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Photon Blockade via Frequency Chirped Excitations

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Abstract. Frequency-chirped systems have attracted widely attentions in both experiments and theory that is motivated by both testing of quantum optics theory and engineering new devices. In this report, we propose to use the frequency-chirped excitations for realizing effective mechanism of Photon Blockade.

Keywords: Photon blockade, Cavity QED, frequency-chirped excitations

1. Introduction

Resonators consisting Kerr-nonlinear element under continuous or pulse driving are widely used for precision measurement [1], modeling nonlinear phenomena [2] and generation of non-classical states of light. In recent years, frequency-chirped systems have attracted widely attentions in both experiments and theory that is motivated by testing fundamental quantum optics theory and for the purposes of developing devices. In this paper, we investigate Kerr-nonlinear resonator in regime of continuous-wave driving with chirped frequency on the base of the master equation in complete quantum analysis of autoresonant transitions in presence of dissipation. This approach allows to consider control of production of photon-number states and enhancing of photon blockade by self-adjusting the drive frequency of resonator. Particularly, the capture of a single photon into the system affects the probability that a second photon is admitted. A simple consequence of photon blockade is the antibunching of photons in emission in analogy to the photon antibunching of resonance fluorescence on a two-level [3,4]. Photon blockade was first observed in an optical cavity coupled to a single trapped atom [5]. The PB has been predicted in cavity quantum electrodynamics (QED) [6], and recently in circuit QED with a single superconducting artificial atom coupled to a microwave transmission line resonator [7,8]. PB was also experimentally demonstrated with a photonic crystal cavity with a strongly coupled quantum dots [9], and was also predicted in quantum optomechanical systems [10,11]. An analogous phenomenon of phonon blockade was predicted for an artificial superconducting atom coupled to a nanomechanical resonator [12], as well as the polariton blockade effect due to polariton-polariton interactions has been considered in [13]. Recently, PB was considered in dispersive qubit-field interactions in a superconductive coplanar waveguide cavity [14] and with time-modulated input [15]. We clarify the chirp effects in Kerr nonlinear resonator by considering photon-number effects and by analyzing phase-space properties of resonator mode. Thus, we focus on analysis of the mean photon number, the probability distributions of photons, the Wigner functions in phase space.

2. Model description

The Kerr nonlinear resonator under CW field and interacting with a reservoir is described by the following Hamiltonian

$$H = \hbar\omega_0 a^+ a + \hbar\chi(a^+)^2 a^2 + \hbar\Omega(a e^{-i\omega t} + a^+ e^{i\omega t}), \qquad (1)$$

where a^+, a are the oscillatory creation and annihilation operators, is the oscillatory frequency, ω is a frequency of driving field and χ is the nonlinearity strength. We consider that field frequency is chirped so it is varying over a time linearly $\omega(t) = \omega + \alpha t$. Considering chirped field and applying rotating wave approximation on Hamiltonian we will have the following Hamiltonian

$$H = \hbar(\Delta - \alpha t)a^+a + \chi(a^+)^2a^2 + \Omega(a^+ + a), \qquad (2)$$

where $\Delta = \omega_0 - \omega$ and α is the chirp rate.

This model seems experimentally feasible and can be realized in several physical systems. Particularly, the effective Hamiltonian (2) describes a qubit off-resonantly coupled to a driven cavity. In fact, it is well known that the Hamiltonian of two-level atom interacting with cavity mode in the dispersive approximation, if the two-level system remains in its ground state, can be reduced to the effective Hamiltonian. This model also describes a nanomechanical oscillator with a^+ and a raising and lowering operators related to the position and momentum operators of a mode quantum motion. An important implementation of Kerr-type resonator has been recently achieved in the context of superconducting devices based on the nonlinearity of the Josephson junction. We have included dissipation and decoherence in Kerr nonlinear resonator on the basis of the master equation:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H,\rho] + \sum_{i=1,2}\left(L_i\rho L_i^\dagger - \frac{1}{2}L_i^\dagger L_i\rho - \frac{1}{2}\rho L_i^\dagger L_i\right), \qquad (3)$$

where $L_1 = \sqrt{(N+1)\gamma}a$ and $L_2 = \sqrt{N\gamma}a^+$are the Lindblad operators, γ is a dissipation rate, and N denotes the meannumber of quanta of a heat bath.

To study the pure quantum effects, we focus on the cases of very low reservoir temperatures, which, however, ought to be still larger than the characteristic temperature $T \gg T_{cr} = \gamma/k_B$. This restriction implies that dissipative effects can be described self-consistently in the frame of the Linblad equation. In our numerical calculation we choose the mean number of reservoir photons $N=0$.

We solve the master equation Eq. (3) numerically based on quantum state diffusion method. The application of this method for studies of NDO can be found in [16-19]. In the calculations, a finite basis of number states $|n\rangle$ is kept large enough so that the highest energy states are never populated appreciably. Solving the equation (3), we calculate the distribution of oscillatory excitation states $P(n) = \langle n|\rho|n\rangle$ as well as the Wigner functionsin terms of the matrix elements $\rho_{nm} = \langle n|\rho|m\rangle$ of the density operator in the Fock state representation.

3. Results

In a classical inharmonic oscillator, the energy expectation can be deterministically increases to large values if the driving force is frequency-chirped and its amplitude is sufficiently large. This phenomenon is commonly known as autoresonance. It leads to excitation and control of nonlinear oscillatory systems by a continuous self-adjustment of systems' parameters to maintain the resonance with frequency-chirped drive. In semi-classical approach for the case of a stronger drive amplitude the response of the nonlinear resonator changes dramatically. If the chirp passes through oscillatory frequency, beyond the threshold the resonator phase becomes locked and the mode amplitude grows

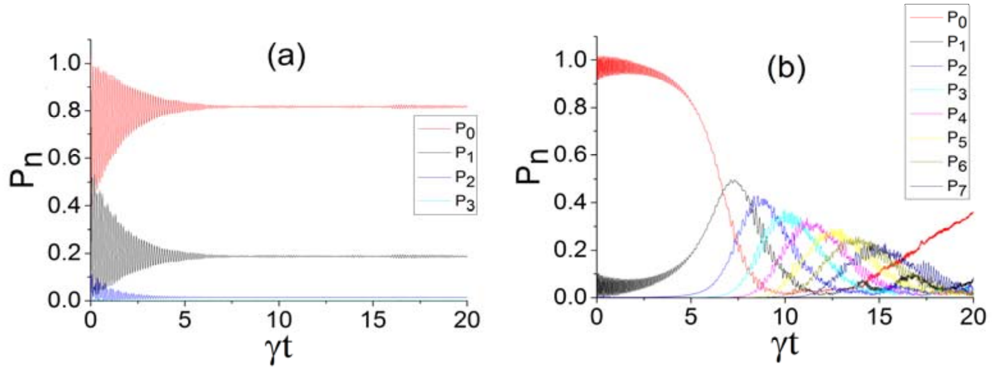

Fig. 1. Time-dependent populations for the following parameters:(a) $\chi/\gamma = 10, \Delta/\gamma = 40\,\Omega/\gamma = 20, \alpha/\gamma^2 = 0$ and (b) $\chi/\gamma = 10, \Delta/\gamma = 40, \Omega/\gamma = 20, \alpha/\gamma^2 = 16$.

with time. In general, autoresonance phenomenon has been observed in many fields of physics, for atomic and molecular systems, nonlinear optics, hydrodynamics, nonlinear waves and quantum wells. In a quantum inharmonic oscillator, the expected time evolution under a similar drive is sequential excitation of single energy levels of the system, or “quantum ladder climbing”. We discussed ladder climbing effect for frequency chirped excitation in presence of decoherence and dissipation.

In Fig. 1 we have demonstrated populations of photon-number states, in plot (a) there is only CW field where we can see that maximum population values are for vacuum state 0.8 and single photon state 0.2, population of higher photon-number states are equal to 0. To be able to generate high

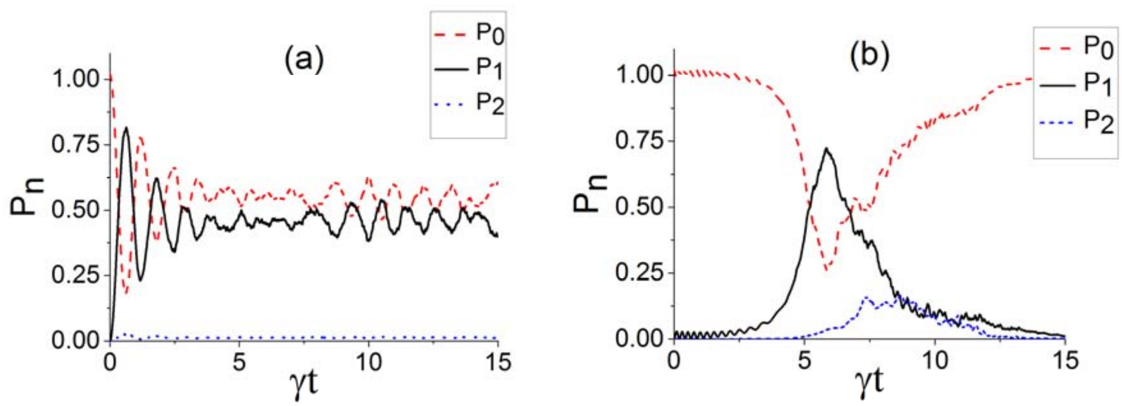

Fig. 2. Time-dependent populations for the following parameters:$(a)\chi/\gamma = 10, \Delta/\gamma = 1.2, \Omega/\gamma = 2.7, \alpha/\gamma^2 = 0$and (b)$\chi/\gamma = 10, \Delta/\gamma = 1.2, \Omega/\gamma = 2.7, \alpha/\gamma^2 = 6$.

population values for multiphoton states we use frequency-chirped field with high chirp rate and high amplitude. Results for frequency-chirped field are illustrated in Fig 1 (b). Existence of chirp field results sequential excitation of system up to $|7\rangle$ photon number state. Population maximum values for each photon state are equally shifted from each other and values are monotonically decreasing by the increase of photon-number state, particularly 0.5 for $|1\rangle$ photon state, 0.42 for $|2\rangle$ photon state and 0.2 for $|7\rangle$ photon number state. We also discussed system behavior in case of lower amplitude and lower chirp rate. This destructs ladder climbing behavior of the system and makes population value peaked in time range Fig 2 (b). In general, from the analytic results and numerical analysis we conclude that in our system under CW field populations are strongly limited [20].

Fig. 2 (a) illustrates that population of $|1\rangle$ state in steady state regime is saturated near 0.5, but in

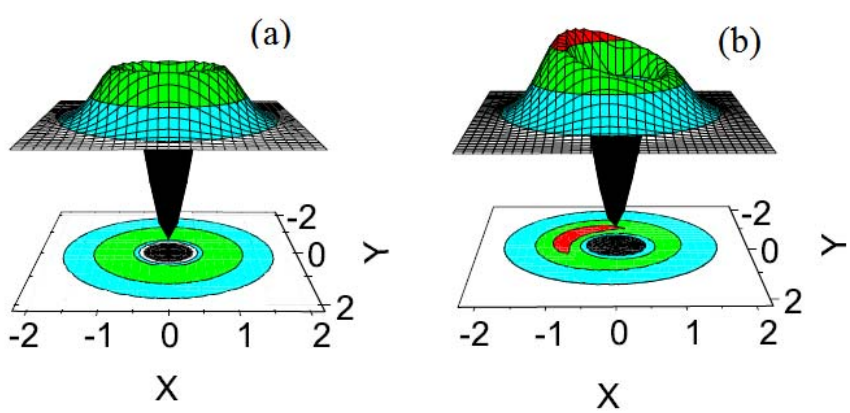

Fig. 3. Wigner function of pure $|1\rangle$ state (a), and (b) Wigner function for the time corresponding to the maximal population of $|1\rangle$ state. Parameters are same as for Fig. 2 (b).

the Fig 2(b) we can see increase of population of $|1\rangle$ state up to 0.75. We have also calculated Wigner function for the time corresponding to the maximal population of $|1\rangle$ state and compared this with Wigner function of pure $|1\rangle$ state to show visual pureness of the state. Having high population for $|1\rangle$ state means that we have a same probability of single photon blockade effect, which means that the generation of two or higher photon number states are blocked.

4. Conclusion

Thus, we have demonstrated mechanism of quantum ladder climbing effect in presence of dissipation and decoherence. We have reached high population values for high photon number states in ladder climbing mode. We have also demonstrated that of frequency-chirped fieldgains the single photon blockade efficiency by 30% breaking the limit of the CW field.

Acknowledgements

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References

[1] A. Imamoglu, H. Schmidt, G. Woods, and M. Deutsch, Phys. Rev. Lett. **79,** 1467 (1997)
[2] M. J Werner and A. Imamoglu, Phys. Rev. A 61, 011801(R) (1999)
[3] H. J. Carmichael, D.F. Walls, J. Phys. B: Atom. Molec. Phys. L9 (1976)
[4] H. J. Kimble, M. Dagenais, L. Mandel, Phys. Rev. Lett. **39**, (1977) 691
[5] K. M. Birnbaum et al., Nature 436, (2005)87
[6]L. Tian and H. J. Carmichael Phys. Rev. A 46, (1992), R6801
[7] A. J. Hoffman et al., Phys. Rev. Lett. 107, 053602 (2011).
[8] C. Lang et al., Phys. Rev. Lett. 106, 243601 (2011).
[9] A. Faraon, I. Fushman, D. Englund, N. Stoltz, P. Petroff, J. Vuckovic, Nat. Phys. 4, 859 (2008).
[10] P. Rabl, Phys. Rev. Lett. 107, 063601 (2011).
[11] A. Nunnenkamp, K. Borkje, and S. M. Girvin, Phys. Rev. Lett. 107, 063602 (2011).
[12] Y. X. Liu, A. Miranowicz, Y. B. Gao, J. Bajer, C. P. Sun, and F. Nori, Phys. Rev. A 82, 032101 (2010).
[13] A. Verger, C. Ciuti, and I. Carusotto, Phys. Rev. B 73, 193306 (2006).
[14] A. J. Hoffman, S. J. Srinivasan, S. Schmidt, L. Spietz, J. Aumentado, H.E. Tureci, and A.A. Houck, Phys. Rev. Lett. 107, 053602 (2011).
[15] A. Faraon, A. Majumdar, and J. Vuckovic, Phys. Rev. A 81, 033838 (2010).
[16] T.V. Gevorgyan, A. R. Shahinyan, and G. Yu. Kryuchkyan, Phys. Rev. A 79, 053828 (2009).
[17] T.V. Gevorgyan, A. R. Shahinyan, and G. Yu. Kryuchkyan, Phys. Rev. A 85, 053802 (2012).
[18] T.V. Gevorgyan, A.R. Shahinyan, Lock Yue Chew and G.Yu. Kryuchkyan, Phys. Rev. E 88, 022910 (2013).
[19] T.V. Gevorgyan and G.Yu. Kryuchkyan, Journal of Modern Optics 60, 860 (2013).
[20] A. Shahinyan, A. Tamazyan, and G.Yu. Kryuchkyan, Eur. Phys. J. D 70: 131 (2016)