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Effects of relative phase in an open ladder system without incoherent pumping

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Abstract. We studied effects of the relative phase between the probe and driving fields on the absorption and dispersion properties in an open three-level ladder system with spontaneously generated coherence but without incoherent pumping. It is shown that by the phase controlling, switching from absorption to lasing without inversion (LWI) and enhancing remarkablely LWI gain can be realized; large index of refraction with zero absorption and the electromagnetically induced transparency can be obtained. We also find that varying the atomic injection and exit rates has a considerable influence on the phase dependent-absorption property of the probe field, existent of the atomic injection and exit rates gives the necessary condition of the realization of LWI, getting LWI is impossible in the corresponding closed system without incoherent pumping.

PACS. 42.50.Gy Effects of atomic coherence on propagation – 42.50.Hz Strong-field excitation of optical transitions in quantum systems

1 Introduction

Recent research into the effects of atomic coherence and quantum interference in quantum optics has led to many novel phenomena such as coherent population trapping (CPT), electromagnetically induced transparency (EIT), lasing without inversion (LWI), high refraction index without absorption, cancellation of spontaneous emission and dynamically irreversible pathways of population transfer, and so on. Due to having important potential application, LWI has attracted much more attention (for example, see recent a review paper [1] and articles [2–7]). A kind of coherence can created by interference of spontaneous emission (usually called as spontaneously generated coherence (SGC)) of either two close lying atomic levels to a common atomic level (V-type atom) [8,9] or by a single excited level to two close lying atomic levels (Λ-type atom) [10]. In a ladder type system, it can also be created in the nearly spaced atomic levels case [11]. There have been considerable interests in the studying SGC [12–27]. It has been shown that atomic systems with SGC are sensitive to the relative phase of the applied fields [27–40]. However, near all of these studies used closed atomic systems. In this paper we investigate the control role of the relative phase between the probe and driving fields on gain (absorption), dispersion and populations from different aspects in an open ladder type three-level system with SGC but without the incoherent pumping. Zhu [41] has shown that the incoherent pumping plays a very important role and gives the necessary condition of the realization of LWI in a closed ladder system without SGC. Qian et al. [24] also have obtained the same conclusion for a closed ladder system with SGC. Our study [40] have revealed that even considering the effect of the relative phase, LWI is still absent in a closed ladder system with SGC but without the incoherent pumping. Different from the above conclusion, present paper shows that LWI can be realized in an open ladder system with SGC but without the incoherent pumping. This paper also obtains some other important results.

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2 Model and equations

The open three level ladder system considered here is shown in Figure 1. The transition $|1\rangle \rightarrow |2\rangle$ is coupled by a weak probe field of frequency ω_a with Rabi frequency $g = \vec{\mu}_{12} \cdot \vec{\varepsilon}_a/\hbar$ while the transition $|2\rangle \rightarrow |3\rangle$ is coupled by a strong driving field of frequency ω_b with Rabi frequency $G = \vec{\mu}_{23} \cdot \vec{\varepsilon}_b/\hbar$. The level $|2\rangle$ ($|3\rangle$) spontaneously decays to the level $|1\rangle$ ($|2\rangle$) at the rate γ_1 (γ_2). The atomic injection rates for levels $|1\rangle$ and $|2\rangle$ are J_1 and J_2, respectively. The atomic exit rate from the cavity is r_0. In the following discussion ,we always make $J_1 + J_2 = r_0$ for keeping the

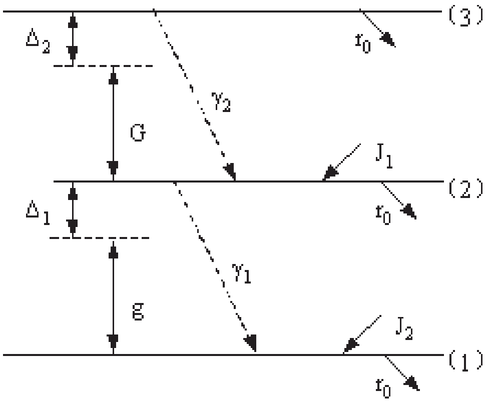

Fig. 1. A three-level ladder system with nearly equispaced levels.

total number of the atoms as a constant. In such a case, the density-matrix motion equations in a rotating frame can be written as

$$\dot{\rho}_{11} = -r_0\rho_{11} + 2\gamma_1\rho_{22} + ig^*\rho_{21} - ig\rho_{12} + J_1 \tag{1a}$$

$$\dot{\rho}_{22} = 2\gamma_2\rho_{33} - (2\gamma_1 + r_0)\rho_{22} - ig^*\rho_{21} + ig\rho_{12} - iG\rho_{23} + iG^*\rho_{32} + J_2 \tag{1b}$$

$$\dot{\rho}_{33} = -(2\gamma_2 + r_0)\rho_{33} + iG\rho_{23} - iG^*\rho_{32} \tag{1c}$$

$$\dot{\rho}_{23} = -(\gamma_1 + \gamma_2 + i\Delta_2)\rho_{23} + iG^*(\rho_{33} - \rho_{22}) + ig\rho_{13} \tag{1d}$$

$$\dot{\rho}_{12} = -(\gamma_1 + i\Delta_1)\rho_{12} + ig^*(\rho_{22} - \rho_{11}) - iG\rho_{13} + 2p\sqrt{\gamma_1\gamma_2}\eta\rho_{23} \tag{1e}$$

$$\dot{\rho}_{13} = -[\gamma_2 + i(\Delta_1 + \Delta_2)]\rho_{13} - iG^*\rho_{12} + ig^*\rho_{23} \tag{1f}$$

constrained by $\rho_{11} + \rho_{22} + \rho_{33} = 1$ and $\rho^*_{mn} = \rho_{nm}$. Where, ρ_{ii} is the atomic population of state $|i\rangle$, and ρ_{ij} is the atomic polarization between states $|i\rangle$ and $|j\rangle$; $\Delta_1 = \omega_{21} - \omega_a$ and $\Delta_1 = \omega_{32} - \omega_b$ denote the frequency detuning of the probe and the driving fields, respectively. Here in the case of nearly equispaced levels, the inclusion of two coupling fields of different frequencies would lead to the optical Bloch equation with additional term $2p\sqrt{\gamma_1\gamma_2}\eta\rho_{23}$, which presents the effect of SGC. Where $p = \vec{\mu}_{12} \cdot \vec{\mu}_{23}/\,|\vec{\mu}_{12}|\,|\vec{\mu}_{23}| = \cos\theta$, θ is the angle between the two induced dipole moments $\vec{\mu}_{12}$ and $\vec{\mu}_{23}$. Using the restriction that each of the linearly polarized field should only couple one of the optical transitions, we can find that the Rabi frequencies are connected to the parameter p by the relation $G = G_0\sqrt{1-p^2} = G_0\sin\theta$ and $g = g_0\sqrt{1-p^2} = g_0\sin\theta$, with $G_0 = |\vec{\mu}_{23}||\vec{\varepsilon}_b|/\hbar$ and $g_0 = |\vec{\mu}_{12}||\vec{\varepsilon}_a|/\hbar$. It is obviously that when $\eta = 1$, the SGC effect presents, strength of SGC will vary with value of θ varying; otherwise $\eta = 0$, the SGC effect is absent. When $J_1 = J_2 = \gamma_0 = 0$, equations (1) reduces to the equations for a closed ladder three level atomic system with SGC [24]. Due to SGC, the properties of the open system dependent not only on amplitudes and detunings but also phases of the the probe and driving fields, thus we have to treat Rabi frequencies as complex parameters. Let ϕ_p and ϕ_c denote the phases of the probe and driving fields, respectively, then we have $g = g_p\exp(i\phi_p)$ and $G = G_c\exp(i\phi_c)$ (g_p and G_c are real parameters) and the relative phase between the probe and the driving fields is $\Phi = \phi_p - \phi_c$. Let $\tilde{\rho}_{ii} = \rho_{ii}$, $\tilde{\rho}_{12} = \rho_{12}\exp(i\phi_p)$, $\tilde{\rho}_{23} = \rho_{23}\exp(i\phi_c)$, $\phi = \phi_c + \phi_p$ and $\tilde{\rho}_{13} = \rho_{13}\exp(i\phi)$, from equations (1) we obtain:

$$\dot{\tilde{\rho}}_{11} = -r_0\tilde{\rho}_{11} + 2\gamma_1\tilde{\rho}_{22} + ig_p(\tilde{\rho}_{21} - \tilde{\rho}_{12}) + J_1, \tag{2a}$$

$$\dot{\tilde{\rho}}_{22} = 2\gamma_2\tilde{\rho}_{33} - (2\gamma_1 + r_0)\tilde{\rho}_{22} - ig_p(\tilde{\rho}_{21} - \tilde{\rho}_{12}) - iG_c(\tilde{\rho}_{23} - \tilde{\rho}_{32}) + J_2, \tag{2b}$$

$$\dot{\tilde{\rho}}_{33} = -(2\gamma_2 + r_0)\tilde{\rho}_{33} + iG_c(\tilde{\rho}_{23} - \tilde{\rho}_{32}), \tag{2c}$$

$$\dot{\tilde{\rho}}_{23} = -(\gamma_1 + \gamma_2 + i\Delta_2)\tilde{\rho}_{23} + iG_c(\tilde{\rho}_{33} - \tilde{\rho}_{22}) + ig_p\tilde{\rho}_{13}, \tag{2d}$$

$$\dot{\tilde{\rho}}_{12} = -(\gamma_1 + i\Delta_1)\tilde{\rho}_{12} + ig_p(\tilde{\rho}_{22} - \tilde{\rho}_{11}) - iG_c\tilde{\rho}_{13} + 2\sqrt{\gamma_1\gamma_2}p\eta_\Phi\tilde{\rho}_{23}, \tag{2e}$$

$$\dot{\tilde{\rho}}_{13} = -[\gamma_2 + i(\Delta_1 + \Delta_2)]\tilde{\rho}_{13} - iG_c\tilde{\rho}_{12} + ig_p\tilde{\rho}_{23}, \tag{2f}$$

where $\eta_\Phi = \eta\exp(i\Phi)$. It is similar to equations (1) that equations (2) are restricted by $\tilde{\rho}_{ij} = \tilde{\rho_{ji}}^*$ and $\tilde{\rho}_{11} + \tilde{\rho}_{22} + \tilde{\rho}_{33} = 1$. The steady-state solutions can be found by setting the time derivatives to zero and reducing equations (2) to a set of coupled 9×9 algebraic equations after splitting into real and imaginary parts. These equations can be treated in all orders using the symbolic computation package Mathemetica or Maple. The dispersion and absorption (gain) of the medium correspond to the real and imaginary parts of $\tilde{\rho}_{12}$, respectively. If $\mathrm{Im}(\tilde{\rho}_{12}) > 0$, the system exhibits gain for the probe field; if $\mathrm{Im}(\tilde{\rho}_{12}) < 0$, the probe field is attenuated. When $\mathrm{Im}(\tilde{\rho}_{12}) > 0$ and simultaneously $\tilde{\rho}_{22}$–$\tilde{\rho}_{11} < 0$, LWI can be realized; if $\mathrm{Im}(\tilde{\rho}_{12}) > 0$ and $\tilde{\rho}_{22}$–$\tilde{\rho}_{11} > 0$, the lasing with inversion occurs.

3 Numerical analysis

In the following we discuss phase controlling of the properties of the open system by numerical calculation result from the steady analytical solutions of equations (2) for $\mathrm{Im}\tilde{\rho}_{12}$, $\mathrm{Re}\tilde{\rho}_{12}$ and $\tilde{\rho}_{22} - \tilde{\rho}_{11}$. It should be pointed out that $\tilde{\rho}_{22} - \tilde{\rho}_{11} < 0$ is always satisfied if we don't give a special statement.

Let us first consider the dependence of the absorption and dispersion properties of the probe field on the relative phase Φ. Figure 2 illustrates $\mathrm{Im}\tilde{\rho}_{12}$ and $\mathrm{Re}\tilde{\rho}_{12}$ as functions of Φ for the open system (a) and the corresponding closed system (b). In Figure 2a, the parameters values are $r_0 = 0.6\gamma_2$, $X = J_2/J_1 = 5$, $\Delta_2 = 18\gamma_2$, $\Delta_1 = -5\gamma_2$, $\gamma_1 = 1.2\gamma_2$, $\theta = \pi/4$, $G_c = 5\sin\theta\gamma_2$, $g_p = 0.1\sin\theta\gamma_2$ and $\eta = 1$. In Figure 2b the parameters values are same as those in Figure 2a but $r_0 = J_1 = J_2 = 0$. Obviously, here the parameters values are scaled by γ_2. From now on, for simplicity we will omit γ_2 when we give the parameters values in the following.

We can see from Figure 2a that for the open system, signs and sizes of $\mathrm{Im}\tilde{\rho}_{12}$ and $\mathrm{Re}\tilde{\rho}_{12}$ exhibit periodically variation with Φ varying, the period is 2π; the switching from absorption to gain without inversion (then LWI),

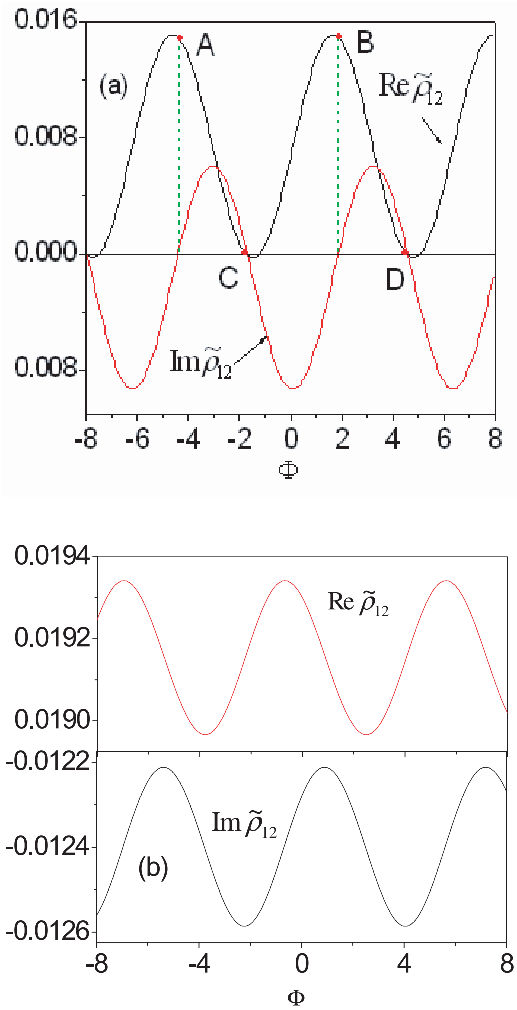

Fig. 2. Im$\tilde{\rho}_{12}$ and Re$\tilde{\rho}_{12}$ versus Φ for the open system (a) and the corresponding closed system (b). In (a), the parameters values are $r_0 = 0.6\gamma_2$, $X = J_2/J_1 = 5$, $\Delta_1 = -5\gamma_2$, $\Delta_2 = 18\gamma_2$, $\gamma_1 = 1.2\gamma_2$, $\theta = \pi/4$, $G_c = 5\sin\theta\gamma_2$, $g_p = 0.1\sin\theta\gamma_2$ and $\eta = 1$. In (b) the parameters values are same as those in (a) but $r_0 = J_1 = J_2 = 0$.

enhancing remarkably LWI gain, large index of refraction (dispersion) with zero absorption [42] (corresponding to A and B) and EIT [43] (corresponding to C and D, at which both absorption and dispersion disappear simultaneously) can be achieved by the relative phase controlling. Figure 2b shows that for the closed system, sizes of Im$\tilde{\rho}_{12}$ and Re$\tilde{\rho}_{12}$ exhibit periodically variation but always there are Re$\tilde{\rho}_{12} > 0$ and Im$\tilde{\rho}_{12} < 0$, so we get the conclusion that LWI, EIT and large index of refraction (dispersion) with zero absorption can't be realized in the closed system for any value of the relative phase. Although this conclusion is obtained from a special example, however, it is generally correct for a closed three-level ladder system with SGC but without the incoherent pumping [40].

Then we discuss the effect of the relative phase on the line profiles of the gain. Figure 3 gives Im$\tilde{\rho}_{12}$ as a function of the probe detuning Δ_1 with different values of Φ for both cases $\eta = 0$ and $\eta = 1$ in the open system, the parameters values are same as those in Figure 2a but $\Delta_2 = 0$. Figure 3a shows that when SGC is absent, the system only exhibits absorption. From Figure 3b we can see that: when $\Phi = 0$, same as the case $\eta = 0$, the system always exhibits absorption; when $\Phi = \pi$, the system always exhibits LWI gain, and the gain curve is symmetrical about $\Delta_1 = 0$, two gain peaks appear at $\Delta_1 \approx \pm G_c$; when $\Phi = \pi/2$ and $\Phi = 3\pi/2$, two gain peaks, the largest LWI gain, can be obtained in the regions $\Delta_1 < 0$ and $\Delta_1 > 0$, respectively; value and spectrum region of LWI gain very obviously with value of Φ varying.

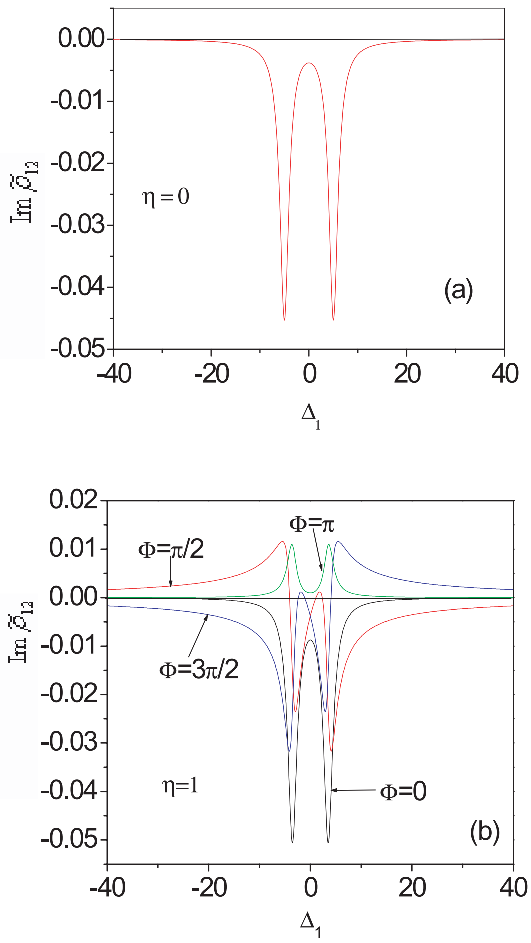

Fig. 3. (Color online) Im$\tilde{\rho}_{12}$ and Re$\tilde{\rho}_{12}$ versus Δ_1 for both cases $\eta = 0$ and $\eta = 1$, for different values of Φ, the other parameters values are same as those in Figure 2a but $\Delta_2 = 0$.

Finally we explore influence of the atomic injection and exit rates on the phase-dependent absorption property of the probe field.

Figure 4 presents Im$\tilde{\rho}_{12}$ and $\tilde{\rho}_{22} - \tilde{\rho}_{11}$ as functions of the atom exit rate r_0 when the ratio of the atomic injection rates keeps a constant, $X(= J_2/J_1) = 5$, the other parameters values are same as those in Figure 2 but $\Delta_2 = 0$. Figure 4 tells us that, corresponding to $\Phi = \pi/2$ and $\Phi = 0$, for any value of r_0 the system always exhibits absorption without or with inversion; however, corresponding to $\Phi = \pi$ and $\Phi = 3\pi/2$, with value of r_0 increasing, absorption without inversion, gain without and with inversion

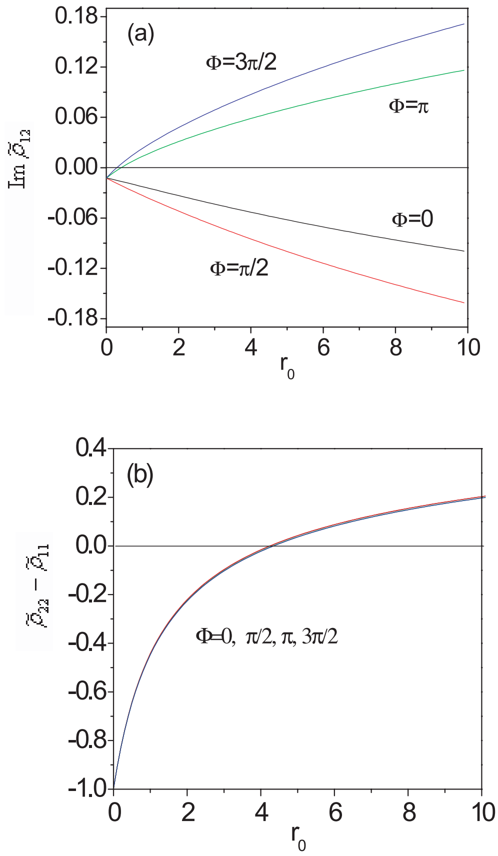

Fig. 4. (Color online) Im$\tilde{\rho}_{12}$ vs. r_0 for different values of Φ, the other parameters values are same as those in Figure 2a but $\Delta_2 = 0$.

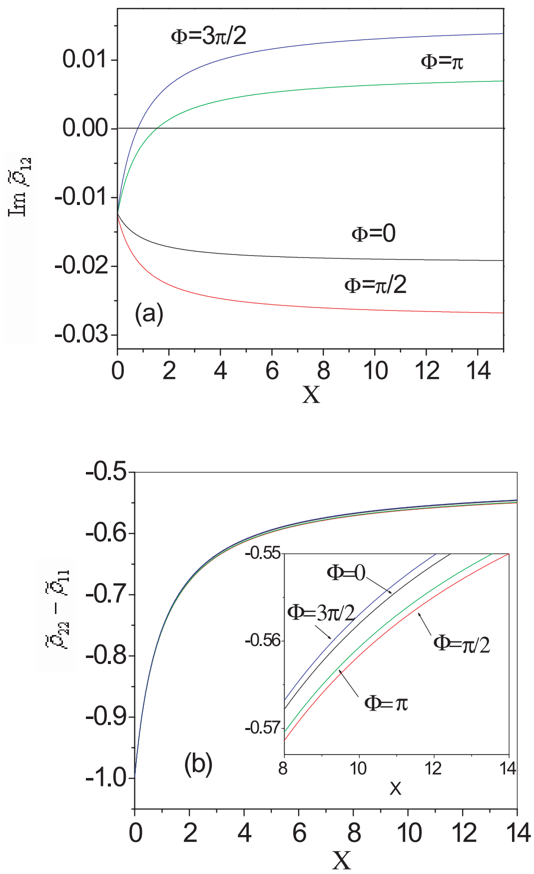

Fig. 5. (Color online) Im$\tilde{\rho}_{12}$ vs. X for different values of Φ, the other parameters values are same as those in Figure 2a but $\Delta_2 = 0$.

appear successively. It is should be pointed out that when the value of r_0 is large enough, values of Im$\tilde{\rho}_{12}$ corresponding to different values of Φ all tend gradually to different constant values, respectively. Figure 4 shows that when $r_0 = 0$, the probe field just gets absorption without inversion for any value of Φ. From $J_1 + J_2 = r_0$ and $X = J_2/J_1$, we know that $r_0 = 0$ means simultaneously $J_1 = J_2 = 0$, and this is the case of the corresponding closed system. This shows again that, even considering the effect of the relative phase, in a closed three-level ladder system with SGC but without an incoherent pumping, LWI can't be gotten. And we can say that existent of the atomic injection and exit rates gives the necessary condition of the realization of LWI in a ladder system with SGC but without the incoherent pumping.

Figure 5 draws the Im$\tilde{\rho}_{12}$ and $\tilde{\rho}_{22} - \tilde{\rho}_{11}$ as functions of the ratio of the injection rates, X, when the atomic exit rate keeps a constant, $r_0 = 0.6$, the other parameters values are same as those in Figure 4. Figure 5 shows that, corresponding to $\Phi = 0$ and $\Phi = \pi/2$, the probe field is always attenuated for any value of X; corresponding to $\Phi = \pi$ and $\Phi = 3\pi/2$, when value of X is small, the system only exhibits probe absorption, with value of X increasing, LWI gain occurs and increases gradually in a certain value region of X.

From Figures 4 and 5 we can see that, varying value of Φ has much larger effect on absorption (gain) Im$\tilde{\rho}_{12}$ than on the population difference $\tilde{\rho}_{22} - \tilde{\rho}_{11}$. Comparing Figure 5 with Figure 4, we know that effect produced by varying the atomic exit rate on the phase-dependent gain (absorption) is obviously larger than that produced by varying the ratio of the atomic injection rates.

4 Discussion

In the following we try to provide some physical interpretation of the results seen in the above figures.

For the steady state, from equation (2e) we obtain

$$\tilde{\rho}_{12} = \frac{1}{\gamma_1 + i\Delta_1}\left[ig_p(\tilde{\rho}_{22} - \tilde{\rho}_{11}) - iG_c\tilde{\rho}_{13} + 2\sqrt{\gamma_1\gamma_2}p\eta(\cos\Phi + i\sin\Phi)\tilde{\rho}_{23}\right]. \quad (3)$$

From equation (3), we can see that $\tilde{\rho}_{12}$ is contributed by three terms: the population difference (PD) term (proportional to $\tilde{\rho}_{22} - \tilde{\rho}_{11}$), the dynamically induced coherence (DIC) term (proportional to $\tilde{\rho}_{13}$), and SGC term (proportional to $\tilde{\rho}_{23}$), an additional term compared with the first two terms that are usual in conventional LWI systems;

and $\mathrm{Re}\tilde{\rho}_{12}$ consists of the DIC and SGC terms. Obviously, the SGC term is periodically manipulated by the relative phase Φ with the period 2π, so values of $\mathrm{Im}\tilde{\rho}_{12}$ and $\mathrm{Re}\tilde{\rho}_{12}$ exhibit periodical variation with Φ varying and the period is 2π.

For the case without inversion, $\tilde{\rho}_{22} - \tilde{\rho}_{11} < 0$, the contribution to LWI gain is only from the DIC and SGC terms. For the open system, the atomic exit and injection will affect considerably DIC and SGC. The effects from DIC, SGC and the atomic injection and exit will produce quantum destructive or constructive interference and this is mainly determined by atomic injection and exit rates, the relative phase and detunings of the driving and probe fields, spontaneously decay and the angle between the two induced dipole moments. In some cases, quantum destructive interference arises and leads to gain decreasing even absorption; and in other cases, quantum constructive interference appears and leads to gain increasing, particularly, in some situations and at suitable values of atomic injection and exit rates the quantum constructive interference is very strong, and this leads to the largest gain. In the corresponding closed system, the quantum constructive interference from DIC, SGC and the atomic injection and exit is absent, so it is impossible to get LWI gain. For exhibiting more clearly the important role of the atomic exit and injection in producing LWI gain, we discuss a special case. Letting $\Phi = 3\pi/2$, $\eta = 1$, $\Delta_1 = \Delta_2 = 0$ and taking the limit $G_c \gg g_p, \gamma_1, \gamma_2, r_0, J_1, J_2$, we obtain

$$\tilde{\rho}_{22} - \tilde{\rho}_{11} = \frac{Q_1}{2(r_0 r_1 + r_0 r_2 + r_1^2 + r_1 r_2)} \tag{4a}$$

$$\mathrm{Im}\tilde{\rho}_{12} = \frac{g_p Q_2}{4G^2 r_1 (r_0 + r_2)}, \tag{4b}$$

where

$$Q_1 = r_0 r_1 + r_0 r_2 - 3r_2 J_1 - 2r_1 J_1 - 2r_1(r_1 + r_2), \tag{4c}$$

$$\begin{aligned} Q_2 = \big[&2r_0 r_1^2 + r_0 r_1 J_1 + r_0^2 r_1 - 2r_1 r_2 (J_2 + 2r_2 \\ &+2r_1 + 3J_1) - r_0^2 r_2 - r_0 r_2 J_2 - 4r_2^2 J_1\big]. \end{aligned} \tag{4d}$$

For the open system, when values of r_0, J_1 and J_2 satisfy the condition

$$\tilde{\rho}_{22} - \tilde{\rho}_{11} \leqslant 0 \quad \text{and} \quad \mathrm{Im}\tilde{\rho}_{12} > 0.$$

LWI gain can be gotten. Obviously, for the closed system $(r_0 = J_1 = J_2 = 0)$,

$$\tilde{\rho}_{22} - \tilde{\rho}_{11} = -1, \quad \mathrm{Im}\tilde{\rho}_{12} = \frac{-g_p(r_1 + r_2)}{G^2} < 0.$$

So we can't get LWI gain.

On the other hand, we can explain some results seen in the above figures in terms of the dressed states of the system. We transfer the bare states $|1\rangle$, $|2\rangle$ and $|3\rangle$ into the dressed states

$$|0\rangle = |1\rangle, \quad |\pm\rangle = \frac{1}{\sqrt{2}}(|2\rangle \pm |3\rangle). \tag{5}$$

This leads to the inversionless condition

$$\rho_{++} + \rho_{--} - \rho_{00} < 0 \tag{6}$$

and the probe gain condition

$$\mathrm{Im}(\rho_{0+} + \rho_{0-}) > 0. \tag{7}$$

From equation (7) we also can see that in the dressed states the probe gain comes from the atomic polarization between states $|0\rangle$ and $|\pm\rangle$. Our calculation result shows that: for the open system, at some values of r_0, J_1 and J_2, the conditions (6) and (7) can be satisfied and LWI gain of the probe field can be obtained. For the corresponding closed system, the inversionless condition (6) can but the probe gain condition (7) can't be satisfied, so the probe amplification is impossible. In addition, the two negative peaks in Figure 2 are due to the Rabi splitting of the upper transition in the dressed states; in Figure 3, when $\Phi = \pi$, the gain profile presents two peaks at $\Delta_1 \approx \pm G_c$, and these correspond to the Aulter-Townes doublet transitions between states $|0\rangle$ and $|\pm\rangle$.

5 Conclusions

In this paper, we investigated the control role of the relative phase between the probe and driving fields on gain (absorption), dispersion and populations from different aspects in an open three-level ladder system with SGC but without an incoherent pumping by using numerical calculation results from the steady state analytical solution of the system. It is shown that by adjusting value of the relative phase, switching from absorption to LWI and enhancing remarkably LWI gain can be realized; large index of refraction with zero absorption and EIT can be achieved. We also find that, varying the atomic injection and exit rates has a considerable influence on the phase dependent-absorption of the probe field; moreover, the effect produced by varying the atomic exit rate is obviously larger than that produced by varying the ratio of the atomic injection rates; existent of the atomic injection and exit rates gives the necessary condition of the realization of LWI, getting LWI is impossible in the corresponding closed system without incoherent pumping.

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