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Squeezed light in optomechanical systems

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Abstract: Squeezed light enhanced optomechanical measurements are demonstrated in both intra-cavity and biological contexts, with respective enhancements of 1.0 and 2.7 dB. Quantum enhanced microrheology of the cytoplasm of a yeast cell is thereby realized.
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1. Introduction

The quantum nature of light places a fundamental limit on the sensitivity of optical measurements. In circumstances with constrained optical power, this limit may only be surpassed using non-classical resources. Despite the promise of non-classical resources, to date the sole example of a real application is in interferometric gravity wave detection where the optical power is constrained due to absorptive heating[1]. Much broader and widely discussed applications are possible in the areas of quantum optomechanics, where ultimately a non-classical light field interacts with a non-classical mechanical oscillator, and biological sensing[2], where low light levels are often required to avoid damaging the specimen. Here we report two distinct experiments which use squeezed light to, for the first time, achieve quantum enhanced sensitivity in biological and cavity optomechanical contexts, with 2.7 and 1.0 dB of enhancement achieved, respectively. The biological experiments, particularly, allow quantum enhanced microrheology to be performed on the cytoplasm of a *Saccharomyces cerevisiae* yeast cell, revealing subdiffusive motion. This provides a pathway towards microrheology of cell mechanics and the cytoskeleton at high frequencies, where motion amplitudes are beneath the sensitivity of current technology.

2. Microcavity experiment

As shown in Fig. 1, phase squeezed light was injected, on resonance, into a silicon chip based microtoroidal resonator. Microtoroidal resonators exhibit high quality mechanical modes, with an example shown in Fig. 1 (*right*), which have been cooled close to their quantum ground state[3]. The output field from the microtoroid was interfered with a bright local oscillator field on a 50/50 beam splitter. The non-classical photon correlations inherent to phase squeezing allowed the mechanical motion of the microtoroid to be transduced with 1 dB higher sensitivity than the quantum noise limit introduced by quantization of light.

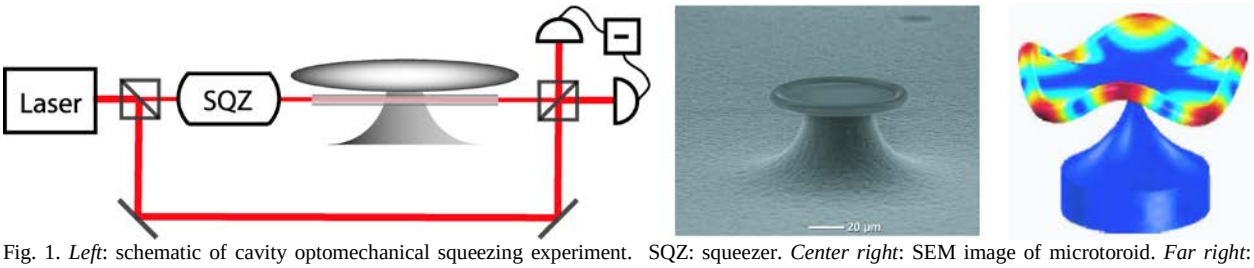

Fig. 1. *Left*: schematic of cavity optomechanical squeezing experiment. SQZ: squeezer. *Center right*: SEM image of microtoroid. *Far right*: microtoroid mechanical mode.

3. Optical tweezers experiment

The apparatus used to demonstrated sub-quantum noise limited sensitivity in a biological context is shown in Fig.~1. A specimen was suspended in water within a sample chamber formed by two microscope coverslips, and trapped with a dual beam optical trap at 1064 nm. An orthogonally polarized amplitude squeezed local oscillator field was spatially engineered using a phase plate for maximum sensitivity to motion of the specimen (see vertical panels on the left of Fig. 2) and injected into an optical tweezers. A further probe laser field, coherent with the squeezed local oscillator field, was injected transversely to the optical axis of the tweezers. Scattering of this field interfered with

the squeezed field, encoding position information about the specimen which could be retrieved via direct detection. Apart from the deleterious effects of optical losses and spatial distortion in the objectives and specimen, a major technical challenge was to minimize exposure to noise sources at the sub~kHz frequencies relevant to biological motion. This was achieved by stroboscopically pulsing the probe field at 3.522~MHz, which had the effect of mixing up the motion into the region of strongest squeezing. This technique should be broadly applicable to squeezed light enhanced sensors.

Motion sensitivity surpassing the quantum noise limit by up to 2.7~dB and 2.4~dB was achieved, respectively, for trapped silica beads and lipid granules within a yeast cell; in both cases allowing the mean squared displacement of the specimen to be more accurately measured than is possible with classical light. The mean squared displacement measurements for yeast with (orange) and without (blue) squeezing are shown in Fig. 2 (*right*), clearing demonstrating the superiority of measurements with squeezed light. The lipid granule exhibits sub-diffusive motion as it interacts with the cells cytoplasm, consistent with recent classical measurements with a different yeast strain[4].

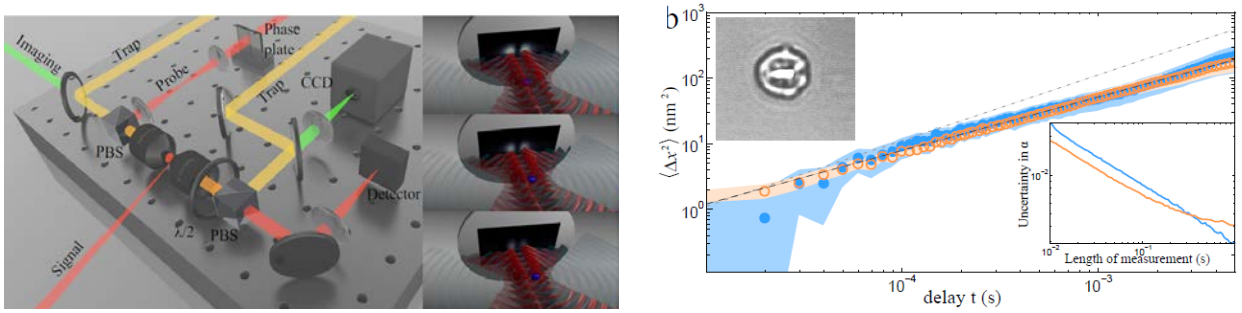

Fig.2. *Left*: experimental schematic, vertical panels show the probe (red) and scattered (blue) fields, illustrating dependence of detected intensity on particle position. *Right*: mean squared displacement measurements on lipid particle within a yeast cell. Orange and blue respectively indicate measurement results and uncertainty with and without squeezed light. Dashed line: expected mean squared displacement for diffusive motion.

4. Conclusion

We have demonstrated optomechanical transduction sensitivity surpassing the quantum noise limit in both cavity optomechanical systems, and optical tweezers. These experiments represent enabling steps towards new practical sensors, including force measurement beyond the standard quantum limit, measurements of the non-Einsteinian Brownian motion[5], and low light level high bandwidth sensing of biological dynamics within living cells[6].

5. Acknowledgements

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