OPTO-MECHANO-FLUIDIC MEMS FOR EXTREMELY HIGH-THROUGHPUT PHOTONIC SENSING OF FLOWING MICROPARTICLES

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ABSTRACT

MEMS microfluidic resonators allow the high-speed label-free mechanical (density, size, deformability) measurement of nanoparticles using kHz-MHz mechanical modes. Further increasing the sampling rate is hard since it requires increasing of mechanical resonance frequency and improving detection sensitivity which is not easy to achieve with electrostatic or piezoelectric transduction methods. To address these challenges, here we present a new label-free technique for sensing rapid free-flowing particles using opto-mechano-fluidic resonator (OMFR). Unlike other optomechanical sensors till date, the OMFR confines the analytes within a simple microchannel, eliminating the dependence on particle diffusion and random binding, and therefore improves the throughput to a potential 10,000 particles/s rate with nearly 100% detection efficiency.

INTRODUCTION

Photonic resonators enable label-free nanoparticle sensing (refractive index, scattering) in fluids near the ultimate limits of detection, by reducing mode volume or by increasing the light-particle interaction time [1,2]. However, photonic measurement of *mechanical* properties (stiffness moduli, mass) of flowing particles remains challenging since these properties do not fundamentally couple to optical fields. State-of-the-art MEMS microfluidic resonant sensors [3, 4] are already capable of sensing the mechanical properties (density, size, deformability) of flowing nanoparticles using kHz-MHz mechanical modes [5], but further increase of speed and sampling-rate can only be obtained by increasing the mechanical resonance frequency and improving detection sensitivity. We propose that the solution lies in optomechanics, using which GHz-frequency mechanical (phonon) modes can be easily coupled to photons without being burdened by the parasitic feedthroughs that are intrinsic to electrostatic and piezoelectric detection methods [6-8]. Such high-frequency modes overcome the fundamental Nyquist limitations and can enable mechanical measurements with extremely high temporal resolution and sensitivity. Till date, most optomechanical sensors that operate in fluids are simply submerged, and thus rely on random diffusion and statistical measurements of large numbers of particles, resulting in low throughput. Recently, a new, hollow opto-mechano-fluidic resonator (OMFR) platform has emerged. The OMFRs can be internally pressure tuned [9], and they support frequencies ranging from 10 MHz – 12 GHz [8]. Since OMFR confines sample fluid within a simple microchannel optomechanical device in a similar way of the suspended microchannel resonator [3], it reduces the viscous and acoustic radiation loss, enabling optomechanical sensing of liquid density [10] and viscosity [11]. Here we present, the first OMFR sensor capable of measuring mechanical properties (density, compressibility) of individual *freely flowing microparticles* in a carrier fluid. We eliminate the reliance on random diffusion of the particles by flowing the sample fluid inside the resonator, therefore improving the throughput to a potential 10,000 particles/s rate. Moreover, the phonon mode spans across both the shell and the fluid, enabling the interaction with analytes in the entire fluid volume (Fig. 1b), thus making a nearly 100% detection efficiency possible.

METHODS

We microfabricate OMFRs through linear laser-drawing of fused-silica capillary preforms (Polymicro Technologies TSP-700850) [12]. The diameter of the device can be locally varied by controlling the laser power during fabrication, forming a microbottle resonator geometry (Fig. 1a,b) of typical diameter 40-60 μm . At the widest region, photonic and phononic modes are co-confined (Fig. 1b,c). A continuous wave laser monitors the fluctuations of the photonic whispering gallery modes (WGMs) of the OMFR (Fig. 1d). Thermal-mechanical fluctuations of the phonon modes (around 30-50 MHz) affect this photonic mode, allowing the phonon mode spectrum to be monitored with extremely high sensitivity in real-time (Fig. 1d) with a real-time spectrum analyzer. We infuse fluid samples with dissolved particles through one end of the OMFR using a syringe pump. The OMFR is vertically oriented and after the pumping is stopped, the particles with a density larger than that of the carrier fluid continue to flow because of gravity. Phonon mode frequency shifts and linewidth perturbations caused by the particles are monitored (Fig. 1d inset), with two digital cameras confirming the particle transits (Fig. 1d). Particle location within the OMFR can be triangulated using these cameras.

Figure 1: (a) Experimental setup. (b) Particles flowing through the core of an opto-mechano-fluidic resonator (OMFR; inset SEM) perturb the frequency and dissipation of (c) the local fluid-shell

hybrid phonon modes (typically 30-50 MHz). (d) The phonon mode fluctuations are detected with extremely high sensitivity using a simple optomechanical test setup (inset shows example fluctuation of phonon spectrum).

RESULTS AND DISCUSSION

We experimentally demonstrate microparticle detections with the OMFR using three different analyte particles: 3 μm yeast cells, 6 μm melamine resin particles, and 11 μm polystyrene particles, (Fig. 2). Real-time spectrograms are collected over long durations from which the center frequency of the phonon mode can be tracked (Fig. 2a), using Lorentzian curve fitting to each of the spectrogram. From the cases presented (Fig. 2a-c) with all three types of particles, we observe that particle transits generally shift phonon frequency to higher values. Less frequently, particle transits shift the phonon frequency lower. We note that the frequency shift is entirely caused by the interaction between phonon and particles since the optical mode is not perturbed during a particle transits evidenced by the unaffected optical transmission during particle transits. Also, these frequency shift pattern generated by heavier-than-water particles doesn't follow the well known mass loading mechanism used by mechanical oscillators. In order to determine the nature of the interaction between phonon and analytes, we first did a multiphysical finite-element model to compute the phonon eigenmodes of the OMFR. The cross-section of the first-order mode shape is visualized in Fig. 1c. It indicates that the observed 30 MHz mode is a breathing mode with the OMFR wall rapidly expanding and contracting. This wall motion creates a pressure field in fluid, with a pressure maximum at the center of the OMFR and a pressure node near the wall. Since the pressure mode is azimuthally symmetric, we can plot the induced frequency shift as a function of the particle radial position shown in Fig. 3a. We notice immediately that the frequency perturbation follows the mode shape of the standing wave. The highest sensitivity happens at the center of the OMFR, while a sensing null locates near the inner OMFR wall.

If we view the OMFR as an acoustic cavity, the interaction of the particle inside the cavity and the pressure mode causes an acoustic potential acting on the particle. In turn, the resonance frequency shifts due to the perturbation [13]. This interaction varies with both the properties of the fluid and particle (size, density, compressibility) [14], and the phonon mode shape [15]. If we assume the small particle only brings perturbation of the pressure field in fluid, p , such that we can approximate the perturbed field, p' , as p , our model describing the frequency modification of the phonon mode, f' , is presented as following:

$$f' = f_0 \sqrt{(1 - \frac{\rho_s - \rho_l}{\rho_s} B) / (1 + \frac{\kappa_s - \kappa_l}{\kappa_l} A)}, \quad (1)$$

$$\text{where } A = \frac{\int_{V_s} p^2 dV}{\int_{V_c} p^2 dV} \text{ and } B = \frac{\int_{V_s} |\nabla p|^2 dV}{k_l^2 \int_{V_c} |p|^2 dV}.$$

Here, we use subscript l standing for the fluid inside OMFR and the subscript s for the sample particle. ρ and κ represents density and compressibility, respectively. The compressibility of the particle, κ_s , is given by $1/\rho_s(c_p^2 - \frac{4}{3}c_s^2)$, with c_p and c_s representing the P-wave and S-wave velocities of the solid-phase particle material, respectively [14]. Whereas $\kappa_l = 1/\rho_l c_l^2$, where c_l is the speed of sound in the fluid. $k_l = 2\pi f_0/c_l$ is the unperturbed wavenumber for phonons in the fluid fraction. The Integration volume are V_c , which is the entire cavity volume within the OMFR, and V_s , which is the sample particle volume. Apparently, the A term is proportional to the acoustic potential energy over the particle volume, and the B

term is proportional to the acoustic kinetic energy over the particle volume.

Figure 2. (a) Real-time spectrogram output from the photodetector measures the phonon mode spectrum. Example trace is measured for 6 μm melamine resin particles flowing through the OMFR. After performing center-frequency fitting, the phonon mode frequency trace is extracted. (b) Similar phonon mode frequency trace is collected for 3 μm yeast cells. (c) During the particle transits of 11 μm polystyrene particles, phonon dissipation is observed to increase, due to the particle material viscoelasticity. (d) A spectrogram example showing the transits of three consecutive 6 μm particles is measured simultaneously by two adjacent phonon modes.

This model indicates that the frequency shift is dependent on density- and compressibility-contrast of the particle relative to the carrier fluid, and to the particle size and position. In the cases presented, the particles are heavier and generally more rigid than the ambient fluid. Thus, when the particle is at the acoustic pressure maximum (OMFR center, Fig. 1c), the potential energy of the phonon field is reduced (A is large) while kinetic energy change is negligible (B is small), resulting in a frequency increase seen experimentally (Fig. 3a). Since both A and B can be computed numerically through simulation, we can predict the phonon mode frequency shift as in Fig. 3b, which agrees well with the experimental data. Using Eqn. 1, we can experimentally measure the density and compressibility of the particle material given we know the phonon mode shape and other properties of the particle. We can even determine the density and compressibility separately since A and B vanish at different location.

Figure 3. (a) Phonon frequency shift is measured with respect to radial position for both 11 μm and 6 μm particles transiting through the same OMFR. (b) Simulation results obtained from our model (Eqn. 1) agree well with the experimental data.

Since the radial phonon modes extend across the entire OMFR cross-section, this system can capture measurements on essentially every particle flowing through the device. We experimentally estimate the throughput of the OMFR to exceed 10,000 particles/s. Our experiments also indicate that the phonon mode dissipation (linewidth) increases during particle transits (Fig. 2c), indicating sensitivity to viscoelasticity of the particle material [11]. Finally, our experiments show that the OMFR is capable of sensing spatially distinct phonon modes (Fig. 2d), which is potentially useful for resolving the dynamic distribution of analytes [5].

CONCLUSION

This work presents a new phonon-mediated optical technique for performing high-throughput mechanical measurements on free-flowing particles in fluid. This resonant measurement technique doesn't depend on random diffusion and spatially decouples the optical mode from the sensing region. While a breathing phonon mode is used to prove the concept here, many more phonon modes spanning from 10 MHz to 12 GHz regimes can be used in a single OMFR structure [Bahl2013], which potentially allows the perfect capture and inertial imaging of every particle that flows through the device. More broadly, the principle we demonstrate here enables optomechanical investigations of defect states in non-solid phase materials.

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