Cavity-less Quantum Optomechanics with Nanostring Mechanical Resonators

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Abstract: We report our research effort to realize single-pass optomechanical systems with sensitivity surpassing the quantum backaction limit. We fabricate high-Q nanostring resonators with 1D phononic crystal shields to reduce mechanical dissipation.

High sensitivity optomechanical systems offer efficient transduction of physical quantities for precision metrology [1, 2], and have led to scientific breakthroughs like the detection of gravitational waves [3]. In the quantum regime, the measurement sensitivity of an optomechanical system is bounded by both measurement imprecision noise and mechanical backaction both due to photon shot noise, leading to a standard quantum limit (SQL). Achieving sensitivity limited by quantum backaction effects can further be utilized to produce ponderomotive squeezing [4], and ground state cooling of mechanical resonators [5]. Realizing the quantum regime of optomechanics requires an optomechanical interaction strength or cooperativity (C) as defined by Eq. 1, to be much larger than the thermal occupation of the mechanical state ($\bar{n}_{th}$). Such experimental endeavors previously relied on utilizing high quality factor (Q_o) optical resonators, which normally require low noise laser systems and cumbersome active stabilization and control [6].

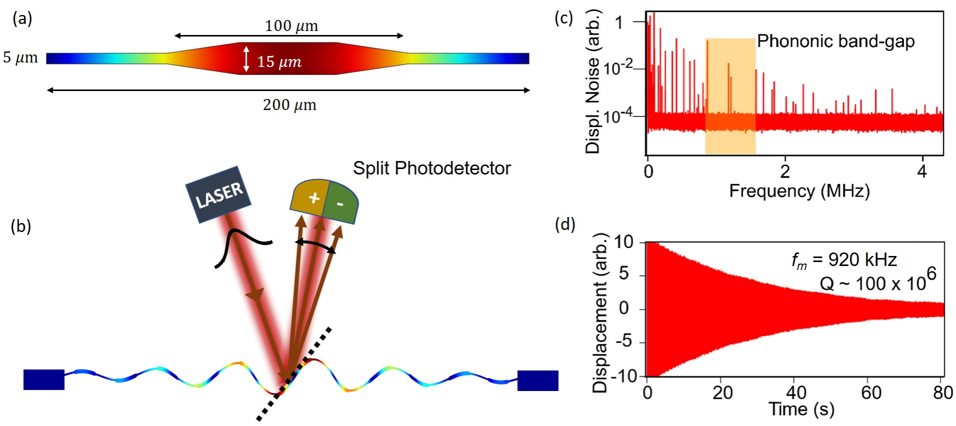

Fig. 1. (a) Width modulated phononic crystal structure unit cell to minimize clamping losses around 1 MHz. (b) Schematic of our optical lever detection scheme to measure the angular deflection of an optical beam reflecting off of a nanostring. (c) Power spectrum of the nanostring resonator thermal displacement noise showing a 500 kHz wide phononic band gap around 1.1 MHz. (d) Driven ringdown mechanical Q_m measurement showing the exponential decay of out-of-plane motion of the central defect mode at 920 kHz.

Here we present our progress on realizing strong optomechanical interactions in a single-pass optical deflection measurement and extend our understanding of the quantum bounds for angular deflection measurement [7, 8]. As defined by Eq. 1, we aim to achieve high optomechanical cooperativity in our system by using high frequency (f_m) and ultra high quality factor (Q_m) nanomechanical resonator with small effective modal mass (m_{eff}).

$$C \equiv \frac{4\bar{N}g_o^2}{\kappa\Gamma_m} \propto \frac{PQ_oQ_m}{m_{eff}} \tag{1}$$

where Γ_m is the mechanical damping rate, g_o is the single-photon optomechanical coupling rate, κ is the cavity decay rate, $\bar{N}$ is the number of circulating photons, and P is the circulating optical power. For our single-pass detection scheme $Q_o \sim 1$.

The quantum optomechanics of optical lever detection (Fig. 1(b)) consists of a mechanically mediated coupling between an input Gaussian optical mode, U_0 (occupied by a coherent laser field) impinging on a mechanically compliant, reflective surface (in our case a High-Q nanostring) and the first-order Hermite Gaussian mode, U_1 (initially occupied by vacuum fluctuations). Amplitude fluctuations in the U_1 mode interfere with the coherent state causing fluctuations in the position of the optical intensity distribution resulting in angular deviations in the reflected field due to mechanical action. can be described as phase fluctuations in the U_1 mode interfering with the reflected U_0 mode. This optomechanical mode coupling thus produces correlations between the amplitude and phase fluctuations of the U_1 mode. By modifying the detection setup with the addition of a single lens to expliot the relative Gouy phase between U_0 and U_1, we can effectively measure a quadrature of the U_1 where these correlations destructively interfere [8], making evident ponderomotive squeezing, and presenting a route to quantum backaction evading measurements similar to that of traditional interferometric optomechanical systems [9].

Our nanomechanical resonators are doubly clamped strings, fabricated from a few tens of nanometer thin films of either low-internal-loss single-crystal silicon or high-stress stoichiometric silicon nitride. We engineer our strings with a width modulated phononic crystal structure (PCS) creating a large acoustic band gap around 1 MHz for out-of-plane motion (Fig. 1(a)). A defect in the crystal structure near the middle of the string creates a localized mode shielded from bending and radiation losses at the clamping region. This soft clamping via phononic crystal structure has been previously demonstrated by several research groups [10, 11]. We design short strings with optimized width to allow efficient free space reflection measurements and provide better heat dissipation of absorbed laser light. We perform photolithography and plasma etching to define the resonator geometry and wet or vapor phase etching to release the suspended structures of our nanostring resonators. We have created micromachined on-chip flexure stages to stretch single-crystal silicon strings and attempted to dilute the mechanical dissipation in these intrinsically low-stress films via externally applied uniaxial strain.

We report a Q_m measurement of about 100 million (Fig. 1(d)) in the central out-of-plane defect mode of the SiN string at a cryogenic temperature of 4 Kelvin. The resonance of this mode is 920 kHz yielding a $Q_m f_m$ of about 1×10^{14} Hz. With these parameters, a large quantum cooperativity can be achieved with a few Watts of reflected laser power. We expect the cryogenic Q_m of silicon string resonator to be orders of magnitude higher, leading to unprecedentedly high coherence of mechanical states and the possiblity of large cooperativity with modest optical power in a single-pass optical measurement.

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