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Phonon blockade in a double cavity optomechanical system containing superconducting qubits driven by squeezed light

Anjan Samanta[1,2] and Paresh Chandra Jana[2]

[1] Department of Physics, Sabang Sajanikanta Mahavidyalaya, Lutunia, Paschim Medinipur, 721166, India
[2]Department of Physics, Vidyasagar University, Paschim Medinipur, 721102, India

Abstract

We have explored the phonon statistics in a mechanical resonator, which is coupled with Superconducting qubits and driven by squeezed light. The quantum nature of a mechanical resonator can be achieved by the phonon blockade mechanism. The non-linearity must be very large as compared to the optical mode line width to suppress the unwanted transitions. We observe the strong phonon antibuncing effect i.e., unconventional phonon blockade mechanism which relies on close to Gaussian states under weak driven squeezed light. By numerical solution of second-order and third-order correlation functions, we analyse the Sub-Poissonian phonon statistics. Due to the high nonlinearity of the system and interaction strength between superconducting qubits and cavities, the phonon blockade effect is controlled. Here squeezing light is the main key that helps for the development of quantum computers, and generates second harmonics. Superconducting qubits help to detect the blockade effect by measuring the states. The present mechanism has much more attractive applications in optical communication and sensitive measurements such as the detection of gravitational waves or noise-free amplifications.

Keywords: Phonon Blockade, Squeeze light, Generation second harmonics.

1. Introduction

Phonon blockade is a quantum phenomenon, where the system is allowed to emit or absorb a single phonon at a time by blocking the simultaneous presence of multiple phonons in the system. Phonons are quantized units of mechanical resonators and are generated during the vibration of the resonator. The mechanism of phonon blockade is similar phenomena of photon blockade or magnon blockade in quantum optics and achieved through strong nonlinear interaction in an optomechanical system, where a mechanical resonator is coupled with an external electromagnetic field. When these interactions are strong, then the vibration energy levels become asymmetrical, and unfavorable for multiple phonons to occupy the same mode simultaneously. Phonon blockade in nanomechanical resonators can be realized theoretically and experimentally and discussed potential applications [1-2]. The entanglement and squeezing of mechanical resonators have been discussed by providing theoretical recognition of the dynamics of phonon blockade [3]. The theoretical background of phonon blockade has been discussed by using the interaction between Josephson qubits and nanomechanical resonators [4] Phonon blockade has been observed in systems: like quantum dots, where the vibrating energy is highly quantized, and the interaction between phonons and the electronic states creates a nonlinear response. Systems exploring phonon blockade have been extremely sensitive to fractional changes in their environment, this theme is applicable for high-precision sensing applications.

2. The model of the system

. We consider a Hamiltonian for describing the optomechanical system. The system has two micro-cavity as depicted in figure-1. One micro-cavity is passive with the decay rate $\kappa_1$that is based on external coupling loss and intrinsic loss. Another micro-cavity is active with an actual loss rate κ_2 that is based on round trip energy gain rate and intrinsic rate. The actual loss rate may be positive (loss) or negative (gain) depending on the round-trip energy gain. Based on gain to loss ratio the optomechanical system behaves like a Passive-Passive (κ_1 and κ_2 both are positive) and Passive –Active system (κ_1 is positive and κ_2 is negative). To observe the phonon blockade mechanism the system is Passive-Active. The optical cavity system coupling with a mechanical resonator with damping rate γ. The Active cavity contains a superconducting two-level atom (a qubit) enclosed in a waveguide and coupled with the mechanical resonator. Here the Qubit has enhanced the anharmonicity which plays a significant role in obtaining phonon blockade. The

E-mail: anjan.samanta744@gmail.com
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nonlinearity χ has arisen by both cavities and it is induced indirectly by the linear coupling between the optical system and the resonators. The two micro-cavity are coupled through the photon tunneling strength g that depends upon the separation between the micro-cavity. The free Hamiltonian of the optomechanical system is $H_o = \omega_1 a_1^\dagger a_1 + \omega_2 a_2^\dagger a_2$ where ω_1 and ω_2 are the resonant frequencies of the two cavities. Here $a_1^\dagger(a_1)$ and $a_2^\dagger(a_2)$ is the photon creation (annihilation) operator. One can design the passive micro-cavity with silica material without gain medium and dopants. Active micro-cavity is designed by silica doped with Er^{3+} ion. One can achieve a 1550 nm band in an active cavity by using a pump laser 1460 nm wavelength. The loss rate of the passive system is$\sim 2\pi \times 10.7\ MHz$, it can be controlled by tuning the resonator gap and the coupling Quality factor is $\sim 4.5 \times 10^7$. The gain rate in the active cavity is $\sim -2\pi \times 10.7\ MHZ$. The photon tunneling strength between the passive and active cavity is $\sim 2\pi \times 5.35\ MHz$, and for silica glass material the Kerr nonlinearity strength is $\sim 2\pi \times 1.07$. The gain-to-loss ratio varies from -3 to +3 [5-10]. The Hamiltonian for representing the mechanical resonator is $H_m = \omega_b b^\dagger b$ where ω_b is its resonance frequency and $b^\dagger(b)$ is the phonon creation(annihilation) operator. In our numerical simulation, we assume $\omega_1 - \omega_2 = \omega_b$, so that cross-coupled relation between optical and mechanical modes is achieved. The two-level quantum system has the ground state $|g>$ and excited state $|e>$ with transition frequency ω_q(order of GHz). The qubit Hamiltonian is described as $H_q = \omega_q \sigma_+ \sigma_-$ where $\sigma_+ = |e><g|$ ($\sigma_- = |g><e|$) is the atomic raising (lowering) operator [11]. Thus the total Hamiltonian [12-13] without driving can be given by ($\hbar = 1$)

$$
\begin{aligned}
H = {} & \omega_1 a_1^\dagger a_1 + \omega_2 a_2^\dagger a_2 + \omega_b b^\dagger b + \\
& \omega_q \sigma_+ \sigma_- + \chi\left(a_1^\dagger a_1^\dagger a_1 a_1 + a_2^\dagger a_2^\dagger a_2 a_2\right) + \\
& g\left(a_2^\dagger \sigma_- + a_2 \sigma_+\right) + J\left(a_1^\dagger a_2 + a_2^\dagger a_2\right) + \\
& \Gamma a_2^\dagger a_2 (b^\dagger + b) + \xi(b^\dagger \sigma_- + b\sigma_+) \ \ldots\ldots \qquad (1)
\end{aligned}
$$

In equation (1) g denotes the interaction term between the atom and Photons in the active cavity, J represents the coupling strength between the active and passive cavity, Γ interaction term between photons in the active cavity with phonon, ξ interaction in between phonon and atom. The mechanical vibration of the moving mirror coupled with the radiation pressure with the cavity field, due to this interaction the moving mirror should be cooled, so that it may execute the quantum regime condition. This type of interaction has been observed in different experimental studies [14-17]. In this system Hamiltonian we consider some assumptions first we have neglected the environmental effect in the theoretical and experimental calculation [18-19] second in the absence of decay the total number of photons must be conserved.

One phonon can be excited in a nonlinear mechanical resonator when it is driven by external laser light. Effective phonon interaction induced by the qubit and phonon antibunching effect was observed for weak coupling regime and controlled detuning between the mechanical resonator and the Qubit. Phonon blockade can be tunable under strong and weak-driven squeezed light. Phonon blockade can be enhanced by controlling different system parameters and the strength and phase of the squeezed light. To reduce the negative impact on the environment, one can use low-temperature and high-frequency mechanical resonators (we use 5 GHz). The optical mode (passive cavity) is driven by squeezed light of field strength is Ω. The driven Hamiltonian has been designed as $H_{d1} = \frac{i}{2}(\Omega_p a_1^{\dagger 2} e^{-i\varphi} e^{-i\omega_d t} - {\Omega_p}^* a_1^2 e^{i\varphi} e^{i\omega_d t})$. The mechanical mode is driven by the weak external field with field strength Ω_{m} the driven Hamiltonian has design as $H_{d2} = \Omega_m b^\dagger e^{-i\omega_d t} + {\Omega_m}^* b e^{i\omega_d t}$. The external field strength is maintained $\{\ |\Omega_p|,\ |\Omega_{\mathrm{m}}|\} < \{\kappa_1, \gamma\}$, where $\kappa_1$and γ are the damping rates of the optical (passive cavity) and mechanical mode. Note that the driving directly the passive cavity and also indirectly drives the active cavity through the coupling parameter J as shown in the figure. So Ω_p (external squeezed light strength) driven to the passive or active cavity and Ω_m driven the mechanical resonator. The involvement of an additional nonlinearity in the optical mode or applying drives to the qubit and the mechanical resonator enables to achievement of strong phonon antibunching and more sub-Poissonian statistics.

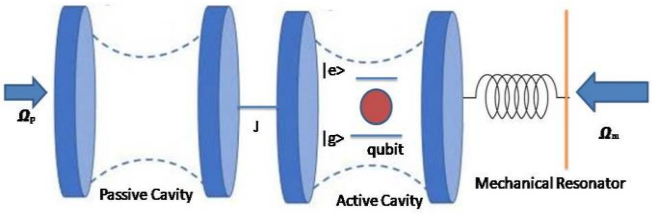

Fig. 1: Represents the two cavities one is active another is passive which is coupled with a Mechanical Resonator. The active cavity contains a semiconducting qubit. The passive cavity is excited by external squeezed light of frequency Ω_p .

3. Results and discussion

In this paper, we analyse the numerical simulation of the Phonon Blockade mechanism [Fig-2, Fig-3] for an optomechanical system described by the Hamiltonian. Effective phonon interaction induced by the qubit and phonon antibunching effect was observed for weak coupling regime and controlled detuning between the mechanical resonator and the Qubit. Phonon blockade can be tunable under strong and weak-driven squeezed light. Phonon blockade can be enhanced by controlling different system parameters and the strength and phase of the squeezed light. To reduce the negative impact on the environment, we have to use low temperature and high frequency of mechanical frequency (we use 5 GHz). So optimal phonon blockade appears near zero detuning and agrees with the analytical result.

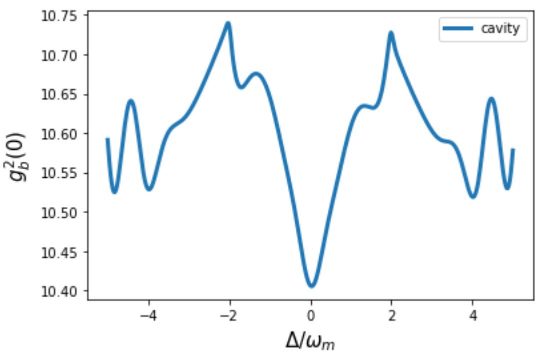

Fig. 2

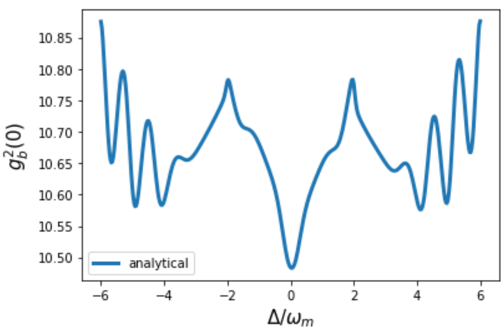

Fig. 3

4. Conclusion

In conclusion, we have discussed the phonon statistics in a mechanical resonator, which is coupled with Superconducting qubits and driven by squeezed light. The quantum nature of a mechanical resonator can be achieved by the phonon blockade mechanism. The non-linearity must be very large as compared to the optical mode line width to suppress the unwanted transitions. We observe the strong phonon antibuncing effect i.e., unconventional phonon blockade mechanism which relies on close to Gaussian states under weak driven squeezed light. By numerical solution of second-order correlation functions, we analyze the Sub-Poissonian phonon statistics. We can control phonon blockade effects by controlling the amplitude and phase of driven squeezed light. Due to the high nonlinearity of the system and interaction strength between superconducting qubits and cavities, the phonon blockade effect is controlled. The present mechanism has much more attractive applications in optical communication and sensitive measurements such as the detection of gravitational waves or noise-free amplifications and use for the development of quantum computers, and generates second harmonics.

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