Nano-Optomechanical Resonators in Microfluidics

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Supporting Information

ABSTRACT: Operation of nanomechanical devices in liquid has been challenging due to the strong viscous damping that greatly impedes the mechanical motion. Here we demonstrate an optomechanical microwheel resonator integrated in microfluidic system that supports low-loss optical resonances at near-visible wavelength with quality factor up to 1.5 million, which allows the observation of the thermal Brownian motion of the mechanical mode in both air and water environment with high signal-to-background ratio. A numerical model is developed to calculate the hydrodynamic effect on the device due to the surrounding water, which agrees well with the experimental results. With its very high resonance frequency (170 MHz) and small loaded mass (75 pg), the present device has an estimated mass sensitivity at the attogram level in water.

KEYWORDS: Optomechanics, microfluidics, nanomechanics, hydrodynamic model, mass sensing, thermal fluctuations

Micro- and nanoscale mechanical resonators have been developed as important tools in both fundamental studies and technological applications. Because of their very small spring constant and mass, even tiny forces acting on the resonator or masses adhering on its surface can greatly alter its dynamics, which can be detected with extremely high precision. Sub-attoNewton (<10⁻¹⁸ N) force sensitivity has been demonstrated,¹ which allows detection of the force from a single electron spin.² As the dimensions of the mechanical devices continue to be scaled down, the mass sensitivity has reached attogram (10⁻¹⁹ kg)³,⁴ zeptogram (10⁻²¹ kg),⁵ and yoctogram (10⁻²⁷ kg)⁶ level, and down to the mass of a single proton in the past few years. A recent demonstration showed that this nanomechanical technology holds a promise to perform mass spectrometry on a single molecule with extremely high resolution.⁷

However, so far most nanomechanical sensors operate in vacuum or air; very few operate in liquid since the enormous fluidic damping rapidly deteriorates the device performance. The mechanical quality factor (Q_m) is dramatically lowered and the displaced fluid effectively adds mass. Both effects make operation in liquids extremely challenging. For example, AFM cantilevers in liquid have very low quality factors: Q_m < 5.⁸,⁹ Moreover, as the resonator dimension is scaled down, the Reynolds’s number is reduced and thus the fluidic viscous damping becomes more significant.¹⁰

One approach to circumvent these problems is to use a hollow resonator structure through which the fluids and analytes flow.¹¹,¹² With this approach attogram sensing has been achieved.¹³ Nevertheless, more general operation of nanomechanical systems in liquid remains an important goal since only then the sensing can take place in environments where many biological and chemical samples naturally reside.¹⁴ Efforts toward this direction include development of schemes that can efficiently actuate and detect the motion of the resonator in the highly dissipative liquid environments, such as thermo-optical excitation,¹⁵,¹⁶ magnetomotive drive and detection,¹⁷ and piezoelectric actuation.¹⁸ Efficient transduction of nanomechanical resonators in fluids also benefits the study of fluid dynamics in new parameter regimes¹⁹–²¹ and the stochastic dynamics of fluid–structure interaction due to Brownian noise.²²,²³

Among all the transduction schemes, cavity-enhanced optical readout has shown superior sensitivity.²⁴ For photonic cavities in water, however, the optical absorption of water itself can severely degrade the optical Q and cause undesirable thermo-optical effects. It is well-known that water is strongly absorptive at telecom wavelengths. The optical extinction coefficient at λ = 1.55 μm is κ = 9.86 × 10⁻²⁵ cm⁻¹, corresponding to a propagation loss of 34 dB/cm. To achieve high Q optical resonances in water, we developed a photonic resonator that operates at near-visible wavelengths λ = 780 nm where κ = 1.43 × 10⁻⁷ cm⁻¹ or equivalently 0.1 dB/cm. This would result in an absorption-limited Q of 10 million. This wavelength also falls within the biological transparency window²⁶ and is therefore useful in biological and medical applications.

The design of the nano-optomechanical resonator in this study is a suspended microwheel structure,²⁷ which mechanically supports radial breathing modes. Figure 1a shows the displacement profile of the fundamental radial breathing mode of a microwheel of 10 μm radius simulated using a finite element method (FEM). The mode displacement is normalized with respect to the maximum displacement at the outer rim of the microwheel. This mode has an effective mass of 65 pg and a
resonance frequency of 175 MHz in vacuum. The mechanical mode is optomechanically coupled to the optical whispering gallery modes, which thus can be used to readout the mechanical motion. Figure 1b shows a cross-sectional plot of the simulated radial electric field distribution of the first four transverse-electric (TE) modes in air. The optical modes are mainly located at the outer rim of the microwheel. Therefore, scattering loss due to the presence of the anchoring spokes at the inner rim has a negligible effect. For the case when the device is immersed in water, simulations show that the TE4 mode is no longer well confined due to the smaller index contrast. The refractive indices of air, water, and silicon nitride used in the simulation are 1, 1.33, and 2.0, respectively.

The device is made out of a 200 nm thick Si₃N₄ (see Supporting Information for details of the fabrication process). Microfluidic channels are etched into the top SiO₂ cladding and are sealed with a thin glass slide. Each device is evanescently coupled via a waveguide, and a pair of gratings is used for coupling light into and out of the waveguides. Figure 1c,d shows SEM images of a device before the cover glass sealing. The free-standing coupling waveguide is supported by a tapered structure for robustness. In fact, the whole device is sturdy enough for direct wet release without the use of critical point drying. This allows repeatedly switching of the device operation between liquid and gaseous environments. Figure 1d shows a device inside a microfluidic channel. Figure 1e is a top-view of the chip showing arrays of devices and two microfluidic channels (highlighted in blue). (f) Optical top view of the chip showing arrays of devices and two microfluidic channels (highlighted in blue). (f) Photo of a fully packaged device aligned to a fiber probe.

Figure 1. Device overview. (a) Normalized displacement profile of the fundamental radial breathing mode. (b) Electric field (radial component) distribution of the first four TE modes (TEₖ) in air, where the index k represents the mode orders in the radial direction. (c) Scanning-electron micrograph showing a top view of the device. As indicated, the coupling gap g is the separation between the microwheel and the coupling waveguide. (d) Angled view SEM image showing the device positioned in the middle of a microfluidic channel (highlighted in blue). (e) Optical top view of the chip showing arrays of devices and two microfluidic channels (highlighted in blue). (f) Photo of a fully packaged device aligned to a fiber probe.

Figure 2. Schematic of the measurement setup. TDL: Tunable diode laser. FPC: Fiber polarization controller. PR: Photoreceiver. DAQ: Data acquisition system.

The device was characterized using the setup shown in Figure 2. A tunable diode laser (New Focus TLB-6712) with a tuning range of 765–781 nm was used to measure the optical transmission. A small portion of the laser output was tapped out and sent to a wavelength meter for wavelength and intensity calibration. A fiber probe was aligned to the top of the grating couplers of the device to couple light between optical fibers and waveguides, and the laser light was adjusted to TE-polarized using a fiber polarization controller for optimal transmission. The transmitted light was collected on a 1 GHz photoreceiver (New Focus 1601). The dc signal was sent to a data acquisition system to measure the transmission while the ac part was sent to an electrical spectrum analyzer. All optical fibers in the setup are single mode fibers (SM800, 5.6 μm core) for 780 nm.

Figure 3a shows the measured optical transmission spectra of a device in air and water. The maximum transmission reaches ~0.3%, corresponding to an insertion loss of ~13 dB per
water is not well con...all the way to zero, and the device undergoes self-sustained oscillations (shaded region). As the detuning is further reduced, the optomechanical effect diminishes and the linewidth approaches its original values while reaching the thermo-optical bistable point.

When the device is immersed in water, the viscous damping is so great that the device could not be set self-oscillating. Nevertheless, with the very high optical $Q$, the highly damped thermomechanical motion can still be resolved in water. Figure 5a shows the noise spectra for device in air and water. In air the radial breathing mode has a frequency of $f_0 = 179.9$ MHz and quality factor of $Q_{M} = 2160$, while in water the frequency is slightly shifted down to $f_0 = 169.4$ MHz and $Q_{M}$ is reduced to 9. For the noise spectrum in water, a noise floor of $S_{N/2} = 15 \text{ am/}\sqrt{\text{Hz}}$ is achieved; in air a lower optical power was used to minimize the effect of the optomechanical backaction resulting in a higher noise floor.

The only 5.8% drop of the resonance frequency after immersion in water is very small compared to other systems. For example, AFM cantilevers working at hundreds of kHz displayed resonance frequencies after immersion at 1/2−1/5 of their original values.\textsuperscript{10} SiN nanostrings resonating at 100 MHz range also showed a >25% decrease.\textsuperscript{13} Another observation is that our quality factor is higher than for cantilever systems, which typically have $Q_{M} \approx 5.9,10,15$.\textsuperscript{17} The smaller frequency shift and higher $Q_{M}$ hints that the hydrodynamic mass loading and damping due to the surrounding water is relatively small for the microwheel structure.

In liquid, the dynamics of a mechanical resonator is strongly affected by the fluidic force $F_f$ acting on it (or against its
motion). For small amplitude oscillations, $F(t)$ has a linear response to the displacement $x(t)$ and can be expressed (in the frequency domain) as $F(f) = m_e(2\pi f)^2\Gamma(f)x(f)$, where $m_e$ is the effective mass of the resonator in vacuum, and $\Gamma(f)$ is the dimensionless “hydrodynamic function”. (The definition adopted here differs from those in refs 22 and 34 by a geometrical factor.) Its real ($\Gamma_r$) and imaginary parts ($\Gamma_i$) renormalize the resonance frequency $f_0 = f_{0r}(1 + \Gamma_r[f_{0r}])^{-1/2}$ and quality factor $Q_0 = (1 + \Gamma_r[f_{0r}])/\Gamma_i[f_{0r}]$ (assuming $Q_0 \gg 1$). For a rectangular (cantilever) structure, the hydrodynamic function can be solved numerically as described in refs 34–36. For the microwheel resonator, we developed a boundary integral method for systems with rotational symmetry and solve the corresponding Green’s equation. The details are discussed in the Supporting Information. Figure 5b plots the resonance frequency and quality factor as a function of ring width. The model shows the same width dependence as the experimental data and the calculated $Q_0 \approx 9$.

The total loaded mass of the device including the water entrained to the resonator motion is $m_w = m_e(1 + \Gamma_r[f_{0r}]) = 75$ pg, which is roughly equal to the sum of the original resonator mass (65 pg) and the mass of water enclosed within the Stokes boundary layer around the device (10 pg; see Supporting Information). The entrained mass of water is thus only 15% of the original mass. This is orders of magnitude smaller than that of cantilevers36,37, where the water mass can be tens of times of the resonator mass. The small water entrainment of our device is the result of the small resonator dimensions, high resonance frequency, and thus small Stokes boundary layer thickness. This is consistent with the good agreement between the experimental results and the theoretical predictions. It also implies that a microfluidic design with even smaller dimensions can be employed without compromising the device performance as long as the walls do not get too close to the boundary layer.

The mass sensitivity of the device is determined by the phase noise of the measurement, which contains both the resonator’s thermal motion ($S_{xx}$) and the measurement imprecision noise ($S_{xx}$). The minimum resolvable mass is given by $\delta m = \frac{m_e}{Q_{xx}}[(S_{xx}[f_{xx}] + S_{xx})\Delta f]^{1/2}$ for a
measurement bandwidth $\Delta f \ll f_v/Q_w$. Figure 5a shows that $(S_x[f_v] + S_m)^{1/2} = 42 \text{ am}/\sqrt{\text{Hz}}$. Assuming the device can be driven to an amplitude of $x_0 = 100 \text{ pm}$, the mass sensitivity is $3.5 \text{ ag}/\sqrt{\text{Hz}}$. This amplitude is well within the linear range of operation as shown by the SEM simulation presented in the Supporting Information. To reach such an amplitude, the device can be driven, for example, by radiation pressure force using a pump–probe scheme. For the present device the estimated required laser power is about 30 mW. With electrodes patterned on the device, electrostatic excitation can also be applied to provide the driving force. So far, attogram sensing in fluid has only been achieved using cantilevers with embedded channels. These results suggest that our optomechanical microwheel resonator is very promising for in situ attogram sensing in water.

**REFERENCES**