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Second-order sideband effects mediated by microwave in hybrid electro-optomechanical systems

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ABSTRACT

We theoretically investigate the second-order sideband effects in a hybrid electro-optomechanical system, and mainly focus on the influence of the microwave signal on the second-order sideband generation. The numerical results show that just by tuning the power and the detuning of the microwave signal, the second-order sideband can be significantly modified. More importantly, while driving this hybrid system by a blue detuned microwave with suitable power, strong second-order sideband effect can be induced. These results can find potential applications in optical frequency converters in the quantum information processing.

1. Introduction

Quantum optomechanics [1–4], coupling the optical and mechanical degrees of freedom together by the radiation pressure of light, has become a rapidly advancing field in recent years. Several two-mode optomechanical systems [5–12], i.e., a single optical mode coupled to a single mechanical mode, have been realized experimentally, and some optomechanical-like systems [13–18] have also been proposed. A lot of interesting phenomena, such as resolved sideband cooling effect [5,15,19], optomechanically induced transparency (OMIT) [9,20,21], signal amplification effect (SAE) [22], electromagnetically induced absorption (EIA) [23], optical bistability (OB) [24,25], quantum squeezing [26,27] and so on, have been extensively researched in such two-mode optomechanical systems both in theory and in experiment.

Recently, there has been a rising interest in hybrid optomechanical systems with three or more degrees of freedom [28–42]. A hybrid electro-optomechanical system [29,30,32–35,37,38,43], in which a microwave field and an optical field are coupled to a common mechanical resonator, has particularly attracted extensive attention. This hybrid system connects the low-frequency electrical signals and the higher-frequency optical signals, so it has potential applications in quantum information network. In such a hybrid system, the quantum state transfer between the optical and microwave cavity has been explored systematically [30,35,38], controllable strong Kerr nonlinearities have been realized theoretically in the weak-coupling regime [32], phonon-mediated electromagnetically induced absorption [34] has been discussed in detail, and many other interesting phenomena [33,37] have also been focused on.

In the present paper, we will systematically investigate the second-order sideband effect in a hybrid electro-optomechanical system. It is well known that many interesting phenomena such as OMIT, SAE, and EIA in optomechanical systems can be explained by the Heisenberg–Langevin equations [21–23]. However, in these works, the second and higher-order terms in the Heisenberg–Langevin equations have not been taken into consideration. As a result, some interesting nonlinear phenomena [44–47] in the optomechanical system have been ignored. Recently, Xiong et al. [44] have proposed an effective method to deal with the nonlinear Heisenberg–Langevin equations. They have explored the second-order sideband process in a generic optomechanical system and observed some interesting phenomena. Motivated by their work, we have discussed the second-order sideband effect in a hybrid electro-optomechanical system and explored the effect of the microwave signal on the second-order sideband process. The numerical results show that the power and the detuning of the microwave signal have significantly influence on second-order sideband effects. More importantly, by a blue detuned microwave driving with suitable power, strong second-order sideband effect can be induced in this hybrid system.

2. Model and method

The hybrid electro-optomechanical system considered in the present paper is composed of an optical cavity and a microwave

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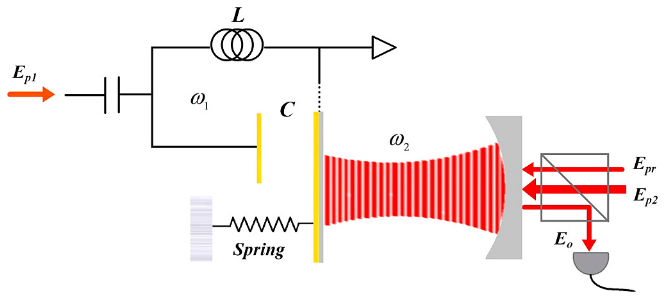

Fig. 1. Schematic for a hybrid electro-optomechanical system.

one, and these two cavities are simultaneously coupled to the same mechanical resonator, as is shown in Fig. 1. In this work, the microwave cavity with a resonance frequency ω_1 is driven by a microwave signal with amplitude E_{p1} and frequency ω_{p1}, while the optical cavity with a resonance frequency ω_2 is driven by a pump laser with amplitude E_{p2} and frequency ω_{p2} as well as a weak probe laser with amplitude E_{pr} and frequency ω_{pr}. In a rotating frame, the Hamiltonian of this hybrid system can be expressed as [34]

$$\begin{aligned} H = {} & \frac{1}{2}\hbar\omega_m(P^2+X^2) + \hbar\Delta_{c1}a_1^\dagger a_1 + \hbar\Delta_{c2}a_2^\dagger a_2 \\ & + \hbar g_1 a_1^\dagger a_1 X - \hbar g_2 a_2^\dagger a_2 X \\ & + i\hbar\sqrt{\eta_1\kappa_1}E_{p1}(a_1^\dagger - a_1) + i\hbar\sqrt{\eta_2\kappa_2}E_{p2}(a_2^\dagger - a_2) \\ & + i\hbar\sqrt{\eta_2\kappa_2}(E_{pr}a_2^\dagger e^{-i\delta t} - E_{pr}^* a_2 e^{i\delta t}), \end{aligned} \tag{1}$$

with $\Delta_{c1} = \omega_1 - \omega_{p1}$, $\Delta_{c2} = \omega_2 - \omega_{p2}$, and $\delta = \omega_{pr} - \omega_{p2}$.

The first term is the energy of the mechanical resonator with frequency ω_m. X and P are respectively the dimensionless position and momentum operators of the resonator with the communication relations $[X, P] = i$. The second term and the third one respectively give the energy of the microwave cavity and the optical cavity, where Δ_{cj} $(j = 1, 2)$ and $a_j(a_j^\dagger)$ are respectively the cavity-pump detuning and the annihilation (creation) operator of the corresponding cavity mode. The fourth and fifth term represent the coupling between the mechanical resonator and the microwave cavity as well as the optical cavity, respectively. g_j is the corresponding coupling strength. The last three terms describe the interaction between the driving field and the cavity field. The amplitude of the driving field is related to the input power P_l by $E_l = \sqrt{P_l/\hbar\omega_l}$ [21,44], where $l = p1$, $p2$, and pr respectively represent the microwave field, the optical pump field, and the optical probe one. κ_1 (κ_2) is the total loss rate which contains an intrinsic loss rate κ_{01} (κ_{02}) and an external loss rate κ_{ex1} (κ_{ex2}). η_j is the coupling parameter between the cavity j and the corresponding driving field, and $\eta_j = \kappa_{exj}/(\kappa_{0j} + \kappa_{exj})$ [21,44]. In this work, we mainly focus on the critical coupling case, i.e., $\eta_1 = \eta_2 = 0.5$.

According to the Heisenberg equation and the communication relations $[a_j, a_j^\dagger] = 1$ and $[X, P] = i$, the temporal evolution of the operators a_1, a_2, and X can be obtained. In this work, we are interested in the mean response of the system to the probe field, so all the operators can be reduced to their expectation values [21,44]. Taking the damping terms into consideration and dropping the quantum and thermal noise terms, we can obtain the Heisenberg–Langevin equations as follows,

$$\frac{da_1}{dt} = -(i\Delta_{c1} + \frac{\kappa_1}{2})a_1 - ig_1 a_1 X + \sqrt{\eta_1\kappa_1}E_{p1}, \tag{2}$$

$$\begin{aligned} \frac{da_2}{dt} = {} & -(i\Delta_{c2} + \frac{\kappa_2}{2})a_2 + ig_2 a_2 X + \sqrt{\eta_2\kappa_2}E_{p2} \\ & + \sqrt{\eta_2\kappa_2}E_{pr}e^{-i\delta t}, \end{aligned} \tag{3}$$

$$\frac{d^2X}{dt^2} + \gamma_m\frac{dX}{dt} + \omega_m^2 X = \omega_m(g_2 a_2^* a_2 - g_1 a_1^* a_1), \tag{4}$$

where $a_j(t) \equiv \langle\hat{a}_j(t)\rangle$, $a_j^*(t) \equiv \langle\hat{a}_j^\dagger(t)\rangle$, $X(t) \equiv \langle\hat{X}(t)\rangle$, and γ_m is the damping rate of the mechanical resonator.

Defining the steady solution of the intracavity field and the mechanical displacement as $\bar{a}_j$ and $\overline{X}$ respectively, by solving the equations (2), (3), and (4), we can obtain the steady solutions as follows:

$$\bar{a}_1 = \frac{\sqrt{\eta_1\kappa_1}E_{p1}}{\kappa_1/2 + i\Delta_1}, \tag{5}$$

$$\bar{a}_2 = \frac{\sqrt{\eta_2\kappa_2}E_{p2}}{\kappa_2/2 + i\Delta_2}, \tag{6}$$

$$\overline{X} = \frac{1}{\omega_m}(g_2|\bar{a}_2|^2 - g_1|\bar{a}_1|^2), \tag{7}$$

where $\Delta_1 = \omega_1 - \omega_{p1} + g_1\overline{X}$ and $\Delta_2 = \omega_2 - \omega_{p2} - g_2\overline{X}$.

Linearizing the operators around the steady state values as $a_j = \bar{a}_j + \delta a_j$ $(j = 1, 2)$ and $X = \overline{X} + \delta X$, the equations (2), (3), and (4) then become as

$$\frac{d\delta a_1}{dt} = -(\frac{\kappa_1}{2} + i\Delta_1)\delta a_1 - ig_1(\bar{a}_1\delta X + \delta a_1\delta X), \tag{8}$$

$$\begin{aligned} \frac{d\delta a_2}{dt} = {} & -(\frac{\kappa_2}{2} + i\Delta_2)\delta a_2 + ig_2(\bar{a}_2\delta X + \delta a_2\delta X) \\ & + \sqrt{\eta_2\kappa_2}E_{pr}e^{-i\delta t}, \end{aligned} \tag{9}$$

$$\begin{aligned} \frac{d^2\delta X}{dt^2} + \gamma_m\frac{d\delta X}{dt} + \omega_m^2\delta X = {} & \omega_m g_2(\delta a_2^*\bar{a}_2 + \bar{a}_2^*\delta a_2 + \delta a_2^*\delta a_2) \\ & - \omega_m g_1(\delta a_1^*\bar{a}_1 + \bar{a}_1^*\delta a_1 + \delta a_1^*\delta a_1). \end{aligned} \tag{10}$$

Considering the second-order sideband but ignoring the higher-order ones, we can define the following ansatz [44],

$$\delta a_1 = \delta a_1^{(1)} + \delta a_1^{(2)}, \delta a_2 = \delta a_2^{(1)} + \delta a_2^{(2)}, \delta X = \delta X^{(1)} + \delta X^{(2)}, \tag{11}$$

with

$$\begin{aligned} &\delta a_1^{(1)} = A_{11}^- e^{-i\delta t} + A_{11}^+ e^{i\delta t},\ \delta a_1^{(2)} = A_{12}^- e^{-2i\delta t} + A_{12}^+ e^{2i\delta t} \\ &\delta a_2^{(1)} = A_{21}^- e^{-i\delta t} + A_{21}^+ e^{i\delta t},\ \delta a_2^{(2)} = A_{22}^- e^{-2i\delta t} + A_{22}^+ e^{2i\delta t} \\ &\delta X^{(1)} = X_1^- e^{-i\delta t} + X_1^+ e^{i\delta t},\ \delta X^{(2)} = X_2^- e^{-2i\delta t} + X_2^+ e^{2i\delta t} \end{aligned}$$

By substituting equation (11) into (8), (9), and (10), respectively, and considering that the second-order sideband is much smaller than the first-order one as well as the probe field, we can obtain two group equations.

The first group describes the linear case,

$$(\frac{\kappa_1}{2} + i\Delta_1 - i\delta)A_{11}^- = -ig_1\bar{a}_1 X_1^-, \tag{12}$$

$$(\frac{\kappa_1}{2} + i\Delta_1 + i\delta)A_{11}^+ = -ig_1\bar{a}_1 X_1^+, \tag{13}$$

$$(\frac{\kappa_2}{2} + i\Delta_2 - i\delta)A_{21}^- = ig_2\bar{a}_2 X_1^- + \sqrt{\eta_2\kappa_2}E_{pr}, \tag{14}$$

$$(\frac{\kappa_2}{2} + i\Delta_2 + i\delta)A_{21}^+ = ig_2\bar{a}_2 X_1^+, \tag{15}$$

$$\begin{aligned} &(\omega_m^2 - \delta^2 - i\delta\gamma_m)X_1^- \\ &= \omega_m g_2[(A_{21}^+)^*\bar{a}_2 + \bar{a}_2^* A_{21}^-] - \omega_m g_1[(A_{11}^+)^*\bar{a}_1 + \bar{a}_1^* A_{11}^-], \end{aligned} \tag{16}$$

$$X_1^+ = (X_1^-)^*. \tag{17}$$