Application Note Parametric Feedback Cooling Beyond the Photon Recoil Limit

Applications: Parametric Feedback Cooling, Optical Trapping

Products: MFLI, VHFLI

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Introduction

Levitated optomechanical systems, such as nanoparticles held in optical traps under high vacuum, serve as a promising platform for exploring quantum physics with massive objects – well beyond what is possible with trapped atoms. Because of their macroscopic mass and extreme isolation from the environment, these systems allow researchers to test quantum mechanics in new regimes, including quantum sensing, studies of decoherence, probing of quantum gravity, dark matter searches, and non-equilibrium thermodynamics.

A key experimental challenge is cooling the particle's motion down to the quantum regime, often achieved using parametric feedback cooling. This technique modulates the trapping potential at twice the mechanical resonance frequency of the particle, providing active control and enabling cooling towards the ground state.

However, conventional optical cooling approaches in these systems are constrained by the photon recoil limit – a fundamental barrier set by the discrete momentum kicks from individual scattered photons – which imposes a classical lower bound on the achievable temperature. Overcoming this limitation is crucial for unlocking the full quantum potential of massive particles.

One way to surpass this limit is to use squeezed light, a special quantum state of light that reduces photon shot noise and thus may decrease the recoil heating rate, enabling optical detection below the standard quantum limit. Noisy Labs provides laser sources capable of delivering squeezed light for such applications, along with dedicated locking technology, improving existing feedback cooling schemes.

At the same time, control electronics that offer real-time, high-performance detection and feedback are essential for any optical cooling experiment. Zurich Instruments' lock-in amplifiers are ideally suited for this task: they support simultaneous multi-channel demodulation of the nanoparticle's motion along all axes, flexible closed-loop feedback, and generation of drive signals for trap modulation. This enables researchers to probe and manipulate levitated optomechanical systems at the quantum level with high sensitivity, with the lock-in amplifier as the centralized hub of the experiment.

Squeezed Light

To understand the effects – and in turn the advantages – of squeezed light on optical cooling, let us review the basic principles.

Photon Statistics and Shot Noise

When photons are detected from a coherent-state field, such as an ideal laser, the arrival events are statistically independent and follow Poisson statistics. The resulting "photon shot noise" sets a fundamental limit on the signal-to-noise ratio of laser-based measurements.

In contrast, detection of a squeezed vacuum field – i.e. a field with no coherent excitation but with fluctuations that can be redistributed – reveals correlated photon pairs. When

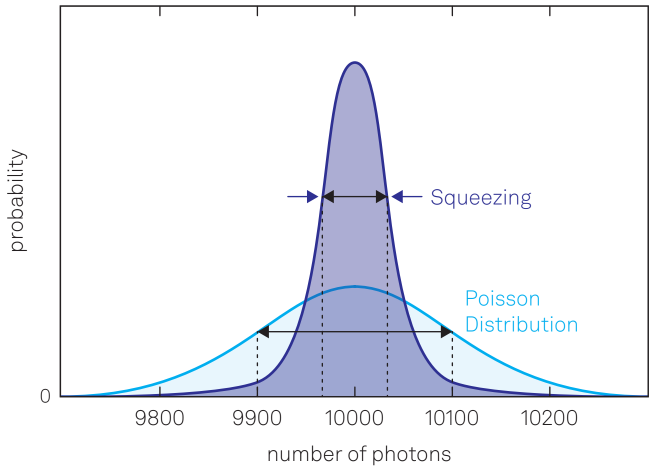

Figure 1. Photon-number probability distributions for a coherent state (light blue) and an amplitude-squeezed state (dark blue) with the same mean photon number. The coherent state follows a Poisson distribution, which gives rise to photon shot noise. The squeezed state exhibits a narrower distribution, corresponding to reduced photon-number fluctuations and, consequently, lower shot noise.

this squeezed vacuum is overlapped with a monochromatic carrier beam, the resulting light exhibits reduced photon shot noise, as depicted in Figure 1.

Quantum Uncertainty Picture

The term “squeezed” can also be understood through the quantum uncertainty of the electromagnetic field. Light in a squeezed vacuum state has a field-strength uncertainty that is smaller than that of a coherent state for certain phases of the wave. To satisfy Heisenberg’s uncertainty relation, a squeezed state must also have phases at which the field uncertainty is anti-squeezed, that is, larger than that of a coherent state.

We distinguish between “amplitude-squeezed states” and “phase-squeezed states.” The only difference lies in the phase relationship between the monochromatic carrier light and the squeezed vacuum state. If the signal of interest is an amplitude modulation of the carrier, the desired phase relation provides amplitude-squeezed states. If the signal is a phase modulation, the desired phase relation provides phase-squeezed states. This is illustrated in Figure 2.

How Noisy Labs Generates Squeezed Light

Noisy Labs uses optical cavities to generate squeezed vacuum states via frequency conversion in nonlinear optical media. This has two main advantages:

- Energy efficiency: the cavity-enhanced process reduces the input power required for the Squeeze Laser. A larger fraction of the light from the driving laser is thus available for the experiment, e.g., for an optical trap.
- Spatial mode quality: the cavity defines the spatial mode of the squeezed beam and is optimized to emit a TEM_{00} mode. This ensures high fringe visibilities and efficient coupling of the squeezed beam into the experimental setup.

Squeezed light therefore holds significant relevance to optomechanical readout. In levitated optomechanics, the particle readout is implemented via homodyne detection and is ultimately limited by optical shot noise. Squeezed light offers a direct route to improving this readout sensitivity without modifying the feedback architecture itself. For motional degrees of freedom whose signals are well mode-matched to the squeezed field, this enables improved feedback cooling performance and facilitates the preparation of quantum motional states.

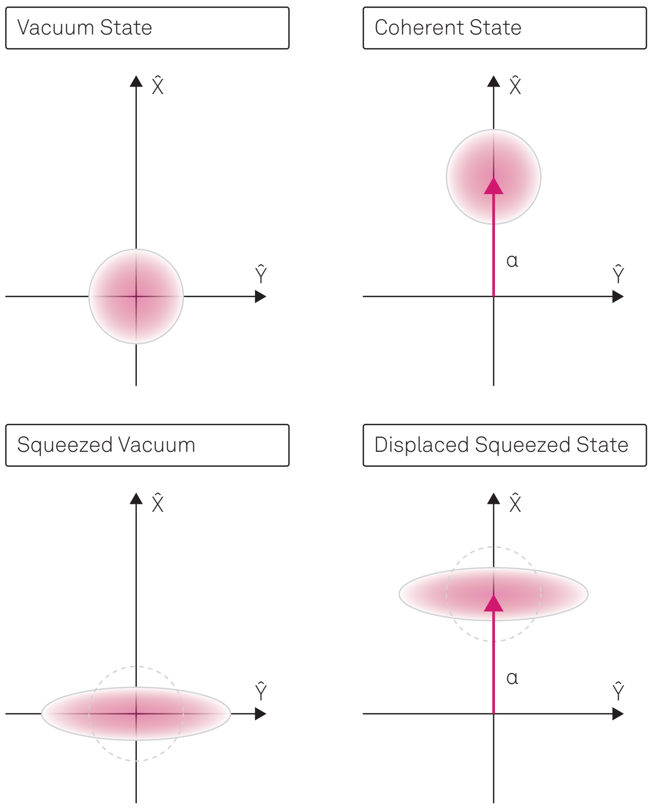

Figure 2. Phase-space representation of four quantum states of light: the vacuum state, the coherent state, the squeezed vacuum state, and the displaced squeezed state. The coherent state is a quantum-mechanical approximation of a conventional laser. The displaced squeezed state is generated by overlapping a coherent state with a squeezed vacuum, e.g., on a 99/1 beam splitter. In this example, the result is an amplitude-squeezed state with a coherent excitation. The reduced uncertainty along the amplitude quadrature ($\hat{X}$) comes at the cost of increased uncertainty along the phase quadrature ($\hat{Y}$), in accordance with Heisenberg’s uncertainty relation.

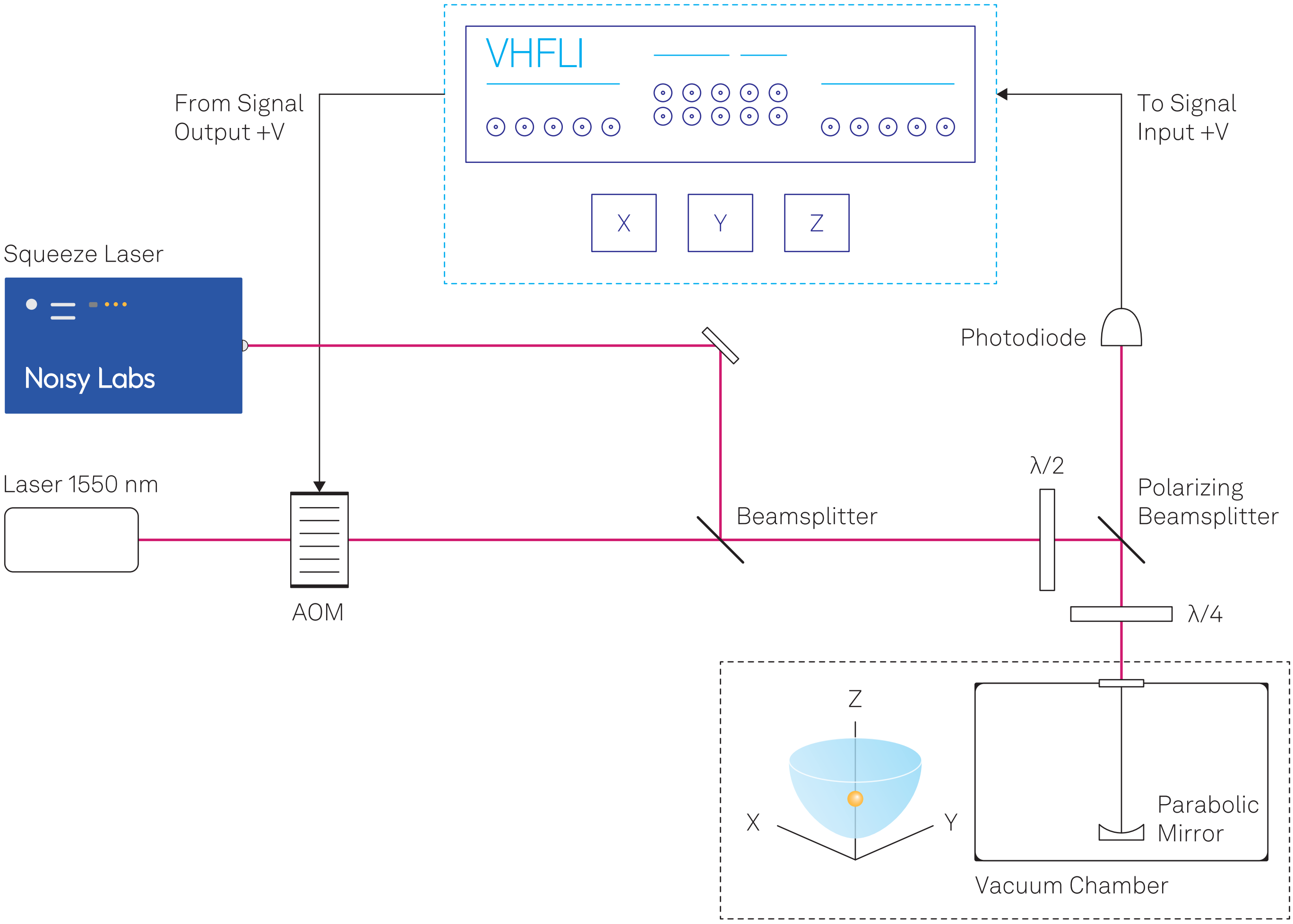

Figure 3. Typical parametric feedback cooling optical setup, with the squeeze laser from Noisy Labs and the lock-in amplifier from Zurich Instruments, see the text for details.

Parametric Feedback Cooling: Concept and Implementation

Parametric Feedback Concept

The key to parametric feedback cooling is modulating the trap stiffness (spring constant) in time at twice the frequency of the particle's oscillatory motion [1]. For each spatial direction i = x, y, z, the trap stiffness is periodically varied as:

$$k_i(t) = k_{0,i} + \delta k_i \cos(2\,\Omega_{m,i}\, t + \phi_i)$$

Where $k_{0,i}$ is the equilibrium spring constant along axis i, $\Omega_{m,i}$ is the mechanical resonance frequency of that axis, δk_i is the modulation depth, and ϕ_i is the relative phase between the feedback signal and the particle's motion. Depending on the feedback phase ϕ_i, the energy of the particle's motion can be either reduced (cooled) or increased (heated). This active modulation enables efficient cooling of all three motional degrees of freedom.

Implementation

Figure 3 illustrates an experimental implementation employing a Squeeze Laser from Noisy Labs and a lock-in amplifier from Zurich Instruments.

An infrared laser generates a tightly focused optical trap, with beam power and frequency controlled via an acousto-optic modulator (AOM). The laser light is superposed with the output of the Squeeze Laser by means of a beam splitter and directed into the vacuum chamber, where a nanoparticle is trapped at the focus of a parabolic mirror. The motion of the particle within the optical potential scatters light, which is collected and directed onto a photodiode for detection.

The photocurrent from the photodiode contains mechanically induced sideband signals encoding the particle's motion along all three spatial axes (x, y, z). This signal is fed into the lock-in amplifier, where it is demodulated at the corresponding mechanical resonance frequencies $\Omega_{m,i}$ for each axis, allowing simultaneous real-time monitoring of the 3D motion.

Zurich Instruments lock-in amplifiers allow this principle to be implemented fully digitally in one single instrument, with flexible and programmable control:

- **Sensing:** The lock-in demodulates the photodiode signal at each resonance frequency $\Omega_{m,i}$ to extract displacement information along all three axes from a single detector.
- **PLL Tracking:** A phase-locked loop locks to for $\Omega_{m,i}$ each axis, tracking thermal and environmental drifts in real time.
- **Parametric Drive:** A second demodulator per axis doubles the locked frequency, generating $2\,\Omega_{m,i}$ the modulation signal that controls the AOM (or EOM), directly implementing the feedback term $\delta k_i \cos(2\,\Omega_{m,i}\,t + \phi_i)$ from the equation above.
- **Phase and Amplitude Tuning:** Digital control enables precise adjustment of the feedback phase ϕ_i and modulation depth δk_i. The phase unwrapping capabilities of the instruments allow for an increased lock range of the PLL, critical for stable cooling.

Implementing cooling in all three spatial directions (i.e., a full 3D Gaussian optical potential) requires at least six independent demodulators. Depending on the frequency requirements, two MFLIs (4 demodulators per instrument) or a single VHFLI (8 demodulators per instrument) is an ideal solution.

Outlook

Gonzalez-Ballestero et al. [2] calculated that control over the squeezed measurement quadrature provides additional flexibility in the measurement–backaction trade-off. In particular, squeezing allows noise to be redistributed between measurement imprecision and backaction. This means that one can exchange increased measurement noise for reduced recoil heating, or vice versa, depending on the chosen measurement quadrature and squeezing angle. This control enables optical detection beyond the standard quantum limit and leads to improved measurement-based feedback cooling schemes, while also extending the coherence time of optically levitated nanoparticles in the quantum regime.

By combining Noisy Labs' squeezed-light sources with the real-time multi-channel feedback capabilities of Zurich Instruments' lock-in amplifiers, researchers can push parametric feedback cooling beyond the photon recoil limit, opening the door to ground-state preparation and quantum-level control of massive levitated particles.

References

[1] J. Gieseler, B. Deutsch, R. Quidant, and L. Novotny, "Subkelvin Parametric Feedback Cooling of a Laser-Trapped Nanoparticle," Phys. Rev. Lett. 109, 103603 (2012).

[2] C. Gonzalez-Ballestero, J. A. Zielińska, M. Aspelmeyer, and O. Romero-Isart, "Suppressing Recoil Heating in Levitated Optomechanics Using Squeezed Light," PRX Quantum 4, 030331 (2023).