Dissipative engineering of entangled mechanical states in a multimode optomechanical system with a squeezed reservoir

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Abstract: We describe a protocol for preparing stationary entangled states of multiple mechanical resonators using a squeezed reservoir in a multimode optomechanical system. We show how this approach can be applied to generate Gaussian cluster states.

Advancing quantum technologies relies on the ability to reliably prepare and control quantum states with high precision. Among the available approaches, opto- and electromechanical systems stand out because they extend quantum control to macroscopic degrees of freedom while naturally linking otherwise distinct physical platforms. When these systems operate in a multimode regime (featuring multiple mechanical and electromagnetic modes coupled coherently), they become flexible architectures for the controlled generation of complex quantum states, with broad potential across quantum applications.

Here we focus on schemes based on engineered dissipation, where the environment of interacting quantum systems is tailored so that controlled dissipation, combined with coherent interactions, drives the system toward desired dynamics. Notably, it has been shown that multipartite entangled steady states of many bosonic modes with passive (particle-conserving) couplings can be obtained by squeezing the environment of a single mode [1]. Within this framework, one can generate any pure Gaussian state obtainable through particle-conserving quadratic operations (such as beam splitters and phase shifts) acting on equally squeezed modes [1], including Gaussian cluster states relevant for continuous-variable measurement-based quantum computation.

We demonstrate [2] that a multimode optomechanical platform can realize this dissipative dynamics (see Fig. 1). Our aim is to engineer the quantum state of the mechanical modes, which interact indirectly via optical fields. When the optical dynamics are fast, these degrees of freedom can be adiabatically eliminated, leading to an effective model for the mechanical modes analogous to that of Ref. [1], though with additional noise affecting all modes. When the optically induced phonon–phonon couplings match the required Hamiltonian and the mechanical noise remains low (as in the dispersive regime, where optically induced dissipation is negligible), the system approaches the targeted steady states.

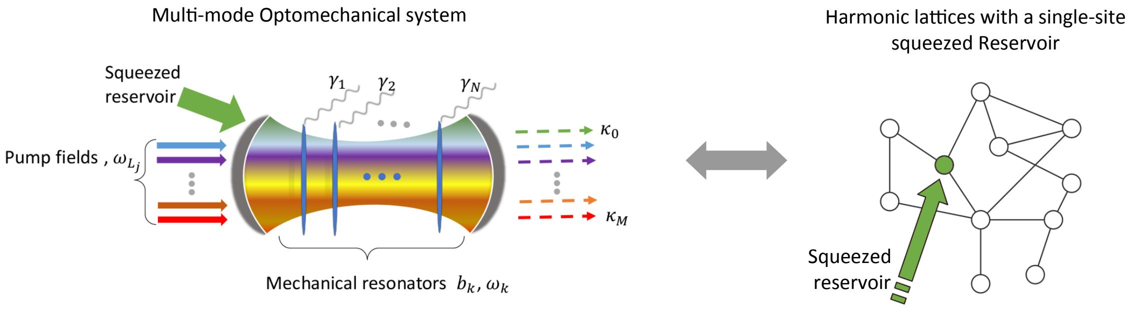

Fig. 1 The dynamics of a multimode optomechanical system with a squeezed reservoir can be mapped to those of a harmonic lattice with a single localized squeezed reservoir, which can sustain highly entangled pure steady states [1].

Finally, we study the performance of this protocol for producing mechanical cluster states on rectangular lattices [2], showing that they can be realized using GHz-frequency mechanical resonators with quality factors on the order of 10^8 (see Fig. 2).

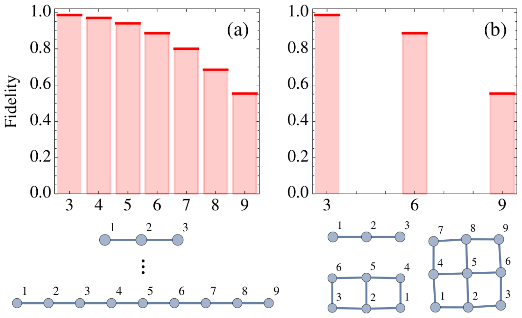

Fig. 2 Fidelity for the preparation of Gaussian cluster states with linear (a) and rectangular (b) graphs.

References

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[2] Nahid Yazdi, Stefano Zippilli, David Vitali, ”Multimode Gaussian steady state engineering in optomechanical systems with a squeezed reservoir”, arXiv:2509.16371 (2025).