Thermometry with Optomechanical Cavities

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Abstract: The thermally-driven motion of a nanomechanical resonator may be employed as an absolute thermometer. We experimentally measure radiation pressure shot noise induced quantum correlations to absolutely calibrate the motional signal transduced onto an optical probe.

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Nano-optomechanical systems are promising sensors for a wide variety of physical quantities from force, acceleration, and displacement to mass, pressure, and temperature. Here, we focus on thermometry with on-chip optomechanical systems. The basic concept is that the average mean square thermally-driven Brownian motion of a nanomechanical resonator is proportional to the absolute temperature of the sample. This motion is read out with a cavity enhanced optical probe. Once the mechanical to optical transduction factor is ascertained, this system can serve as an on-chip photonic temperature standard. Pairing this standard with on-chip thermometers such as silicon photonic cavities [1, 2], whose large thermo-optical coefficient makes them fast and sensitive, will create robust, field-calibratable devices with all optical addressing.

Determining the mechanical-to-optical transduction factor is vital for accurate thermometry and is experimentally challenging, typically requiring detailed knowledge of the system parameters such as the mechanical resonator effective mass, optomechancial coupling rate, optical cavity decay rate, and optical losses. However, methods such as taking the ratio of the anti-Stoke to Stokes Raman scattering rate in material [3] or engineered optomechanical systems [4, 5] provides a fundamental, parameter-free calibration. This ratio is given by $n_m/(n_m+1)$ in the limit of small Stokes shift, where n_m is the average phonon occupation number of the mechanical mode. Using linear optical detection, e.g. optical heterodyne, Raman ratio techniques amount to measuring the quantum correlations induced on the output by the optomechanical interaction [6, 7]. Common additional complications with Raman ratio techniques include correctly accounting for the optical density of states at the anti-Stokes and Stokes scattering frequencies, especially if narrowband optical resonant enhancement is employed and unraveling detector dispersion and nonlinearity. To address these and other systematic effects, we investigate techniques such as driving the mechanics with an additional coherent force to act as a classical calibration tone and cross correlation measurements [8-10].

Our system consists of a silicon nitride optomechanical crystal [11] (Fig. 1), chosen for its relatively high mechanical resonance frequency, and consequently small n_m. A suspended nanobeam waveguide is patterned with holes that act as Bragg scatterers for both acoustic and optical waves. A defect is introduced into the periodic hole array to create colocalized acoustic and optical resonances with a strong optomechanical interaction. The silicon nitride optomechanical crystal is evanescently coupled to a tapered optical fiber to allow for optical addressing. Two optical modes with differing resonant wavelengths are addressed with two separate lasers, but both are optomechanically coupled to the same mechanical resonator. One mode is driven with strongly amplitude modulated light to provide a coherent force on the mechanics. The other mode is driven resonantly with a shot-noise-limited laser, and serves as the optical readout of the mechanics. Light collected from this mode is detected with optical heterodyne. From the heterodyne signal, we can compute either the power spectrum of the heterodyne signal, giving direct access to the anti-Stokes and Stokes scattering peaks (Fig. 2(a)), or digitally mix down the photodiode signal to simultaneously access one or more optical quadratures (Fig. 2(b)), allowing for quadrature cross correlation measurements. Computing the spectrum of correlations between two carefully chosen orthogonal optical quadratures reveals the radiation pressure shot noise induced quantum correlations free from additional background signals. The size of this correlation provides the calibrated increment for absolute thermometry.

These types of measurements are quite demanding for megahertz [4] and gigahertz [5] frequency mechanical resonators and have been performed previously only at cryogenic temperatures and with additional optical cooling. For example, at room temperature, the average mechanical phonon occupation, n_m, of our 3.6 GHz mechanical resonator is about 1700 quanta, meaning that the difference between the anti-Stokes and Stokes scattering peaks is only about $1/n_m$, or equivalently the quantum correlations are buried under uncorrelated noise on the order of n_m times larger. However, our measurement techniques should allow us to discern these small effects from cryogenic to room temperature. Our preliminary experimental results demonstrate the direct measurement of optomechanically-induced quantum correlations over a wide temperature range.

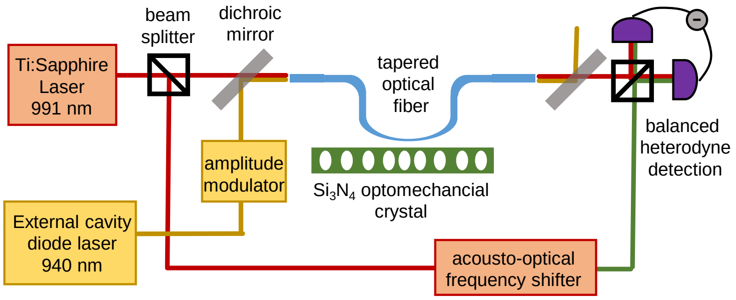

Fig. 1 Experimental Setup. Two lasers resonant with two optical modes of the Si_3N_4 optomechanical crystal are combined on a dichroic mirror and sent through a tapered optical fiber evanescently coupled to the optomechanical crystal. One laser is amplitude modulated at the mechanical resonance frequency to provide a coherent optical force. A portion of the other laser is split off and frequency shifted to serve as a local oscillator. After interacting with the cavity, the second beam and frequency shifted local oscillator are interfered to perform balanced heterodyne detection of the optomechanical Raman sidebands on the second beam.

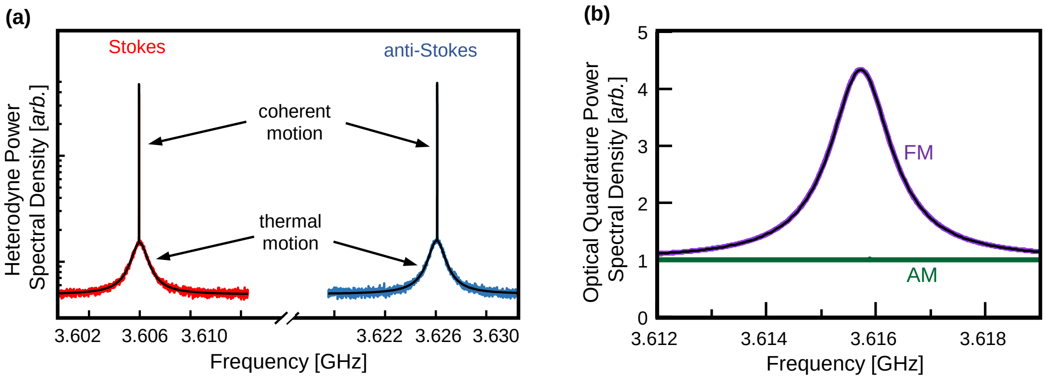

Fig. 2. (a) Heterodyne power spectrum of mechanical sidebands. Lorentzian components are indicative of thermal motion. Sharp peaks are the result of optically driven coherent motion. Anti-Stokes sideband is blue. Stokes sideband is red. Fits are black. (b) Optical quadrature spectrum resulting from digitally mixing down heterodyne signal for an on resonant optical probe. Frequency quadrature (FM) is purple and shows Lorentzian spectrum of thermally driven motion. Amplitude quadrature (AM) is green and is dominated by shot noise. For both plots the parameters are: temperature 294 K, optical resonance wavelength 991 nm, optical linewidth ≈10 GHz, mechanical resonance frequency 3.616 GHz, mechanical linewidth 1.3 MHz, optomechanical cooperativity<<1, heterodyne local oscillator offset frequency 10 MHz.

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