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Effects of relative phase on transient evolution in an open resonant ladder-type atomic system*

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In an open ladder-type resonant atomic system, variation in relative phase between probe and driving fields does not affect the transient evolution of populations, but it has remarkable effects on gain and dispersion of the probe field. No matter whether an incoherent pump is present or absent, transient and stationary gains without inversion (GWI) always can be obtained by choosing an appropriate value of the relative phase. When the incoherent pump is absent，the values of transient and stationary GWIs are much larger and the time interval required to reach the stationary value is longer than those when the incoherent pump is present. Varying the exit rate and the ratio between injection rates can obviously change the phase-dependent GWI. In addition, in the transient evolution process, the phenomenon of high dispersion (refractive index) without absorption occurs at some values of relative phase. In the corresponding closed system, the stationary GWI can be obtained by choosing an appropriate value of relative phase only when incoherent pump exists, moreover the gain is smaller than that in the open system.

Keywords: open system, relative phase, transient evolution, gain without inversion
PACC: 4250

1. Introduction

The generation of lasing without inversion (LWI) is the result of quantum coherence and interference in an atomic system. The study of LWI has important theoretical significance and potential applications, so it has received considerable attention (for example, see a recent review paper[1] and Refs.[2–6]). There are many ways to generate quantum coherence and interference. Generally, they can be realized by coherent driving fields or by initial coherence injections, the interference between different spontaneous emission paths also can lead to the generation of coherent superposition state. The interference effect caused by spontaneous emission is known as spontaneously generated coherence (SGC). There have been considerable interests in studying SGC.[7−17] It has been shown that atomic systems with SGC are sensitive to the relative phase of applied fields.[18−28] For an LWI system, it is necessary to study the transient evolution of atomic response in order to understand the dynamic process of producing LWI and find the way of increasing LWI gain, i.e. gain without inversion (GWI). The effect of the relative phase between the driving and probe fields on the dynamic transient evolution in a closed Λ-type three-level system was discussed in Ref.[24]. In the present paper, we investigate the effects of the relative phase on transient evolution of populations, gain and dispersion and analyse the influence of modulation role of the atomic exit rate and ratio between the atomic injection rates on phase-dependent transient evolution of LWI gain in an open ladder-type three-level system.

2. The model and equations of motion

The open three-level ladder system considered here is shown in Fig.1. The transition $|1\rangle \rightarrow |2\rangle$ is coupled by a weak probe field of frequency $\omega_{\rm a}$ with Rabi frequency $g = \boldsymbol{\mu}_{12} \cdot \boldsymbol{\varepsilon}_{\rm a}/\hbar$ while the transition $|2\rangle \rightarrow |3\rangle$ is coupled by a strong driving field of frequency $\omega_{\rm b}$ with Rabi frequency $G = \boldsymbol{\mu}_{23} \cdot \boldsymbol{\varepsilon}_{\rm b}/\hbar$. An incoherent pump field with pump rate $2R$ is applied between levels $|1\rangle$

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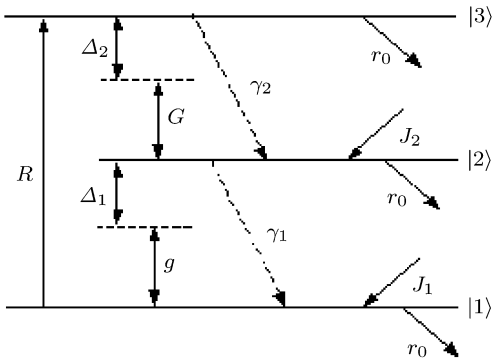


Fig.1. Open ladder-type three-level system.

and $|3\rangle$. The levels $|2\rangle$ and $|3\rangle$ spontaneously decay to the levels $|1\rangle$ and $|2\rangle$ at the rate γ_1 and γ_2, respectively. 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 total number of the atoms as a constant. In the electric dipole and rotating waving approximations the semi-classical density matrix equations of motion for the system can be written as

$$\begin{aligned}
\dot{\sigma}_{11} =& -(2R + r_0)\sigma_{11} + 2\gamma_1\sigma_{22} + \mathrm{i}g^*\sigma_{21} \\
& - \mathrm{i}g\sigma_{12} + J_1, \qquad (1a)\\
\dot{\sigma}_{22} =& 2\gamma_2\sigma_{33} - (2\gamma_1 + r_0)\sigma_{22} - \mathrm{i}g^*\sigma_{21} + \mathrm{i}g\sigma_{12} \\
& - \mathrm{i}G\sigma_{23} + \mathrm{i}G^*\sigma_{32} + J_2, \qquad (1b)\\
\dot{\sigma}_{33} =& 2R\sigma_{11} - (2\gamma_2 + r_0)\sigma_{33} + \mathrm{i}G\sigma_{23} \\
& - \mathrm{i}G^*\sigma_{32}, \qquad (1c)\\
\dot{\sigma}_{23} =& -(\gamma_1 + \gamma_2 + \mathrm{i}\Delta_\mathrm{c})\sigma_{23} \\
& + \mathrm{i}G^*(\sigma_{33} - \sigma_{22}) + \mathrm{i}g\sigma_{13}, \qquad (1d)\\
\dot{\sigma}_{12} =& -(R + \gamma_1 + \mathrm{i}\Delta_\mathrm{p})\sigma_{12} + \mathrm{i}g^*(\sigma_{22} - \sigma_{11}) \\
& - \mathrm{i}G\sigma_{13} + 2\sqrt{\gamma_1\gamma_2}\cos\theta\eta\sigma_{23}, \qquad (1e)\\
\dot{\sigma}_{13} =& -[\gamma_2 + R + \mathrm{i}(\Delta_\mathrm{p} + \Delta_\mathrm{c})]\sigma_{13} \\
& - \mathrm{i}G^*\sigma_{12} + \mathrm{i}g^*\sigma_{23}. \qquad (1f)
\end{aligned}$$

And the above equations are constrained by $\sigma_{ij} = \sigma_{ji}^*$ and $\sigma_{11} + \sigma_{22} + \sigma_{33} = 1$. Here σ_{ii} is the atomic population of state $|i\rangle$, and σ_{ij} is the atomic polarization between states $|i\rangle$ and $|j\rangle$; $\Delta_\mathrm{p}(= \omega_{21} - \omega_a)$ and $\Delta_\mathrm{c}(= \omega_{32} - \omega_b)$ denote the frequency detunings of the probe and 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 $2\sqrt{\gamma_1\gamma_2}\cos\theta\eta\sigma_{23}$ which presents the effect of SGC, and θ is the angle between the two induced dipole moments $\boldsymbol{\mu}_{12}$ and $\boldsymbol{\mu}_{23}$. Using the restriction that each linearly polarized field couples only one of the optical transitions, we can find that the Rabi frequencies are connected by the relation $G = G_0\sin\theta$ and $g = g_0\sin\theta$, with $G_0 = |\boldsymbol{\mu}_{23}|\,|\boldsymbol{\varepsilon}_b|/\hbar$ and $g_0 = |\boldsymbol{\mu}_{12}|\,|\boldsymbol{\varepsilon}_a|/\hbar$. It is obvious that when $\eta = 1$, the SGC effect is present and its strength will vary with value of θ ; otherwise $\eta = 0$, the SGC effect is absent. When $J_1 = J_2 = \gamma_0$=0, Eqs.(1a)–(1f) reduce to the equations for a closed three-level ladder atomic system with SGC.[29] Owing to SGC, the properties of the open system depend on not only amplitudes and detunings but also phases of 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 will have $g = g_\mathrm{p}\exp(\mathrm{i}\phi_\mathrm{p})$ and $G = G_\mathrm{c}\exp(-\mathrm{i}\phi_\mathrm{c})$, where g_p and G_c are real parameters. Let $\rho_{ii} = \sigma_{ii}$, $\rho_{12} = \sigma_{12}\exp(\mathrm{i}\phi_\mathrm{p})$, $\rho_{23} = \sigma_{23}\exp(\mathrm{i}\phi_\mathrm{c})$, and $\rho_{13} = \sigma_{13}\exp(\mathrm{i}\phi)$, where $\phi = \phi_\mathrm{c} + \phi_\mathrm{p}$. Moreover, let $P = 2\sqrt{\gamma_1\gamma_2}\cos\theta\eta_\Phi$, where $\eta_\Phi = \eta\exp(\mathrm{i}\Phi)$ with $\Phi(\Phi = \phi_\mathrm{p} - \phi_\mathrm{c})$ denoting the relative phase between probe and driving fields, then Eqs.(1a)–(1f) can be written as

$$\begin{aligned}
\dot{\rho}_{11} =& -(2R + r_0)\rho_{11} + 2\gamma_1\rho_{22} \\
& + \mathrm{i}g_\mathrm{p}(\rho_{21} - \rho_{12}) + J_1, \qquad (2a)\\
\dot{\rho}_{22} =& 2\gamma_2\rho_{33} - (2\gamma_1 + r_0)\rho_{22} - \mathrm{i}g_\mathrm{p}(\rho_{21} - \rho_{12}) \\
& - \mathrm{i}G_\mathrm{c}(\rho_{23} - \rho_{32}) + J_2, \qquad (2b)\\
\dot{\rho}_{33} =& 2R\rho_{11} - (2\gamma_2 + r_0)\rho_{33} \\
& + \mathrm{i}G_\mathrm{c}(\rho_{23} - \rho_{32}), \qquad (2c)\\
\dot{\rho}_{23} =& -(\gamma_1 + \gamma_2 + \mathrm{i}\Delta_\mathrm{c})\rho_{23} + \mathrm{i}G_\mathrm{c}(\rho_{33} - \rho_{22}) \\
& + \mathrm{i}g_\mathrm{p}\rho_{13}, \qquad (2d)\\
\dot{\rho}_{12} =& -(R + \gamma_1 + \mathrm{i}\Delta_\mathrm{p})\rho_{12} + \mathrm{i}g_\mathrm{p}(\rho_{22} - \rho_{11}) \\
& - \mathrm{i}G_\mathrm{c}\rho_{13} + P\rho_{23}, \qquad (2e)\\
\dot{\rho}_{13} =& -[\gamma_2 + R + \mathrm{i}(\Delta_\mathrm{p} + \Delta_\mathrm{c})]\rho_{13} \\
& - \mathrm{i}G_\mathrm{c}\rho_{12} + \mathrm{i}g_\mathrm{p}\rho_{23}. \qquad (2f)
\end{aligned}$$

Similar to Eqs.(1a)–(1f), Eqs.(2a)–(2f) are restricted by $\rho_{ij} = \rho_{ji}^*$ and $\rho_{11} + \rho_{22} + \rho_{33} = 1$. The dispersion and the gain (absorption) of the probe field correspond to the real and the imaginary parts of ρ_{12}, respectively. If $\mathrm{Im}\rho_{12} > 0$, the probe field is gained; if $\mathrm{Im}\rho_{12} < 0$, the probe field is attenuated. When both $\mathrm{Im}\rho_{12} > 0$ and $\rho_{22} - \rho_{11} < 0$ are simultaneously satisfied, amplification without inversion (AWI) occurs and the LWI can be realized; if $\mathrm{Im}\rho_{12} > 0$ and $\rho_{22} - \rho_{11} > 0$, the lasing with inversion appears. The dispersion is determined by $\mathrm{Re}\rho_{12}$, and $\mathrm{Re}\rho_{12} > 0$ corresponds to the red shift of the probe field frequency; $\mathrm{Re}\rho_{12} < 0$ the blue shift.[30] When $r_0 = J_1 = J_2$=0, Eqs.(2a)–(2f)

are the equations describing the corresponding closed ladder-type system.

3. Numerical analysis

It should be pointed out that in the following discussion, the condition $\rho_{22} - \rho_{11} < 0$ is always satisfied unless otherwise stated, so the gain appearing in the discussion means LWI gain. We set initial conditions as $\rho_{22} = \rho_{11} = 0.5$, $\rho_{33} = 0$, and $\rho_{ij} = 0$ $(i \neq j,\ i,j = 1,2,3)$. Let values of parameters R, $G_{\rm c}$, $g_{\rm p}$, $\Delta_{\rm c}$, $\Delta_{\rm p}$, r_0, J_1, and J_2 be in units of γ_2 in numerical calculation and c $(c = J_2/J_1)$ denote the ratio between injection rates. We will investigate mainly the effects of the relative phase on the transient evolutions of populations, gain and dispersion and analyse the modulation role of the atomic exit rate and the ratio between atomic injection rates in the phase-dependent transient evolution of LWI gain in the open ladder-type three-level system by using the numerical solution of Eqs.(2a)–(2f) when incoherent pump is present or absent in the case where both probe and driving fields are in resonance.

Numerical calculation result shows that no matter whether the incoherent pump is present or absent, the transient evolution behaviour of populations does not vary with relative phase (Φ), but the transient evolution behaviour of populations in the two situations have a significant difference for identical values of Φ. As an example, transient evolution of populations for $\Phi = \pi/8$ is given in Fig.2. From Fig.2 we can see that when the incoherence pump is present the populations ρ_{33} and ρ_{22} of the excited states are bigger but the population ρ_{11} of the ground state is much smaller than those when the incoherence pump is absent.

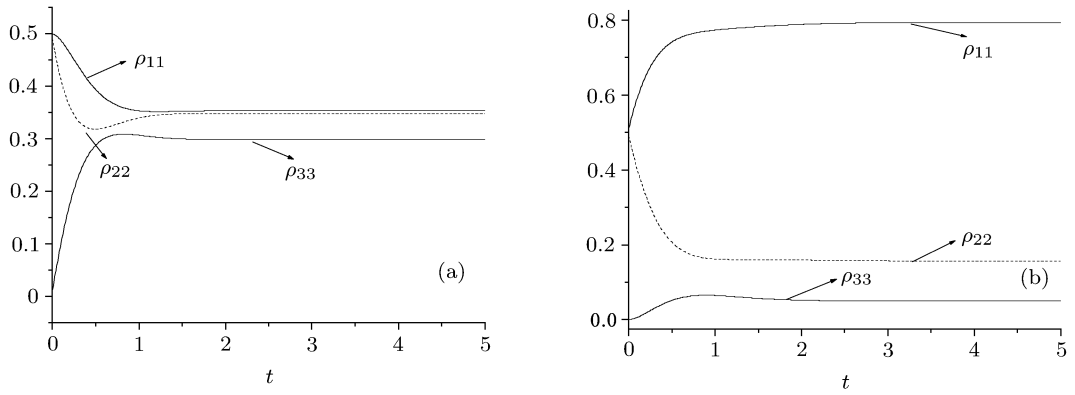


Fig.2. Transient evolution of populations for $\Phi = \pi/8$ in the open system, where parameter values are $r_2 = 1$, $\Delta_{\rm c} = 0$, $\Delta_{\rm p} = 0$, $\theta = \pi/8$, $G_{\rm c} = 3\sin\theta$, $G_{\rm p} = 0.01\sin\theta$, $\eta = 1$, $J_1 = 0.1, J_2 = 0.5$, and $r_0 = 0.6$. (a) R=1.02, c=5, $\Phi = \pi/8$, (b) R=0, c=5, $\Phi = \pi/8$.

Figure 3 gives the transient evolutions of gain and dispersion of the probe field. From Figs.3(a) and 3(c) we see that the transient evolution behaviour of gain without the incoherence pump is similar to that with the incoherence pump: when $\Phi = \pi/2, 3\pi/2$, there is no gain (Imρ_{12}=0); in the region $\pi < \Phi < 3\pi/2$, the transient and the steady values of gain are positive and increase with Φ decreasing, and its maximum value appears at $\Phi = \pi$, the probe field is amplified; in the range of $0 \leq \Phi < \pi/2$, the transient and the steady values are negative, their absolute values increase with Φ decreasing and the maximum value of gain appears at $\Phi = 0$, the probe field displays an absorptive character; two curves corresponding to Φ_1 and $\Phi_2(= \Phi_1 - \pi)$ are symmetric about Im$\rho_{12} = 0$. Moreover, the numerical calculation result shows that in the ranges of $\pi/2 \leq \Phi < \pi$ and $3\pi/2 \leq \Phi < 2\pi$, the values of Imρ_{12} are positive and negative, respectively, and the transient and the steady values of gain and absorption increase with Φ increasing.

From Figs.3(b) and 3(d) we see that the evolution behaviour of dispersion without the incoherence pump is similar to that with the incoherence pump: when $\Phi = \pi, 0$, Re$\rho_{12} = 0$, i.e. there is no dispersion; the value of dispersion is negative in the range $\pi < \Phi \leq 3\pi/2$, but it is positive in the range $0 < \Phi \leq \pi/2$. The transient and the steady values increase with Φ increasing in the above range, and the maximum values of dispersion occur at $\Phi = \pi/2, 3\pi/2$, separately. Moreover, the numerical calculation result shows that

in the ranges $\pi/2 \leq \Phi < \pi$ and $3\pi/2 \leq \Phi < 2\pi$, the dispersion values are positive and negative, respectively, and the transient and the steady values both decrease with Φ increasing. Although the transient evolution behaviour without the incoherence pump is similar to that with the incoherence pump, some obvious differences exist. (1) The times of gain (dispersion) peak appearing ($t \approx 0.6$) and arriving at the steady state ($t \approx 1.85$) with the incoherence pump are earlier than those ($t \approx 1$ and $t \approx 3$, respectively) without the incoherence pump. (2) The transient and the steady values of gain and dispersion without the incoherence pump are twice larger than those with the incoherence pump for identical values of Φ. Figure 3 also shows that when $\Phi = \pi, 0$, the system has no dispersion ($\mathrm{Re}\rho_{12} = 0$), but the gain (absorption) reaches its maximum value; when $\Phi = \pi/2, 3\pi/2$, the system has no gain ($\mathrm{Im}\rho_{12} = 0$), but the dispersion arrives at its maximum value, and the phenomenon of the high dispersion (refractive index) with zero absorption[31–33] appears.

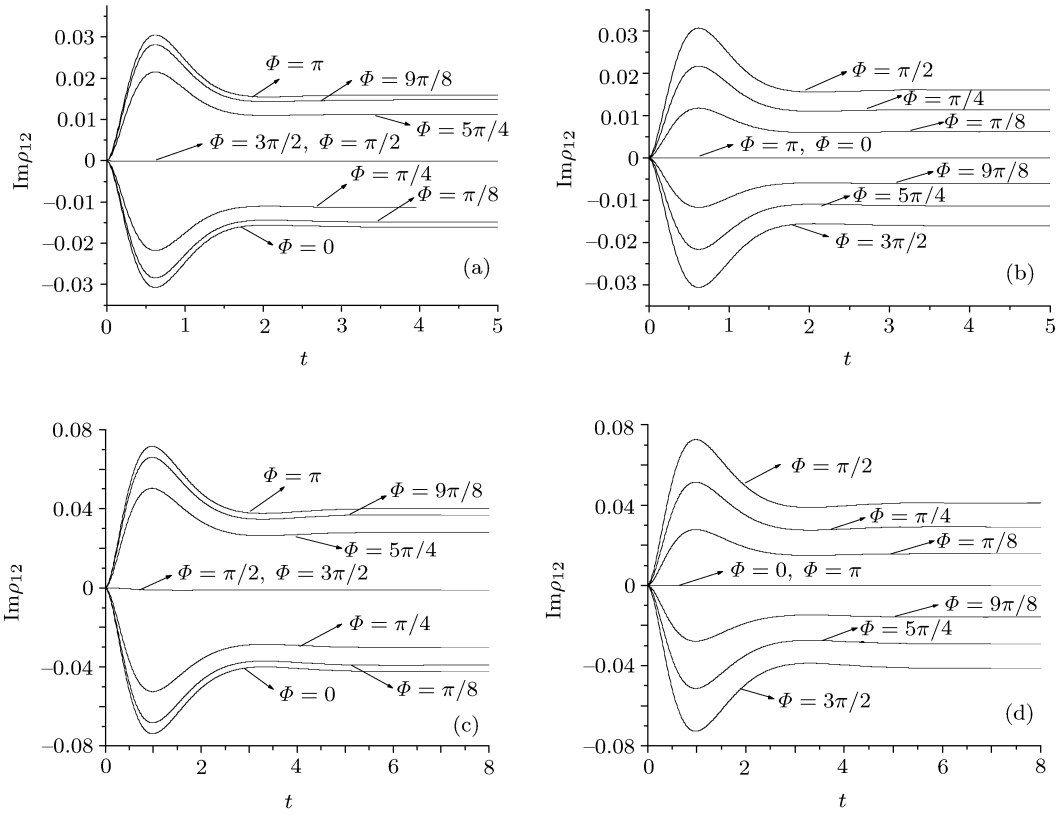


Fig.3. Transient evolutions of gain and dispersion for different values of Φ in the open system, where the other parameter values are the same as those in Fig.2. (a) R=1.02, c=5, (b) R=1.02, c=5, (c) R=0, c=5, (d) R=0, c=5.

The main difference between the open system and the corresponding closed system is caused by introducing injection rates and exit rate. Figure 4 shows that in a certain value range (about 1–5) of the ratio between the atomic injection rates, c ($c = J_2/J_1$), with the value of c increasing, the gain peak value increases and the gain peak appears more lately and the time of arriving at the steady state delays; the value of c may not be very small, or else there is no gain to be generated. In addition, numerical calculation result shows that the value of c may not be very large, or else the gain is no longer LWI gain. Figure 4(b) gives the transient evolution of the gain when the incoherence pump is absent, and the evolution behaviour is similar to that with the incoherence pump (Fig.4(a)). Comparing Fig.4(a) with Fig.4(b) indicates that when the incoherence pump is absent, the value range of c in which the LWI gain can be obtained extends obviously; the transient and the stationary gain values increase considerably; the times of the gain peak appearing and reaching the stationary state are evidently delayed.

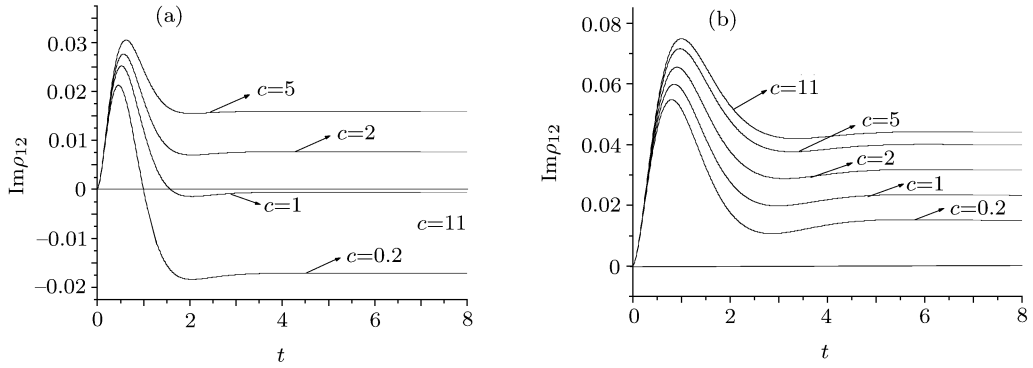


Fig.4. Transient evolution of gain for different ratios between the injection rates when $\Phi = \pi$ in the open system, where the other parameter values are the same as those in Fig.2. (a) R=1.02, r_0=0.6, $\Phi = \pi$, (b) R=0, r_0=0.6, $\Phi = \pi$.

Figure 5 shows the transient evolutions of gain for different values of exit rate r_0. Comparing Fig.5 with Fig.4, we find that the modulation role of the atomic exit rate r_0 in the phase-dependent transient evolution of LWI gain is similar to that of ratio between atomic injection rates.

Figure 6 exhibits the transient evolutions of gain and dispersion for different values of relative phase Φ in the corresponding closed three-level ladder atomic system with and without the incoherent pump separately.

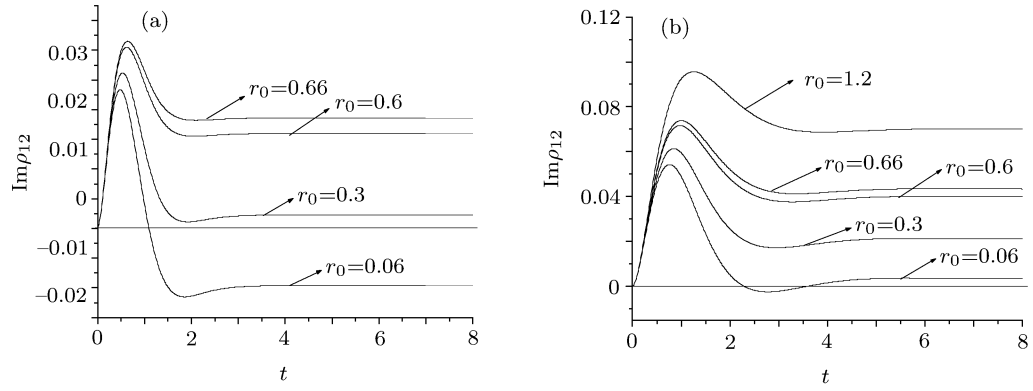
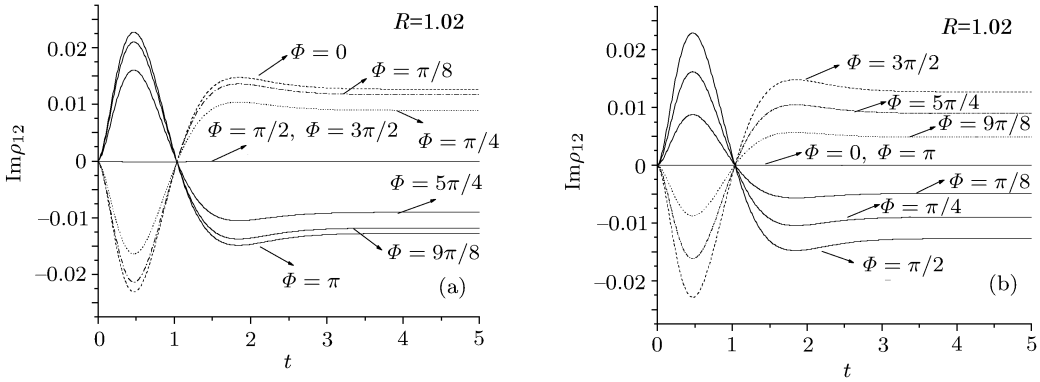


Fig.5. Transient evolutions of gain for different exit rates when $\Phi = \pi$ in the open system, where the other parameter values are the same as those in Fig.2. (a) R=1.02, c=5, $\Phi = \pi$, (b) R=0, c=5, $\Phi = \pi$.



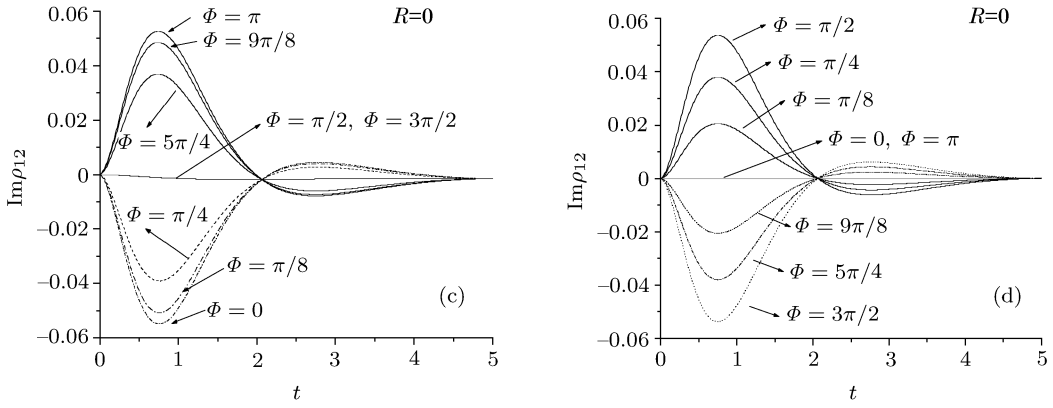


Fig.6. Transient evolutions of gain and dispersion for different values of Φ in the corresponding closed system, where other parameter values are the same as those in Fig.2.

A comparison between Fig.6 and Fig.3 shows that the transient evolution behaviours of gain and dispersion in the closed system are much different from those in the open system for identical values of Φ. When the incoherence pump is absent, in the closed system all the stationary values of the gain and the dispersion are zero although the transient values of the gain and the dispersion occur as nonzero values. Even though transient and steady gains can be obtained in both the closed and the open systems when the incoherence pump is present, the transient and the steady values of gain in the closed system are much smaller than those in the open system.

4. Conclusions

In this paper, we analyse the effects of relative phase (Φ) between probe and driving fields on transient evolutions of gain, dispersion and populations, and the effects of modulation role of the exit rate and the ratio between injection rates on phase-dependent LWI gain in the open ladder-type atomic system. The highlights of the present study are summarized as follow. (1) In the open system, no matter whether the incoherence pump is present or absent, variation in value of Φ does not execute any influence on the transient evolution behaviour of populations, but it has considerable effects on LWI gain and dispersion of the probe field. (2) In the open system, when the incoherence pump is absent, the transient evolution behaviours of gain and dispersion are similar to those with the incoherence pump, but the transient and the stationary values of gain and dispersion are much larger than those with the incoherence pump, and the times of gain peak appearing and arriving at a stationary state are later than those with the incoherence pump. (3) In the open system, in the transient evolution process, high dispersion (with high refractive indices) without absorption appears for some values of relative phase for both cases with and without the incoherence pump. (4) In the open system, phase-dependent LWI gain increases with the ratio between injection rates, c (the exit rate r_0), increasing in a certain range of c (r_0). Moreover, the range of c (r_0) in which the LWI gain can be obtained when the incoherence pump is absent is much larger than that when the incoherence pump is present. (5) The transient evolution behaviours of gain and dispersion in the corresponding closed ladder–type system are much different from those in the open system for identical values of Φ. (6) In the closed system, a stationary LWI gain can be obtained only when the incoherent pump is present, moreover the gain is smaller than that in the open system.

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