OPTOMECHANICAL VISCOMETER

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ABSTRACT

Recently, the first microfluidic optomechanical device driven by radiation pressure – and capable of operating with non-solid states of matter (viscous fluids, bioanalytes) – was demonstrated. Here we show that the vibrational noise spectrum of the device mechanical modes enables quantification of the viscosity of fluids inside the device. A linear relation between the spectral linewidth and square root of viscosity is predicted and experimentally measured in the low viscosity regime. For the first time, an all-optical sensor of liquid viscosity using a microfluidic optomechanical resonator is demonstrated. Our result is a step towards performing high-frequency studies of fluids and boundary layer viscosities, and performing high-throughput viscoelastic measurements on flowing cells.

INTRODUCTION

The optical and mechanical modes of high-Q resonant systems can be parametrically coupled through optical radiation-pressure induced mechanical instabilities [1-3]. Ultra-sensitive optomechanical sensors based on this concept have been demonstrated for measuring acceleration [4,5], mass [6,7], and atto-Newton forces [8,9], but are all solid-state techniques. Recently, opto-mechano-fluidic resonators (OMFRs) were demonstrated [10] that enable optomechanical sensing with liquids [11] and gases [12]. In OMFRs, a liquid is confined inside the resonator, rather than outside it, preventing acoustic energy from being lost [13]. The optically actuated mechanical vibrational modes of OMFRs are able to penetrate into the fluid within [10,11] and permit an opto-mechanical interface to the fluid. Furthermore, OMFRs vibrational modes extend to the GHz regime, which is important to study the viscoelastic nature of the fluid, since such nature becomes prominent when the frequency is high. OMFRs can thus provide a novel path towards high-resolution analysis of the viscoelastic properties of fluids and bioanalytes. In this work we demonstrate an experimental system for optomechanically measuring the dynamic viscosity, μ , of various test fluids.

METHODS

The fabrication of OMFRs (Fig. 1a) has been reported in [10]. Briefly, fused-silica capillary preforms are heated and softened by means of high-power CO₂ lasers and then drawn linearly into microcapillaries. Modulation of the laser power varies the capillary diameter creating “bottle”-shaped OMFRs. We test two devices in this work - “Device 1” with 238 μm widest diameter and 21 μm wall thickness, and “Device 2” with 150 μm widest diameter and 13 μm wall thickness. One end of the device is left open while the other is connected to a syringe by which analytes can be infused (Fig. 1d). The sensing volume needed in Fig 1d is about 20 nl, and can be brought lower by reducing the capillary diameter and modifying fabrication parameters.

Continuous-wave 1550 nm laser light is coupled into the optical whispering-gallery modes (Q-factor $\sim 10^7$, Fig. 1b) of the OMFR through a tapered optical fiber. The radiation pressure of light actuates eigenmechanical oscillations (Q-factor $\sim 10^3$ - 10^4 , Fig. 1c) through the optomechanical parametric instability [11], allowing the measurement of density of infused fluids [10,11]. Mechanical modulation of the device geometry generates optical

sidebands of the input light (Fig. 1d). We electronically measure the noise spectrum (Lorentzian lineshape) of the mechanical mode using low input optical power, by observing the beating between input and scattered light on a photodetector (Fig. 1d). Here, $\Omega_{\text{mech}} = 8$ MHz and $\Omega_{\text{mech}} = 13$ MHz vibrational modes are selected for Device 1 and Device 2, respectively, corresponding to high-order wineglass modes (Fig 1c). The mechanical losses in these hybrid shell-fluid modes are obtained through optical measurement of their stochastic thermal fluctuations (Fig. 2b,c). To calibrate the optomechanical viscometers we use four viscosity standard oils (Cannon Instrument Company – Table 1) whose densities are closely matched so as to minimize frequency variations through effective mass change.

Figure 1: (a) SEM of a fused-silica opto-mechano-fluidic resonator (OMFR) based viscometer. (b) Ultra-high-Q circumferential optical whispering gallery mode (WGM) of the OMFR. (c) Multiphysical simulation of solid OMFR shell and coupled pressure waves in fluid, for a high-order wineglass mode (8 MHz - Device 1 and 13 MHz - Device 2); (d) Light is coupled to ultra-high-Q optical WGMs through a tapered fiber, enabling extremely sensitive measurement of the vibrational noise spectrum. Fluid viscosity affects damping of the shared fluid-shell mechanical modes.

RESULTS AND DISCUSSION

Because of liquid entrainment, viscous damping occurs at the solid-fluid interface [14] caused by both shear and normal motion of the fluid relative to a vibrating plate (as in the case of the OMFR shell). For thin shells or plates, the damping is primarily caused by the shear motion of the fluid relative to the resonator wall. The attenuation coefficient due to viscous damping, α , is proportional to $\sqrt{\mu}$ at low values of viscosity [14,15]. The attenuation coefficient saturates due to the viscoelastic nature of the fluid at high viscosity. Using Maxwell's model [14], a critical viscosity value, μ_c , which separates low and high viscosity regimes, can be determined by:

$$\mu_c = \tau G_\infty \quad (1)$$

$$2\pi\Omega_{mech}\tau = 1 \quad (2)$$

where τ is the viscoelastic relaxation time in the liquid and G_∞ is the high-frequency elastic rigidity modulus. Given a typical G_∞ value of 1 GPa [14], the μ_c for a 10 MHz device is 1.6×10^9 cP (centipoise), indicating that our experiment is well within the linear regime. And the relationship between attenuation coefficient, α , and Q_{visc} is given by:

$$Q_{visc} = \pi\Omega_{mech}/(v\alpha) \quad (3)$$

where v is the speed of sound in the fluid. Since the intrinsic Q-factor of the shell mechanical modes is very high, the acoustic energy loss mostly occurs from viscous damping associated with the fluid, and partially from the tapered fiber that is contact with the device. Q_{visc} can thus be measured.

$$\frac{1}{Q_{measured}} = \frac{1}{Q_{visc}} + \frac{1}{Q_{taper}} + \frac{1}{Q_{other\ sources}} \quad (4)$$

We know that the linewidth of the vibrational spectrum is inversely proportional to Q by:

$$Q_{measured} = \Omega_{mech} / \text{Linewidth} \quad (5)$$

We plot the experimentally measured mechanical mode linewidth vs root-viscosity $\sqrt{\mu}$ in Fig. 2a for both devices. The attenuation increases linearly at first and saturates in the end. Since the viscosity values tested here fall well in the low viscosity regime, we suspect this saturation is caused by the taper contact. Each device has multiple vibrational modes that can be used in their linear regions as a viscometer.

Table 1. Experimentally measured mechanical frequencies of the acoustic resonant modes, and properties of the calibration viscosity oils.

Test oil sample	Density (g/cc)	Dynamic viscosity (cP)	Device 1 frequency (MHz)	Device 2 frequency (MHz)
N2	0.76	2.17	8.29	12.9
N4	0.79	5.25	8.37	13.4
S6	0.87	9.57	8.64	13.8
N44	0.82	90.2	8.42	13.1

Figure 2: Calibration and sensing with optomechanical viscometers. (a) Measured linewidth of selected mechanical modes on Device 1 and Device 2 operating with viscosity standard oils. (b) Vibrational noise spectrum of 8 MHz mode on Device 1 with N44 viscosity oil, and (c) N2 viscosity oil.

Viscometer sensitivity and dynamic range are both influenced by the OMFR shell thickness. As discussed in [14], the attenuation rate is inversely proportional to the plate thickness because a thicker plate can transmit more wave energy compared with the amount lost in viscous dissipation. Thus a thicker plate should be used for the obtaining wider sensing range, while a thinner plate should be used

for better sensitivity. However, as revealed by [16], the usage of thick shell can prevent the acoustic modes from penetrating into the liquid. On the other hand, a thin shell is more sensitive to undesired pressure effects when pumping liquids [12]. A suitable shell thickness must be sought.

CONCLUSION

Many different optical techniques – such as refractive index measurement [17], fluorescence [18], and surface enhanced Raman spectroscopy [19] – have been used together with microfluidics, enabling several unique biochemical sensor technologies. The introduction of OMFRs provides a new mechanical degree of freedom to perform such bio-analyses. Here we have demonstrated, for the first time, an all-optical sensor of liquid viscosity based on a simple microfluidic optomechanical resonator. Our result supplements the established microrheological techniques [20,21] since it neither contaminates the fluid with dispersed particles, nor does it require fluid transparency. As the device is made entirely of fused silica it is capable of operating in high temperature and harsh environments and is also biocompatible. The electronics-free fiber-optic interface further enables remote operation of this viscometer.

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