Optomechanical Sensing in the Nonlinear Saturation Limit

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Abstract:

The leap from former bulky electronic and optical components to integrated devices has revolutionized computing, information processing and sensing technologies. Compact chip-scale devices allow confinement of light into sub-wavelength volumes to enable strong light matter interactions. The interaction of light with mechanical motion has enabled design of highly sensitive opto-mechanical sensors that are used in many areas of scientific research. These sensors have a limited dynamic range of sensing in order to allow for high sensitivity of detection. Here, we demonstrate that the dynamic range can be enhanced by a new measurement technique using a suspended silicon microdisk resonator that supports high-*Q* optical and mechanical modes.

Summary of Research:

Interaction of light with mechanical motion has enabled many interesting phenomena including cooling and mechanical lasing, quantum state control of light and mechanical motion, nonlinear and chaotic dynamics and so on [1]. Light-matter interactions inside optical microcavities have been shown to be excellent sensors [2]. For instance, these devices have been used in force sensing [3], acceleration and gyration measurements [4], electric magnetic fields sensors [5], scanning-probe microscopy [6], chemical and biological sensors [7], and so on. In most sensors there is a trade-off between the sensitivity that determines the smallest change in the input that can be detected, and the dynamic range that determines the largest change in the input that can be transduced without saturation. Cavity based optical sensors rely on the change in the resonance frequency of the cavity mode due to the change in the environment. This is manifested in the change in the transmission of an optical signal through the cavity. The nonlinear nature of the Lorentzian lineshape of the cavity mode puts an upper limit on the maximum change in its resonance frequency that can be measured. Increasing this dynamic range requires increasing the cavity linewidth which decreases the sensitivity to the resonance shift, manifesting the sensitivity-dynamic range trade-off mentioned earlier. Here we demonstrate a technique that extends the dynamic range beyond the traditional limit.

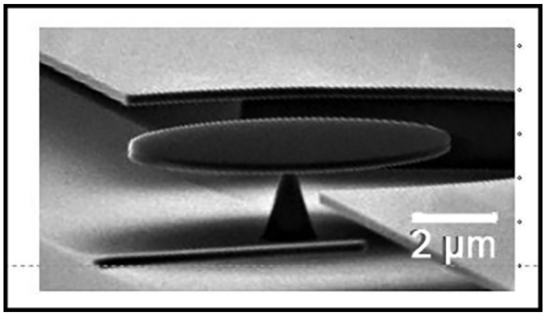

Figure 1: SEM image of the silicon microdisk resonator.

The scanning electron microscopic (SEM) image in Figure 1 shows a high-*Q* silicon microdisk resonator fabricated from a standard silicon-on-insulator (SOI) wafer using electron-beam lithography (JEOL 9500). The microdisk has a radius of about 4 µm and thickness of 260 nm. A C_4F_8/SF_6 chemistry was utilized in an inductively coupled plasma-reactive ion etching (ICP-RIE) process on the Unaxis 770 deep silicon etcher. The recipe was optimized for smooth device sidewalls, which reduces scattering losses and improves the optical quality (*Q*) of the device. Additionally, a hydrofluoric acid (HF) undercut was employed to suspend the silicon microdisk above the oxide layer.

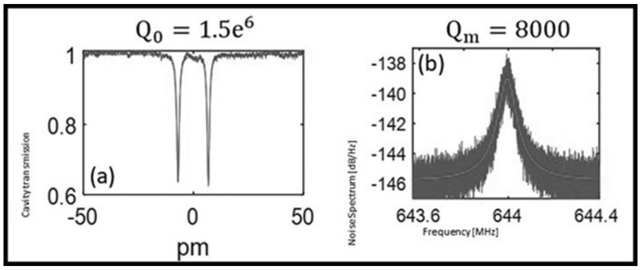

Figure 2: (a) Spectrum of an optical resonance of the microdisk with an intrinsic Q *of 1.5 million. (b) Thermal noise spectrum of the mechanical breathing mode with a* Q *of 8000 measured in vacuum.*

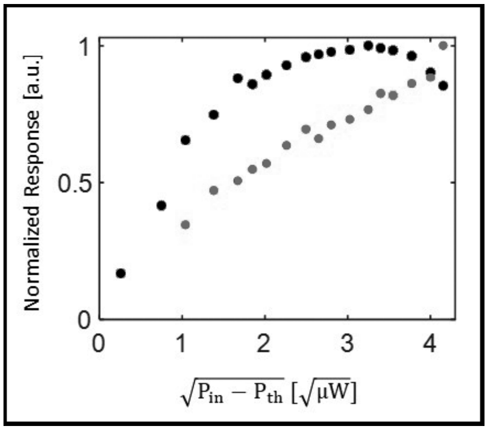

Figure 3: Measured modulation amplitude for increasing pump power using only the first harmonic (black) and the first three harmonics (grey).
P_{th}*: Lasing threshold power,* P_{in}*: Input laser power.*

This undercut was done in several steps using a dilute HF bath to precisely control the undercut. The pedestal width is estimated to be between 100 and 200 nm. The resonator supports optical modes with quality factor as high as 1.5 million as shown in Figure 2(a). The device also supports a radial breathing mechanical mode with a resonance frequency of 644 MHz and a *Q*-factor of around 8000 in vacuum as shown in Figure 2(b).

Typically, in a sensing experiment, a modulation signal is applied to the cavity to modulate the resonance frequency in time. In optomechanical systems, this can be done by coherent oscillations induced by radiation pressure [8]. In this case, the cavity starts coherent mechanical oscillations after a power threshold is reached and the mechanical energy increases linearly with the input optical power. Theoretically, the dynamics can be modelled as a harmonic oscillator with time dependent resonance frequency. In the limit where the mechanical resonance frequency exceeds the cavity linewidth, we have shown that the mechanical motion can be estimated unambiguously by the first three harmonics of the modulation [9]. This is a new technique that allows the measurement of modulation amplitudes that exceed the ordinarily achievable dynamic range, given by the cavity linewidth.

We run a pump-probe experiment where a low-*Q* resonance drives these mechanical oscillations while a high-*Q* mode acts as a probe to measure the modulation amplitude. We compare the measured modulation amplitude using the traditional method using only the first harmonic, and our proposed approach using the first three harmonics of the modulation signal. Figure 3 shows the results. We can clearly see that the measurement using the traditional approach of using only the first harmonic saturates while our technique gives a linear response proving an increase of dynamic range. We measure a maximum modulation amplitude of over six times larger than the dynamic range would ordinarily allow.

Conclusions:

We have demonstrated a new sensing technique for micro-resonator based optomechanical sensors. Experimentally, we have shown how our proposed approach can extend the dynamic range of these sensors far beyond what is traditionally achievable.

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