EIT-like phenomenon with two atomic ensembles in a cavity

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We study the spectra of collective low excitations of two atomic ensembles coupled indirectly through a single-mode cavity field. When the left ensemble is driven with an external optical field, its corresponding response spectrum to the incident optical light shows an electromagnetically induced transparency- \textit{(EIT)-} like phenomenon when the layers are arranged in the sequence of node-antinode but not in the sequence of antinode-node. In the case of antinode-antinode sequence, the response spectrum shows an EIT-like phenomenon with two transparent windows. We also investigate the fluctuation spectra of the atomic collective excitation modes, which show similar EIT-like phenomena.

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I. INTRODUCTION

It is well known that photon system is a prior candidate for quantum information processing such as quantum computing or quantum cryptography due to its fast and easy-getting advantages. Since the direct coupling between photons is absent according to the theory of quantum electrodynamics (QED), people proposed to store the information of photons into an atomic-ensemble-based quantum memory so that one could indirectly manipulate photon by photon through the atomic ensemble based on electromagnetically induced transparency \textit{(EIT)}. Therefore, the EIT is used to effectively overcome the strong absorption of an atomic medium on a propagating beam of electromagnetic radiation \cite{1,2}. It plays a role in manipulating the photons for quantum information storage and non-linear optical processes \cite{3,4}. Actually, the EIT phenomenon is a result of the Fano interference between transitions of atomic internal energy states \cite{5,6}, and induces many strange optical phenomena in the dispersion medium \cite{7,8}.

The conventional EIT phenomena were implemented for the three-level or four-level systems which look “dark” for the probe light \cite{9,10}. Recently, the EIT analog in quantum optomechanical systems, i.e., optomechanically induced transparency \textit{(OMIT)}, was suggested \cite{11} and confirmed experimentally \cite{12}. Most recently, it was also discovered that there may also exist the EIT-like phenomena for the reflectivity spectrum of X-ray in the system of two layers \cite{13}. Here, two layers consist of the Mössbauer isotope \textit{^{57}Fe} nuclei, which are exactly modeled as two-level systems with a resonant transition of 14.4 kev for Mössbauer effect. It was observed the EIT-like phenomenon appears for the cavity configuration where the layers are arranged in the sequence of node-antinode and disappears in the antinode-node sequence. Such observation was explained with a proposed three-level configuration, which was usually required for obtaining EIT effect, but actually the \textit{^{57}Fe} nuclei for the considered problems are only modeled as two-level systems rather than three-level ones.

On the other hand, the EIT effect may have a classical analogue that is referred to three-level configuration directly: A system of two coupled harmonic oscillators \textit{(HOs)} can exhibit the EIT-like effect \cite{14} wherein a transparency window exists as the coupling induces split in absorption spectrum. Furthermore, two of the authors of the present paper \cite{15} even used the coupled bosonic modes to describe the low excitations of the atomic ensemble with EIT configuration. These studies actually gave a description of two coupled HOs for the EIT effect with atomic ensembles. With these considerations, it is possible to qualitatively understand the experiment \cite{15} as an EIT-like phenomenon, that is, as a classical analogue with coupled bosonic modes formed by the single-mode cavity field and collective excitation modes of two ensembles/layers of two-level systems rather than three-level configuration.

In this paper, we consider a model system similar to the two-layer system in the X-ray quantum optics experiment \cite{15}. But in constrast to the latter case, in our model the two HOs, which are realized by atomic collective excitation modes, are indirectly coupled by a quantized single-mode cavity field. We first bosonize the low excitations of two atomic ensembles inside the single mode cavity. The quantized single-mode cavity field provides a coupling between these two bosonic modes. From the quantum Langevin equations of our system’s variables for the two bosonic modes (with one of them driven by external field) and cavity mode, we find that the steady-state response intensities of two atomic ensembles show a transparency window in some conditions, e.g., when the layers are arranged in the sequence of node-antinode (instead of the sequence of antinode-node).

Indeed, the response spectra of two collective excita-
tion modes to the external driving field show that if the two atomic ensembles are placed in proper positions, e.g., in the antinode-node sequence, the EIT-like window would appear for the driven ensemble, and can be explained as a classical analogue of EIT for two coupled HOs in Ref. [14]. In the exchanged node-antinode sequence, the EIT-like window disappears. These could reflect qualitatively the basic spirit hidden in the X-ray scattering experiment in Ref. [13], where the reflectivity spectrum shows EIT phenomenon in certain sequence and not in the opposite sequence. If we put both the atomic ensembles to the antinodes of the cavity field, the spectra of both the ensembles would appear with two EIT-like windows. This is very similar to the AC Stark effect in atomic optics [25]. To confirm the above predictions based on a simple model, we also calculate the fluctuation spectra, which display the similar EIT-like phenomena.

This paper is organized as follows. In Sec. II, we describe our model with an effective Hamiltonian in terms of the collective excitation operators of atomic ensembles. In Sec. III, we calculate the response spectra of the collective excitation modes to the external driving field to show the EIT-like phenomena occurred in our scheme. In Sec. IV, we calculate the fluctuation spectra of system to confirm the results in Sec. III. Finally, we make conclusions and give some remarks in Sec. V.

II. THE MODEL AND HAMILTONIAN OF TWO ENSEMBLES IN A CA VITY

As shown in Fig. 1, the model under consideration consists of two ensembles of two-level atoms coupling with a single-mode cavity field. The left atomic ensemble is driven by a classical external field of frequency $\omega_f$. The model Hamiltonian reads (hereafter, we take $\hbar = 1$)

$$H = \omega_c c^\dagger c + \frac{\omega_a}{2} \sum_{i=1}^{N_a} \sigma_{z,a}^{(i)} + \frac{\omega_b}{2} \sum_{j=1}^{N_b} \sigma_{z,b}^{(j)} + \left[ g_a c^\dagger \sum_{i=1}^{N_a} \sigma_{+,a}^{(i)} + g_b c^\dagger \sum_{j=1}^{N_b} \sigma_{+,b}^{(j)} + \Omega e^{-i\omega_f t} \sum_{i=1}^{N_a} \sigma_{+,a}^{(i)} + \text{H.c.} \right].$$ (1)

Here, $c$ ($c^\dagger$) is the annihilation (creation) operator of the cavity field of frequency $\omega_c$. And $\sigma_z^{(s)} = |e\rangle_s \langle e| - |g\rangle_s \langle g|$, $\sigma_+^{(s)} = |e\rangle_s \langle g|$, and $\sigma_-^{(s)} = |g\rangle_s \langle e|$ ($s = a, b$) are the Pauli matrices for the $l$-th atom in the left ensemble ($s = a$) or the right ensemble ($s = b$) with the same energy level spacing $\omega_a = \omega_b$, the number of atoms $N_a$/$N_b$, and the excited and ground states of atoms $|e\rangle_s$/$|g\rangle_s$, respectively. It is pointed out that each ensemble is arranged in a thin layer whose size in the direction of cavity axis has been assumed to be much smaller than the wavelength of cavity field. Thus all the atoms in the left/right ensemble couple to the single-mode cavity field with the identical coupling strength $g_a$/$g_b$. Due to the same reason, the coupling coefficient between the external driving field and the atoms in the left ensemble, $\Omega$, is also identical.

In order to simplify the model Hamiltonian we introduce the following operators of atomic collective excitation modes [17, 19, 20] for the two atomic ensembles

$$A^\dagger = \frac{1}{\sqrt{N_a}} \sum_{i=1}^{N_a} \sigma_{+,a}^{(i)}, \quad A = (A^\dagger)^\dagger,$$ (2)

and

$$B^\dagger = \frac{1}{\sqrt{N_b}} \sum_{j=1}^{N_b} \sigma_{+,b}^{(j)}, \quad B = (B^\dagger)^\dagger.$$ (3)

In the low-excitation limit with large $N_a$ and $N_b$, the above operators satisfy the standard bosonic commutation relations

$$[A, A^\dagger] \approx [B, B^\dagger] \approx 1, \quad [A, B] = [A, B^\dagger] = 0.$$ (4)

And we can also have

$$\sum_{i=1}^{N_a} \sigma_{z,a}^{(i)} = 2A^\dagger A - N_a,$$ (5)

$$\sum_{j=1}^{N_b} \sigma_{z,b}^{(j)} = 2B^\dagger B - N_b.$$ (6)

Then, Hamiltonian (1) can be rewritten in terms of the atomic collective operators $A$ ($A^\dagger$) and $B$ ($B^\dagger$) as

$$H = \omega_c c^\dagger c + \omega_a A^\dagger A + \omega_b B^\dagger B + (G_A c A^\dagger + G_B c B^\dagger + \chi A^\dagger e^{-i\omega_f t} + \text{H.c.})$$ (7)
with $G_A \equiv \sqrt{N_A}g_A$, $G_B \equiv \sqrt{N_B}g_B$ and $\chi \equiv \sqrt{N_a}\Omega$. For simplicity here we have assumed all these coupling strengths are real. In the interaction picture with respect to $H_0 = \omega_f (c_1^\dagger A + A^\dagger B)$, the interaction Hamiltonian is given in the time-independent form as

$$H_I = \Delta_c c_1^\dagger A + \Delta_A A^\dagger A + \Delta_B B^\dagger B + (G_A c_1^\dagger + G_B B^\dagger + \chi A^\dagger + H.c.),$$  

(8)

where the detunings $\Delta_r \equiv \omega_r - \omega_f$ for $r = a, b, c$. We note that during the derivation of Eq. (7) we have neglected the constant terms $-(1/2)\omega_a N_a$ and $-(1/2)\omega_b N_b$ since they have not any affect to our result in the context.

III. THE RESPONSE SPECTRUM FOR TWO ATOMIC ENSEMBLES IN A CAVITY

In our model the external optical driving field can be considered as a probe one which is incident from the left side and drives the first (left) atomic ensemble. Let us first study the response spectra of atomic collective excitation modes to the driving. To this end, we investigate the steady-state solution of variables resorting to the quantum Langevin equations from Eq. (5)

$$\dot{c} = -i\Delta_c c - i G_A a - i G_B B - \frac{\kappa}{2} c + \sqrt{\kappa c}(t),$$  

(9)

$$\dot{A} = -i\Delta_A A - i G_A c - i\chi - \frac{\gamma_A}{2} A + \sqrt{\gamma_A} A(t),$$  

(10)

$$\dot{B} = -i\Delta_B B - i G_B c - \frac{\gamma_B}{2} B + \sqrt{\gamma_B} B(t).$$  

(11)

Here $\kappa$ is the decay rate of the cavity and $\gamma_A, \gamma_B$ the decay rates of collective modes $A$ and $B$, the operators $c(t), A(t)$ and $B(t)$ denote the corresponding noises with the vanishing average values, i.e., $\langle c(t) \rangle = \langle A(t) \rangle = \langle B(t) \rangle = 0$. These noise operators satisfy the following fluctuation relations

$$\langle c(t) c^\dagger(t') \rangle = [N(\omega_c) + 1]\delta(t - t'),$$  

(12a)

$$\langle A(t) A^\dagger(t') \rangle = [N(\omega_a) + 1]\delta(t - t'),$$  

(12b)

$$\langle B(t) B^\dagger(t') \rangle = [N(\omega_b) + 1]\delta(t - t'),$$  

(12c)

where

$$N(\omega_r) = \frac{1}{\exp \left( \frac{\omega_r}{k_B T} \right) - 1}, \quad (r = a, b, c)$$  

(13)

are, respectively, the average thermal excitation numbers of the cavity mode and atomic collective modes at temperature $T$.

The steady-state values of the atomic ensembles-cavity system are given by

$$A_s \equiv \langle A \rangle = -\frac{\chi F_A}{\Delta_a - i\frac{\kappa}{2}},$$  

(14)

$$B_s \equiv \langle B \rangle = \frac{\chi f_A f_B}{\Delta^{(0)}_a - i\frac{1}{2}\kappa^{(0)}_a},$$  

(15)

$$c_s \equiv \langle c \rangle = \frac{\chi f_a}{\Delta^{(0)}_a - i\frac{1}{2}\kappa^{(0)}_a},$$  

(16)

where

$$F_A = 1 + \frac{G_A f_a}{\Delta^{(0)}_a - i\frac{1}{2}\kappa^{(0)}_a}$$  

(17)

is the modified factor of the coupling coefficient between the left atomic ensemble and external driving field, and

$$f_a = \frac{G_A}{\Delta_a - i\frac{\kappa}{2} \gamma_A}, \quad f_b = \frac{G_B}{\Delta_b - i\frac{\kappa}{2} \gamma_B}. $$  

(18)

Here the effective decay rate and detuning between the cavity and external driving field are given by

$$\kappa^{(0)}_a = \kappa + \frac{G_A^2 \gamma_A}{\Delta^2_a + \frac{1}{4} \gamma^2_A} + \frac{G_B^2 \gamma_B}{\Delta^2_b + \frac{1}{4} \gamma^2_B},$$  

(19)

and

$$\Delta^{(0)}_a = \Delta_a - \frac{G_A^2 \Delta_a}{\Delta^2_a + \frac{1}{4} \gamma^2_A} - \frac{G_B^2 \Delta_b}{\Delta^2_b + \frac{1}{4} \gamma^2_B},$$  

(20)

respectively.

The steady-state values of all the three bosonic modes are proportional to the driving strength of the external probe field $\chi$. In what follows in this section, we will investigate the steady-state response spectra (mean excitation populations $|A_s|^2$ and $|B_s|^2$) of the two collective excitation modes of atomic ensembles.

Let us first consider the case of antinode-nodesquence that the left atomic ensemble is placed at an antinode and the right one close to a node of the single-mode cavity field. That is, the left (right) ensemble is strongly (weakly) coupled to the cavity field. Seen from Fig. 2a, in this case the response of the left ensemble appears with an EIT window, which is similar to the case of two coupled HOs in Ref. 16 although our system behaves as a system of three bosonic modes. This is expected since the present system will reduce to the model of two coupled bosonic modes when the right ensemble is placed close to the node with a very small coupling to the cavity and

![FIG. 2. (Color online) Plot of the response intensities of atomic ensembles $|A_s|^2$ (red solid curve) and $|B_s|^2$ (blue dashed curve) in arbitrary units according to Eq. (14) and Eq. (15) vs the detuning $\Delta_a$. Here, the atomic ensembles are arranged in (a) the antinode-node sequence with $G_A = 10$, $G_B = 1$, $\gamma_A = 90$, and $\gamma_B = 9$, or in (b) the node-antinode sequence with $G_A = 1$, $G_B = 10$, $\gamma_A = 9$, $\gamma_B = 90$. All the frequencies are in units of $\kappa$. And we assumed the degenerated case $\omega_a = \omega_b = \omega_c = 10^7$, that is, $\Delta_a = \Delta_b = \Delta_c$.](image-url)
leads to negligible contribution. As discussed in Ref. 16, this effect is similar to the AC Stark splitting in quantum optics 23.

Note that the above EIT-like phenomenon for the left driven ensemble happens when its coupling strength to the cavity field is larger than the decay rate of the field: $G_A > \kappa$, even when $\gamma_A > \kappa, G_A$. If we exchange the positions of the two atomic ensemble to make it in the node-antinode sequence so that $G_A \lesssim \kappa, \gamma_A$, the EIT-like phenomenon for the left ensemble would disappear, as in Fig. 2(b). This phenomenon results from the weak coupling of the driven ensemble to the cavity compared with the corresponding decay rates. It is noted that in both the above cases the response of the right ensemble is still a Lorentz-type peak without EIT window due to the weak coupling of the left driven ensemble to the cavity field (see the blue dash line in Fig. 2(a)) or the weak coupling of the left driven ensemble to the cavity field (see the blue dash line in Fig. 2(b)).

Now let us consider the response spectra of the ensembles when both the atomic ensembles position at (or near) the antinodes of the cavity field, e.g., $G_A = G_B = 10\kappa$ in Fig. 3. If both the decay rates of the atomic collective excitation modes are not so large, e.g., $\gamma_A = \gamma_B = 5\kappa$ ($< G_A, G_B$) as shown in Fig. 3(a), the response spectra of both the ensembles appear with two pronounced EIT-like windows which are expected to occur in a system of three coupled HOs. This is a simple generalization of the classical analog of EIT-like mechanism in a system of two coupled HOs 16. However, when the decay rates of the ensembles are very large, e.g., $\gamma_A = \gamma_B = 50\kappa$ ($> G_A, G_B$) in Fig. 3(b), the response of the driven ensemble appears with only one EIT-like window and the one of the right ensemble appears without any EIT window. In the case of $\gamma_A = 50\kappa$ and $\gamma_B = 5\kappa$ in Fig. 3(c), the driven ensemble has the response with two-window EIT-like phenomenon and the right one with one-window EIT-like phenomenon. Shown in Fig. 3(d) with $\gamma_A = 5\kappa$ and $\gamma_B = 50\kappa$, due to the fact that the strong decay rate of the right ensemble destroys its action on the other modes, the response of the driven ensemble happens with one EIT-like window, similar to the case of two coupled HOs. At the same time, the strong coupling of the right ensemble to the cavity field makes it have a weak EIT-like response to the external field driving on the left ensemble.

IV. THE FLUCTUATION SPECTRUM FOR TWO ATOMIC ENSEMBLES IN A CAVITY

In this section, we will consider the fluctuation spectra of the atomic ensembles in the cavity when the left ensemble is driven. To account for the effects of the quantum fluctuations we decompose each bosonic operator in the Langevin equations (9), (10), and (11) as the sum of its steady-state value and a small fluctuation, e.g., $c = c_s + \delta c$. Substituting these quantities into the Langevin equations and linearizing the resulting equations for the fluctuations, one has

$$\delta c = -i\Delta_c \delta c - iG_A \delta A - iG_B \delta B - \frac{\kappa}{2} \delta c + \sqrt{\kappa} c_{in}(t) \quad (21)$$
$$\delta \hat{A} = -i\Delta_A \delta \hat{A} - iG_A \delta c - \frac{\gamma_A}{2} \delta A + \sqrt{\gamma_A} A_{in}(t) \quad (22)$$
$$\delta \hat{B} = -i\Delta_B \delta \hat{B} - iG_B \delta c - \frac{\gamma_B}{2} \delta B + \sqrt{\gamma_B} B_{in}(t) \quad (23)$$

For the experimental perspective the frequency domain is more useful. Thus by Fourier-transferring these equations into the frequency domain like

$$\tilde{y}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} y(t) e^{i\omega t} dt \quad (24)$$

for any operator $y(t)$, it is easy to find the following solutions
\[
\delta \hat{c}(\omega) = \frac{i}{\omega - \Delta_{\text{eff}}(\omega) + i\frac{\kappa_{\text{eff}}(\omega)}{2}} \times \left[ \sqrt{\kappa_{\text{in}}(\omega)} + \frac{G_A \sqrt{\gamma_A} \hat{A}_{\text{in}}(\omega)}{\omega - \Delta_a + i\frac{\Delta_a}{2}} + \frac{G_B \sqrt{\gamma_B} \hat{B}_{\text{in}}(\omega)}{\omega - \Delta_b + i\frac{\Delta_b}{2}} \right],
\]

\[
\delta \hat{A}(\omega) = \frac{G_A \delta \hat{c}(\omega) + i \sqrt{\gamma_A} \hat{A}_{\text{in}}(\omega)}{(\omega - \Delta_a) + i\frac{\Delta_a}{2}}, \quad \delta \hat{B}(\omega) = \frac{G_B \delta \hat{c}(\omega) + i \sqrt{\gamma_B} \hat{B}_{\text{in}}(\omega)}{(\omega - \Delta_b) + i\frac{\Delta_b}{2}},
\]

where

\[
\Delta_{\text{eff}}(\omega) = \Delta_c + \frac{G_A^2 (\omega - \Delta_a)}{(\omega - \Delta_a)^2 + \frac{\Delta_a^2}{4}} + \frac{G_B^2 (\omega - \Delta_b)}{(\omega - \Delta_b)^2 + \frac{\Delta_b^2}{4}},
\]

\[
\kappa_{\text{eff}}(\omega) = \kappa + \frac{\gamma_A G_A^2}{(\omega - \Delta_a)^2 + \frac{\Delta_a^2}{4}} + \frac{\gamma_B G_B^2}{(\omega - \Delta_b)^2 + \frac{\Delta_b^2}{4}}.
\]

Now we calculate the fluctuation spectra of the cavity field and the atomic collective-excitation modes, \(S_{cA,B}(\omega)\), which are defined as \[24]\]

\[
S_y(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} (\delta y(t - \tau) \delta y^\dagger(t)) e^{i\omega \tau} d\tau, \quad (y = c, A, B).
\]

The explicit forms of the fluctuation spectra of the collective-excitation modes for the atomic ensemble are

\[
S_A(\omega) = \frac{G_A^2 S_c(\omega) + \gamma_A [N(\omega_a) + 1] [1 + 2G_A^2 K_A(\omega)]}{(\omega - \Delta_a)^2 + \frac{\Delta_a^2}{4}},
\]

\[
S_B(\omega) = \frac{G_B^2 S_c(\omega) + \gamma_B [N(\omega_b) + 1] [1 + 2G_B^2 K_B(\omega)]}{(\omega - \Delta_b)^2 + \frac{\Delta_b^2}{4}}.
\]

where

\[
S_c(\omega) = \frac{[N(\omega_c) + 1] \kappa + \frac{G_A^2 \gamma_A}{(\omega - \Delta_a)^2 + \frac{\Delta_a^2}{4}} [N(\omega_a) + 1] + \frac{G_B^2 \gamma_B}{(\omega - \Delta_b)^2 + \frac{\Delta_b^2}{4}} [N(\omega_b) + 1]}{[(\omega - \Delta_{\text{eff}}(\omega))^2 + \frac{\Delta_{\text{eff}}^2(\omega)}{4}]},
\]

is the fluctuation spectrum of the cavity field. Here we take

\[
K_A(\omega) = \frac{(\omega - \Delta_a) [\omega - \Delta_{\text{eff}}(\omega)] - \frac{1}{4} \gamma_A \kappa_{\text{eff}}(\omega)}{[(\omega - \Delta_{\text{eff}}(\omega))^2 + \frac{1}{4} \kappa_{\text{eff}}^2(\omega)] [(\omega - \Delta_a)^2 + \frac{1}{4} \gamma_A^2]},
\]

\[
K_B(\omega) = \frac{(\omega - \Delta_b) [\omega - \Delta_{\text{eff}}(\omega)] - \frac{1}{4} \gamma_B \kappa_{\text{eff}}(\omega)}{[(\omega - \Delta_{\text{eff}}(\omega))^2 + \frac{1}{4} \kappa_{\text{eff}}^2(\omega)] [(\omega - \Delta_b)^2 + \frac{1}{4} \gamma_B^2]}.
\]

For simplicity, in this paper we just consider the simple resonant case of \(\omega_a = \omega_b = \omega_c\), that is, \(N(\omega_a) = N(\omega_b) = N(\omega_c)\). Note that the thermal photon number for optical field (like visible light or X-ray) is approximately zero even at room temperatures. So we just consider this noise response spectrum with \(N(\omega_a) = N(\omega_b) = N(\omega_c) = 0\).

Seen from Fig. (a), the fluctuation spectrum of the driven left ensemble appears with asymmetrical configuration: The EIT-like phenomenon appears in the case of antinode-sequence (the red solid curve) and disappears in the opposite sequence (the blue dotted curve), as similar to the response spectra as given in Fig. (a). However, the fluctuation spectrum of the right atomic ensemble in Fig. (b), happens with some different features compared to the response spectrum of the right atomic ensemble as shown in Fig. (b). The former will appear with EIT-like window in the case of node-sequence and the latter will only have Lorentz-type spectrum for the same, given parameters.

It follows from Eq. (20) and Eq. (31) that the fluctuation spectra of excitation for the right and the left atomic ensembles have similar expressions since they equally couple to single mode cavity field. From Fig. 4 we can see that the spectra have symmetric two peaks at \(\omega/\kappa = \pm G_A\) (see the red solid curve in Fig. (a)) for the left atomic ensemble and at \(\omega/\kappa = \pm G_B\) (see the blue dotted line in Fig. (b)) for the right one, respectively. When we further enhance the coupling coefficients \(G_A\) and \(G_B\), the EIT-like windows which occur above would disappear. Thus the EIT-like windows are con-
FIG. 4. (Color online) The fluctuation spectra of the driven ensembles, (a) $S_A(\omega)$ in Eq. (30) and (b) $S_B(\omega)$ in Eq. (31) in arbitrary units. Here, $\omega_i = 10^7$, and $\Delta_e = \Delta_a = \Delta_b = 0$ (in units of $\kappa$). The red solid curve corresponds to the antinode-node sequence with the parameters $G_A = 10$, $G_B = 1$, $\gamma_A = 90$ and $\gamma_B = 9$, and the blue dotted curve corresponds to the node-antinode sequence with the parameters $G_A = 1$, $G_B = 10$, $\gamma_A = 9$ and $\gamma_B = 90$.

trolled by the amount coupling coefficients under certain conditions.

V. CONCLUSION WITH A REMARK

In conclusion, the EIT-like phenomena was shown to happen for two two-level atomic ensembles inside a cavity when one of them is driven by a laser. The theoretical prediction was made for realistic systems without referring an assumption of three-level configuration, which usually is used for the argument of EIT mechanism. We attribute the EIT-like phenomena to a simplified model: the three coupled HOs consisting of the single cavity mode and two collective low-excitation modes of the two-level atomic ensembles.

Essentially, the EIT (or EIT-like) phenomenon we studied here for the two ensembles of two-level atoms inherently has the same mechanism as the the EIT effect for a single ensemble with three-level configuration. This is because both could be modeled mathematically as the system of two coupled HOs. In this sense, it is possible to find such EIT-like phenomena in various hybrid systems, such as an atomic ensemble coupled to a nano-mechanical resonator or a superconducting transmission line.

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