Quantum memories for squeezed and coherent superpositions in a driven-dissipative nonlinear oscillator

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Quantum oscillators with nonlinear driving and dissipative terms have gained significant attention due to their ability to stabilize cat-states for universal quantum computation [1, 2, 3]. Recently, superconducting circuits have been employed to realize such long-lived qubits stored in coherent states [4]. We present a generalization of these oscillators, which are not limited to coherent states, in the presence of different nonlinearities in driving and dissipation, exploring different degrees. The master eqation describing the time evolution of such oscillators is given by

$$\rho t = -i[H_n, \rho] + \gamma_1 D[]\rho + \gamma_m D[^m]\rho \equiv \mathcal{L}\rho, \quad (1)$$

where in the Liouvillan superoperator $\mathcal{L}$ we distinguish three different terms. First, the unitary evolution described by the Hamiltonian, which in the rotation frame and after the parametric approximation is

$$H_n = \Delta + i\eta_n \left[^n e^{i\theta_0 n} - ()^n e^{-i\theta_0 n}\right] . \quad (2)$$

This models an n-photon drive with $n \geq 1$, where the detuning between the natural oscillator frequency ω_0 and the frequency of the driving force ω_s is denoted by $\Delta = \omega_0 - \omega_s$. This n-photon parametric process produces squeezing effects for $n > 1$ and will be called the squeezing term in the following. The parameter η_n controls the driving strength and ϕ represents its phase.

Specifically, we present an extensive analysis of the asymptotic dynamical features and of the storage of squeezed states. We demonstrate that coherent superpositions of squeezed states are achievable in the presence of a strong symmetry, thereby allowing for the storage of squeezed cat-states. In the weak symmetry regime, accounting for linear dissipation, we investigate the potential application of these nonlinear driven-dissipative resonators for quantum computing and quantum associative memory [5] and analyze the impact of squeezing on their performance [6].

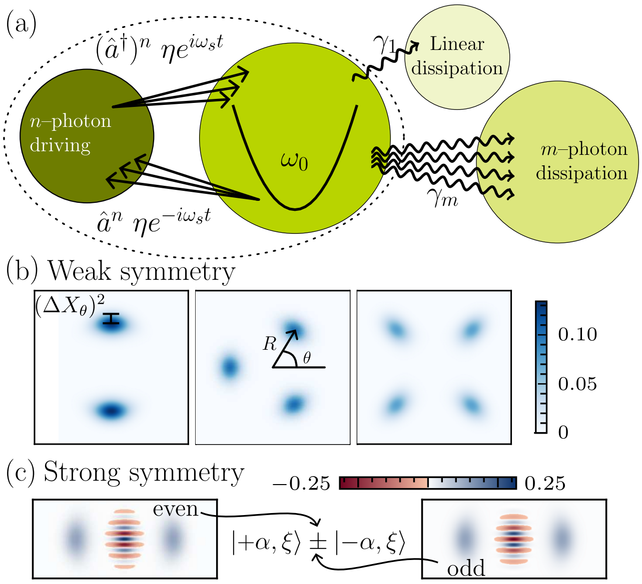

Fig. 1. (a) Sketch of the driven-dissipative nonlinear oscillator with the three processes involved in the master equation: nonlinear periodic driving with degree n, linear dissipation with rate γ_1 and nonlinear dissipation of degree m. The driving force pushes the system with strength η and frequency ω_s that may deviate from the natural oscillator frequency ω_0. The dissipative terms emit photons out of the system at rates γ_1 and γ_m for the single- and multi-photon processes respectively. (b) Wigner distribution of the steady states generated in the weak symmetry regime with $\gamma_1 > 0$. From left to right: $(n, m) = \{(2, 3), (3, 4), (4, 3)\}$. (c) Wigner distribution of the two steady states (corresponding to even and odd parity eigenstates) present in the strong symmetry regime with $\gamma_1 = 0$ and $(n, m) = (2, 4)$.

[1] B M Terhal, J Conrad, and C Vuillot. Towards scalable bosonic quantum error correction. *Quantum Science and Technology*, 5(4):043001, jul 2020.

[2] Weizhou Cai, Yuwei Ma, Weiting Wang, Chang-Ling Zou, and Luyan Sun. Bosonic quantum error correction codes in superconducting quantum circuits. *Fundamental Research*, 1(1):50–67, 2021.

[3] Mazyar Mirrahimi, Zaki Leghtas, Victor V Albert, Steven Touzard, Robert J Schoelkopf, Liang Jiang, and Michel H Devoret. Dynamically protected cat-qubits: a new paradigm for universal quantum computation. *New Journal of Physics*, 16(4):045014, 4 2014.

[4] Raphaël Lescanne, Marius Villiers, Théau Peronnin, Alain Sarlette, Matthieu Delbecq, Benjamin Huard, Takis Kontos, Mazyar Mirrahimi, and Zaki Leghtas. Exponential suppression of bit-flips in a qubit encoded in an oscillator. *Nature Physics*, 16(5):509–513, May 2020.

[5] Adrià Labay-Mora, Roberta Zambrini, and Gian Luca Giorgi. Quantum associative memory with a single driven-dissipative nonlinear oscillator. *Phys. Rev. Lett.*, 130:190602, May 2023.

[6] Adrià Labay-Mora, Roberta Zambrini, and Gian Luca Giorgi. Quantum memories for squeezed and coherent superpositions in a driven-dissipative nonlinear oscillator, 2023.