Membrane-based optomechanical accelerometry

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Abstract: Optomechanical accelerometers promise quantum-limited readout, high bandwidth, self-calibration, and radiation-pressure stabilization. We present a simple, scalable platform that enables these benefits with sub-μg sensitivity and 10 kHz bandwidth, based on a pair of vertically integrated SiN membranes.

Optomechanical accelerometers employ a mechanical resonator as a test mass and an optical cavity for displacement based readout. Advantages over electromechanical approaches include quantum-noise-limited readout (enabling thermal-noise-limited acceleration sensitivity), high bandwidth (limited by the cavity response time), in-situ calibration (using the optical wavelength as a ruler), and radiation-pressure actuation (for tailoring or stabilizing the mechanical susceptibility). Numerous platforms have been explored in the last decade, based on photonic crystal [1], whispering gallery mode, and Fabry-Pérot cavities [2] coupled to tethered or levitated test masses with frequencies varying from 10 Hz to 100 kHz and thermal sensitivities ranging from 10 n$g_0/\sqrt{\text{Hz}}$ to 10 $\mu g_0/\sqrt{\text{Hz}}$. Despite this progress, platforms that meet the unique technical demands of optomechanical accelerometry—in particular, the ability to monolithically integrate a relatively large and compliant test mass with an optical microcavity—remain an open line of investigation.

We propose a simple and scalable platform for optomechanical accelerometry based on an pair of vertically-integrated Si_3N_4 membranes with different stiffnesses, forming an optical cavity (Fig. 1). Si_3N_4 membranes possess a set of compelling features which motivate this design, including the ability to achieve ultra-high quality (Q) factors, approaching 1 billion, using phononic engineering [3]; the ability to tune resonance frequencies using radiation pressure, thermal, and electrostatic forces; parts-per-million optical loss; and the ability to operate as a high reflectivity mirror by photonic crystal patterning [4]. Another advantageous feature of membranes is their Q versus mass scaling: due to an effect called dissipation dilution [3], the Q of tensily stressed membranes increases with area, enabling large $Q \times m$ factors (yielding low thermal acceleration) in a relatively compact form factor.

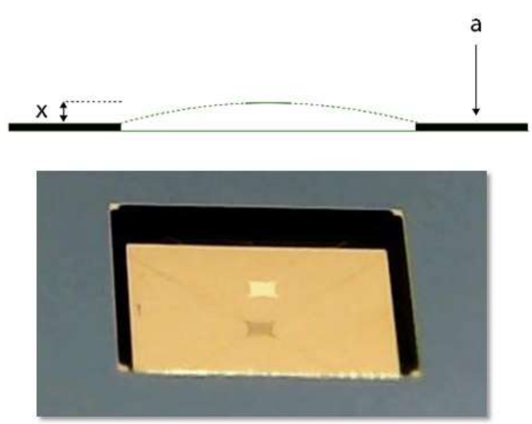

Fig. 1. Vertically integrated optomechanical accelerometer based on a pair of 100 nm-thick Si_3N_4 membranes with different stiffnesses. The width of the membrane window is 2.5 mm.

As a demonstration, we study the device shown in Fig. 1, consisting of an ultra-high-Q ($\approx 10^7$), millimeter-scale Si_3N_4 trampoline monolithically suspended above a square membrane on opposite sides of a 200-μm Si chip. An acceleration applied to the chip results in a displacement of the trampoline (mass $m \approx 10$ ng, frequency $\omega \approx 2\pi \times 40$ kHz) relative to the stiffer square membrane ($m \approx 1\mu$g, $\omega \approx 2\pi \times 150$ kHz). This displacement can be read out by monitoring the resonance frequency of the etalon formed by the membranes, yielding an acceleration sensitivity limited by thermal motion of the trampoline to $a_{\text{th}} = \sqrt{4k_BT\omega/mQ} \approx 0.6\ \mu g_0/\sqrt{\text{Hz}}$.

In practice the performance of the accelerometer is limited by the low finesse of the etalon ($\mathscr{F} \approx 2$), which limits the displacement sensitivity of the optical readout. As shown in Fig. 2, we achieve a shot-noise-limited sensitivity $x_{\mathrm{imp}} \approx 7 \times 10^{-15}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$ for a side-of-fringe measurement with $250\,\mu$W of near-infrared (850 nm) optical power, corresponding to a thermal-noise-limited bandwidth of 100 Hz (near resonance) and a broadband sensitivity of $\omega^2 x_{\mathrm{imp}} \approx 40\,\mu g/\sqrt{\mathrm{Hz}}$. Achieving broadband thermal sensitivity for the same optical power could be achieved by increasing the finesse to $\mathscr{F} \sim 100$, which is well-within the proven performance of PtC mirrors [4]. Alternatively the frequency of the membrane could be reduced to 10 kHz by using a centimeter-scale membrane [4].

Independent of finesse constraints, we highlight the virtues of the high rigidity and radiation pressure actuation available to this platform by using feedback cooling to enhance a weak stochastic acceleration measurement [5]. As shown in Fig 2e-f, we introduce a secondary optical beam (650 nm, 50 μW) to cold damp the fundamental trampoline mode from room temperature to an effective temperature of 15 mK (9×10^3 thermal phonons), and perform a 1000 second long average of the area beneath the thermal noise peak. The observed $\approx 3\%$ relative variance of the area corresponds to the ability to resolve a stochastic acceleration at the level of 100 $\mathrm{n}g_0/\sqrt{\mathrm{Hz}}$.

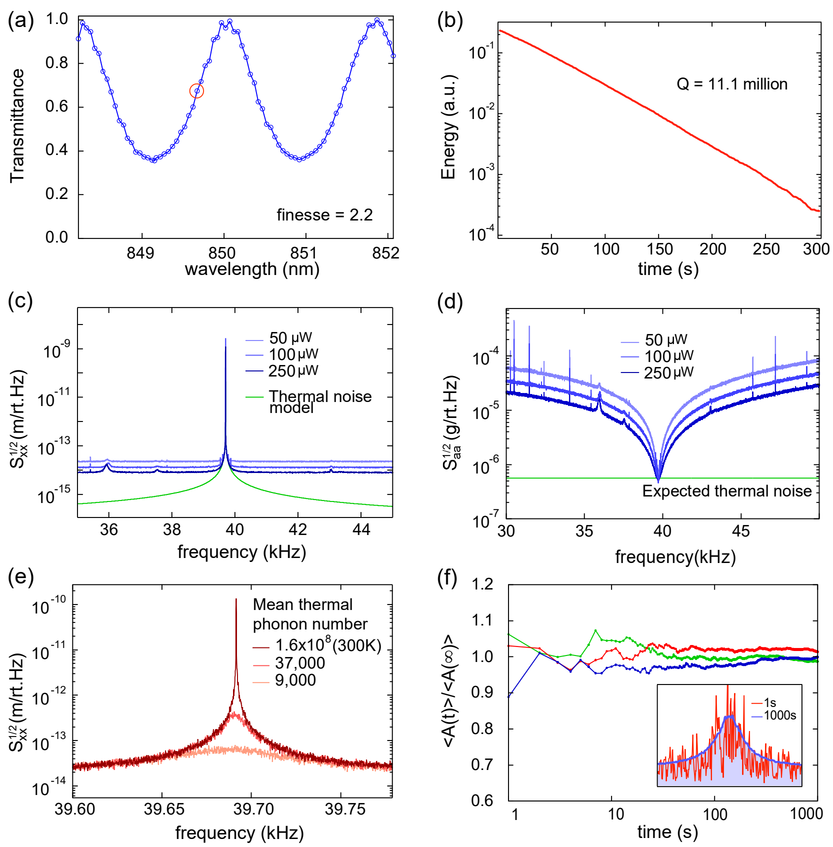

Fig. 2. (a) Etalon transmission fringe; (b) Ring-down of the fundamental trampoline mode; (c) Side-of-fringe (red point in (a)) displacement measurements vs transmitted power; (d) acceleration sensitivity inferred from (c); (e) radiation pressure cold damping; (f) averaging of damped peak in (e).

Looking forward, we envision a $\mathscr{F} \sim 100$, centimeter-scale membrane optomechanical accelerometer operating in a 4 K cryostat in order to achieve sub-$ng_0/\sqrt{\mathrm{Hz}}$ acceleration measurements. This system will allow searches for fundamental weak forces produced by ultralight dark matter[6] and spontaneous waveform collapse.

References

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