NONLINEAR COOLING OF A QUANTUM MICRO-CIRCUIT

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Abstract: *The cooling effects of a quantum LC micro-circuit coupled inductively with a single or an ensemble of artificial qubits are investigated. For appropriate bath temperatures and the resonator's quality factors, we demonstrate an effective cooling well below the thermal background. In particular, we found that for larger samples the cooling efficiency is significantly improved by the coupling to the multi-qubit ensemble.*

Keywords: *Cooling, LC circuit, Josephson junction, multi-qubit systems*

I. Introduction

The ability to cool interacting quantum systems below the values imposed by the thermal fluctuations of the environmental reservoir of each subsystem is actually of great interest [1]. Via engineering superconducting elements as artificial atoms and coupling them to a photon field of a resonator or to vibrational states of a nano-mechanical resonator one can demonstrate interesting phenomena such as single artificial atom lasing or cooling. In particular, schemes to ground-state cooling of mechanical resonators were proposed in [2]. A flux qubit was experimentally cooled [3] using techniques somewhat related to the well-known optical sideband cooling methods (see, e.g., Ref. [1] and references therein). Lasing effects of a Josephson-junction charge qubit, embedded in a uperconducting resonator, was experimentally demonstrated in [4]. Single-qubit lasing and cooling at the Rabi frequency was proposed in [5], while a mechanism of simultaneously cooling of an artificial atom and its neighboring quantum system was analyzed in [6]. Few-qubit lasing in circuit QED was discussed in Ref. [7]. A LC oscillator can be cooled via its nonlinear coupling to a Josephson flux qubit [8]. The cooling of a nanomechanical resonator via a Cooper pair box qubit has been recently suggested in Ref. [9] while cooling carbon nanotubes to the phononic ground state with a constant electron current was achieved in [10].

Here, we describe a cooling scheme via coupling a pumped multi-particle ensemble (i.e. artificial atoms or qubits) to a single mode of a quantum LC circuit. Our motivation is to present an efficient method allowing for a rapid cooling of the resonator mode. The multi-qubit system can be formed by an independent N particle sample. By independent, we mean that each particle spontaneously decays individually and all of them are maximally coupled with the oscillator mode and with the same phase. We found that the cooling phenomenon is better for such independently interacting qubits if the quantum dynamics of the LC oscillator is slower than that of the qubits. Apart from a fundamental interest, these systems have a great feature in various applications such as novel quantum sources of light (single photon sources, for instance), quantum processing of information or entanglement. However, at MHz frequency ranges thermal fluctuations affect considerably the LC oscillators, i.e., populate their energy levels and induce additional decoherences. Therefore, a suitable method to cool these systems can be very useful.

The paper is organized as follows. In Sec. II we introduce the system of interest. Section III describes the obtained results. We finalize the article with conclusions presented in Section IV.

II. System of interest

We consider the cooling effects of a quantum oscillator mode, i.e. a quantum LC circuit coupled inductively with a single or a collection of two-level Josephson flux qubits. The two-level particles are pumped with a moderately intense magnetic flux, possessing detuning $\delta\omega$, and damped spontaneously via their interactions with the environmental electromagnetic field reservoir. The single-particle spontaneous decay rate is γ. Both subsystems interact with thermostats at effective temperatures T_1 and T_2. We shall consider that particles are independent. The frequency of the oscillator is much lower than the qubit's tunnel splitting, i.e. $\omega_c << \Delta$. Therefore, the qubit is driven with Rabi frequencies near resonance with the oscillator frequency that affect the oscillator, increasing its oscillation amplitude [8].

III. Results and discussion

In the mean-field, dipole, Born-Markov and secular approximations, the combined system is characterized by the following master equation:

$$(d/dt)\rho + i[H, \rho] = -\Lambda_a\rho - \Lambda_c\,\rho. \quad (1)$$

Here, the $[H, \rho]$ term describes the coherent evolution of the system. The quantum dissipation due to spontaneous emission into surrounding electromagnetic field reservoir is described by the $\Lambda_a\rho$ term, while the damping of the quantum oscillator mode is given by the last term in Eq. (1).

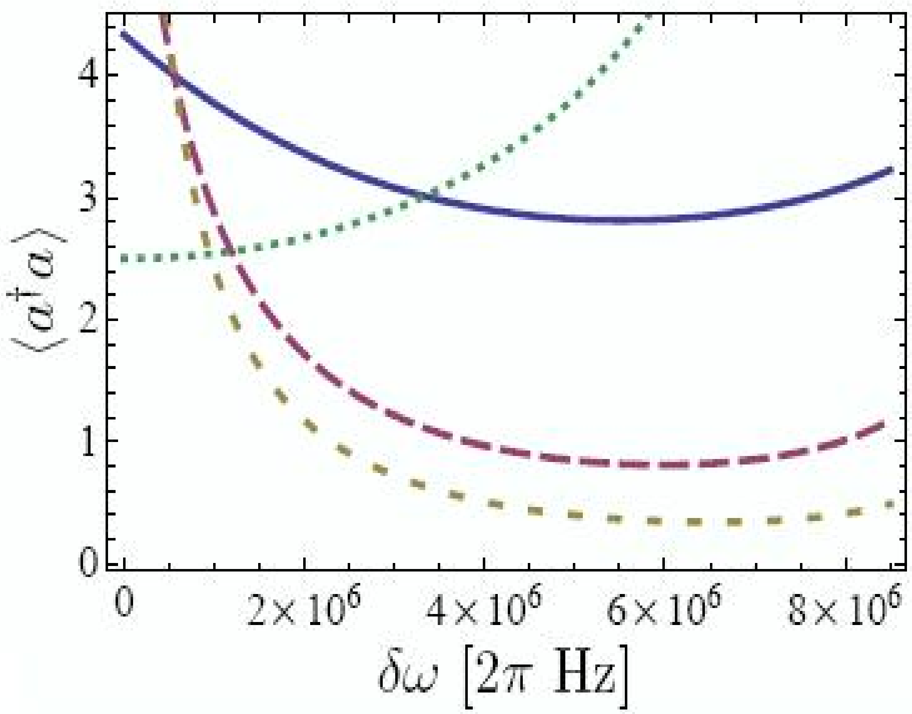

Fig.1. (color online) The mean photon number $\langle n\rangle$ into the quantum circuit as function of $\delta\omega$ and different numbers of independent qubits. The solid line is for N = 1, the long-dashed line stands for N = 10, while the short-dashed curve corresponds to N = 30. The dotted curve shows the saturation photon number n_0 for N = quibits

We have solved numerically Eq. (1) when the qubit quantum dynamics is faster that the one of the LC resonator. Figure (1) depicts the mean photon number in the oscillator mode which is coupled with N independent qubits. We have used typical parameters here. To elucidate the role of many particles regarding the cooling issue, we fix the involved parameters and change the number of qubits. Already for N = 10 particles, the cooling efficiency is significantly improved in comparison to the single-qubit case, i.e. N = 1. Better cooling can be achieved by increasing further the number of qubits (see the short-dashed curve in Fig. 1). Evidently, the qubits are in their lower dressed-state when cooling occurs. Finally, we discuss the time scaling for the cooling phenomenon. The cooling rates depend on the number of qubits and, therefore, the cooling may occur faster than for a single artificial particle [8].

IV. Conclusion

In summary, we described a scheme that is able to cool a quantum LC micro-circuit coupled inductively to externally pumped artificial particles (Josephson flux qubits) and damped through their interaction with the environmental electromagnetic field reservoir. If the qubit's dynamics is faster than the one of the LC oscillator, the cooling of the oscillators degrees of freedom occurs when controlling the qubit quantum dynamics. We found that the cooling phenomenon is better for an ensemble of independent qubits rather than for a single artificial particle.

V. References

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