Effects of the dipole-dipole interaction on dynamic properties and atomic coherent trapping of a two-atom system

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We investigate the effect of the dipole-dipole interaction on the dynamic properties and the atomic coherent trapping of a two-identical-atom system in the presence of a laser field by means of quantum-electrodynamics theory. The influence of the dipole-dipole interaction on the collapses and revivals of the atomic population is revealed. The conditions of the atomic coherent trapping are given. A way to measure optically the coupling strength between the atoms is pointed out. We also show that the effect of the dipole-dipole interaction may be screened due to the coherent field in certain atomic superposition states.

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I. INTRODUCTION

The dipole-dipole interaction between atoms is one of the most important features for the many-atom system. It is the cause of the van der Waals attraction which plays a considerable role in various chemical physics processes [1–3]. Agarwal, Narducci, and Apostolids [4] studied the effect of the dipole-dipole interaction on resonance fluorescence in an ensemble of two-level atoms and predicted that the dipole-dipole interaction is responsible for splitting the usual Rabi sideband of the resonance spectrum into a doublet and for enhancing the height of additional peaks located at twice the Rabi frequency from the resonance. The results of Kim, Oliveira, and Knight and Lawande, Jagatap, and Lawande [5,6] showed that the properties of quantum jumps in two two-level atoms is the same as that in two-photon processes when the atoms are close together. Leonardi and Seminara found [7,8] that the decay rate of spontaneous emission of two close atoms in a damped cavity can be enhanced and inhibited due to the dipole-dipole interaction. All these favorable results stimulated us to further study the effect of the dipole-dipole interaction on the dynamic properties of two-atom systems, which is the basic model to be extended to the many-atom system.

As we know, the atomic dynamic behavior in the Jaynes-Cummings (JC) model [9] can exhibit some very interesting features, such as the collapse and revival phenomenon [10] and atomic coherent trapping [11,12]. Deng, [13], Igbal *et al.* [14], and Xu, Zhang, and Chai [15] investigated the time evolution of atomic populations in the model with two identical two-level atoms in a strongly quantized radiation field, but they did not take the effect of the dipole-dipole interaction into account. Joshi and coworkers [16,17] discussed the effect of the dipole-dipole interaction on the collapses and revivals of the system where two identical atoms interacted with a single-mode radiation field, but their result is valid only for the conditions where the amplitude of the dipole-dipole interaction is small and both atoms are initially in their ground states. Their result cannot completely reveal the effect of the dipole-dipole interaction on the properties of the system. Furthermore, little attention is paid to the effect of atomic coherent trapping due to the dipole-dipole interaction.

The aim of this paper is to further study the effects of the dipole-dipole interaction on the atomic dynamic properties and the atomic coherent trapping in the model in which two identical atoms are interacting with a single-mode radiation field with various initial atomic excitations. First, we present a model and deduce the state vector of the system at time t. Then, in Sec. III, we investigate the influence of the dipole-dipole interaction on the collapses and revivals of the atomic population in initial conditions in which both atoms are in their ground states. In Sec. IV, the effect of the dipole-dipole interaction on atomic coherent trapping is revealed under various initial conditions. A way to measure optically the coupling strength between the atoms is pointed out. We also show that the effect of the dipole-dipole interaction on the system can be screened due to the coherent field in certain atomic superposition states. Finally, we draw a conclusion.

II. EXACT SOLUTION OF THE STATE VECTOR FOR THE MODEL

In the dipole approximation and the rotating-wave approximation, the Hamiltonian of two identical two-level atoms interacting with a single-mode radiation field can be written in the form [7–9]

$$H = H_0 + H_D \quad (\hbar = 1) \tag{1}$$

in which

$$H_0=\omega a^\dagger a+\sum_i \omega_0 S_i^z+\sum_i g(S_i^+ a+S_i^- a^+) , \tag{2}$$

$$H_D=\Omega(S_1^+S_2^- +S_1^-S_2^+) , \tag{3}$$

where $S_i^+(S_i^-)$ is the ladder operator for the ith atom, a ($a^\dagger$) is the annihilation (creation) operator for the field mode (frequency ω), g is the atom-field coupling constant, and ω_0 is atomic transition frequency. The term H_D, which describes the effect of the virtual off-resonance photon exchange between the atoms, appears simply as the dipole-dipole Van der Waals coupling. The parameter Ω is the dipole-dipole interaction coefficient given by [7,8]

$$\Omega=|\mathbf{d}|^2(1-3\cos^2\theta)/R^3 , \tag{4}$$

where R is the modulus of the interaction distance $\mathbf{R}_{ii'}=\mathbf{r}^{(i)}-\mathbf{r}^{(i')}$ and θ is the angle between $\mathbf{R}_{12}$ and $\mathbf{d}$ which represents the dipole matrix. For simplicity, we assume ω_0 and ω to be exactly resonant, i.e., $\omega_0=\omega$.

If the ith atom is initially in a coherent superposition of the excited state $|e\rangle$ and the ground state $|g\rangle$, i.e.,

$$|\Psi_A^i(0)\rangle=\cos(\theta_i)|e\rangle+\sin(\theta_i)\exp(-i\varphi_i)|g\rangle \quad (i=1,2) \tag{5}$$

then the two two-level atoms are initially in the state

$$|\Psi_A(0)\rangle=|\Psi_A^1(0)\rangle\otimes|\Psi_A^2(0)\rangle=\cos(\theta_1)\cos(\theta_2)|e,e\rangle+\sin(\theta_1)\cos(\theta_2)\exp(-i\varphi_1)|g,e\rangle + \sin(\theta_2)\cos(\theta_1)\exp(-i\varphi_2)|e,g\rangle+\sin(\theta_1)\sin(\theta_2)\exp(-i(\varphi_1+\varphi_2))|g,g\rangle , \tag{6}$$

and the field is in the coherent field at time $t=0$,

$$|\Psi_F(0)\rangle=\sum_n F_n|n\rangle , \tag{7}$$

$$F_n=\exp(-\bar{n}/2)\bar{n}^{n/2}\exp(in\zeta)/\sqrt{n!} , \tag{8}$$

where $\bar{n}=|\alpha|^2$ is the mean photon number, ζ is the angle of α, and for simplicity we assume $\zeta=0$. Correspondingly, the state vector of the total system at $t=0$ can be defined as

$$|\Psi_{\rm AF}(0)\rangle=|\Psi_A(0)\rangle\otimes|\Psi_F(0)\rangle . \tag{9}$$

Therefore, in the interaction picture, the state vector of this atom-field coupling system at time t can be described by

$$|\Psi_{\rm AF}^I(t)\rangle=\sum_n[C_1^n(t)|g,g,n\rangle+C_2^n(t)|e,g,n\rangle + C_3^n(t)|g,e,n\rangle+C_4^n(t)|e,en\rangle] . \tag{10}$$

Substituting Eq. (10) into the Schrödinger equation in the interaction picture, we obtain

$$i\frac{d}{dt}\begin{bmatrix} C_1^n(t) \\ C_2^{n-1}(t) \\ C_3^{n-1}(t) \\ C_4^{n-2}(t)\end{bmatrix}=\begin{bmatrix} O & D & D & O \\ D & O & \Omega & D' \\ D & \Omega & O & D' \\ O & D & D' & O\end{bmatrix}\begin{bmatrix} C_1^n(t) \\ C_2^{n-1}(t) \\ C_3^{n-1}(t) \\ C_4^{n-2}(t)\end{bmatrix} \tag{11}$$

with

$$D=g\sqrt{n} , \quad D'=g\sqrt{n-1} .$$

Considering the initial condition of the system as described by Eq. (9), we obtain the solution of Eq. (11) as follows:

$$C_1^0(t)=B_1e^{iat}+B_2e^{ibt}-ADD'/[2(D^2+D'^2)] , \tag{12}$$

$$C_2^{n-1}(t)=-(aB_1e^{iat}+bB_2e^{ibt})/(2D)+D_1e^{i\Omega t}/2 , \tag{13}$$

$$C_3^{n-1}(t)=-(aB_1e^{iat}+bB_2e^{ibt})/(2D)-D_1e^{i\Omega t}/2 , \tag{14}$$

$$C_4^{n-2}(t)=D'(B_1e^{iat}+B_2e^{ibt})/D+AD^2/[2(D^2+D'^2)] , \tag{15}$$

where

$$A=2\{F_{n-2}\cos(\theta_1)\cos(\theta_2)-D'F_n\sin(\theta_1)\sin(\theta_2)\exp[-i(\varphi_1+\varphi_2)]/D\} , \tag{16}$$

$$B_1=(b-a)_{-1}\{DF_{n-1}[\sin(\theta_1)\cos(\theta_2)\exp(-i\varphi_1)+\sin(\theta_2)\cos(\theta_1)\exp(-i\varphi_2)] + bD^2(D^2+D'^2)^{-1}F_n\sin(\theta_1)\sin(\theta_2)\exp[-i(\varphi_1+\varphi_2)]+bDD'(D^2+D'^2)^{-1}F_{n-2}\cos(\theta_1)\cos(\theta_2)\} , \tag{17}$$

$$B_2=(a-b)_{-1}\{DF_{n-1}[\sin(\theta_1)\cos(\theta_2)\exp(-i\varphi_1)+\sin(\theta_2)\cos(\theta_1)\exp(-i\varphi_2)] + aD^2(D^2+D'^2)^{-1}F_n\sin(\theta_1)\sin(\theta_2)\exp[-i(\varphi_1+\varphi_2)]+aDD'(D^2+D'^2)^{-1}F_{n-2}\cos(\theta_1)\cos(\theta_2)\} , \tag{18}$$

$$D_1=F_{n-1}[\sin(\theta_1)\cos(\theta_2)\exp(-i\varphi_1)-\sin(\theta_2)\cos(\theta_1)\exp(-i\varphi_2)] , \tag{19}$$

$$a=(\tfrac{1}{2})[-\Omega+\sqrt{\Omega^2+8(D^2+D'^2)}]\ ,\quad b=(\tfrac{1}{2})[-\Omega-\sqrt{\Omega^2+8(D^2+D'^2)}]\ . \tag{20}$$

By substituting Eqs. (12)–(15) into Eq. (10) we get the state vector of the system at time t. Then we can discuss the effect of the dipole-dipole interaction on the dynamic properties and the atomic coherent trapping of the system.

III. INFLUENCE OF THE DIPOLE-DIPOLE INTERACTION ON THE PROPERTIES OF QUANTUM COLLAPSES AND REVIVALS

Noticing that the Poissonian distribution of the photon number is well localized around $\bar{n}$ with $\Delta n=\sqrt{\bar{n}}$, we make the approximation

$$F_{n-1}\approx F_{n-2}\approx F_n\ ,\quad D\approx D' \tag{21}$$

while we sum with respect to n [13,16–18] for $\bar{n}\gg 1$. The population for both of the atoms to be in ground state $|g,g\rangle$ at time t is given by

$$\begin{aligned}
P_1(t)-&\sum_n |C_1^n(t)|^2\\
=&\sum_n F_n^2\{(\tfrac{1}{4})[\cos^2(\theta_1)\cos^2(\theta_2)+\sin^2(\theta_1)\sin^2(\theta_2)-(\tfrac{1}{2})\sin(2\theta_1)\sin(2\theta_2)\cos(\varphi_1+\varphi_2)]\\
&+[4(a-b)^2]^{-1}[(a^2+b^2)(\cos^2(\theta_1)\cos^2(\theta_2)\\
&\qquad+\sin^2(\theta_1)\sin^2(\theta_2)+(\tfrac{1}{2})\sin(2\theta_1)\sin(2\theta_2)\cos(\varphi_1+\varphi_2)]\\
&-2D\Omega[\sin(2\theta_1)\cos(\varphi_1)+\sin(2\theta_2)\cos(\varphi_2)]+2D^2[\sin^2(\theta_1)\cos^2(\theta_2)+\sin^2(\theta_2)\cos^2(\theta_1)\\
&\qquad+(\tfrac{1}{2})\sin(2\theta_1)\sin(2\theta_2)\cos(\varphi_1+\varphi_2)]\}\\
&-(a-b)^{-2}\{\cos[(a-b)t]\{D^2[\sin(2\theta_1)\sin(2\theta_2)\sin(\varphi_1)\sin(\varphi_2)-\cos(2\theta_1)\cos(2\theta_2)]\\
&\qquad+(\tfrac{1}{4})\Omega D[\cos(\varphi_1)\sin(2\theta_1)+\cos(\varphi_2)\sin(2\theta_2)]\}\\
&\qquad+D\sqrt{\Omega^2+16D^2}(\tfrac{1}{4})\sin[(a-b)t][\sin(2\theta_1)\sin(\varphi_1)\cos(2\theta_2)+\cos(2\theta_1)\sin(\varphi_2)\sin(2\theta_2)]\\
&\qquad+[2(a-b)]^{-1}[\cos(at)(b[\cos^2(\theta_1)\cos^2(\theta_2)-\sin^2(\theta_1)\sin^2(\theta_2)]\\
&\qquad\qquad+D[\cos(\varphi_1)\sin(2\theta_1)\cos(2\theta_2)+\cos(\varphi_2)\sin(2\theta_2)\cos(2\theta_1)]\\
&\qquad\qquad+\sin(at\{(b/2)\sin(2\theta_1)\sin(2\theta_2)\sin(\varphi_1+\varphi_2)\\
&\qquad\qquad\quad+D[\sin(\varphi_1)\sin(2\theta_1)+\sin(\varphi_2)\sin(2\theta_2)]\}\\
&\qquad\qquad-\cos(bt)\{a[\cos^2(\theta_1)\cos^2(\theta_2)-\sin^2(\theta_1)\sin^2(\theta_2)]\\
&\qquad\qquad\quad+D[\cos(\varphi_1)\sin(2\theta_1)\cos(2\theta_2)+\cos(\varphi_2)\sin(2\theta_2)\cos(2\theta_1)]\}\\
&\qquad\qquad+\sin(bt)\{(a/2)\sin(2\theta_1)\cos(2\theta_2)\sin(\varphi_1+\varphi_2)\\
&\qquad\qquad\quad+D[\sin(2\theta_1)\sin(\varphi_1)+\sin(2\theta_2)\sin(\varphi_2)]\})]\}\ .
\end{aligned} \tag{22}$$

Similarly, we can obtain the expressions of the atomic population of the states $|e,g\rangle$, $|g,e\rangle$, and $|e,e\rangle$ at time t. Starting from Eq. (22) and other population equations, we may discuss the effect of the dipole-dipole interaction on the dynamic behavior of the system in various atomic preparations.

If we choose $\theta_1=\theta_2=0$ corresponding to both atoms in their excited states $|e\rangle$ initially, then the population inversion $P(t)=P_4(t)-P_1(t)$ at time t can be given as follows:

$$\begin{aligned}
P(t)=&\sum_n F_n^2[-ab/2(a-b)^2]\cos[(a-b)t]+[\Omega/2(a-b)]\sin(\Omega t/2)\sin[(a-b)t/2]\\
&+(\tfrac{1}{2})\cos(\Omega t)\cos[(a-b)t/2]+\tfrac{1}{4}+(a^2+b^2)[4(a-b)^2]^{-1}\ .
\end{aligned} \tag{23}$$

By making use of Eq. (23) and by numerical calculation we can get the time evolution of population inversion $P(t)$ for different values of the parameter Ω which shows the influence of the dipole-dipole interaction on the population $P(t)$. In each case, we fix the mean photon number $\bar{n}$ and the atom-field coupling constant g.

In Fig. 1, we plot $P(t)$ with $\Omega=0$, which means that the effect of the dipole-dipole interaction can be neglected

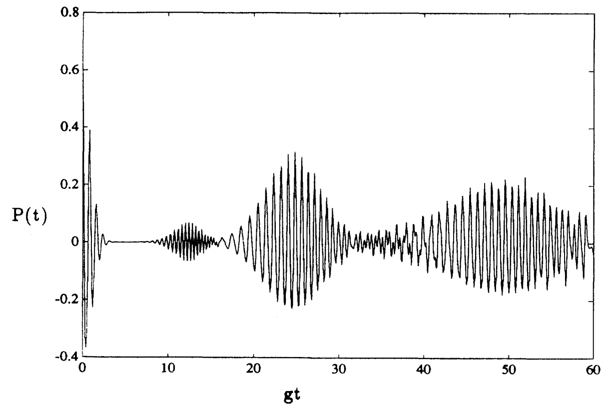

FIG. 1. The time evolution of the population inversion $P(t)$ for $\bar{n}=16$ and $\Omega=0$.

when the distance between two atoms is very large. The time evolution of $P(t)$ obviously shows the quantum collapse and revival in the system. Comparing Fig. 1 with the result of one atom J+C model [10], our result shows that because of the atomic cooperative effect [19], the quantum collapse is no longer Gaussian in form, and revivals become larger in number. In Figs. 2, 3, and 4, $P(t)$ are plotted with $\Omega=g$, $4g$, and $16g$, respectively. We can see that the time evolution $P(t)$ is more complicated than that in Fig. 1. The envelope function of quantum collapse depends on Ω, and the revival time is also related to Ω. As gt increases from 2.5 to 10, the population inversion $P(t)$ is nearly a constant in Fig. 1, but for a larger coupling parameter Ω, as shown in Fig. 4, the range in which $P(t)$ remains constant will increase. It is evident that all these differences are due to the effect of various dipole-dipole interactions.

When the two atoms are close, Ω becomes very large. The time dependence of population $P(t)$ is shown in Fig. 5. We can see that the range in which $P(t)$ remains a constant becomes larger, and the phenomenon of revival

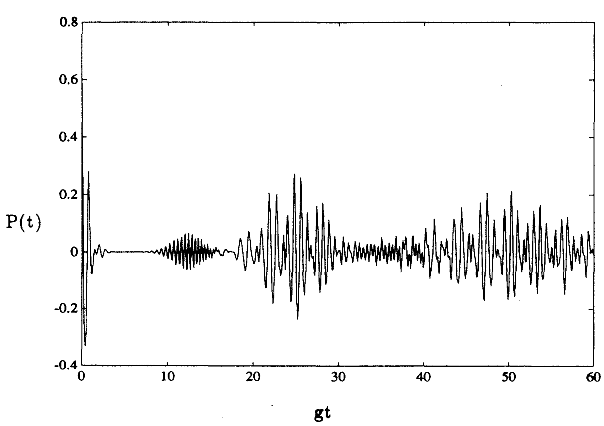

FIG. 2. The time evolution of the population inversion $P(t)$ for $\bar{n}=16$ and $\Omega=g$.

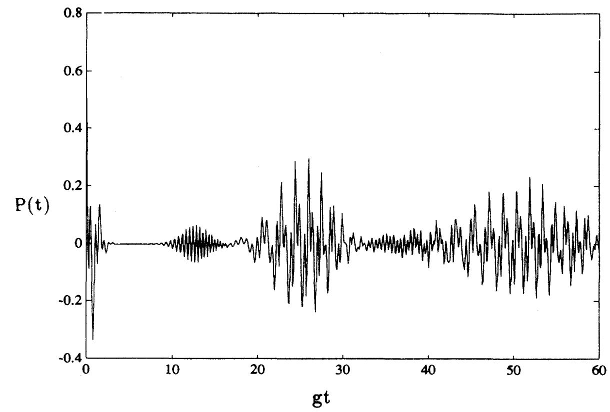

FIG. 3. The time evolution of the population inversion $P(t)$ for $\bar{n}=16$ and $\Omega=4g$.

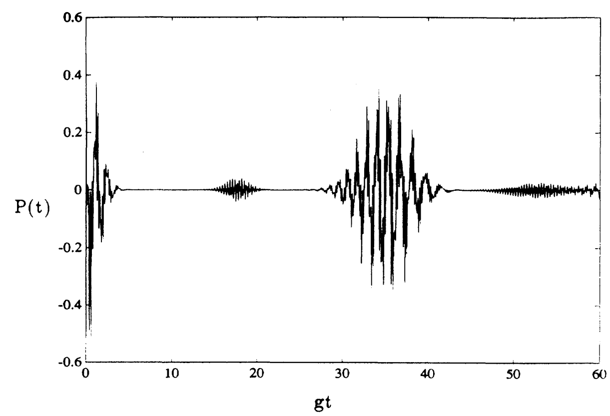

FIG. 4. The time evolution of the population inversion $P(t)$ for $\bar{n}=16$ and $\Omega=16g$.

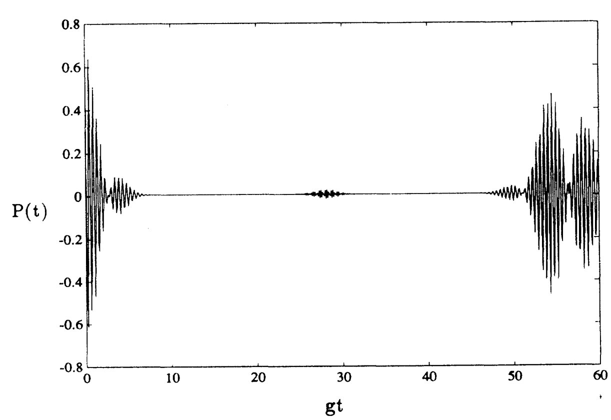

FIG. 5. The time evolution of the population inversion $P(t)$ for $\bar{n}=16$ and $\Omega=32g$.

and collapse is similar to the case which is exhibited in the effective two-photon J+C model [20]. The reason may be understood as follows.

When the dipole-dipole interaction is so intense that Ω satisfies the condition $\Omega^2 \gg 16g^2\bar{n}$, we can make an approximation for a and b while considering the properties of the Poissonian distribution of the coherent field as

$$a \approx 2g^2(2n-1)/\Omega \ , \tag{24}$$

$$b \approx -\Omega - 2g^2(2n-1)/\Omega \ . \tag{25}$$

After substituting Eqs. (24) and (25) into Eq. (23), the population inversion $P(t)$ may be written as

$$\begin{aligned} P(t) &\approx \sum_n F_n^2(\tfrac{1}{2}+(\tfrac{1}{2})\cos[2g^2(2n-1)t/\Omega)] \\ &= \tfrac{1}{2}+(\tfrac{1}{2})\exp[-2\bar{n}\sin^2(2g^2t/\Omega)] \\ &\qquad \times\cos[\bar{n}\sin(4g^2t/\Omega)-2g^2t/\Omega] \ . \end{aligned} \tag{26}$$

It is evident that Eq. (26) is the same as that describing the evolution of the atomic population in the effective two-photon J+C model [20]. This means that the dynamic properties of two two-level atoms are similar to that of the effective two-photon J+C model due to the dipole-dipole intense interaction.

The model of a cascade three-level atom interacting with a one- or two-mode field has been investigated [21] recently, and it has been found that this model can be exactly replaced by the effective two-photon J+C model if the detuning Δ obeys $\Delta^2 \gg 2g^2\bar{n}$. Here, for the system of two two-level atoms we may employ three symmetric states [19], i.e., $|g,g\rangle$, $|e,e\rangle$, $2^{-1/2}(|e,g\rangle+|g,e\rangle)$, and one antisymmetric state $2^{-1/2}(|e,g\rangle-|g,e\rangle)$. When the two atoms are close together, the antisymmetric state is decoupled, and there appears to be a level shift in the state $2^{-1/2}(|e,g\rangle+|g,e\rangle)$ due to the dipole-dipole interaction [5]. Because of this, the one-atom excited state $2^{-1/2}(|e,g\rangle+|g,e\rangle)$ is detuned whereas the two-atom excited state satisfies the two-photon resonance condition. If the dipole-dipole interaction is so intense that the parameter Ω satisfies $\Omega^2 \gg 16g^2\bar{n}$, the probability of one-photon transition is very small and the dynamic properties of the system is mainly governed by two-photon transitions between the states $|e,e\rangle$ and $|g,g\rangle$. So the atomic dynamic behavior of the system resembles the properties of the effective two-photon J+C model.

IV. EFFECTIVE OF THE DIPOLE-DIPOLE INTERACTION ON THE ATOMIC COHERENT TRAPPING OF TWO ATOMS SYSTEM

Zaheer and Zubairy [11] and Zhou, Hu, and Peng [12] considered a two-level atom, initially prepared in a coherent superposition of the upper and lower levels, i.e., $2^{-1/2}(|e,g\rangle \pm |g,e\rangle)$, interacting with a single-mode field in an ideal cavity. They found that the population inversion is far from exhibiting revivals and collapses, and it remains a constant. (Here we have assumed $\zeta=0$ in Ref. [11]). For the system of two two-level atoms we can derive the atomic coherent trapping conditions according to Eq. (22) as follows:

$$I_1: \ \varphi_1=\varphi_2=0, \ \ \theta_1+\theta_2=\pi/2 \ ,$$
$$\theta_1=(\tfrac{1}{2})\arcsin(a/2D) \ , \tag{27}$$

$$I_2: \ \theta_1=\theta_2=\pi/4, \ \ \varphi_1=-\varphi_2=\arccos(-a/2D) \ , \tag{28}$$

$$I_3: \ \theta_1=\pi/4, \ \ \theta_2=-\pi/4, \ \ \varphi_1=\varphi_2=0 \ . \tag{29}$$

The conditions under which the atomic coherent trapping in the two two-level-atom system occurs is more complicated than in a one-atom system due to the effect of the dipole-dipole interaction and the atomic cooperative effect. When $\Omega=0$, Eqs. (27) and (28) reduce to

$$\theta_1=\theta_2=\pi/4, \ \ \varphi_1=\varphi_2=0 \ . \tag{30}$$

Equations (29) and (30) are the atomic coherent trapping conditions in the model of two two-level atom interacting with a single-mode coherent field whereas the effect of the dipole-dipole interaction is neglected.

After substitution of Eqs. (28) and (29) into Eq. (22), respectively, the population is obtained as

$$P_1(t)=P_1(0)=\tfrac{1}{4} \ . \tag{31}$$

It is clear that in these two cases, $P_1(t)$ is not related to the parameter Ω. But for the case I_1, by using the photon number distribution properties of the coherent field, we obtain that $P_1(t)$ satisfies

$$P_1(t)\approx(-\Omega+\sqrt{\Omega^2+16g^2\bar{n}})^2/64g^2\bar{n}\approx P_1(0) \ . \tag{32}$$

Equation (32) (plotted in Fig. 6) shows that $P_1(t)$ is a nonlinear function of Ω.

In Fig. 6, we can find that $P_1(t)$ varies nonlinearly from $\frac{1}{4}$ to 0 when Ω increases. The reason is that the energy levels corresponding to the states $|e,g\rangle$ and $|g,e\rangle$ are shifted by the effect of the dipole-dipole interaction. Hence, the probability of one-atom transitions $|e,e\rangle \leftrightarrow |g,e\rangle \leftrightarrow |g,g\rangle$ and $|e,e\rangle \leftrightarrow |e,g\rangle \leftrightarrow |g,g\rangle$ decreases, while the populations of the states $|e,g\rangle$ and $|g,e\rangle$ increase with increasing Ω, and the population of the state $|g,g\rangle$ decreases. If $\Omega^2 \gg 16g^2\bar{n}$, which initially corresponds to one atom in its excited state $|e,g\rangle$ or

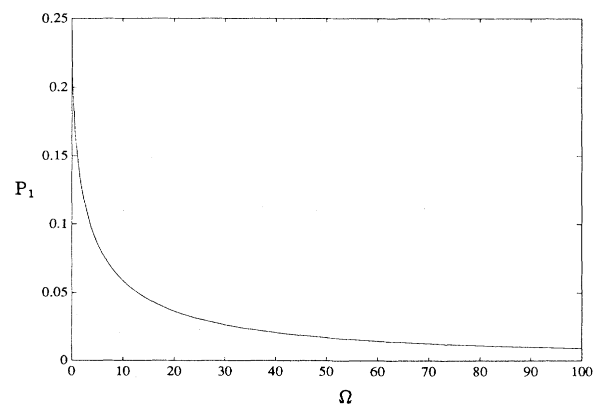

FIG. 6. The evolution of population P_1 as a function of Ω.

$|g,e\rangle$, the two atoms are only oscillating between the states $|e,g\rangle$ and $|g,e\rangle$ and the probability of a one-photon transition is nearly equal to zero due to the extreme coupling between the two atoms. In this case, the two-atom system does not radiate photons. Therefore, the probability of the two atoms in the state $|g,g\rangle$ is equal to zero and the total population of the two atoms in the states $|e,g\rangle$ and $|g,e\rangle$ is written as

$$P_2(t)+P_3(t)=1-[P_1(t)+P_4(t)]=1-2P_1(t)=1 \ . \tag{33}$$

It is remarkable that when the two atoms are initially in cases I_1 and I_2, the population of two atoms in the state $|e,g\rangle$ obeys as follows, respectively:

$$P_2(t)=\tfrac{1}{4}\sum_n F_n^2\left[2-\frac{a^2}{4D^2}-2\left[1-\frac{a^2}{4D^2}\right]^{1/2}\cos(a+2\Omega)t\right] \quad (\text{case } I_1) \ , \tag{34}$$

$$P_3(t)=\tfrac{1}{4}\sum_n F_n^2\left[1-\frac{a}{D}(1-a^2/4D^3)^{1/2}\sin(a-\Omega)t\right] \quad (\text{case } I_2) \ . \tag{35}$$

Here we have used Eqs. (12)–(15). It is evident from Eqs. (34) and (35) that $P_2(t)$ is simply related to the effect of the dipole-dipole interaction. This means that if we prepare the initial atomic state as described by Eqs. (27) or (28), we can directly obtain the parameter Ω of the coupling strength which is related to the van der Waals force by means of Eqs. (34) or (36) when we measure the population of the two atoms in the states $|e,g\rangle$ or $|g,e\rangle$.

Furthermore, for the case I_3, we can find that the population of the two atom in the states $|e,g\rangle$ and $|g,e\rangle$ satisfy

$$P_2(t)=P_3(t)=\tfrac{1}{4} \ . \tag{36}$$

It is evident from Eq. (36) that $P_2(t)$ and $P_3(t)$ are far from the collapses and revivals and remain constant. So for case I_3, we find that all atomic populations $P_i(t)$ $(i=1,2,3,4)$ in the states $|e,e\rangle$, $|g,e\rangle$, $|e,g\rangle$, and $|g,g\rangle$ are equal to $\frac{1}{4}$, which is just the result when the effect of the dipole-dipole interaction is neglected. Because both the initial state of the atoms and the time evolution of $P_i(t)$ are independent of the dipole-dipole interaction coefficient Ω, and $P_i(t)$ $(i=1,2,3,4)$ are equal to the results when $\Omega=0$, this shows that the effect of the dipole-dipole interaction between the two atoms described as Eq. (3) has been screened by the intensive atom-field coupling. This conclusion is similar to that in Ref. [22] in which Carbonaro and Persico have discussed the model of two two-level atoms interacting with an intense radiation field and both atoms have a dipole moment in the upper and lower states, found by using the dressed transformation [23] that the effective dipolar interaction between the dressed atoms of the pair is seen to vanish for an appropriate value of the field intensity.

V. CONCLUSIONS

We now wish to draw some conclusions from the above results and also emphasize some of the main applications. In the model of two two-level atoms interacting with a single-mode coherent field, the dipole-dipole interaction has an important effect on the properties of the system. The various amplitudes of the dipole-dipole interaction can bring different laws of revival and collapse for the population inversion. Under certain initial conditions, the atomic coherent trapping of the two-atom systems will be exhibited, and the population $P_1(t)$ will decrease nonlinearly from $\frac{1}{4}$ to 0 with increasing parameter Ω. When the two atoms are initially in an appropriate state satisfying Eqs. (27) or (28), the population of the states $|e,g\rangle$ or $|g,e\rangle$ is simply related to the amplitude of the dipole-dipole interaction, which give us a possible optical way to measure the coupling strength between the atoms. Moreover, when one atom is initially in the state $2^{-1/2}(|e\rangle+|g\rangle)$, and the other in the state $2^{-1/2}(|e\rangle-|g\rangle)$, the time evolution of the populations which are far from the revival and collapse phenomenon and remain a constant, is similar to that of the two-atom systems for which the dipole-dipole interaction is neglected. In this case, the effect of the dipole-dipole interaction may be screened due to atom-field coupling.

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