlled and repeatable fashion. This enables the response of both the PDH and CEAMLAS readouts to be directly compared for a calibrated AFM tip motion.

Fig. 2. laser: 1550nm external cavity diode laser, PM: phase modulator, AM: amplitude modulator, ω_{PM} : RF source at 130MHz, ω_{AM} : RF source at 85MHz, mixer: double balanced RF mixer, T: microtoroid resonator, LPF: low pass filter, det: RF photo-receiver and, tip: atomic force microscope tip with PZT actuator.

Recording the CEAMLAS error signal whilst the laser frequency is scanned across WGM resonance yields figure 3(A). Whilst the off resonance error signal is negative, as the laser approaches WGM resonance, the error signal crosses through zero and is positive exactly on resonance indicating that the WGM is slightly over-coupled [9,10]. The error signal peak is flat on resonance, ensuring that the CEAMLAS signal is immune to laser frequency noise and cavity detuning to first order. Figure 3(B) highlights this immunity by plotting the CEAMLAS error signal when the laser frequency is driven by a large 16 kHz dither. On resonance, the response to frequency noise drops by ~ 25 dB.

Using the PDH system, the laser was locked to a WGM resonance, the CEAMLAS servo was engaged and the

AFM tip was driven by a 1 Hz square wave moving the tip by 30nm. Figure 4(A) shows the laser frequency actuation, recorded at point “A” in figure 2, required to maintain laser resonance as the WGM is detuned due to the AFM tip motion. We have also plotted a parallelogram of best fit showing the noise-averaged frequency actuation. This demonstrates that a frequency detuning of 4.7 MHz is required to maintain resonance due to 30 nm of tip motion within the WGM evanescent field. The standard deviation of the frequency actuation is 286 kHz for a measurement time of 100 ms, showing similar detuning sensitivity to Dantham et al [2]. The signal to noise ratio (SNR) for a 30 nm square wave tip motion is therefore $4.7 \text{ MHz}/286 \text{ kHz} = 16.4$.

Fig. 3. A: CEAMLAS error signal as the laser frequency is scanned across the WGM resonance. 0 MHz corresponds to the laser carrier being on resonance with the WGM mode. B: CEAMLAS error signal as the laser is scanned across WGM resonance while the laser is current modulated at 16 kHz producing a large sinusoidal frequency modulation.

The corresponding CEAMLAS actuation signal was recorded at point “C” figure 2. Figure 4(B) plots the taper-WGM gap actuation voltage, and a parallelogram of best fit, when the AFM tip is driven by a 30nm square wave. A gap actuation voltage of 10.5 mV is required to maintain impedance matching as the AFM tip moves by 30nm. The standard deviation of the gap actuation voltage is 0.16 mV over a 100 ms measurement time. The SNR for the closed loop CEAMLAS measurement is therefore $10.5 \text{ mV}/0.16 \text{ mV} = 65.6$, an improvement of a factor of 4 compared to the PDH measurement.

The ability of both PDH and CEAMLAS to detect real time dynamics was tested by driving the AFM tip with a 1 kHz sine wave of amplitude 12 nm peak-to-peak. Figure 5(A) plots the PDH error signal recorded at point “B” in figure 2 whilst figure 5(B) plots the CEAMLAS error signal recorded at point “D” in figure 2. Whilst the PDH error signal can detect the 1 kHz tip motion with an SNR of 5.5 dB, the CEAMLAS error signal yields an SNR of 22.3 dB for the same tip motion. With the

Fig. 4. A: Laser frequency actuation signal and, B: Taper-WGM gap actuation voltage as the AFM tip is driven by a 30 nm square wave at 1 Hz.

AFM tip used here, the CEAMLAS sensitivity is 16.8 dB greater and can therefore detect tip dynamics a factor of ~ 7 smaller.

Fig. 5. A: Trace (i) PDH error signal when the AFM tip is driven by a 1 kHz sine wave with amplitude 16 nm p-p. Trace (ii) PDH error signal when the AFM tip is stationary. B: Trace (i) CEAMLAS error signal when the AFM tip is driven by a 1 kHz sine wave with amplitude 16 nm p-p. Trace (ii) CEAMLAS error signal when the AFM tip is stationary.

Whilst the PDH error signal provides a sensitive read-

out of dispersion, laser frequency noise, interferometer mechanical motion and WGM thermorefractive noise [6] compromise the achievable sensitivity. This is clearly visible in figure 5(A), trace (ii) where the measurement noise is seen to increase by more than 30 dB between 2 kHz and 1 kHz. Likewise, in figure 4(A), there is a large random noise component as well as a significant linear frequency drift. Hence the ability to detect both dynamic and static WGM detuning events is experimentally limited to a sensitivity far worse than fundamental PDH limits suggest. Conversely, the CEAMLAS error signal, being immune to both laser frequency noise and cavity detuning, operates in a significantly lower noise environment and demonstrates substantially better performance for both static and dynamic measurements.

We have demonstrated two measurement techniques suitable for WGM sensors: PDH which measures interferometer dispersion and, CEAMLAS which measures interferometer dissipation. These two techniques are therefore capable of measuring complementary nanoparticle features: PDH measures the volume-refractive index product of the particle while CEAMLAS measures the particle scattering cross section. The ratio of these two measurements aids the identification of particle composition whilst the absolute signal levels reveal particle size information. In addition, both measurement techniques provide high speed, real time signals allowing for the study of nano particle dynamics including arrival times of individual particles and the interaction of nano particles with microfluidic structures.

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