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From strong coupling to single-phonon-level operations
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ABSTRACT

Backward Brillouin scattering in whispering-gallery-mode micro-resonators offers an exciting avenue to pursue both classical and quantum optomechanics applications. Our team—the Quantum Measurement Lab—together with our collaborators, are currently utilizing this regime and the favourable properties it affords for non-Gaussian motional state preparation of the acoustic field. In particular, the high mechanical frequencies, and low optical absorption and heating provide a promising route to overcome current hindrances within optomechanics. Three of our recent experimental results in this area include: (i) Brillouin optomechanical strong coupling, (ii) single-phonon addition or subtraction to a thermal state of the acoustic field, and (iii) performing phase-space tomography of non-Gaussian states generated by single- and multi-phonon subtraction. This SPIE presentation will cover these three results, what they enable, and the broader direction of our lab including the prospects of this platform for quantum-memory applications.

Keywords: Brillouin scattering, cavity optomechanics, Brillouin optomechanics, quantum optics

1. INTRODUCTION

One of the key aims of cavity optomechanics is to generate and control non-classical mechanical or acoustic degrees of freedom. Owing to the significant potential to contribute to both applied and fundamental physics that such control can provide, multiple different experimental approaches are being pursued across the globe to explore this direction. One promising path is to simultaneously: (i) utilize high mechanical frequencies (> GHz) so that conventional cryogenic cooling provides high-purity initial states, (ii) achieve low mechanical decoherence rates sufficient for state preparation and then utilization, (iii) achieve strong optomechanical coupling for coherent light-mechanics control operations, (iv) achieve low optical absorption and heating, and (v) achieve high optical measurement efficiency important for high-fidelity mechanical state characterization. Though tremendous progress is being made in the field, meeting all of these requirements simultaneously remains an important outstanding goal.

In this talk, we will describe our work towards simultaneously meeting all of these requirements utilizing Brillouin optomechanics in whispering-gallery-mode microresonators and will highlight three recent advances in our experimental collaboration. The first is the observation of Brillouin optomechanical strong coupling where...
the coupling rate achieved for anti-Stokes scattering far exceeds the optical and mechanical damping rates giving rise normal-mode splitting.1 Secondly, utilizing these microcavity-enhanced interactions, we perform single-phonon addition and subtraction to an initial thermal state of the acoustic field and observe the counter-intuitive doubling of the mean phonon number.2 And, thirdly, using a heterodyne measurement of the anti-Stokes signal, we perform state tomography of non-Gaussian states of the acoustic field generated by single- and multi-phonon subtraction operations.3

2. BRILLOUIN OPTOMECHANICAL STRONG COUPLING

Strong coupling is a key ingredient throughout quantum optics and enables a wide range of applications. Notably, when the coupling rate between light and a matter system exceeds the damping rates, one can then use the optical field to control the state of matter. In particular, this can aid a coherent state swap between light and matter for quantum memory applications.

To observe Brillouin optomechanical strong coupling, we use a silica optical micro-rod-resonator (cf. Fig. 1(a)) and utilize a pair of optical modes that are approximately spaced by the Brillouin shift. Then, by pumping the lower-frequency mode of the pair (cf. Fig. 1(b)), we resonantly drive the anti-Stokes interaction, which can be modeled by a light-mechanics beam-splitter operation. Observing the back-reflected signal with a heterodyne detector we can then observe the mechanical response as a function of pump power (cf. Fig. 1(c)). For low input-pump power we observe a small Lorentzian signal as expected for a damped stochastically-driven harmonic oscillator and as the pump power increases a second peak emerges and normal-mode-splitting is observed. Note also that as the pump power is increased, due to the optical Kerr and photothermal effects, the detuning in the interaction is also changed and an avoided crossing can be observed.

For the largest pump powers in this experiment, we achieved a coupling rate of $G/2\pi = 39$ MHz, which exceeds both the optical ($\kappa/2\pi = 3$ MHz) and mechanical ($\gamma/2\pi = 21$ MHz) amplitude decay rates. These results1 take important steps towards deterministic light-mechanics state-swap operations, which are key to quantum memory and other quantum information applications.

Figure 1. Brillouin optomechanical strong coupling. (a) Artist’s impression of an optical micro-rod-resonator with optical tapered fibre coupling. (b) Optical pumping scheme showing two optical resonances. (c) Experimental Brillouin strong coupling spectra with optical pump power.

3. SINGLE-PHONON ADDITION AND SUBTRACTION TO A MECHANICAL THERMAL STATE

A very powerful technique in quantum optics for state engineering is to perform single-quantum addition or subtraction. These operations have been used to great success for optical fields and are now being explored for mechanical systems.4 A counter-intuitive result is that when either of these operations are applied to a thermal state, the mean number of quanta approximately doubles in both cases.

We perform single-phonon addition and subtraction to a high-frequency acoustic mode via Brillouin scattering.2 These operations are achieved by weakly pumping the Stokes and anti-Stokes interactions in a similar optical microresonator used for the strong coupling work above. Then, performing single-photon detection on
the scattered signal fields heralds a single-phonon addition or subtraction operation to the acoustic mode, respectively. Following a heralding click, to verify the action of these operations on the initial thermal state of the acoustic mode, we use a heterodyne detector to monitor the variance of the acoustic signal. By taking an ensemble average of many thousands of measurement runs we observe this doubling in the mechanical occupation to a high precision (cf. Fig. 2).

Figure 2. Acoustic field readout about single-phonon addition and subtraction operations. The grey lines indicate the optical vacuum level, and the red and blue lines in the two plots indicate the observed heterodyne variance about single-phonon addition (above) and subtraction (below).

4. TOMOGRAPHY OF NON-GAUSSIAN MECHANICAL MOTION GENERATED VIA SINGLE- AND MULTI-PHONON SUBTRACTION

Building on the previous two experiments, in this subsequent work we greatly improved the overall readout efficiency of the acoustic mode and utilized the heterodyne measurement to perform state tomography of the acoustic mode for an initial thermal state as well as a single-phonon and two-phonon subtracted state.\textsuperscript{3} The experimentally observed phase-space distributions for the acoustic mode are shown in Fig. 3.

For quantum state tomography experiments, both inefficiency and any added noise degrade the quality of the distribution generally by a convolution with a Gaussian. The quality of the tomography or reconstruction is then fully quantified by the $s$ parameter. For an $s > -1$ Wigner negativity can be observed and for more negative values the resulting phase-space distribution will always be positive and ‘blurred’. In this work we advance the forefront of optics-based mechanical state tomography by more than an order of magnitude and resolve the non-Gaussianity of the phase-space distributions generated by single- and two-phonon subtraction.

5. OUTLOOK

Owing to the excellent properties of the materials that can be used for such microresonators, we have achieved three of the five criteria outlined in the introduction above. The remaining challenges include performing these experiments at cryogenic temperatures to minimize the mechanical decoherence, and further improvements to the overall readout efficiency. Brillouin optomechanics provides an exciting avenue to circumvent existing roadblocks such as weak coupling and optical-field-induced heating in optomechanics. Moreover, further technical improvements to the state tomography approach utilized here will enable the observation of a mechanical state with a negative Wigner function.\textsuperscript{5} These works help to bridge the realm of Brillouin scattering with quantum optomechanics, and offer an exciting approach for quantum-information applications, such as quantum memories and quantum networking, and for probing the foundations of physics.\textsuperscript{6}
Figure 3. Experimental $s$-parametrized Wigner functions $W_s$ (bottom row), with slices through $P_m = 0$ (top row), for an (a) initial, (b) single-phonon subtracted, and (c) two-phonon subtracted mechanical thermal state. The phase-space distributions are plotted in units of the mechanical zero-point fluctuations $x_{ZP}$ and are obtained through heterodyne detection of the optical anti-Stokes signal. The generation of non-Gaussianity from the originally Gaussian phase-space distribution is observed for single-phonon subtraction, which further grows upon two-phonon subtraction. The dash-dotted lines indicate the theoretically predicted maxima for the $W_s$ functions. The phase-space distribution of the optical vacuum contribution is shown in the inset in (a).

REFERENCES