

Multi-normal mode-splitting for an optical cavity with electromagnetically induced transparency medium

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Abstract: We theoretically study the cavity transmission spectra with three-level atoms coupled by a coherent external control field in the superstrong coupling regime (atoms-cavity coupling strength $g\sqrt{N}$ is near or larger than the cavity free-spectral range Δ_{FSR}). When satisfying the superstrong coupling condition by increasing the number of the interaction atoms, more than one FSR cavity modes interact with atoms and each mode will split three peaks, which can be well explained by the linear dispersion enhancement of electromagnetically induced transparency medium due to the largely increased atomic density in the cavity.

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1. Introduction

Vacuum Rabi-splitting (or normal-mode splitting) is a feature in strongly coupled atom-cavity systems [1, 2, 3, 4]. In the traditional cavity-quantum electrodynamics (C-QED), high finesse microcavities are normally used to enhance the single-photon coupling strength g ($= \sqrt{\frac{\mu^2 \omega_c}{2\hbar \epsilon_0 V_M}}$, where ω_c is the resonant frequency of the cavity, μ is the atomic dipole matrix element, V_M is the cavity mode volume), so the strong-coupling condition of $g > \kappa, \gamma$ can be satisfied even with a single atom [1, 2, 3, 4] (where κ is the cavity decay rate and γ is the atomic decay rate). Two normal-mode splitting peaks (i.e. Rabi sidebands) appear in the cavity transmission spectrum due to such strong atom-cavity interaction, with the frequency space between the two side peaks given by $2g$. In this regime the quantum dynamics of a few microscopic quantum degrees of freedom dominates the behavior of the system and quantum fluctuations are typically large. In the other regime of involving an assemble of atoms, The atom-cavity coupling strength g can be enhanced to be $g\sqrt{N}$, where N is the number of atoms in the cavity mode volume [5, 6]. Normal-mode splitting with the double-peak structure in assemble of two-level atoms has

been demonstrated in atomic beams [7, 8], cold atomic cloud [9, 10] Bose-Einstein condensate [11, 12, 13], and Doppler-broadened two-level atoms in a hot atomic vapor cell [14]. These results had only been studied under the condition of $g\sqrt{N} \ll \Delta_{FSR}$, in which the mode splitting only occurs for one cavity resonant mode near the atomic resonance. $\Delta_{FSR} = 2\pi \times c/L_c$ is the free spectral range (FSR) of the empty optical cavity and c is the speed of light in vacuum. Studies of atom-cavity interactions have been extended to the system of an optical cavity with coherently prepared multilevel atoms. Three-peak structure in the transmission spectrum of a cavity containing a three-level atoms dressed by a strong external field were observed, which consists of two broad sidebands representing the vacuum Rabi splitting and a narrow central peak manifested by the dark-state resonance of the two-photon Raman transition [15, 16]. With the high-density, nonlinear regime of atom-cavity coupling for a gas of three-level atoms, the two side peaks in the transmission spectrum split into two pairs of peaks as the temperature increases and each pair of peaks will emerge into one peak due to nonlinearity as the cavity input power increased [17].

Interesting effects in atoms-cavity coupling system, such as cavity-mediated collective light scattering due to the self-organized atoms in the intracavity optical lattice and collective atomic motion, were observed in such system [18, 19, 20, 21]. The normal-mode splitting and collective mechanical effects have also been studied in such atoms-cavity system [9]. The coherent backscattering between the two propagating directions of a longitudinal mode has enhanced the coupling between the atoms in the optical lattice and the cavity fields, even when the fields are detuned far from the atomic resonance [18, 19, 20, 21]. The collective interactions between the atomic ensemble and light can realize the squeezed atomic ensemble for sub-shot-noise sensitivity, which is generated with a enhanced quantum nondemolition (QND) interaction between the atoms and an off-resonant probe beam in the cavity [22, 23]. The coherent coupling between a BEC and a cavity field, demonstrated experimentally, push the studies of quantum micromechanics using collective motion of a trapped ensemble of ultracold atoms as macroscopic resonator [24]. The giant dipole moments of intersubband transitions in quantum wells have been demonstrated for ultrastrong light-matter coupling (here, $g\sqrt{N}$ is large enough to amount to a significant fraction of the two-level transition frequency) [25].

Recently, a new “superstrong coupling” regime of the cavity quantum electrodynamics (cavity-QED) was discussed: i.e. $g\sqrt{N} > \Delta_{FSR}$ with a microscopic number of atoms [26]. More recently, the “superstrong coupling” was investigated experimentally in an optical cavity and two-level atoms, i.e. $g\sqrt{N}$ is near or larger than Δ_{FSR} with macroscopic numbers of atoms [27]. In such case, more than one cavity modes will “see” and interact with atoms. The normal-mode splitting can occur for more than one FSR cavity modes (therefore denoted as the multi-normal-mode splitting). In this paper we theoretically study a composite cavity and three-level atoms system in the superstrong coupling regime. When $g\sqrt{N} \ll \Delta_{FSR}$, only one cavity resonant mode near the atomic resonance occurs the mode splitting and become three peaks (we denote all three peaks as single normal-mode splitting in the composite cavity and three-level atoms system), just as shown in Ref. [15, 16]. When satisfying the superstrong coupling condition for $g\sqrt{N} > \Delta_{FSR}$ by increasing the number of the interaction atoms, more than one FSR cavity modes interact with atoms and each mode will split three peaks (we denote this phenomenon as multi-normal mode-splitting for an optical cavity with electromagnetically induced transparency medium). This phenomenon can be explained very well by using the linear absorption and dispersion theory of the cavity transmission, and by taking into account the sensitive dependence of the index of refraction of the intracavity EIT medium on the atomic density.

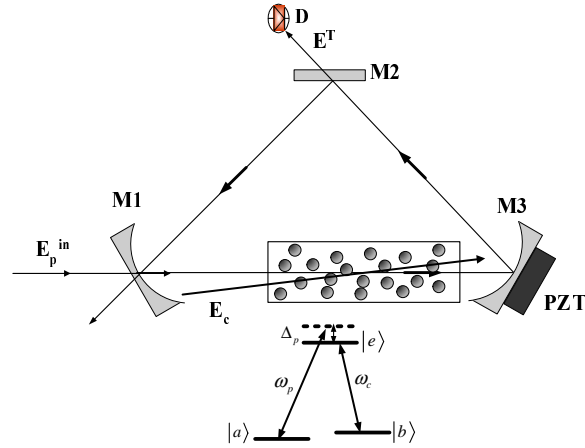


Fig. 1. A schematic diagram of a ring cavity containing the three-level atoms coupled by a coherent external control field. The optical cavity length, which is fixed on atomic transition frequency, is adjusted by piezoelectric transducer (PZT) mounted on the mirror M3. The frequency of the input laser (as probe light) is scanned to measure the transmission spectra.

2. Theoretical model and analysis

In the model of the coupled atoms-cavity system, the cavity is a ring cavity with length L_c , containing N identical three-level atoms coupled by a coherent external control field as shown in Fig.1. Since we don't consider Doppler effect in this paper, our scheme is suitable for the ring or standing-wave cavity. The cavity mode couples the atomic transition $|a\rangle - |e\rangle$. The classical control laser E_c drives the atomic transition $|b\rangle - |e\rangle$. The cavity input and output mirrors have amplitude reflection (transmission) coefficients of $r_1(t_1)$ and $r_2(t_2)$, respectively, with $r_i^2 + t_i^2 = 1$. The three-level atomic medium has a length $L_a < L_c$ with N atoms in the cavity volume. The intensity transmission function of a probe laser for the coupled atoms-cavity system is given by [7]

$$T_c(\omega_L) = |t_c(\Delta)|^2 = \frac{t_1^2 t_2^2 e^{-\alpha L_a}}{(1 - r_1 r_2 e^{-\alpha L_a/2})^2 + 4 r_1 r_2 e^{-\alpha L_a/2} \sin^2(\phi/2)}, \quad (1)$$

where

$$\phi(\omega_L) = 2\pi(\Delta - \Delta_{ac})/\Delta_{FSR} + (n-1)L_a\omega_L/c \quad (2)$$

is the round-trip phase shift experienced by the intracavity field going through the cavity. αL_a is the single-pass intensity absorption of the atomic medium and n is the refractive index. $\Delta = \omega_L - \omega_a$ and $\Delta_{ac} = \omega_c - \omega_a$ are laser-atom and atom-cavity frequency detunings, respectively. For a cavity with the finesse $F = \pi\sqrt{r_1 r_2}/(1 - r_1 r_2)$, the cavity linewidth is given by $\kappa = \Delta_{FSR}/F$. The frequency-dependent intensity-absorption coefficient and the refractive index of the atomic medium are given by

$$\alpha = 2\frac{\omega_a}{c} \text{Im}[(1 + \chi)^{1/2}] \quad (3)$$

$$n = \text{Re}[(1 + \chi)^{1/2}], \quad (4)$$

respectively, where χ is the susceptibility of EIT medium.

For the three-level atoms which interact with the coherent control and probe lasers, the motion equations of the density matrix are given as [28, 29]

$$\begin{aligned}\dot{\rho}_{be} &= -(\gamma_{be} - i\Delta_c)\rho_{be} + i\frac{\mu_{be}E_c^*}{2}(\rho_{bb} - \rho_{ee}) + i\frac{\mu_{ea}E_p^*}{2}\rho_{ba} \\ \dot{\rho}_{ea} &= -(\gamma_{ea} - i\Delta_p)\rho_{ea} + i\frac{\mu_{ea}E_p}{2}(\rho_{ee} - \rho_{aa}) + i\frac{\mu_{be}E_c}{2}\rho_{ba} \\ \dot{\rho}_{ba} &= -[\gamma_{ba} - i(\Delta_p + \Delta_c)]\rho_{ba} - i\frac{\mu_{be}E_c^*}{2}\rho_{ea} + i\frac{\mu_{ea}E_p}{2}\rho_{be}\end{aligned}\quad (5)$$

where ρ_{ij} is the density matrix element, γ_{ij} and μ_{ij} is the decay rate and electronic dipole, Δ_p and Δ_c are the detuning of the probe and coupling laser respectively. In this paper, we only consider $\Delta_c = 0$ and the amplitude of the coherent control laser is more larger than that of the probe laser ($|E_p| \ll |E_c|$). Hence most of the atoms leave in the ground state, so $\rho_{aa} \simeq 1$ and $\rho_{ee} \simeq \rho_{bb} = 0$. If the system is an equilibrium state, we can get

$$\rho_{ea} \simeq -\frac{i\mu_{ea}E_p}{\gamma_{ea} - i\Delta_p + \frac{\Omega_c^2/4}{\gamma_{ba} - i\Delta_p}}, \quad (6)$$

where $\Omega_c = \mu_{be}E_c$ is the Rabi frequency of the coupling laser. Thus the complex susceptibility of the EIT medium is obtained from Eq. (6) [28, 29, 30]

$$\begin{aligned}\chi &= -\frac{i\mu_{ea}^2 N_D}{\hbar\epsilon_0} \frac{1}{\gamma_{ea} - i\Delta_p + \frac{\Omega_c^2/4}{\gamma_{ba} - i\Delta_p}} \\ &= -\frac{i3\pi c^3 N_D}{\omega_a^3} \frac{\gamma_{ea}}{\gamma_{ea} - i\Delta_p + \frac{\Omega_c^2/4}{\gamma_{ba} - i\Delta_p}},\end{aligned}\quad (7)$$

where N_D is the number density of atoms in the cavity mode volume. Here, the angle sustained by the cavity mode is small, and the transverse decay rate can be very closely approximated by the atomic free-space decay rate $\gamma_{ea} = \mu_{ea}^2 \omega_a^3 / 3\pi\hbar\epsilon_0 c^3$. When the condition $|\chi| \ll 1$ is satisfied, the absorption coefficient and the refractive index of the atomic ensemble can be expressed as

$$\begin{aligned}\alpha &= \frac{\omega_a}{c} \text{Im}[\chi] \\ n &= 1 + \text{Re}[\chi]/2.\end{aligned}\quad (8)$$

This is the linear-dispersion theory with Eqs. (1) and (8) used to study the multi-normal-mode splitting of the transmission spectra in the coupled atoms-cavity system.

We consider a situation with three-level atoms (such as rubidium atoms) inside a macroscopic optical ring cavity of 35 cm long. In such system, $\gamma_{ea} = 2\pi \times 6$ MHz, $\gamma_{ba} = 2\pi \times 10$ kHz and $\Delta_{FSR} = 2\pi \times 856$ MHz. The input mirror $M1$ and output mirror $M2$ of the ring cavity all have 2% transmittance, and $M3$ is a high reflector. The mirrors $M1$ and $M3$ have the same radius of curvature with 50 mm and the $M2$ is the plane mirror. The cavity transmission spectra are given by scanning the frequency of the input probe laser. We will only consider the case of $\Delta_{ac} = 0$ throughout this work (the optical cavity length was fixed to resonate the atomic transition $|a\rangle - |e\rangle$).

First, we consider the case of $\Omega_c = 0$ (without the control light), which corresponds to the two-level atoms interacting with the cavity modes. For an empty cavity, the cavity transmission peaks are Lorentzian in shape and occur at $\phi(\Delta) = m2\pi$, where $m = 0, \pm 1, \pm 2, \dots$, with equal

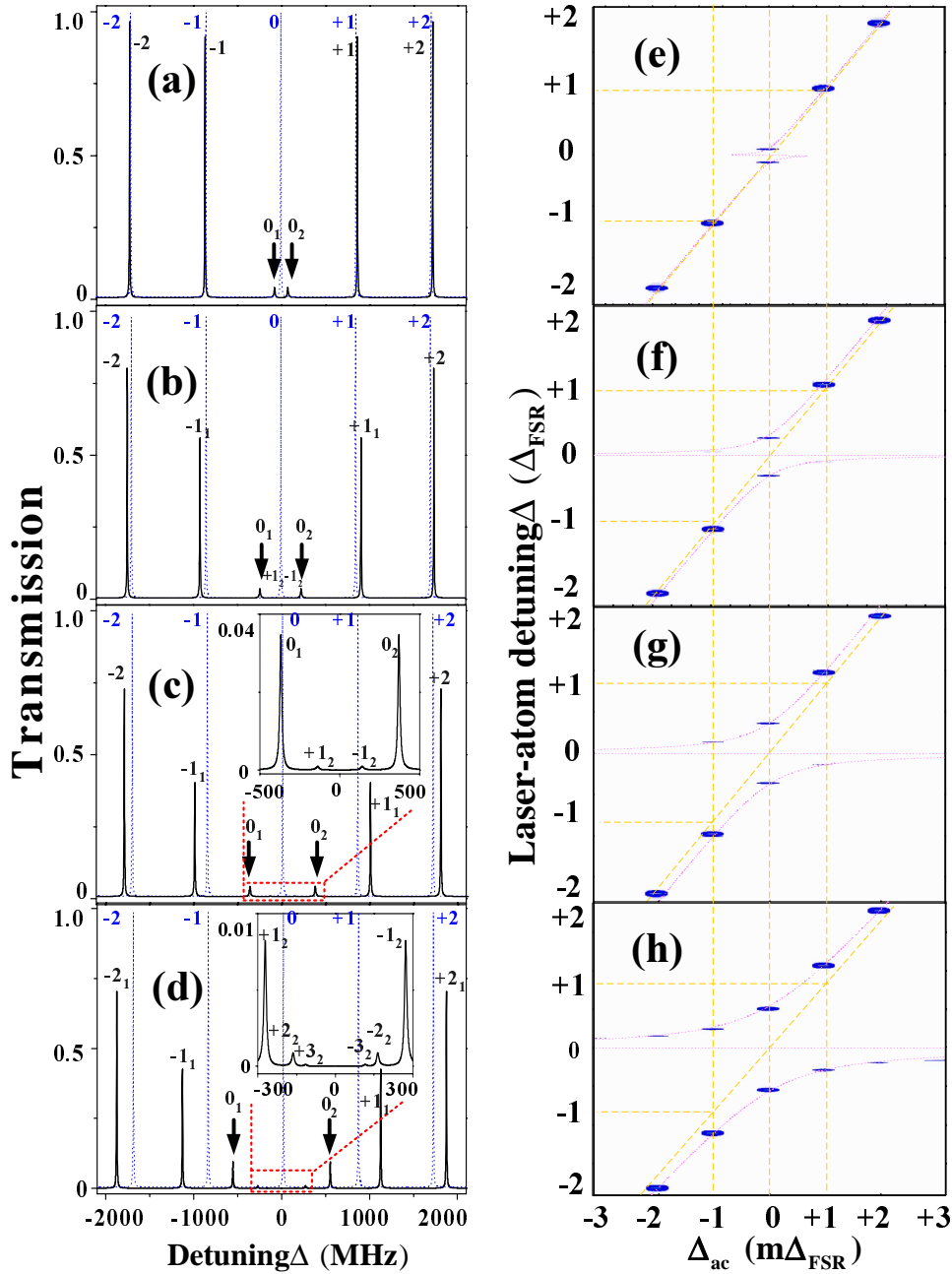


Fig. 2. (Color online). Theoretical calculations of the transmission spectra of the coupled atoms-cavity system with the two-level atoms with different atomic density. For comparison, the cavity transmission spectrum for the empty cavity (blue dashed) is plotted in (a)-(d). $m = \{\dots, -2; -1; 0; +1; +2; \dots\}$ label the FSR empty cavity modes and $m' = \{\dots, \{-2_1; -2_2\}; \{-1_1; -1_2\}; \{0_1; 0_2\}; \{+1_1; +1_2\}; \{+2_1; +2_2\}; \dots\}$ the multi-normal-mode splitting peaks. (a) $N_D L a = 3.15 \times 10^{15} m^{-2}$; (b) $N_D L a = 3.15 \times 10^{16} m^{-2}$; (c) $N_D L a = 7.85 \times 10^{16} m^{-2}$; (d) $N_D L a = 1.77 \times 10^{17} m^{-2}$; (e), (f), (g) and (h) are the replots of the multi-normal-mode splitting peaks of (a), (b), (c) and (d) with blue elliptical points, respectively. The function $\phi(\Delta)/2\pi = \Delta/\Delta_{FSR} + Re[\chi(\Delta)]L_a/2\lambda_L$ is also plotted in (e), (f), (g) and (h) with pink dot line.

mode spaces given by Δ_{FSR} , as can be easily seen from Eq. (1). Each mode is the normal longitudinal mode of the empty cavity. With an intracavity (two-level) atomic medium, the cavity transmission structure is significantly modified. The detailed analysis was given in Ref. [27]. Here we present it simply in order to compare with the EIT medium. When the atomic density is higher, more cavity modes (such as $m = +(-)2$ and $m = +(-)3$, et al) will participate in the mode-splitting process, which form the multi-normal-mode splitting structure ($m = +1$ is split into $m' = +1_1$ and $m' = +1_2$; $m = -1$ into $m' = -1_1$ and $m' = -1_2$; $m = +2$ into $m' = +2_1$ and $m' = +2_2$; etc.) for two-level atom-cavity system, as shown in Fig. 2(d). Figures 2(e), 2(f), 2(g) and 2(h) (which are the re-plots of Figs. 2(a), 2(b), 2(c) and 2(d), respectively, with the FSR cavity mode number m as the horizontal axis) give a more clear insight into the positions and heights of the multi-normal-mode splitting peaks. Such plots are the typical avoided-crossing plots commonly used in cavity-QED. Note that the peaks of the multi-normal-mode splitting don't occur exactly at the frequencies with $\phi(\Delta) = m2\pi$ due to the absorption, and slightly shifts away (outside) from the position of the function $\phi(\Delta) = m2\pi$. The function of $\phi(\Delta)/2\pi = \Delta/\Delta_{FSR} + Re[\chi(\Delta)]L_a/2\lambda_L$ is also plotted in Figs. 2(e), 2(f), 2(g) and 2(h) with $\phi(\Delta)/2\pi$ as the horizontal axis and Δ/Δ_{FSR} as the vertical axis. Thus from the Fig. 2, we know that the avoided-crossing curve corresponds to the dispersion of the two-level atoms, which is only transformed linearly. The central part of the avoided-crossing curve, compared with the transformed dispersive curve, is disappeared due to the strong absorption of the two-level atoms.

Now we consider the three-level atoms, which are coupled by a coherent external control field, interacting with the cavity modes. The narrow transparency window appears in the absorption spectrum and is accompanied by a very steep variation of the dispersive profile for the EIT medium [31, 32, 33, 34]. When the atomic density is high enough to satisfy $\Delta_{FSR} \gg g\sqrt{N} \gg \gamma_a, \kappa$, $\phi(\Delta) = 0$ will have three real solutions due to the dispersion introduced by the three-level atoms. Thus we know that the center peak ($m=0$) in the cavity transmission is split into three peaks $m' = \{0_1; 0_2; 0_3\}$ (as shown in Fig. 3a) including two side peaks $m' = 0_1$ and 0_2 located at $\pm g\sqrt{N}$, which is the standard normal-mode splitting, and a very narrow peak $m' = 0_3$ at the center, which is originated from the very steep dispersion at center transparency window. The very narrow peak at center demonstrates that the steep normal dispersion can reduce the cavity linewidth [35]. Under this condition, the other cavity modes are also not affected by the atoms. When $g\sqrt{N}$ is near or larger than Δ_{FSR} , not only the center cavity mode ($m = 0$) has mode splitting, other cavity modes (such as $m = \pm 1$) will interact with the atoms and have their own mode splitting peaks (i.e. $\phi(\Delta) = 2\pi$ and $m' = \{+1_1; +1_2; +1_3\}$ or $\phi(\Delta) = -2\pi$ and $m' = \{-1_1; -1_2; -1_3\}$ will also have three real solutions labeled in the figure), as shown in Figs. 3(b) and 3(c). Their two splitting peaks i.e. $m' = +1_1$ and $+1_2$ come originally from the splitting of the two-level atoms, however $m' = +1_3$ from the very steep dispersion at center transparency window. The positions of their three splitting peaks present asymmetric structure as shown in Figs. 3(b) and 3(c). When the atomic density gets even higher, more cavity modes (such as $m = +(-)2$ and $m = +(-)3$, et al.) will participate in the mode-splitting process, which form the multi-normal-mode splitting structure for three-level atom-cavity system, as shown in Fig. 3(d). Figures 3(e), 3(f), 3(g) and 3(h) (which are the re-plots of Figs. 3(a), 3(b), 3(c) and 3(d), respectively) give a more clear insight into the positions and heights of the multi-normal-mode splitting peaks for three-level atoms. Figs. 3(e), 3(f), 3(g) and 3(h), including the curves of the function of $\phi(\Delta)/2\pi = \Delta/\Delta_{FSR} + Re[\chi(\Delta)]L_a/2\lambda_L$, present the relationship between the avoided-crossing curve and the dispersion of the three-level atoms.

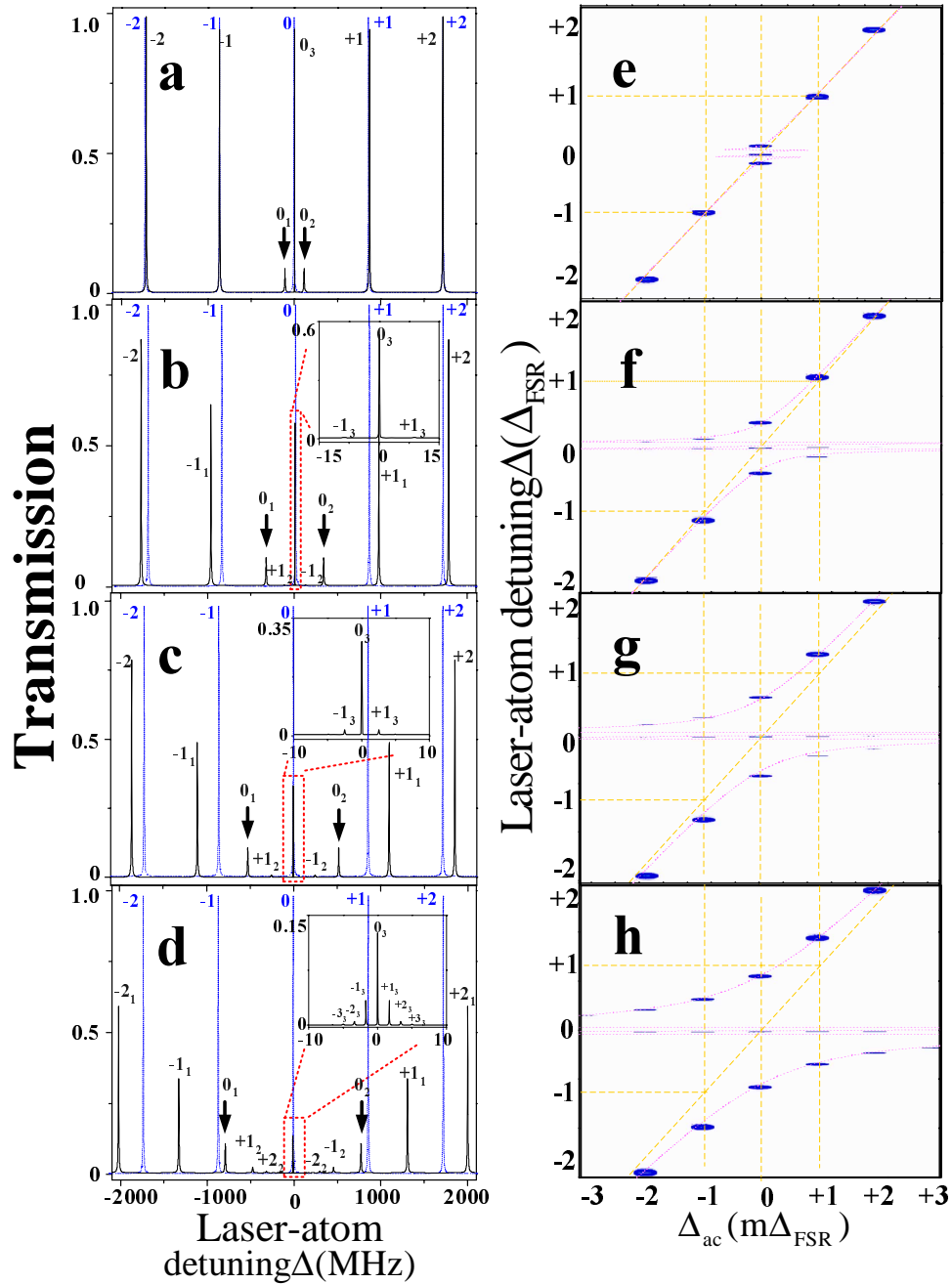


Fig. 3. (Color online). Theoretical calculations of the transmission spectra of the coupled atoms-cavity system with the three-level atoms with different atomic density. The cavity transmission spectrum for the empty cavity (blue dashed) is plotted in (a)-(d). $m = \{\dots; -2; -1; 0; +1; +2; \dots\}$ label the FSR empty cavity modes and $m' = \{\dots; \{-2_1; -2_2; -2_3\}; \{-1_1; -1_2; -1_3\}; \{0_1; 0_2; 0_3\}; \{+1_1; +1_2; +1_3\}; \{+2_1; +2_2; +2_3\}; \dots\}$ the multi-normal-mode splitting peaks. The Rabi frequency of the coupling laser is $\Omega_c = 2\pi \times 60 \text{ MHz}$. The other parameters are same as the Fig.2. (e), (f), (g) and (h) are the re-plots of the multi-normal-mode splitting peaks of (a),(b) (c) and (d) with blue elliptical points, respectively. The function $\phi(\Delta)/2\pi = \Delta/\Delta_{\text{FSR}} + \text{Re}[\chi(\Delta)]L_a/2\lambda_L$ is also plotted in (e), (f), (g) and (h) with pink dot line.

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3. Conclusion

In summary, we have studied theoretically the cavity transmission spectra in a system with three-level atoms under the “superstrong coupling” condition of $g\sqrt{N}$ larger or equal to Δ_{FSR} . Each FSR cavity mode is split into three peaks in the composite cavity and three-level atoms system. In the atoms-cavity superstrong coupling region, mode-splitting with three peaks occurs in many FSR cavity modes due to the interactions with the intracavity atoms. This phenomenon can be qualitatively explained by using the linear absorption and dispersion theory of the cavity transmission. From this work, we may give clear explanation for the phenomenon in recent experimental work [17], which is the two side peaks in the transmission spectrum “splitting” into two pairs of peaks as the temperature increases. In fact, the splitting peaks come from the splitting of the different cavity modes as shown in Fig. 3(b). This work also stimulate theoretical and experimental investigations of the cavity with the different atomic medium (e.g. multi-level atoms) in the “superstrong coupling” region. For example, recently Li, et al. have experimentally studied EIT in a dense rubidium gas with the propagation of two optical fields in the presence of an added microwave field that is coupled to the hyperfine levels of Rb atoms, which are in a three-level Λ configuration [36]. The contributions to the transmission of the probe field are determined by the interface of the Λ -scheme EIT and the parametric process involving the microwave field, which give several ways to control the coherence and the transmission of the probe field. So we may investigate the influence on the multi-normal mode-splitting in the composite cavity and three-level atoms system with the additional microwave field.

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