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Simultaneous radiation pressure induced heating and cooling of an opto-mechanical resonator

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Cavity opto-mechanics enabled radiation-pressure coupling between optical and mechanical modes of a micro-mechanical resonator gives rise to dynamical backaction, enabling amplification and cooling of mechanical motion. Due to a combination of large mechanical oscillations and necessary saturation of amplification, the noise floor of the opto-mechanical resonator increases, rendering it ineffective at transducing small signals and thereby cooling another mechanical resonance of the system. Here, we show amplification of one mechanical resonance in a micro-mechanical ring resonator while simultaneously cooling another mechanical resonance by exploiting two closely spaced optical whispering gallery mode cavity resonances. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3694772]

Mechanical oscillators coupled to the electromagnetic mode of an opto-mechanical cavity have emerged as an important new frontier in photonics and have enabled interesting experiments in cavity opto-mechanics. Recent work has shown resonators with mechanical displacement sensitivities close to the zero point motion of the mechanical modes.[1] Optical forces have also been shown to exist in these opto-mechanical systems which can be used for a variety of applications including static motion of micro mechanical structures,[2,3] setting up oscillations (heating) of the vibrational modes,[4–7] and cooling of vibrational modes to achieve ground state.[1,8,9] The opto-mechanical systems can be either stand alone opto-mechanical resonators on chip which are interrogated by evanescent coupling from fiber taper that provide lower insertion loss[5–7] or on-chip systems which incorporate waveguides along with opto-mechanical resonators on the same chip.[2,10]

The ultimate sensitivity of optical sensing of mechanical motion is fundamentally set by the standard quantum limit (SQL).[11] However, well before the SQL is reached, backaction forces may dominate and severely alter the dynamics of the intrinsic mechanical motion of the sensor. Due to a combination of large mechanical oscillations and necessary saturation of amplification, the noise floor of the opto-mechanical sensor increases, rendering it ineffective at transducing small signals. Parametric instability is predicted to be a potential problem in the context of the advanced laser interferometer gravitational observatory (LIGO)[12] and, more generally, in many cavity opto-mechanical systems designed for ultra-precise sensing. This can be controlled by designing elaborate feedback schemes.[11,12] Here, we show amplification of one mechanical resonance in a silicon nitride micro-mechanical ring resonator while simultaneously cooling another mechanical resonance by exploiting two closely spaced optical whispering gallery mode cavity resonances. The possibility of simultaneous heating and cooling can open up avenues in studying coherent phonon exchange and phonon dynamics between different acoustic modes and be of interest in MEMS gyroscopes and studying aspects of condensed-matter and many-body physics at the macroscale.

The opto-mechanical ring resonator is designed in silicon nitride and supported on a silicon dioxide pedestal. The micro-mechanical ring has an outer radius of 40 μm and width of 6 μm. We use grating couplers and an integrated waveguide of width 800 nm to couple light evanescently to the resonator. To fabricate the device, we start with silicon wafers that have 4 μm silicon dioxide thermally grown and deposit 300 nm silicon nitride using low pressure chemical vapor deposition (LPCVD). The resonators, waveguides, and grating couplers are defined using electron beam lithography. The pattern is transferred into the nitride device layer using CHF_3/O_2 reactive ion etch. We deposit SiO_2 cladding using plasma enhanced chemical vapor deposition (PECVD) to reduce grating transmission losses. A second mask is then used to pattern release windows near the resonator using contact photolithography. This is followed by a partial etch into the cladding and a timed release etch in buffered oxide etchant to undercut the devices. The samples are then dried using a critical point dryer to prevent stiction. The resulting

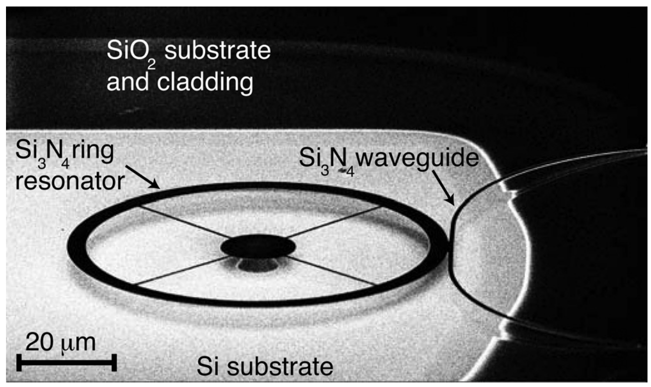

FIG. 1. SEM of the released opto-mechanical resonator. The silicon nitride ring thickness is 300 nm and it has an outer radius of 40 μm and width of 6 μm. The distance between the resonator and the waveguide at the point of closest approach is 50 nm. The released silicon nitride ring is supported by spokes of width 500 nm and supported on a central silicon dioxide pedestal.

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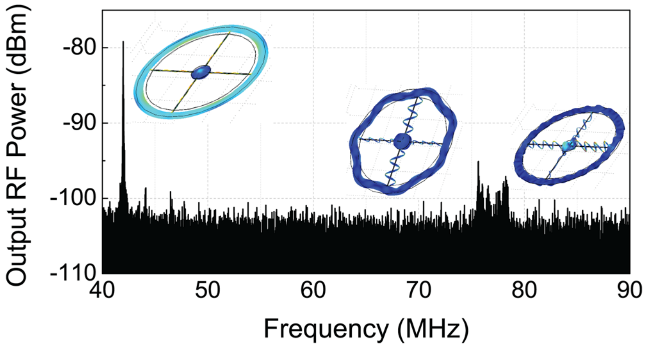

FIG. 2. (Color online) RF spectrum at the output of the avalanche photodetector. The peaks observed correspond to the Brownian noise mechanical motion of the micro-ring. The fundamental radial expansion mode of the micro-ring at a frequency of 41.97 MHz causes strong intensity modulation of the laser light as compared to a group of azimuthal composite mechanical modes around 77 MHz. An optical resonance with total optical quality factor of 200 000 was used to probe the opto-mechanical response of the resonator. The laser power used was 5 dBm. The input and output grating couplers each introduce a loss of 8 dB. Finite element method (FEM) simulations of the mechanical mode shapes are shown as insets.

devices have cladding over the gratings and the tapered section of the waveguide. Figure 1 shows a scanning electron micrograph (SEM) of the released resonator.

We probe the interaction between the optical and mechanical modes of the ring resonator using an avalanche photodetector to convert motion induced intensity modulation into RF signals.[10] We choose an optical mode with an optical quality factor of $\approx$200 000 (and intrinsic Q > 500 000), and the laser wavelength is fixed such that it corresponds to a 3 dB drop in optical transmission off-resonance. At low input laser powers (5 dBm), the input light coupled into the cavity is modulated by the Brownian noise motion of the mechanical modes of the micro-ring as shown in Figure 2. The fundamental radial expansion mode of the micro-ring at a frequency of 41.97 MHz causes strong intensity modulation of the laser light as compared to a group of azimuthal composite mechanical modes around 77 MHz. This can be attributed to higher effective path length change associated with the radial expansion mode, which causes greater modulation of the laser light.[4]

The fundamental radial expansion mode of the ring at 41.97 MHz has mechanical Q $\approx$ 2000 measured in air. As we increase the laser power, self-sustained oscillations are observed for this mode above the input threshold power as shown in Figure 3. The sharp threshold behavior is characteristic of radiation pressure induced parametric instability.[4] Figures 4 and 5 show heating and cooling of this mechanical mode obtained by blue detuning and red detuning the laser with respect to the cavity, respectively. The mechanical mode is heated by blue detuning the input laser light (1550.55 nm) with respect to the cavity (1550.6 nm). The linewidth of the peak narrows and the frequency increases, as expected for heating of the mechanical mode. When the laser is red detuned (1550.672 nm) with respect to the cavity, the mechanical mode is cooled. The linewidth increases from 42.4 kHz to 92.5 kHz as the laser power is increased from 10 dBm to 14 dBm. This corresponds to an effective temperature of 138 K. The effective temperature is inferred by the linewidth of the mechanical resonance.[13]

Interaction of mechanical modes of nanomechanical resonators with multiple optical modes has been shown before,[14] which enables both heating and cooling. However, this scheme causes either heating or cooling of the mechanical mode, depending on which optical resonance is pumped. Here, we explore the feasibility of using two closely spaced whispering gallery modes to simultaneously achieve heating of one mechanical mode while cooling another mechanical mode using a single pump laser. The micro-ring resonator heats up due to thermal absorption as the laser power is increased, which leads to the characteristic shark fin optical

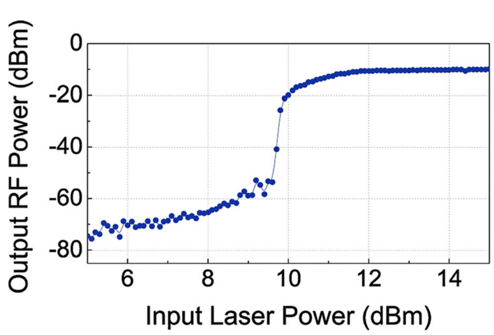

FIG. 3. (Color online) (a) Variation of RF power at the output of the photodetector with the input laser power, for the fundamental radial expansion mode of the micro-ring at 41.97 MHz. As the laser power is increased, self-sustained oscillations are observed for this mode. The sharp threshold behavior shown is characteristic of radiation pressure induced parametric instability.

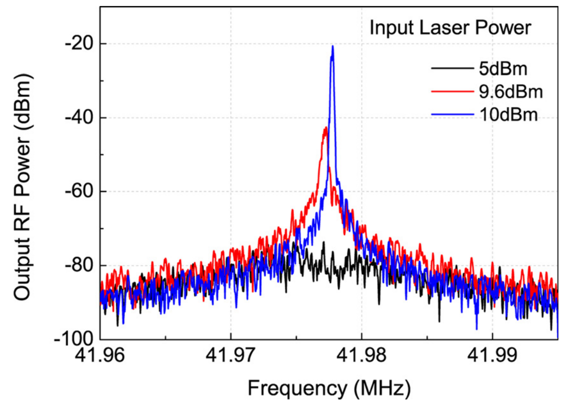

FIG. 4. (Color online) The mechanical mode is heated by blue detuning the input laser light (1550.55 nm) with respect to the cavity (1550.6 nm). The linewidth of the peak narrows and the frequency increases with increase in input optical power, as expected for heating of the mechanical mode.

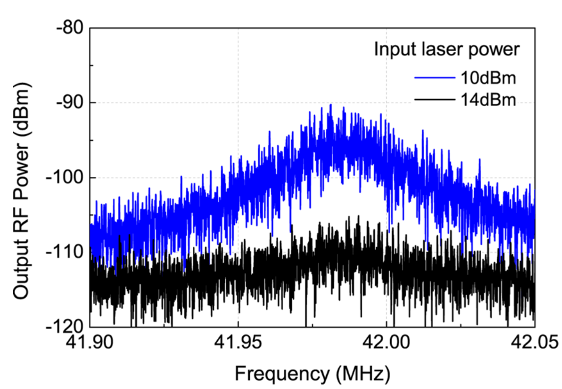

FIG. 5. (Color online) When the laser is red detuned (1550.672 nm) with respect to the cavity, the mechanical mode is cooled. The linewidth increases from 42.4 kHz to 92.5 kHz as the laser power is increased from 10 dBm to 14 dBm. This corresponds to an effective temperature of 138 K.

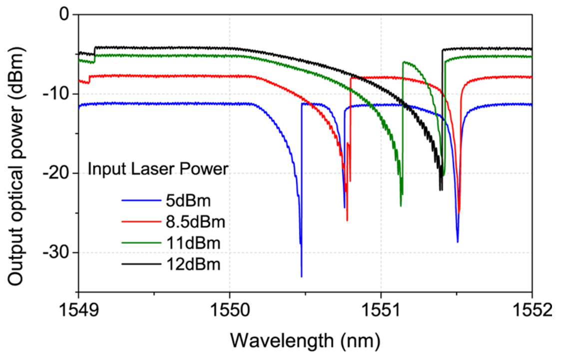

FIG. 6. (Color online) Optical spectrum of the silicon nitride opto-mechanical resonator for different input laser powers. The modal refractive indices of multiple optical mode families have different temperature dependence. The shark-fin shape of the optical resonances is attributed to thermal absorption.

spectrum[15] owing to temperature dependence of the modal refractive index. Due to the rich mode spectrum of a silicon nitride micro-ring resonator, situations may arise where the resonator has multiple optical mode families. The modal refractive indices of these mode families may have different temperature dependence. As shown in Figure 6, one of the optical modes is far more sensitive to the laser power. As such, it is possible to fix the laser wavelength such that the pump laser light is red detuned with respect to one of the cavity modes and blue detuned with respect to the other in thermal equilibrium.[15]

Figure 7 shows increased RF power for the Brownian noise motion peaks when the laser power is increased. The laser light (1550.55 nm) is blue detuned with respect to the pair of optical resonances at 1550.6 nm. Figure 8 shows the RF spectrum when the laser (1550.587 nm) is blue detuned with respect to one optical resonance and red detuned with respect to the other. In this case, the fundamental radial mode of vibration is heated as the pump laser power is increased while a group of azimuthal composite mechanical modes is cooled. Figure 9 shows the cooling of these modes more clearly, with the linewidth for the mode at 76.7 MHz increasing from 150 kHz to 250 kHz as the laser power is increased from 10 dBm to 11 dBm. This corresponds to an effective temperature of 180 K.

The possibility of simultaneous heating and cooling of mechanical modes can open up avenues in studying coherent

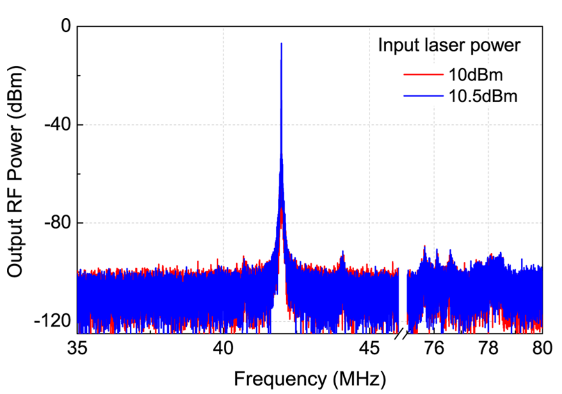

FIG. 7. (Color online) When the laser light (1550.55 nm) is blue detuned with respect to the pair of optical resonances around 1550.6 nm, the RF power for the Brownian noise motion peaks increases when the laser power is raised from 10 dBm to 10.5 dBm.

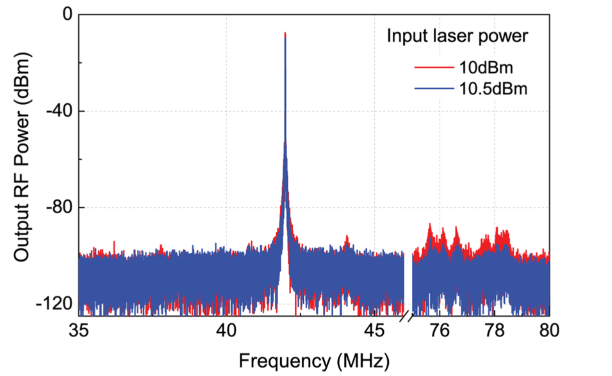

FIG. 8. (Color online) RF spectrum when the laser (1550.587 nm) is blue detuned with respect to one optical resonance and red detuned with respect to the other. In this case, the fundamental radial mode of vibration at 41.97 MHz is heated as the pump laser power is increased from 10 dBm to 10.5 dBm, while a group of azimuthal composite mechanical modes centered around 77 MHz is cooled.

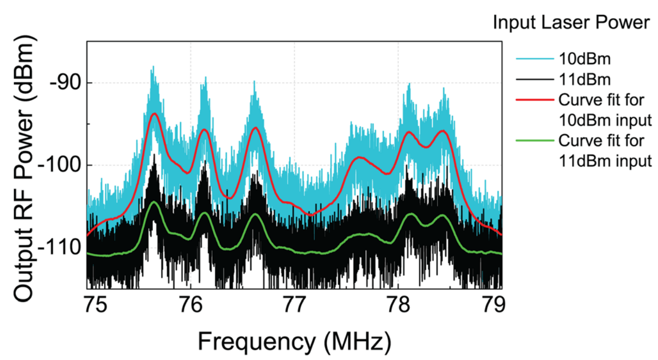

FIG. 9. (Color online) Increasing the laser input power from 10 dBm (blue curve) to 11 dBm (black curve) results in cooling of the composite mechanical modes of the resonator. For instance, the linewidth of the mode at 76.7 MHz increases from 150 kHz to 250 kHz by increasing the laser power. This corresponds to an effective temperature of 180 K. The red and green curves are smoothed curve fits for the blue and black curves, respectively.

phonon exchange and phonon dynamics between different acoustic modes, mediated by an optical media and enable significant advances in ultra-precise sensing. Mode-matched MEMS gyroscopes simultaneously require high Q along the drive and sense axis for improved sensitivity. However, the high Q along sense axis reduces the effective bandwidth of the sensor. Simultaneously heating (to achieve narrow linewidths along the drive axis) and cooling (maintaining high signal to noise ratio (SNR) while increasing bandwidth) promise high sensitivity and high resolution, while maintaining large bandwidth and high dynamic range. Cooling multiple closely spaced mechanical modes to ground state will also provide an exciting toolset for studying aspects of condensed-matter and many-body physics at the macro-scale.

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