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Optomechanical dynamics in detuned whispering-gallery modes cavity

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ABSTRACT

The dynamics of a microresonator in detuned whispering-gallery modes (WGM) cavity opto-mechanical system are investigated by the quantum Langevin equation. A WGM cavity coupling to two parallel waveguides is devised to study the transmission and reflection of this system. In single mode WGM cavity, without optomechanical coupling, both the transmission and reflection of the cavity present a Lorentzian dip and peak. When the coupling between the cavity mode and mechanical mode is considered, the transmission and reflection of the optomechanical cavity show “W” and “M” shape mode splitting. Moreover, under the action of a controlling and a probe laser, the output field at the probe frequency presents electromagnetically induced transparency (EIT)-like spectrum in the system. We give the physical origin of EIT-like and the pump-probe response for the WGM shares all the features of the Λ system in atoms. Further, due to backscattering, the two traveling waves in WGM are coupled with a rate γ. The transmission and reflection of the optomechanical cavity display three modes splitting in the spectra with optomechanical coupling between the two cavity modes and the mechanical mode.

1. Introduction

Over recent years it has become experimentally possible to study the coupling of optical and mechanical degrees of freedom by means of cavity-enhanced radiation pressure. Optomechanical systems with sufficiently strong coupling are predicted to exhibit quantum effects and are a topic of considerable interest such as radiation pressure-driven oscillations [1] and dynamic backaction cooling [2,3,4]. Now, optomechanical systems are one of the fascinating and rapidly growing fields in quantum optics and their application in information technology [5]. Experiments and theoretical proposals aiming to study quantum aspects of the interaction between optical cavities and mechanical objects have focused on cavities in which one of the mirrors is free to move (Fabry–Perot cavity) [6–10] or whispering gallery mode resonators (WGMRs) [4,11–14] in which light is confined to a waveguide by total internal reflection. Fabry–Perot optomechanical cavity [8–10,15] has been investigated widely and Schliesser et al. have also given a summary about WGM cavity optomechanics [16,17]. The WGM cavity optomechanical systems have potential application in both theoretical scheme and experiments. Resolved-sideband cooling and position measurement of a micromechanical oscillator close to the Heisenberg uncertainty limit were demonstrated in WGM optomechanical cavity [18]. Recently, optomechanically induced transparency (OMIT) has been demonstrated in WGM optomechanical cavity system [13].

As we know, electromagnetically induced transparency (EIT) [19–22] has been discovered in the atomic vapors, which has led to many different applications, most notably in the context of slow light [23–25] and the production of giant nonlinear effects. For the atomic systems, EIT occurs due to quantum interference effects induced by coherently driving the atom with an external laser [21,26]. Recently, Agarwal and Huang have demonstrated EIT-like spectrum in Fabry–Perot cavity optomechanical system [27]. Moreover, OMIT and slow light with optomechanics were proposed [28–30,16,17]. Here, we devise an optomechanical system which contains a WGM cavity coupling to two parallel waveguides to study the transmission and the reflection of the optomechanical cavity as shown in Fig. 1(c). The transmission and reflection of the optical output of this optomechanical system are investigated firstly. With the simultaneous presence of control and probe fields in the cavity, the existence and physical origin of OMIT in WGM microresonator were demonstrated. Our results demonstrate that the resonant interference required for coherent manipulation of light can indeed be achieved via optomechanical system without the use of atomic resonance. Further, the double cavity modes as shown in Fig. 1(a) are also investigated and we study the transmission and reflection of the optomechanical cavity by numerical solution. This work therefore has broad implications for optical communications and quantum information processing.

In this article, we investigated the dynamics of a microresonator in detuned WGM cavity optomechanical system by the quantum Langevin equation under the resolved-sideband regime. The transmission and reflection of the single mode cavity present the mode splitting with optomechanical coupling. In addition, at red-detuned pump, with the simultaneous presence of control and probe fields in this cavity

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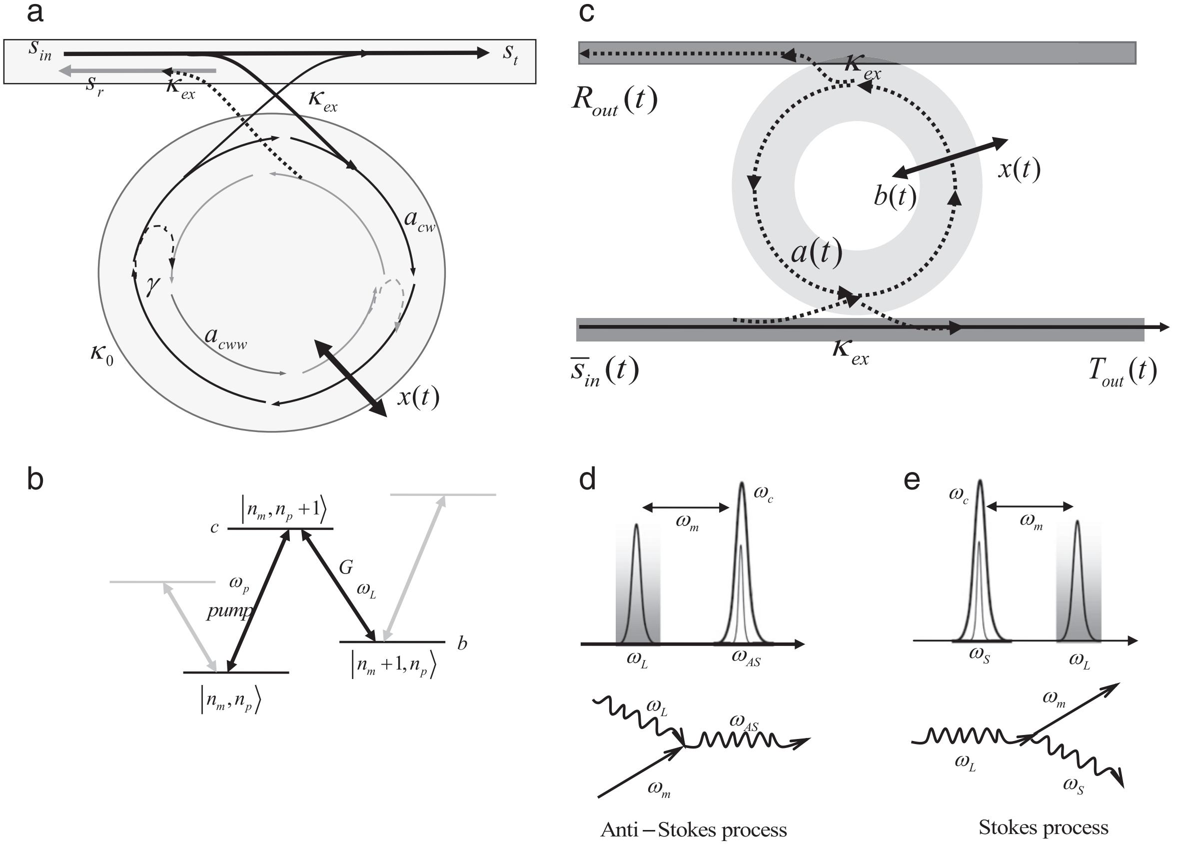

Fig. 1. (a) The microcavity optomechanical system is driven near resonance by coupling light into and out of it using an optical fiber taper waveguide with a cavity-waveguide coupling rate κ_{ex}. The coupling between the clockwise and counterclockwise whispering-gallery modes at a rate γ. κ_0 is the intrinsic photon loss rate of the WGM. (b) Level scheme of the optomechanical system. The number of photons and phonons is denoted by n_p and n_m, respectively. The pumped laser propagating in the optical fiber coupled to the WGM cavity emerge couple states $|n_m,n_p\rangle \leftrightarrow |n_m,n_p+1\rangle$. The coupling between the mirror and the field cavity is tuned close to red-sideband transitions generating couple states $|n_m+1,n_p\rangle \leftrightarrow |n_m,n_p+1\rangle$, in which a mechanical excitation quantum is annihilated (mechanical occupation $n_m+1 \rightarrow n_m$) when a photon is added to the cavity (optical occupation $n_p \rightarrow n_p+1$). The two couplings create a set of Λ-type transitions analogous to that in electromagnetically induced transparency. (c) Schematic of the optomechanical system which contains a WGM cavity coupling to two parallel waveguides. WGM resonator is pumped by a laser coupling with a waveguide. An impinging field $s_{in}(t)$ drives the intracavity field $c(t)$ inducing a control field. The cavity resonance frequency depends on the displacement $x(t)$ of a cavity boundary from its equilibrium position. (d) Anti-Stokes (ω_{AS}) progress annihilating a phonon ω_m. (e) Stokes scattering (ω_S) producing a phonon ω_m.

optomechanical system, a famous phenomenon called OMIT is discovered with a two-photon resonance. We give a physical origin of this phenomenon in this optomechanical system. Further, backscattering causes the coupling between the two traveling waves in WGM optomechanical cavity with mode coupling rate γ, and we calculate steady state solutions of the two cavity modes by numerical solution. Using the input–output theory, the transmission and the reflection of the optomechanical cavity are obtained. With the coupling between the two cavity modes and the mechanical mode, the transmission and the reflection spectra present three modes splitting.

2. Model and Hamiltonian of the optomechanical system

The optomechanical cavity investigated here is represented in Fig. 1 (a) which is WGM microresonator [31,32]. The WGMs are typically excited through an external waveguide, and for a nearly phase-matched system the forward propagating mode through the waveguide excites only the copropagating mode in the resonator (the clockwise cavity mode). However, light scattering both in the bulk and at surface inhomogeneities leads to a significant population of the mode in which light orbits in the opposite direction which induces counterclockwise propagating modes [33–36]. If the loss rates in the system are low enough, the backscattering can lead to coherent coupling of the clockwise and counterclockwise modes with mode coupling rate γ, producing a pair of standing wave modes. As a result, the WGMs have a degeneracy double mode with the same frequency ω_c circulating around the disk in opposite directions. The input laser power is P_{in} with frequency ω_L propagating forward through the waveguide, and $\bar{s}_{in} = \sqrt{2P_{in}/\hbar\omega_L}$ is corresponding to the input laser power. The forward propagating mode through the waveguide coupling to the WGM cavity induces two cavity modes a_{cw} and a_{ccw} with the same frequency ω_c. The optomechanical Hamiltonian of the WGM resonator with two coupled counterpropagating modes can be written as (in a frame rotating at the laser frequency ω_L)

$$\begin{aligned} H = {} & \hbar(\omega_c-\omega_L)\left(a^\dagger_{cw}a_{cw} + a^\dagger_{ccw}a_{ccw}\right) + \hbar\omega_m b^\dagger b - \hbar\gamma\left(a^\dagger_{cw}a_{cw} + H.c\right) \\ & + \hbar g\left(b^\dagger + b\right)\left(a^\dagger_{cw}a_{cw} + a^\dagger_{ccw}a_{ccw}\right) + i\hbar\sqrt{2\kappa_{ex}}\left(\bar{s}_{in}a^\dagger_{cw} - H.c\right). \end{aligned} \qquad (1)$$

The first term in Eq. (1) is the energy of the two cavity field, and a_{cw} (a_{ccw}) describes the annihilation operator of the clockwise (counterclockwise) propagating modes. The second one denotes the energy of the mechanical mode, modeled as harmonic oscillator with frequency ω_m and described by the annihilation (creation) operator b ($b^\dagger$). The third term gives the coupling between the two cavity modes with mode coupling rate γ. The fourth term describes the Hamiltonian interaction between the clockwise and counterclockwise cavity modes coupled to the mechanical mode with the same optomechanical coupling rate $g = g_0 x_0$ for the WGM resonator of radius R, where $g_0 = -\omega_c/R$ and $x_0 = \sqrt{\hbar/2m\omega_m}$ designate the zero-point fluctuation of the mechanical oscillator's position. The last term in Eq. (1) gives the coupling between the