Effects of an applied low frequency field on the dynamics of a two-level atom interacting with a single-mode field*

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The effects of an applied low frequency field on the dynamics of a two-level atom interacting with a single-mode field are investigated. It is shown that the time evolution of the atomic population is mainly controlled by the coupling constants and the frequency of the low frequency field, which leads to a low frequency modulation function for the time evolution of the upper state population. The amplitude of the modulation function becomes larger as the coupling constants increase. The frequency of the modulation function is proportional to the frequency of the low frequency field, and decreases with increasing coupling constant.

Keywords: two-level atom, low frequency field, single-mode field
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1. Introduction

The Jaynes–Cummings model (JCM)[1] is usually used to describe the interaction between a two-level atom and a single mode field. In the last few decades, the JCM has been extended to many directions, for example, the interaction between a three-level atom and a two-mode squeezing vacuum field,[2] the interaction between a two-level atom and a single mode field in a leaky cavity[3] or in an additional Kerr medium,[4] the nonlinear dynamical evolution of a driven two-photon system,[5] the dissipation in the generalized JCM,[6] and the interaction between a two-level atom and a field with time-varying frequency.[7,8]

In their theoretical study, Alsing *et al.* proposed a driven JCM (DJCM), in which a two-level atom and a single mode of cavity fields interact with each other and at the same time may be driven by an external coherent field.[9] Many interesting effects are predicted in the DJCM, for example, quasi-energies and steady states,[9] a nonlinear quantum oscillator,[9] super-revivals,[10] etc. After investigating the DJCM, Li and Gao found that one could use an external field to control the non-classical effects in the JCM.[11] Recently, Evers and Keitel proposed a scheme in which an external low frequency field was added to an atomic two-level system in vacuum, and they showed that the simple scheme could considerably slow down the usual exponential decay of the upper state population.[12]

In the present paper, we investigate the effects of an applied low frequency field on the dynamics of a two-level atom interacting with a single-mode field. Just as in Ref. [12], we assume that the strength of the low frequency field is sufficiently strong, and the frequency is much lower than the decay width of the atomic system. The collapse-revival behaviours associated with the atomic population are also mentioned.

2. Theory model and dynamic equations

We consider a two-level atom with two states ($|e\rangle$ and $|g\rangle$) interacting with a single-mode field of frequency ω as shown in Fig. 1, where δ is the detuning between the transition $|e\rangle \to |g\rangle$ and the single-mode field, and an external field with a low frequency ϖ is applied to the system. Then in addition to the usual JCM, the atom may interact with the low frequency field and exchange one or more low frequency pho-

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tons during the atomic transition. We assume that the coupling between the transition $|e\rangle \to |g\rangle$ and the external field is very weak, which positively depends on the strength of the low frequency field.

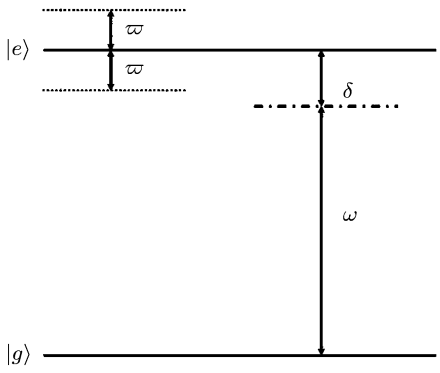


Fig. 1. Two-level atom interacting with a single-mode field and an applied low frequency field.

We consider only a single-mode field interacting with the atom, which is different from the case of spontaneous emission in the free space studied in Ref. [12]. The Hamiltonian of the model can be written as $H = H_0 + H_{\rm I}$, with a free Hamiltonian part,

$$H_0 = \hbar\omega_{\rm g} |g\rangle \langle g| + \hbar\omega_{\rm e} |e\rangle \langle e| + \hbar\varpi b^+ b + \hbar\omega a^+ a, \quad (1)$$

and the interaction part $H_{\rm I}$,[12,13]

$$\begin{aligned} H_{\rm I} = {} & \hbar[g^* a\sigma_+ + g a^+ \sigma_-] \\ & + \hbar[g^* \bar{g}_1 b a\sigma_+ + g\bar{g}_1 b a^+ \sigma_- \\ & + g^* \bar{g}_1^* b^+ a\sigma_+ + g\bar{g}_1^* b^+ a^+ \sigma_-] \\ & + \hbar[g^* \bar{g}_2 (b)^2 a\sigma_+ + g\bar{g}_2 (b)^2 a^+ \sigma_- \\ & + g^* \bar{g}_2^* (b^+)^2 a\sigma_+ + g\bar{g}_2^* (b^+)^2 a^+ \sigma_-] \\ & + \cdots, \end{aligned} \quad (2)$$

where $\hbar\omega_{\rm g}$ and $\hbar\omega_{\rm e}$ are the energies of the ground state and the exited state of the atom respectively, $b(b^+)$ is the annihilation (creation) operator for the low frequency photon, $a(a^+)$ is the single-mode photon annihilation (creation) operator, $\sigma_+(\sigma_-)$ is the atomic raising (lowering) operator, g is the coupling constant between the atomic transition and the single-mode field, $\bar{g}_i (i = 1, 2, 3, \ldots, N)$ are the coupling constants representing the probability for an i-photon transition of the low frequency field, and $1 \gg \bar{g}_1 \gg \bar{g}_2 \ldots$. In the interaction Hamiltonian (2), the first part refers to the atomic transition without the participation of the applied low frequency field; the second part represents the atomic transition interacting with one low frequency photon; the third part denotes the atomic transition interacting with two low frequency photons, and so on.

By inserting the completeness relation $\sum_{n=0}^{\infty} |n\rangle \langle n| = 1$, where $|n\rangle$ is the low frequency field state of n photons, into Hamiltonian (2), we rewrite the interaction Hamiltonian as

$$\begin{aligned} H_{\rm I} = \hbar \sum_{n=0}^{\infty} \{ & g^* a |e, n\rangle \langle g, n| + g a^+ |g, n\rangle \langle e, n| \\ & + g^* \bar{g}_1 \sqrt{n} a |e, n-1\rangle \langle g, n| + g\bar{g}_1^* \sqrt{n} a^+ |g, n\rangle \langle e, n-1| \\ & + g^* \bar{g}_1^* \sqrt{n+1} a |e, n+1\rangle \langle g, n| + g\bar{g}_1 \sqrt{n+1} a^+ |g, n\rangle \langle e, n+1| \\ & + g^* \bar{g}_2 \sqrt{n(n-1)} a |e, n-2\rangle \langle g, n| + g\bar{g}_2^* \sqrt{n(n-1)} a^+ |g, n\rangle \langle e, n-2| \\ & + g^* \bar{g}_2^* \sqrt{(n+1)(n+2)} a |e, n+2\rangle \langle g, n| + g\bar{g}_2 \sqrt{(n+1)(n+2)} a^+ |g, n\rangle \langle e, n+2| \\ & + \ldots \}. \end{aligned} \quad (3)$$

We assume that the external field is initially prepared in a strong coherent state with a large photon number $\bar{n} \gg 1$, which satisfies the approximation $\bar{n} - 1 \approx \bar{n} + 1 \approx \bar{n}$. During the interaction, only the terms around the mean number of photons, $\bar{n}$, have a major effect. By introducing equivalent coupling constants

$$\begin{aligned} & g^{(0)} = g, \quad g^{(-1)} = g\bar{g}_1^* \sqrt{n} \approx g\bar{g}_1^* \sqrt{\bar{n}}, \quad g^{(+1)} = g\bar{g}_1 \sqrt{n+1} \approx g\bar{g}_1 \sqrt{\bar{n}}, \\ & g^{(-2)} = g\bar{g}_2^* \sqrt{n(n-1)} \approx g\bar{g}_2^* \bar{n}, \quad g^{(+2)} = g\bar{g}_2 \sqrt{(n+1)(n+2)} \approx g\bar{g}_2 \bar{n}, \end{aligned} \quad (4)$$

and generalized ladder operators

$$\sigma_+^{(j)} = \sum_{n=0}^{\infty} |e, n+j\rangle \langle g, n|, \quad \sigma_-^{(j)} = (\sigma_+^{(j)})^+, \quad (5)$$

in the interaction picture, the interaction Hamiltonian can be written as

$$\begin{aligned} V &= \mathrm{e}^{\mathrm{i}\,H_0 t} H_{\mathrm{I}} \mathrm{e}^{-\mathrm{i}\,H_0 t} \\ &= \hbar\{(g^{(0)*} a\sigma_+^{(0)} \mathrm{e}^{\mathrm{i}\,\delta t} + \mathrm{H.c.}) \\ &\quad + (g^{(-1)*} a\sigma_+^{(-1)} \mathrm{e}^{\mathrm{i}(\delta-\varpi)t} + \mathrm{H.c.}) \\ &\quad + (g^{(+1)*} a\sigma_+^{(+1)} \mathrm{e}^{\mathrm{i}(\delta+\varpi)t} + \mathrm{H.c.}) \\ &\quad + (g^{(-2)*} a\sigma_+^{(-2)} \mathrm{e}^{\mathrm{i}(\delta-2\varpi)t} + \mathrm{H.c.}) \\ &\quad + (g^{(+2)*} a\sigma_+^{(+2)} \mathrm{e}^{\mathrm{i}(\delta+2\varpi)t} + \mathrm{H.c.}) \\ &\quad + \dots\}. \end{aligned} \tag{6}$$

Following the summation over all low frequency photon numbers, the atomic ladder operator to and from one of the upper states $\sigma_\pm^{(i)}$ and the coupling constants $\bar{g}_i (i = 1, 2, 3, \dots, N)$ are replaced by the corresponding semi-classical entities, for simplicity, without change of notation. The state vector of the system can be written in a general form as

$$\begin{aligned} |\psi(t)\rangle = \sum_m \Bigg\{ &\sum_{j=-N}^{N} C_m^{(j)}(t) \sigma_+^{(j)} |g\rangle |m\rangle \\ &+ G_m(t) |g\rangle |m\rangle \Bigg\}, \end{aligned} \tag{7}$$

where m denotes the photon number of the single-mode field. We assume that the atom is initially in an exited state, and the single-mode field is in a coherent state,

$$\begin{aligned} |C_m^{(0)}(0)|^2 &= \rho_{mm}(0) = \frac{\langle m\rangle^m \mathrm{e}^{-\langle m\rangle}}{m!}, \\ C_m^{(j\neq 0)}(0) &= G_m(0) = 0 \end{aligned} \tag{8}$$

with $\langle m\rangle$ being the average photon number of the single-mode field. The dynamic equation of the coefficients $C_m^{(j)}(t)$ and $G_m(t)$ can be obtained through the Schrödinger equation. As we have mentioned that the low frequency field is sufficiently strong, e.g. $\bar{n}$ is very large and $1 \gg \bar{g}_1 \gg \bar{g}_2 \dots$, we assume that $\bar{g}_1\sqrt{\bar{n}} \sim 1$ and $\bar{g}_2\bar{n} \ll 1$ and neglect the higher order terms with $j \geq 2$ in the following calculation, which are associated with multi-photon processes. Under this approximation, the interaction picture Hamiltonian can be written as

$$\begin{aligned} V = \hbar[&(g^{(0)*} a\sigma_+^{(0)} \mathrm{e}^{\mathrm{i}\,\delta t} + \mathrm{H.c.}) \\ &+ (g^{(-1)*} a\sigma_+^{(-1)} \mathrm{e}^{\mathrm{i}(\delta-\varpi)t} + \mathrm{H.c.}) \\ &+ (g^{(+1)*} a\sigma_+^{(+1)} \mathrm{e}^{\mathrm{i}(\delta+\varpi)t} + \mathrm{H.c.})], \end{aligned} \tag{9}$$

and the state vector is simplified into

$$\begin{aligned} |\psi(t)\rangle = \sum_m \{&C_m^{(0)}(t) |e\rangle |m\rangle + C_m^{(-1)}(t) |e\rangle |m\rangle \\ &+ C_m^{(+1)}(t) |e\rangle |m\rangle + G_m(t) |g\rangle |m\rangle\}. \end{aligned} \tag{10}$$

Based on the Schrödinger equation, we obtain the following dynamic equation for the coefficients $\tilde{C}_m^{(j)}(t)$ and $\tilde{G}_m(t)$,

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} \tilde{C}_m^{(0)}(t) \\ \tilde{C}_m^{(-1)}(t) \\ \tilde{C}_m^{(+1)}(t) \\ \tilde{G}_{m+1}(t) \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & g^{(0)*}\sqrt{m+1} \\ 0 & -\varpi & 0 & g^{(-1)*}\sqrt{m+1} \\ 0 & 0 & \varpi & g^{(+1)*}\sqrt{m+1} \\ g^{(0)}\sqrt{m+1} & g^{(-1)}\sqrt{m+1} & g^{(+1)}\sqrt{m+1} & -\delta \end{pmatrix} \begin{pmatrix} \tilde{C}_m^{(0)}(t) \\ \tilde{C}_m^{(-1)}(t) \\ \tilde{C}_m^{(+1)}(t) \\ \tilde{G}_{m+1}(t) \end{pmatrix} \tag{11}$$

with $\tilde{C}_m^{(0)}(t) = C_m^{(0)}(t)$, $\tilde{C}_m^{(-1)}(t) = \mathrm{e}^{\mathrm{i}\,\varpi t} C_m^{(-1)}(t)$, $\tilde{C}_m^{(+1)}(t) = \mathrm{e}^{-\mathrm{i}\,\varpi t} C_m^{(+1)}(t)$, $\tilde{G}_{m+1}(t) = \mathrm{e}^{\mathrm{i}\,\delta t} G_{m+1}(t)$.

For simplicity, we let $\delta = 0$ and $|g^{(-1)}| = |g^{(+1)}| = g^{(1)}$. The four eigen-values $\Omega_i (i = 1, 2, 3, 4)$ of Eq. (11) are

$$\begin{aligned} \Omega_1 &= -\Omega_2 \\ &= \sqrt{\frac{[\varpi^2 + (m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)] - \sqrt{[\varpi^2 + (m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)]^2 - 4\varpi^2|g^{(0)}|^2(m+1)}}{2}}, \end{aligned} \tag{12}$$

$$\begin{aligned} \Omega_3 &= -\Omega_4 \\ &= \sqrt{\frac{[\varpi^2 + (m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)] + \sqrt{[\varpi^2 + (m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)]^2 - 4\varpi^2|g^{(0)}|^2(m+1)}}{2}}. \end{aligned} \tag{13}$$

Under the initial condition (8), we obtain the time dependent coefficient,

$$\tilde{C}_m^{(0)}(t) = 2\tilde{C}_{m,1}^{(0)} \cos(\Omega_1 t) + 2\tilde{C}_{m,3}^{(0)} \cos(\Omega_3 t) \tag{14}$$

with

$$\tilde{C}^{(0)}_{m,1} = \tilde{C}^{(0)}_{m,2} = \frac{\sqrt{\rho_{mm}(0)}}{2} \frac{\Omega_3^2(\varpi^2 - \Omega_1^2)}{\varpi^2(\Omega_3^2 - \Omega_1^2)}, \tag{15}$$

and

$$\tilde{C}^{(0)}_{m,3} = \tilde{C}^{(0)}_{m,4} = \frac{\sqrt{\rho_{mm}(0)}}{2} \frac{\Omega_1^2(\varpi^2 - \Omega_3^2)}{\varpi^2(\Omega_1^2 - \Omega_3^2)}. \tag{16}$$

From now on we focus on the time evolution of the upper state population

$$P^{(0)}(t) = \sum_m |2\tilde{C}^{(0)}_{m,1}\cos(\Omega_1 t) + 2\tilde{C}^{(0)}_{m,3}\cos(\Omega_3 t)|^2 = 4\sum_m |\tilde{C}^{(0)}_{m,1}|^2\cos^2(\Omega_1 t) + 4\sum_m |\tilde{C}^{(0)}_{m,3}|^2\cos^2(\Omega_3 t) + 8\sum_m \mathrm{Re}[(\tilde{C}^{(0)}_{m,1})^*\tilde{C}^{(0)}_{m,3}]\cos(\Omega_1 t)\cos(\Omega_3 t). \tag{17}$$

3. Results and discussion

The upper state population $P^{(0)}(t)$, expression (17), could be easily solved analytically. In our calculation, the average photon number $\langle m\rangle$ is set to be 25, i.e. $\langle m\rangle = 25$, and the frequency is measured in units of $g^{(0)}$. Figure 2 shows the time evolutions of $P^{(0)}(t)$ at $\varpi = 0.5g^{(0)}$ with different coupling constants. For comparison we include the case of $g^{(1)} = 0$, which represents the standard JCM [see Fig. 2(a)]. When $g^{(1)} \neq 0$, the applied low frequency field has an effect on the $P^{(0)}(t)$. It is found that temporal evolution of the population is modulated by a low frequency cosine function, and the average value of $P^{(0)}(t)$ decreases from 0.5 to about 0.25 for $g^{(1)} = 0.5g^{(0)}$, to about 0.28 for $g^{(1)} = g^{(0)}$, and to about 0.38 for $g^{(1)} = 2.0g^{(0)}$. With increasing coupling constant, the modulation strength increases, but the modulation frequency decreases.

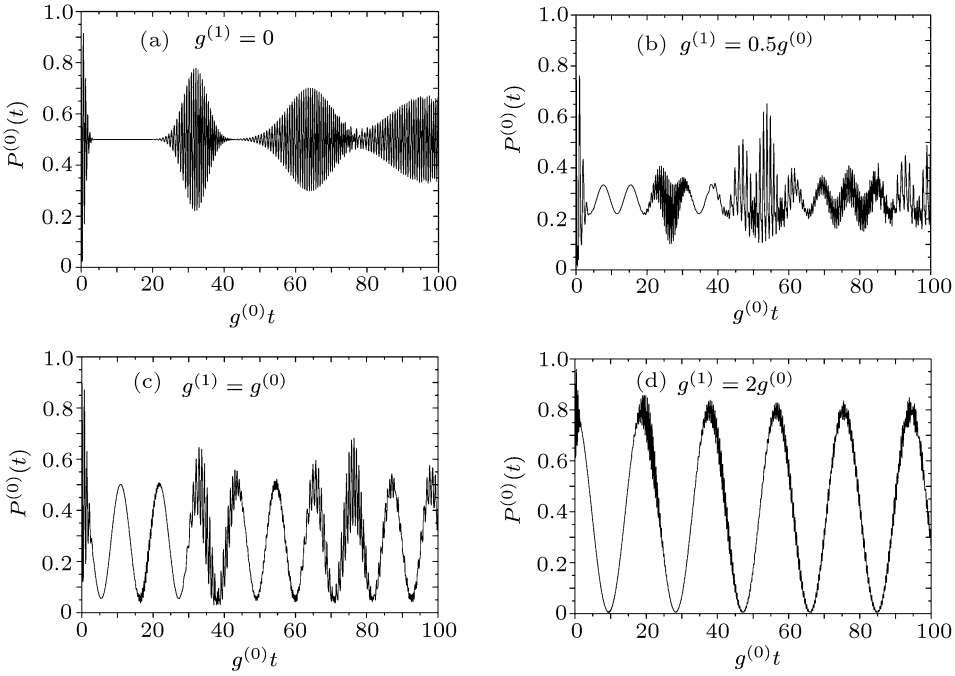


Fig. 2. Time evolutions of the upper state population $P^{(0)}(t)$ for $\varpi = 0.5g^{(0)}$, and (a) $g^{(1)} = 0.0$, (b) $g^{(1)} = 0.5g^{(0)}$, (c) $g^{(1)} = g^{(0)}$, (d) $g^{(1)} = 2.0g^{(0)}$.

In Fig. 3, we show the time evolution of the upper state population $P^{(0)}(t)$ for various frequencies of the low frequency field, with coupling constant fixed. Here we see that as the frequency of the low frequency field

increases, the modulation becomes faster, but the modulation strength remains almost invariant.

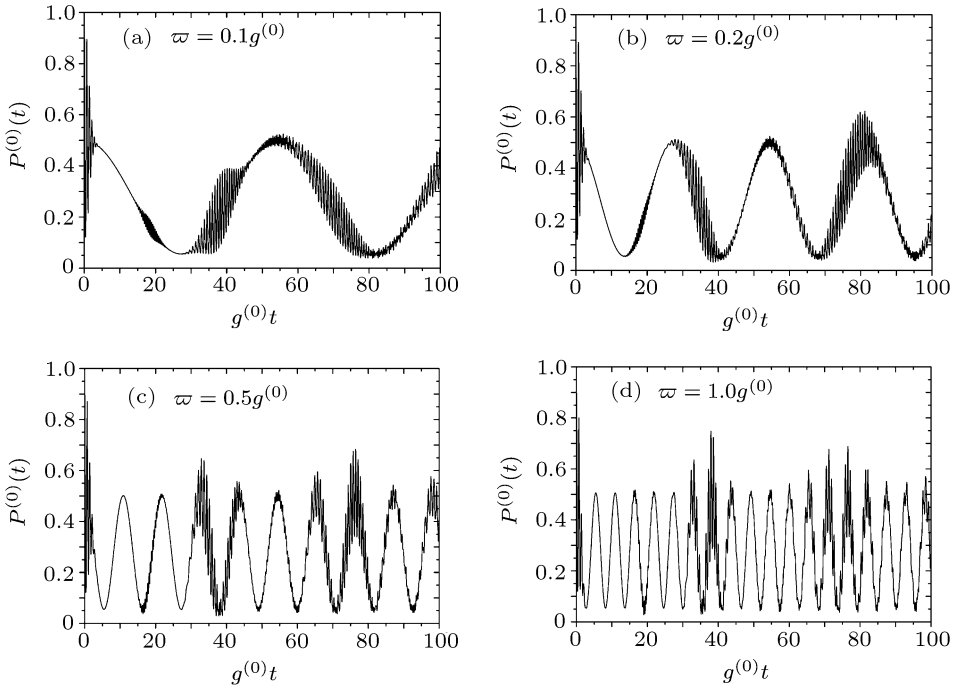


Fig. 3. Time evolutions of the upper state population $P^{(0)}(t)$ for $g^{(1)} = g^{(0)}$, and (a) $\varpi = 0.1g^{(0)}$, (b) $\varpi = 0.2g^{(0)}$, (c) $\varpi = 0.5g^{(0)}$, (d) $\varpi = 1.0g^{(0)}$.

To give a deeper insight into the behaviour of the modulation, we first investigate the dependence of Ω_1, Ω_3, $\tilde{C}^{(0)}_{m,1}$ and $\tilde{C}^{(0)}_{m,3}$ on photon number m, then we discuss the contributions of the three terms in expression (17) to $P^{(0)}(t)$. We rewrite expression (12) as

$$\Omega_1 = \sqrt{\frac{(m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)}{2}} \sqrt{1 + \beta^2 - \sqrt{1 - \beta^2 \left[\frac{2(|g^{(0)}|^2 - 2|g^{(1)}|^2)}{(|g^{(0)}|^2 + 2|g^{(1)}|^2)} - \beta^2 \right]}} \tag{18}$$

with

$$\beta = \frac{\varpi}{\sqrt{(m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)}}. \tag{19}$$

In the special case where the frequency of the applied field is sufficiently low, $\varpi \ll \sqrt{(m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)}$, that is, $\beta \ll 1$, we have

$$\Omega_1 = \varpi \sqrt{\frac{|g^{(0)}|^2}{|g^{(0)}|^2 + 2|g^{(1)}|^2} + o(\beta^2)}, \tag{20}$$

which implies that Ω_1 is approximately proportional to the frequency of the low frequency field and independent of m. In this case the first term in expression (17) can be approximately expressed as

$$P_1(t) = 4\cos^2(\Omega_1 t) \sum_m |\tilde{C}^{(0)}_{m,1}|^2 = 2 \sum_m |\tilde{C}^{(0)}_{m,1}|^2 + 2\cos(2\Omega_1 t) \sum_m |\tilde{C}^{(0)}_{m,1}|^2. \tag{21}$$

The second term in expression (21) is a modulation term with frequency $2\Omega_1$, which modulates the population $P^{(0)}(t)$.

We rewrite expression (13) as

$$\Omega_3 = \sqrt{\frac{(m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)}{2}} \sqrt{1 + \beta^2 + \sqrt{1 - \beta^2 \left[\frac{2(|g^{(0)}|^2 - 2|g^{(1)}|^2)}{(|g^{(0)}|^2 + 2|g^{(1)}|^2)} - \beta^2 \right]}}. \tag{22}$$

When $\beta \ll 1$, it is approximately equal to

$$\Omega_3 = \sqrt{(m+1)(|g^{(0)}|^2 + 2|g^{(1)}|^2)}\left[1 + \frac{|g^{(1)}|^2}{(|g^{(0)}|^2 + 2|g^{(1)}|^2)}\beta^2 + o(\beta^4)\right], \tag{23}$$

which implies that Ω_3 is approximately proportional to the strength of the single mode field $\sqrt{m+1}$, and the dependence on the frequency of the low frequency ϖ can be neglected.

In Fig. 4, we have plotted the coefficients $\tilde{C}^{(0)}_{m,1}$ and $\tilde{C}^{(0)}_{m,3}$ as a function of m for different coupling constants. It is found that the non-vanishing $\tilde{C}^{(0)}_{m,1}$ or $\tilde{C}^{(0)}_{m,3}$ occurs in the region around $\langle m \rangle = 25$, which is the average photon number of the single mode field we assumed before. With increasing coupling constant, the value of $\tilde{C}^{(0)}_{m,1}$ increases, while the value of $\tilde{C}^{(0)}_{m,3}$ decreases. Through expressions (15) and (16) of $\tilde{C}^{(0)}_{m,1}$ and $\tilde{C}^{(0)}_{m,3}$, we can also infer that when the value of ϖ is very low the dependence of $\tilde{C}^{(0)}_{m,1}$ and $\tilde{C}^{(0)}_{m,3}$ on ϖ can be neglected.

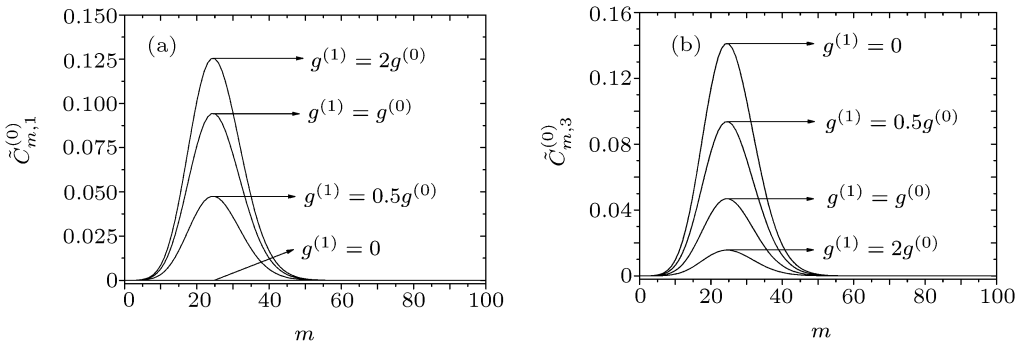


Fig. 4. Dependences of coefficients $\tilde{C}^{(0)}_{m,1}$ and $\tilde{C}^{(0)}_{m,3}$ on the photon number m, for $\varpi = 0.5g^{(0)}$.

From the discussion above, we see that when the coupling constant is large enough, the first term in expression (17) plays a dominant role, while the second and third terms become much smaller than the first term. Since the first term is a modulation function with frequency $2\Omega_1$, it strongly modulates the time evolution of the upper state population $P^{(0)}(t)$. The modulation frequency $2\Omega_1$ is approximately proportional to the frequency of the low frequency field when the value of ϖ is very low.

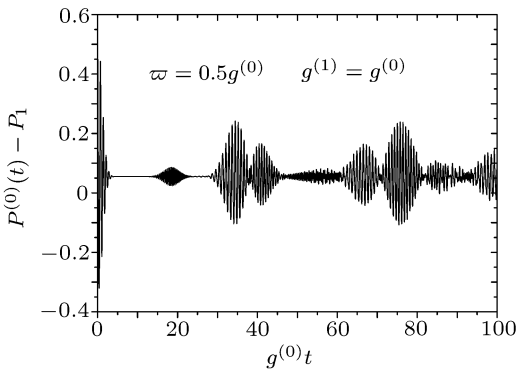


Fig. 5. Time evolution of $P^{(0)}(t) - P_1$ corresponding to the parameters in Fig. 2(c).

In order to understand the modulation behaviour, we subtract the first term from $P^{(0)}(t)$ and plot the curve of $P^{(0)}(t) - P_1$. The curve of $P^{(0)}(t) - P_1$ corresponding to the case shown in Fig. 2(c) is plotted in Fig. 5. Comparing Fig. 5 with Fig. 2(c), we find that by subtracting the first term from the upper state population, the cosine function modulation behaviour is eliminated.

4. Conclusion

We investigate the effect of an applied low frequency field on the dynamics of a two-level atom interacting with a single-mode field. In particular, we study the time evolutions of the atomic population for different coupling constants and different frequencies of the applied low frequency field and discuss the contributions of the three terms from the analytical expression of the atomic population. It is shown that the time evolution of the atomic population can be modulated by an external low frequency field and the coupling constants and the frequency of the additional

field act as distinct control parameters for the system. By increasing the coupling constants, the modulation strength increases, but the modulation frequency decreases. With the increase of the frequency of low frequency field, the frequency of the modulation function increases, which is proportional to the frequency of the low frequency field, while the modulation strength remains almost invariant.

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