Quantum interference effects on ground-state optomechanical cooling

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Quantum interference effects on ground-state optomechanical cooling

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We propose a fast ground-state optomechanical cooling scheme by use of the two-mode optical cavity with a quarter-wave plate put inside. Two cavity modes are orthogonally polarized and one cavity mode dissipates to the external environment at the fast rate while the other dissipates at the slow rate. The quarter-wave plate provides linear mixing interaction between these two cavity modes. The cooling process is dominated by scattering process via the fast-decay channel, which is significantly enhanced as compared with that obtained in the resolved-sideband optomechanical cooling scheme. Meanwhile, the heating process is significantly suppressed by exploiting the destructive quantum interference between the two cavity modes with the help of quarter-wave plate.

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I. INTRODUCTION

Quantum optomechanical techniques provide a universal tool to study macroscopic mechanical systems that operate in quantum regime, with no significant thermal noise remaining. Thus, it is essential to cool the systems down to the quantum limit. Extraordinary efforts have been made to achieve the ground-state cooling of optomechanical systems over the past decade using radiation pressure force [1–3]. Also many applications of the optomechanical systems have been intensively exploited, such as the enhancement of the sensitivity of displacement measurements [4], the probe of the ultimate quantum mechanical limits at the nanoscale [5] and high-fidelity optomechanical quantum state transfer [6]. Among these optomechanical cooling techniques, cavity optomechanics becomes a potential candidate in many applications. This is because for example optical resonantor or electromagnetic resonator such as a superconducting LC circuit, provides the possibility to realize the resonant interactions with a very large enhancement of the interaction [7]. Recently, the cooling of the mechanical resonator via the radiation pressure force has been experimentally demonstrated in the resolved-sideband regime [8, 9], where the system is implemented in the high-finesse cavity, corresponding to decay rate κ lower than the vibrational motion of the cavity with frequency ν. For example, the decay rate and vibration frequency are $\nu/2\pi \sim 70$MHz and $\kappa/2\pi \sim 5$MHz respectively in the resolved-sideband optomechanical cooling experiment [9], and the theoretical predicted cooling limit is $\langle n\rangle \approx \kappa^2/16\omega_m^2$ with the cooling rate proportional to κ.

The efficiency of the cooling dynamics is influenced because of the low cooling rate proportional to the small decay rate κ in the resolved-sideband cooling scheme. Elste *et al.* [10] and Xuereb *et al.* [11] have respectively pointed out that via the destructive interference of quantum noise, ground-state cooling can be obtained outside the resolved-sideband limit in the microwave and optical domain. Moreover, the quantum interference due to mechanical effect can be utilized to alter the properties of the optomechanical system, such as the pump-probe response [12, 13]. Because of the significance of interference in quantum system, we propose the optomechanical cooling scheme by exploiting the interference effects to improve the cooling efficiency in the different way. Our scheme is based on interference effects between the cavity fields, very similar to the electromagnetically induced transparency (EIT) cooling of atoms [14].

We consider an optomechanical cooling system consisting of a two-mode optical cavity with a quarter-wave plate put inside. The two-mode optical cavity is the significant apparatus in many aspects such as the optomechanical cooling scheme of levitated spheres with doubly resonant fields [15]. In our system, two cavity modes are orthogonally polarized and one dissipates to the external environment at the fast rate while the other dissipates at the slow rate, and the quarter-wave plate provides the linear mixing interaction between these two modes. We show that the cooling process is dominated by the dissipation via fast-decay channel, which is significantly enhanced as compared with that obtained in the resolved-sideband optomechanical cooling scheme. At the same time, by exploiting the complete destructive quantum interference between the two cavity modes with the help of the quarter-wave plate, heating process relevant to the fast-decay rate can be significantly suppressed. Further, the correction on heating rate relevant to the slow-decay rate is also discussed. Finally, the fast ground-state optomechanical cooling of the mechanical oscillator is achieved. The paper is organized as follows. In Sec. II, the system is introduced and the master equation for the vibrational motion of mechanical oscillator is derived, the quantum interference effects on the cooling dynamics are discussed in detail in Sec. III and the conclusion is presented in Sec. IV.

II. THE DESCRIPTION OF THE MODEL AND DERIVATION OF THE MASTER EQUATION

We consider the optomechanical system consisting of a two-mode optical cavity with a quarter-wave plate put inside, as shown in Fig.1. The two-mode optical cavity comprises of two fixed end mirrors and a harmonically bound end mirror allowed to oscillate under the action of radiation pressure induced by the two intracavity light fields. These two

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intracavity modes are orthogonally polarized, which are respectively driven by two laser fields with the equal frequency $\omega_L = \omega_{L1} = \omega_{L2}$ and Rabi frequencies $\Omega_j (j = 1, 2)$. The plate provides the linear mixing interaction between the two cavity modes. In the rotating frame at the laser frequencies ω_L, the Hamiltonian is given by ($\hbar = 1$)

$$H = \nu b^\dagger b + \sum\nolimits_j [-\Delta_j a_j^\dagger a_j + \frac{\Omega_j}{2}(a_j + a_j^\dagger)] + i\frac{g}{2}(a_1^\dagger a_2 - a_2^\dagger a_1) + \nu \sum\nolimits_j \eta_j a_j^\dagger a_j (b + b^\dagger), \quad (1)$$

where a_j and b are the annihilation operators of the j-th cavity mode of frequency ω_j and phonon mode of frequency ν that describes the harmonic vibration of the oscillator, $\Delta_j = \omega_{Lj} - \omega_j$ is the detuning of the cavity mode from the laser field and g is the coupling strength of the linear mixing interaction between the two intracavity modes depending on the rotated angle of the plate with respect to the crystal neutral axes. The optomechanical couplings via radiation pressure forces are characterized by the dimensionless parameters $\eta_j = (\omega_j/\nu)(l_\nu/L_j)$, with $l_\nu = 1/\sqrt{2m\nu}$ the zero point motion of the mechanical resonator mode, m its effective mass and L_j the j-th effective optical wave length [16, 17]. For the typical value of optomechanical parameters realized in experiment is $\eta \sim 10^{-4}$. The optomechanical cooling induced by two linearly coupled cavity modes can also be realized in the similar system "membrane in the middle" [18].

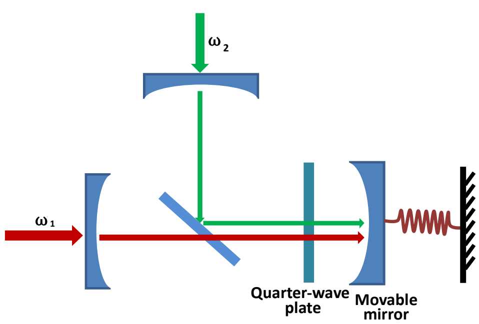

FIG. 1. (Color online) Schematic diagram of the optomechanical system comprising of a two-mode optical cavity and a quarter-wave plate put inside. The cavity consists of two fixed end mirrors and a harmonically movable end mirror and is driven by two laser fields. The inserted plate provides a linear mixing between the two orthogonally polarized intracavity fields.

The losses of optical cavity fields are described Liouvillian operators $\mathcal{L}_{a_j}\rho$, which are given in the form

$$\mathcal{L}_{a_j}\rho = \frac{\kappa_j}{2}(2a_j\rho a_j^\dagger - a_j^\dagger a_j \rho - \rho a_j^\dagger a_j), \quad (2)$$

with κ_j the decay rate of the j-th cavity mode. With respect to the intrinsic dissipation of the mechanical oscillator, due to the high mechanical quality factor Q_m which can exceed 10^4, it is adequate to neglect the heating process caused by the dissipation of the oscillator in the following under the relations $Q_m/\bar{n}_i \gg 1$ and $\bar{n}_i\omega_m/Q_m \ll \kappa$ ($\bar{n}_i$ is the initial phonon occupancy) [9].

Obviously, the density operator obeys the master equation

$$\dot{\rho} = -i[H, \rho] + \mathcal{L}_{a_1}\rho + \mathcal{L}_{a_2}\rho. \quad (3)$$

However it is difficult to exactly solve the master equation because of the existence of the nonlinear terms. Hence we apply the linearization approach [19] by assuming that each operator in the system can be written as the sum of its mean value and a small fluctuation: $a_j \to \alpha_j + a_j, b \to \beta + b$, with $\alpha_j = \langle a_j \rangle$, $\beta = \langle b \rangle$ and the redefined fluctuation operators a_j and b in the right hand side. The c-number components α_j and β can be obtained from the Eq.(3) as

$$\begin{aligned}
\dot{\alpha}_1 &= (i\Delta_1 - \frac{\kappa_1}{2})\alpha_1 - i\eta_1\nu\alpha_1(\beta + \beta^*) + \frac{g}{2}\alpha_2 - i\frac{\Omega_1}{2}, \\
\dot{\alpha}_2 &= (i\Delta_2 - \frac{\kappa_2}{2})\alpha_2 - i\eta_2\nu\alpha_2(\beta + \beta^*) - \frac{g}{2}\alpha_1 - i\frac{\Omega_2}{2}, \\
\dot{\beta} &= -(i\nu + \gamma)\beta - i\eta_1\nu\, |\alpha_1|^2 - i\eta_2\nu|\alpha_2|^2, \quad (4)
\end{aligned}$$

in which the decoupling approximation such as $\langle a_j(b+b^\dagger)\rangle = \alpha_j(\beta + \beta^*)$ is applied, and $\gamma = \omega_m/Q_m$ is damping rate of the phonon mode. We focus on the regime $\eta_j|\alpha_j| \ll 1$ and the steady-state solutions for the Eqs.(4) to the lowest order in the small parameters η_j and γ are obtained as

$$\begin{aligned}
\alpha_1 &= [(\Delta_2 + i\frac{\kappa_2}{2})\frac{\Omega_1}{2} + i\frac{g\Omega_2}{4}]/f(\Delta_1, \Delta_2), \\
\alpha_2 &= [(\Delta_1 + i\frac{\kappa_1}{2})\frac{\Omega_2}{2} - i\frac{g\Omega_1}{4}]/f(\Delta_1, \Delta_2), \\
f(\Delta_1, \Delta_2) &= (\Delta_1 + i\frac{\kappa_1}{2})(\Delta_2 + i\frac{\kappa_2}{2}) - \frac{g^2}{4}, \\
\beta &= -\sum\nolimits_j \eta_j\, |\alpha_j|^2\,. \quad (5)
\end{aligned}$$

The term β represents the slightly displacement from the equilibrium position of the movable mirror. In the shifted representation we include the radiation pressure-induced optical resonance shift into the redefined effective detuning $\Delta_j' = \Delta_j + 2\eta_j^2|\alpha_j|^2\nu$. However in the limit $\eta_j|\alpha_j| \ll 1$, $\Delta_j' \approx \Delta_j$. The form of Liouvillian operators remains invariant and the Hamiltonian changes into the form

$$\begin{aligned}
H &= H_0 + V, \\
H_0 &= \nu b^\dagger b - \sum\nolimits_j \Delta_j a_j^\dagger a_j, \\
V &= i\frac{g}{2}(a_1^\dagger a_2 - a_2^\dagger a_1) + \nu\sum\nolimits_j \eta_j(\alpha_j a_j^\dagger + \alpha_j^* a_j)(b + b^\dagger).
\end{aligned} \quad (6)$$

Under the assumption that the cavity fields weakly couple to the harmonic motion of the oscillator such that $\eta_j\alpha_j\nu$ are smaller than κ_1 or κ_2, the cavity variables arrive the steady state much fast and can be adiabatically eliminated. It is feasible to apply the second-order perturbation method with respect to the small optomechanical coupling rate $\eta_j\alpha_i\nu$ [20–22], and finally the reduced master equation for phonon mode obeys the equation in the rotating frame of the vibrational frequency ν

$$\begin{aligned}
\dot{\rho}_b &= \tfrac{1}{2}A(-\nu)(2b\rho_b b^\dagger - b^\dagger b\rho_b - \rho_b b^\dagger b) \\
&\quad + \tfrac{1}{2}A(\nu)(2b^\dagger\rho_b b - bb^\dagger\rho_b - \rho_b bb^\dagger), \quad (7)
\end{aligned}$$

where ρ_b is the reduced density operator of the phonon mode and $A(\pm\nu)$ are heating and cooling parameters respectively, which can be calculated by using the quantum regression theorem [23, 24] and obtained as

$$A(\pm\nu) = \nu^2 \sum_j \kappa_j \left|\mathcal{T}_{a_1}^{\kappa_j,\mp} + \mathcal{T}_{a_2}^{\kappa_j,\mp}\right|^2, \tag{8}$$

with

$$\begin{aligned}
\mathcal{T}_{a_1}^{\kappa_1,\mp} &= \frac{\eta_1(\Delta_2 \mp \nu - i\frac{\kappa_2}{2})[(\Delta_2 + i\frac{\kappa_2}{2})\frac{\Omega_1}{2} + i\frac{g\Omega_2}{4}]}{f(\Delta_1 \mp \nu, \Delta_2 \mp \nu)f(\Delta_1, \Delta_2)},\\
\mathcal{T}_{a_2}^{\kappa_1,\mp} &= \frac{\eta_2\frac{g}{2}[\frac{g\Omega_1}{4} + i(\Delta_1 + i\frac{\kappa_1}{2})\frac{\Omega_2}{2}]}{f(\Delta_1 \mp \nu, \Delta_2 \mp \nu)f(\Delta_1, \Delta_2)},\\
\mathcal{T}_{a_1}^{\kappa_2,\mp} &= \frac{\eta_1\frac{g}{2}[\frac{g\Omega_2}{4} - i(\Delta_2 + i\frac{\kappa_2}{2})\frac{\Omega_1}{2}]}{f(\Delta_1 \mp \nu, \Delta_2 \mp \nu)f(\Delta_1, \Delta_2)},\\
\mathcal{T}_{a_2}^{\kappa_2,\mp} &= \frac{\eta_2(\Delta_1 \mp \nu - i\frac{\kappa_1}{2})[(\Delta_1 + i\frac{\kappa_1}{2})\frac{\Omega_2}{2} - i\frac{g\Omega_1}{4}]}{f(\Delta_1 \mp \nu, \Delta_2 \mp \nu)f(\Delta_1, \Delta_2)}.
\end{aligned} \tag{9}$$

The terms $\kappa_j \left|\mathcal{T}_{a_1}^{\kappa_j,\mp} + \mathcal{T}_{a_2}^{\kappa_j,\mp}\right|^2$ indicate the scattering processes of photons into the external modes of electromagnetical field via the decay channel with rate κ_j. The amplitudes $\mathcal{T}_{a_1}^{\kappa_j,\mp}$ ($\mathcal{T}_{a_2}^{\kappa_j,\mp}$) describe optomechanical couplings to the cavity mode a_1 (a_2), which dissipates from the decay channel κ_1 or κ_2 with the help of the quarter-wave plate. The scattering processes are depicted in Fig.2. Note that the term is the coherent sum of two individual amplitudes and they are able to interfere with each other. If we remove the quarter-wave plate, the amplitudes $\mathcal{T}_{a_2}^{\kappa_1,\mp}, \mathcal{T}_{a_1}^{\kappa_2,\mp}$ become zero since these two scattering processes are accomplished assisted by the plate, and then the heating and cooling parameters are changed into the sum of two independent terms $\kappa_1|\mathcal{T}_{a_1}^{\kappa_1,\mp}|^2$ and $\kappa_2|\mathcal{T}_{a_2}^{\kappa_2,\mp}|^2$, each of which corresponds to that obtained in the resolved-sideband optomechanical cooling scheme [16].

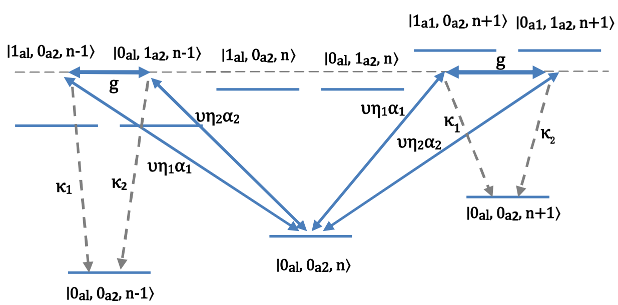

FIG. 2. (Color online) Schematic illustration of the scattering processes in the shifted representation for the perturbative optomechanical coupling.

From the master equation in Eq.(7), we can obtain the steady-state vibrational phonon number n_f and the cooling rate W as

$$n_f = \frac{A(\nu)}{W}, \quad W = A(-\nu) - A(\nu). \tag{10}$$

It is obvious that the final phonon number n_f is proportional to the heating parameter $A(\nu)$ and inversely proportional to the cooling rate W. In order to obtain the efficient ground-state cooling for the mechanical oscillator, $A(\nu)$ should be suppressed while W should be enhanced.

III. QUANTUM INTERFERENCE EFFECTS ON THE COOLING DYNAMICS

In order to understand the quantum interference effects on the cooling dynamics, we consider the case that the cavity mode a_1 decays at the fast rate while a_2 decays at the slow rate, i.e. in the regime $\kappa_1 \gg \kappa_2$. The regime is practical in the setup of the doubly resonant optical cavity, for example in the resolved-sideband cooling scheme the optical cavity is designed to have two optical resonances, where the cooling cavity field has the damping rate about 10MHz while the readout cavity field has the decay rate as high as GHz [9, 25]. From Eqs.(8)-(9), scattering processes are mainly accomplished via the fast-decay channel, and we now study main part of the heating and cooling parameters $A^{(m)}(\pm\nu)$ by neglecting the term κ_2–namely, $\kappa_2 = 0$ and arrive

$$A^{(m)}(\pm\nu) = \nu^2\kappa_1 \left|\mathcal{T}_{a_1}^{\kappa_1,\mp} + \mathcal{T}_{a_2}^{\kappa_1,\mp}\right|^2 \tag{11}$$

proportional to fast-decay rate κ_1. Thus, the heating process is suppressed when $\left|\mathcal{T}_{a_1}^{\kappa_1,-} + \mathcal{T}_{a_2}^{\kappa_1,-}\right|^2 = 0$, and after some calculations the parameters should satisfy the relations

$$\begin{aligned}
\nu &= (\Delta_2 + \frac{\eta_2}{\eta_1}\Delta_1),\\
(\frac{g}{2})^2\Omega_1 &- \Delta_1\Delta_2\Omega_1 - \frac{\kappa_1}{2}\frac{g}{2}\Omega_2 = 0.
\end{aligned} \tag{12}$$

The cooling parameter $A^{(m)}(-\nu)$ becomes

$$A^{(m)}(-\nu) = 4\nu^4\eta_1^2\kappa_1 \frac{(\Delta_2\Omega_1/2)^2 + (g\Omega_2/4)^2}{|f(\Delta_1 + \nu, \Delta_2 + \nu)f(\Delta_1, \Delta_2)|^2}. \tag{13}$$

The fast-decay rate can reach about two orders of magnitude larger than that in the resolved-sideband cooling scheme, leading to the enhancement of the cooling rate. Efficient cooling is achieved by maximizing the rate $A^{(m)}(-\nu)$ together with the ratio $A^{(m)}(-\nu)/A(\nu)$, since $1/n_f \approx A^{(m)}(-\nu)/A(\nu)$ due to the small heating rate $A(\nu)$ under the conditions in Eq.(12). By inspection of Eqs.(8), (9) and (13), we find out that

$$1/n_f \propto \left|\frac{f(\Delta_1 - \nu, \Delta_2 - \nu)}{f(\Delta_1 + \nu, \Delta_2 + \nu)}\right|^2, \tag{14}$$

with

$$\begin{aligned}
&|f(\Delta_1 + \nu, \Delta_2 + \nu)|^2\\
&= [(\Delta_1 + \nu)(\Delta_2 + \nu) - g^2/4]^2 + \frac{\kappa_1^2}{4}(\Delta_2 + \nu)^2\\
&= (\Delta_2 + \nu)^2\left[\kappa_1^2/4 + \left((\Delta_1 + \nu) - \frac{g^2}{4(\Delta_2 + \nu)}\right)^2\right].
\end{aligned} \tag{15}$$

Thereby from Eq.(15) the condition

$$(\Delta_1 + \nu)(\Delta_2 + \nu) - g^2/4 = 0 \tag{16}$$

can minimize $|f(\Delta_1+\nu,\Delta_2+\nu)|^2$. The contribution $f(\Delta_1-\nu,\Delta_2-\nu)$ is off-resonant, and therefore weakly dependent on Δ_j. Thus the condition in Eq.(16) minimizes the steady phonon number and simultaneously maximizes the cooling rate.

We can take the parameter $\eta_1=\eta_2=\eta=5\times10^{-4}$, $\Delta_1=\Delta_2=\nu/2$, $\kappa_1=8/3\nu$, $\kappa_2=0.1\nu$, $g=3\nu$, $\Omega_2=\Omega_1=\Omega$ to satisfy the conditions of Eqs.(12) and (16). For the laser driving strength Ω, it is feasible to take the value 500ν because the corresponding effective coupling strengths between the cavity fields and mechanical oscillator depend on $\eta_1|\alpha_1|\approx0.09$ and $\eta_2|\alpha_2|\approx0.03$, which are well in the regime $\eta_j|\alpha_j|\ll1$. As compared the coupling strength with decay rate κ_1, the perturbation approach is validated since the cavity variables reach the steady state much fast and can be adiabatically eliminated. With this group of parameters we calculate the cooling rate 0.0221ν.

The elimination of the main part of heating parameter $A^{(m)}(\nu)$ can be explained from the scattering processes sketched in Fig.2 with the interaction described by the Hamiltonian in Eq.(6). By neglecting the heating process via the slow-decay cavity mode a_2, the main heating process is caused by the dissipation from the excitation state of cavity field a_1 $|1_{a_1},0_{a_2},n+1\rangle$, where n is the phonon number. It is obvious that there exist two transition paths $|0_{a1},0_{a2},n\rangle\rightarrow|1_{a1},0_{a2},n+1\rangle$ and $|0_{a1},0_{a2},n\rangle\rightarrow|0_{a1},1_{a2},n+1\rangle\rightarrow|1_{a1},0_{a2},n+1\rangle$ to lead the excitation from the state $|0_{a1},0_{a2},n\rangle$ into the state $|1_{a_1},0_{a_2},n+1\rangle$. The transition amplitude can be concretely expressed by using the resolvent of the Hamiltonian [26] and given by

$$\mathcal{T}_{fi}=\langle\varphi_f|\Big(V+V\frac{1}{E_i-H_0}V\Big)|\varphi_i\rangle,\tag{17}$$

where the final state is $|\varphi_f\rangle=|1_{a1},0_{a2},n+1\rangle$ and the initial state is $|\varphi_i\rangle=|0_{a1},0_{a2},n\rangle$. It can be verified that when the parameters satisfy the relations in Eqs.(12) the transition amplitude $\mathcal{T}_{fi}$ becomes zero, which means that complete destructive interference occurs between the two transition paths, leading to the elimination of the excitation in state $|1_{a_1},0_{a_2},n+1\rangle$.

We now turn to the correction on the heating parameter $A^{(c)}(\nu)$ caused via the dissipation of slow-decay cavity mode a_2, which takes the form

$$A^{(c)}(\nu)\simeq\nu^2\kappa_2\left|\mathcal{T}_{a_1}^{\kappa_2,-}+\mathcal{T}_{a_2}^{\kappa_2,-}\right|^2.\tag{18}$$

Under the conditions in Eq.(12), $\eta_j|\alpha_j|\ll1$ and with the relations $\eta_1=\eta_2=\eta$ and $\Omega_1=\Omega_2=\Omega$, the term $A^{(c)}(\nu)$ becomes

$$A^{(c)}(\nu)=\kappa_2\nu^2\big(\frac{\Omega}{2}\eta\big)^2\frac{1+(2\nu/\kappa_1)^2}{\Delta_1^2[(g/2)^2+\Delta_2^2]},\tag{19}$$

proportional to the slow-decay rate κ_2, thus the final phonon number is of the order of magnitude κ_2/κ_1, which is verified by the numerical plot of the final phonon number as a function of detuning Δ in Fig. 3, in which the phonon number takes the minimum value 0.0168 around the detuning $\Delta=0.5\nu$.

If we remove the quarter-wave plate, the scheme is changed into the cooling of mechanical oscillator via the dynamical backaction induced by two independent cavity fields. However, due to the existence of fast-decay cavity field a_1, which dominates the heating and cooling processes, effective optomechanical cooling can not occur outside the resolved-sideband region, i.e. $\kappa_1>\nu$. Suppose that cooling dynamics is induced by the slow-decay cavity mode a_2, which is well within the resolved-sideband cooling regime. When the laser is tuned to mechanical oscillator's lower sideband, cooling occurs [16]. The heating and cooling parameters $A^{(s)}(\pm\nu)$ can be calculated from Eqs. (8)-(9) by setting $g,\kappa_1=0$, which is obtained as

$$A^{(s)}(\pm\nu)=\frac{\kappa_2\nu^2(\Omega_2\eta_2/2)^2}{(\Delta_2^2+\kappa_2^2/4)[(\Delta_2\mp\nu)^2+\kappa_2^2/4]},\tag{20}$$

proportional to the rate κ_2. When the detuning Δ_2 is tuned to the value $-\nu$, resolved-sideband optomechanical cooling would occur. However, in order to validate the perturbation approach, i.e. fulfilling the condition $\eta_2\alpha_2\nu\ll\kappa_2$ where the cavity variables can be adiabatically eliminated, we should weaken the laser-driving strength Ω_2 taken above because of $\kappa_2\ll\kappa_1$, which will reduce the effective coupling strength between the cavity field and mechanical oscillator. Thus the cooling rate will further slow down. For example in experimental realization the cooling rate takes the value around 0.0035ν [9]. Therefore, by exploiting the quantum interference effects between two linearly coupled optical cavity modes with the help of a quarter-wave plate we can obtain the fast ground-state optomechanical cooling. Compared with the "membrane in the middle" system [18], where the heating and cooling region can be significantly altered by the interference between the two coupled cavity modes with equal decay rate, we focus on the improvement of cooling dynamics based on the respective fast and slow decay rates and the interference effects.

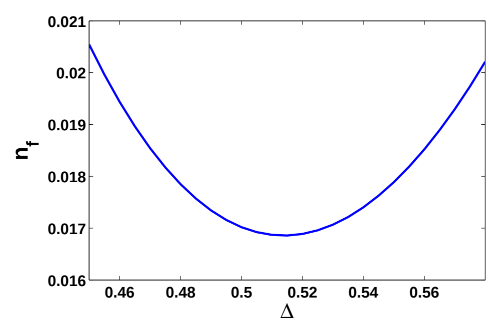

FIG. 3. (Color online) The numerical calculation of final phonon number n_f as a function the detuning Δ in unit of ν with the parameters: $\eta_1=\eta_2=\eta=5\times10^{-4},\Delta_1=\Delta_2=\nu/2,\kappa_1=8/3\nu,\kappa_2=0.1\nu,g=3\nu,\Omega_2=\Omega_1=\Omega=500\nu$.

IV. CONCLUSION

In summary, we have presented a fast ground-state optomechanical cooling scheme by use of the two-mode optical cavity with a quarter-wave plate put inside. The two cavity modes are orthogonally polarized and one mode dissipates at the fast rate while the other dissipates at the slow rate. The quarter-wave plate provides linear mixing interaction between these two cavity modes. The cooling is dominated by scattering process via the fast-decay channel, which is significantly enhanced. Simultaneously, the heating process is suppressed by exploiting the complete destructive interference between the two optical modes with the help of the quarter-wave plate. In addition, the correction on the heating rate relevant to the slow-decay channel is also discussed.

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