NANO-OPTOMECHANICAL DISK RESONATORS OPERATING IN LIQUIDS FOR SENSING APPLICATIONS

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ABSTRACT

We demonstrate that miniature optomechanical disk resonators can operate in liquids as ultrafast and ultrasensitive densimeters, viscometers and mass sensors. We develop numerical and analytical models that describe the fluid-structure interactions at play around these GHz mechanical devices. We test them experimentally by immersing disks of varying dimensions in four distinct liquids of varying density and viscosity. Using optomechanical techniques, we measure the thermomechanical noise spectrum of a disk vibrating in water at 1.3 GHz. The resonator stability measured in liquids, together with the models, allows estimating the limits of detection for mass deposition, and for density and viscosity analysis; beating current technologies by several orders of magnitude.

INTRODUCTION

State of the art

Vibrating nano and micromechanical resonators have been the subject of extensive research for the development of ultrasensitive sensors for mass spectrometry, chemical sensing and biomedical analysis [1, 2, 3]. In summary, the sensitivity of these devices to mass deposition is proportional to the resonator own mass and improves if mechanical dissipation is reduced [4]. By miniaturizing the devices and operating in high-vacuum conditions, mass detection down to the yoctogram (10^{-24} g; the proton mass) has been achieved [5]. Translation of these achievements to liquids, the natural environment for biology, has remained elusive because of large energy losses in viscous environments [6]. Amongst the novel structures and approaches proposed to circumvent this problem, microchannels have been the most efficient to date [7, 8]. By placing the liquid inside the resonator while having it vibrate in vacuum, energy losses are mitigated. However, these devices can hardly be miniaturized to the nanoscale, limiting future improvement of their sensing capabilities. Other approaches, such as the use of higher-order modes or contour/extensional modes [9], and self-oscillation techniques [10], have been suggested but are less advanced.

Nano-optomechanical disk resonators

Here we highlight the potential of miniature semiconductor disk resonators in this context. They combine confined optical whispering gallery modes of high quality factor ($Q_{opt}>10^5$ in air) and giant optomechanical coupling, leading to displacement sensitivity down to 10^{-17} m/√Hz. This allows the detection of the thermomechanical vibration associated to their GHz radial-breathing contour-modes, even in liquids, and despite the low amplitudes of motion involved [11]. These disk resonators are potentially powerful mechanical sensors, thanks to their low mass (pg), very high frequency, and moderate dissipation in liquid environments [12], and they can be miniaturized to the nanoscale. Here we study chips integrating an array containing tens of optomechanical disk resonators, having all a thickness of 320 nm, which are optically addressed by on-chip bus waveguides. They are fabricated out of Gallium Arsenide, and immersed in distinct liquids, with a simple droplet deposition technique (Figure 1).

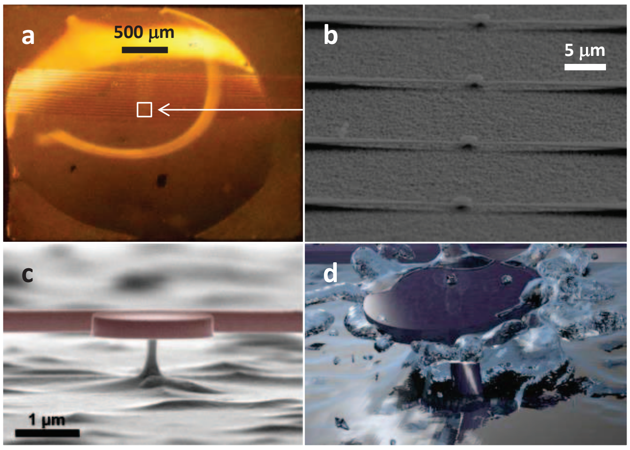

Figure 1: (a) Top-view optical micrograph of a chip containing an array of disk resonators, together with their optical coupling waveguides, which are immersed in a liquid droplet. (b) Scanning electron micrograph (side-view) of four GaAs disk with their tapered suspended coupling waveguides. (c) Side view of a single resonator with its waveguide. (d) Artistic illustration of the disk-liquid interaction.

Summary

By using four liquids of distinct physical properties, we investigate the responsivity of optomechanical disk resonators to changes in density and viscosity of the liquid. We interpret our experimental results with new analytical models that depict viscous and acoustic fluid-structure interactions at play. In addition, we measure here for the first time the thermomechanical noise spectrum of a 1.3 GHz disk immersed in water, and experimentally analyze the stability of the mechanical frequency and quality factor in liquid. These latter measurements, combined with our models and with an analysis of the dynamic range of disk contour modes, allows clarifying the detection limits of such devices.

EXPERIMENTAL RESULTS

Density and viscosity sensor

The mechanical response of a resonator immersed in a liquid is expected to depend on its dimensions and mechanical properties, as well as on the mechanical properties of the liquid. This motivates us to immerse disks of different radiuses in liquids of different viscosities and densities. Figure 2 shows, for different disk radiuses, the relative mechanical frequency shift Δf/f and the mechanical quality factor Q_m measured on the radial-breathing mode of disks immersed in these liquids. Figure 2a clearly shows that Δf/f increases in magnitude as the density of the liquid increases, whatever the size of the disk. This fact is expected from the addition of inertial mass by the liquid. Regarding mechanical dissipation, and whatever the disk radius, Q_m decreases as the viscosity of the liquid increases. This is expected from the usual picture of viscous dissipation of motion in a liquid. The exact dependence of Q_m with the viscosity of the liquid is however complex, and is for example affected abruptly by the disk radius. This latter fact points towards complementary sources of dissipation of another kind.

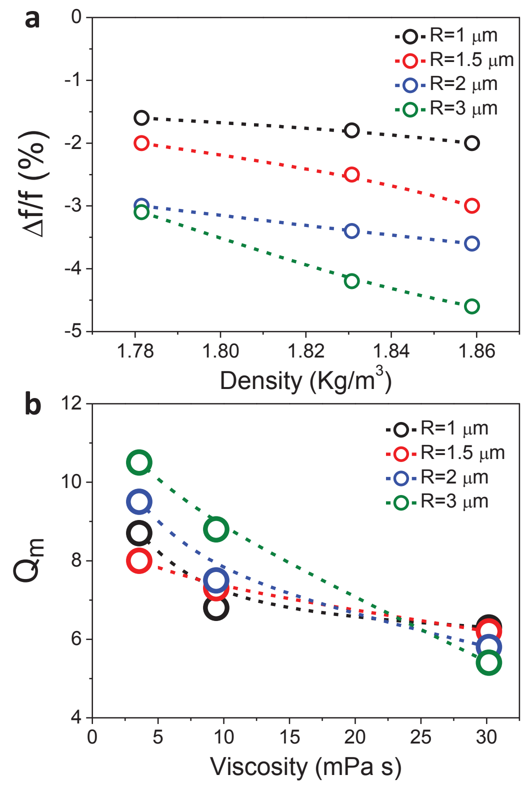

Figure 2: (a) Relative mechanical frequency shift as a function of the fluid density, measured for four distinct disk radiuses. (b) Mechanical quality factor as a function of the liquid viscosity, measured for four distinct disk radiuses.

To go further in the understanding, we developed analytical models of both viscous and acoustic interactions for the radial breathing contour mode of a disk vibrating in a liquid [11 and supplements therein]. Formula are obtained for both the relative frequency shift Δf/f and the mechanical quality factor Q_m of the mode in two limit cases: the viscous case, where the liquid is incompressible and displays linear shear viscous friction; and the acoustic case, where the liquid is compressible but has no shear nor longitudinal friction associated to viscosity. In the viscous case, we obtain:

$$Q_{viscous} = \frac{\rho_s \omega H R}{8.36 \cdot \mu + (3.18 \cdot H + R)\sqrt{2\rho\omega\mu}} \tag{1}$$

and in the acoustic case:

$$\left(\frac{\Delta f}{f}\right)_{acoustic} = -0.954 \frac{H}{R} \frac{\rho}{\rho_s} \left[\frac{1}{4 + \left(\frac{1}{4} \frac{\lambda}{\sqrt{1-\nu^2}} \frac{c_s}{c}\right)^4} + \frac{2.4}{4 + \left(\frac{3}{5} \frac{\lambda}{\sqrt{1-\nu^2}} \frac{c_s H}{c\, R}\right)^4} \right] \tag{2}$$

where H, R, ρ_s, c_s and ν are respectively the disk thickness and radius, and the density, speed of sound and Poisson's ratio of the disk material; while ρ and c are the density and speed of sound of the liquid surrounding the disk. ω is the mechanical angular frequency that can be expressed as $\omega = \frac{\lambda}{R}\sqrt{\frac{E}{\rho_s\,(1-\nu^2)}}$, where E is the Young's modulus of the disk material and λ a frequency parameter that only depends on ν. Similar expressions for $Q_{acoustic}$ and $(\Delta f/f)_{viscous}$ are given in ref [11]. Note that in the acoustic case, the frequency shift can be expressed as a function of dimensionless parameters $(\Delta f/f)_{acoustic} = g\left(\frac{H}{R}, \frac{\rho}{\rho_s}, \frac{c_s}{c}, \nu\right)$. In consequence, by miniaturizing the device at constant *H/R*, the acoustic interaction remains unaltered.

In figure 3 we compare our analytical models with experimental results obtained by immersing the devices in two fluids that behave close to the two limit cases: purely acoustic or purely viscous. Theory and experiments are in good agreement, with a residual discrepancy stemming from the neglected interactions (viscous or acoustic respectively).

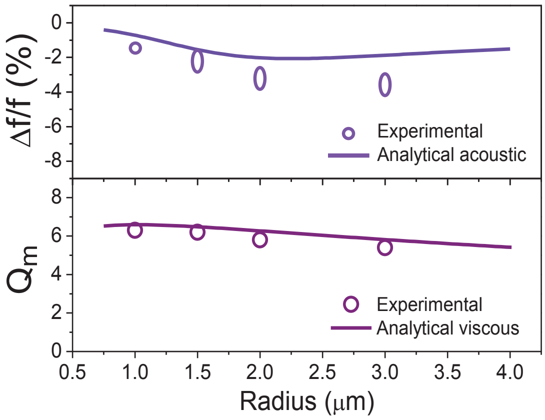

Figure 3: Upper panel: Relative mechanical frequency shift measured in a low-viscosity fluid (μ=3.5 mPa·s), as a function of disk radius (open circles), and results of our analytical acoustic model (solid line). Lower panel: Mechanical quality factor measured in a high-viscosity fluid (μ=30 mPa·s), as a function of disk radius (open circles), and results of our analytical viscous model (solid line). Symbols vertical size corresponds to the error bar.

Brownian motion in water

While above measurements were performed in perfluorinated liquids, which are non-compatible with biological experiments, we also tested one of our devices (1 µm radius) in water, whose properties are closer to a typical biological environment such as serum. Figure 4a shows a measurement of the thermomechanical noise spectrum of a nano-optomechanical disk immersed in water. The device shows a radial-breathing mechanical frequency of 1.3 GHz and a quality factor above 10, which is a remarkably high value for a miniature device operating under similar frequency and environmental conditions. Frequencies in the GHz range open-up ultrafast detection capabilities with increased sensitivity. Figure 4b shows a measurement of the frequency and quality factor stability in liquid, which finally set the sensitivity of our resonators in sensing applications. For a 1s acquisition time of the thermomechanical noise vibration, the standard deviation in the measured mechanical frequency and quality factor amounts to 0.3% and 8% respectively.

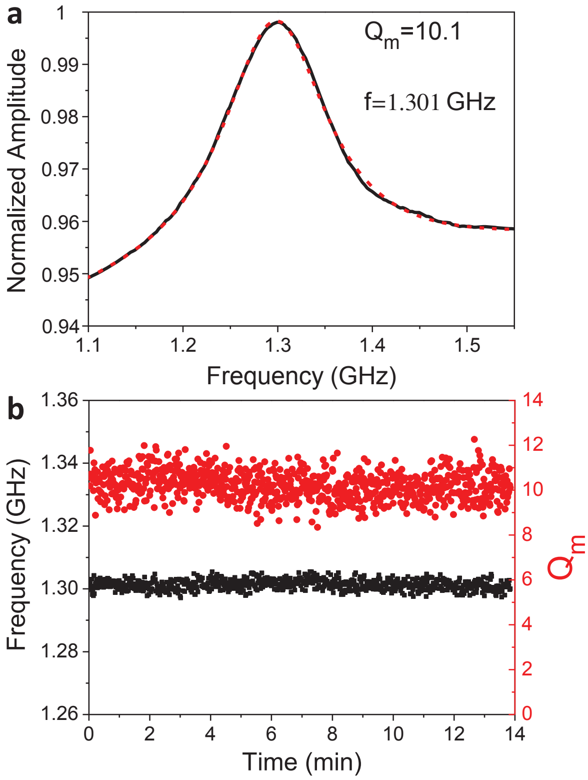

Figure 4: (a) Thermomechanical spectrum of a 1-µm radius disk vibrating in water at 1.3 GHz, acquired during 1 minute (solid black line), together with a Lorentzian fit (dashed red line). (b) Mechanical frequency (black) and quality factor (red) stability of a thermomechanical measurement over a total duration of 14 minutes (1s acquisition time).

These latter measurements, combined with our analytical models of fluidic interactions around the disks, allow estimating the detection limits of our devices, considering that the dynamic range of the measurement is determined by the threshold of mechanical non-linearity of disk contour modes [13,14]. Figure 5 shows the mass and density resolution that could be achieved in a situation of driven mechanical motion. For 1 s acquisition time, it shows a resolution of 28 femtogram in mass and $4 \cdot 10^{-4}$ kg/m^3 in density. These values could be improved by reducing technical noises such as electrical, thermal or mechanical fluctuations of the set-up, eventually approaching the thermomechanical limit of detection [15] (red line in figure 5). This latter limit, in terms of mass, density and viscosity measurement, would respectively reach 14 yoctogram, $2 \cdot 10^{-7}$ kg/m^3 and $5 \cdot 10^{-9}$ Pa·s (for 1 s integration time). This represents a 3 orders of magnitude improvement over current state-of-the-art techniques.

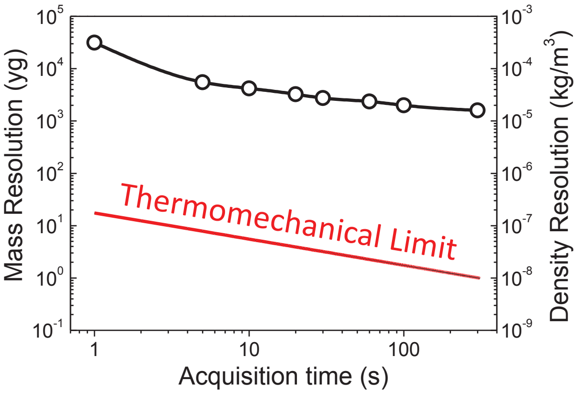

Figure 5: Mass and density resolution for a 1-µm radius optomechanical disk immersed in water, inferred from our experimental data, in a situation of driven mechanical motion at the non-linearity threshold (black open circle). The thermomechanical limit is shown in red.

CONCLUSIONS

Nano-optomechanical disk resonators finally emerge as probes of rheological information of unprecedented sensitivity and speed. While putting miniature disk fluidic sensors on a firm ground, our results also provide a first frame to depict nano-optomechanical dissipation in liquids. This will be of importance for future optomechanical applications in aqueous environments, ranging from biology to chemistry.

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