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Optical-Tweezer Phonon Laser

RESEARCHERS

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Lasers—devices that amplify light based on stimulated emission of optical photons—have enabled wide-ranging technological and scientific advances since their first demonstration in 1960.[1] Theoretical and experimental advances have since extended the essential physics behind laser operation to the regime of mechanical vibrations, bringing about the concept of a "phonon laser," which amplifies mechanical vibrations through the analogous process of stimulated emission of mechanical phonons. Such devices could find application in high-precision sensing, mechanical-state engineering and information processing.

In recent work, we merged the phonon laser with another transformational technology: the optical tweezer.[2] This technique, which brought dramatic new capabilities for manipulating matter on the micro and nano scales, gained the 2018 Nobel Prize in Physics for its principal inventor, Arthur Ashkin.[3]

In our work, a levitated nanosphere in an optical tweezer forms a mechanical resonator with multiple degrees of freedom; our study focused on the center-of-mass modes. Using optical feedback based on picometer-scale measurements of the nanosphere's center of mass to modulate the intensity of light in the tweezer, we demonstrated and modeled the essential physics of stimulated emission of center-of-mass phonons into the vibrational mode, resulting in an optical-tweezer phonon laser.

The applied feedback signals are derived from a parametric cooling loop, which reduces the number of center-of-mass phonons and provides the necessary nonlinearity, and an anti–damping signal, which gives rise to linear amplification analogous to a laser gain medium. The combined effect of both feedback signals leads to threshold behavior in the steady-state phonon number and a transition from thermal to nearly Poissonian phonon statistics.

We expect this demonstration to have broad applicability in levitated-optomechanics experiments[4] as a source of coherent phonons at the mesoscale, providing new approaches to precision metrology as well as a pathway toward the generation of nonclassical optomechanical (e.g., levitated Schrödinger cat) states. OPN

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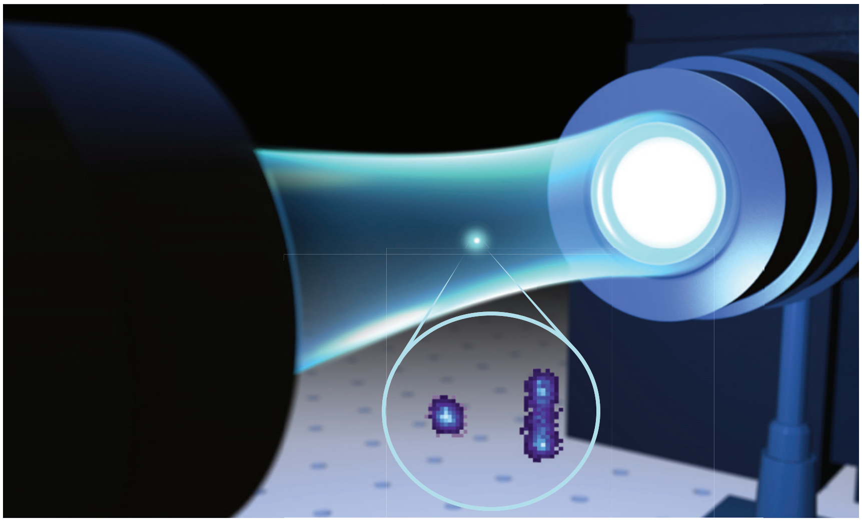

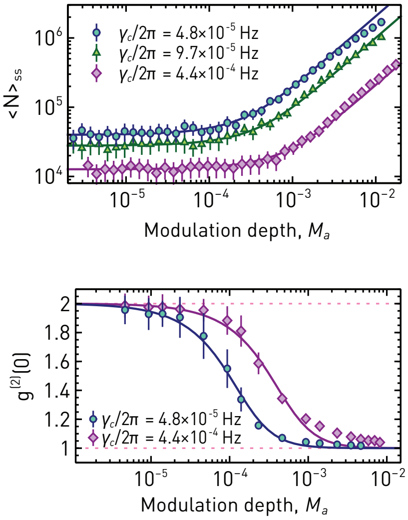

Left: Artist's rendering of a silica nanosphere levitating in an optical tweezer. The inset shows a density map of particle center-of-mass motion revealing (left) Brownian motion below threshold and (right) coherent oscillation above threshold. Top right: Threshold behavior of the steady-state phonon number as a function of linear gain (given by the optical modulation depth, M_a) for various nonlinear cooling strengths, γ_χ. Bottom right: Second-order phonon autocorrelation function at zero-time delay, showing the transition from thermal to nearly Poissonian phonon statistics.