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Effects of Driving-field Phase Fluctuation on an Open Four-level System*

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Abstract The effects of phase fluctuation on absorption, dispersion and population difference in an open four-level atomic system have been analyzed by using the numerical simulation from the steady analytical solution. It is shown that variation of the linewidth cannot change the property of the inversionless lasing of the system; increasing R_L reduces the magnitude of the gain and requires a larger $\bar{\Omega}$ value for the onset of the gain; when the exit rate is small, effects of the finite linewidth R_L on the gain, dispersion and population difference is very weak; the system can still get a high refractive index without absorption when the linewidth does not equal to zero.

Keywords Open system; Lasing without inversion; Phase fluctuation; Incoherent pumping rate

CLCN O431.2; O432.1+2 **Document Code** A

0 Introduction

Quantum coherence[1~3] and interference have led to a number of important optical consequences such as lasing without inversion (LWI), electromagnetically induced transparency and subrecoil cooling of atoms. In particular, LWI has attracted much more attention (for instance, see Refs[4 ~ 10]) due to its important science sense and potential wide application. However, the phase of the driving field is usually assumed to be fixed in many studies on LWI. In practice, the phase is fluctuant. Recently, Zhu et al[10] presented a theoretical model of an four-level system and the driving field is still assumed as a well-defined fixed phase in its study. In this paper, the effects of the phase are investigated fluctuation on the gain, dispersion and population difference in an open four-level system from different respects.

1 Motion equation and exact steady-state solutions

Consider an open four-level system with the ground state $|1\rangle$ and excited states $|2\rangle$, $|3\rangle$, and $|4\rangle$ as illustrated in Fig. 1. The transition $|1\rangle \leftrightarrow |2\rangle$ of frequency ω_{21} is driven by a strong coherent field of frequency ω_d with Rabi frequency 2Ω. The transition $|1\rangle \leftrightarrow |3\rangle$ of frequency ω_{31} is incoherently pumped with a rate Λ. A weak probe field with Rabi frequency $2g$ is applied to the transition $|1\rangle \leftrightarrow |3\rangle$. $2\gamma_{ij}$ is the spontaneous decay rate from state $|i\rangle$ to state $|j\rangle$. The transition $|2\rangle \leftrightarrow |3\rangle$ and $|4\rangle \leftrightarrow |1\rangle$

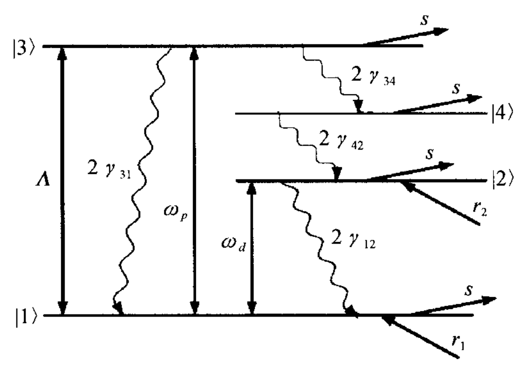

Fig. 1 The open four-level atomic system

are forbidden. If the probe laser is amplified, lasing can be established on the transition $|1\rangle \rightarrow |3\rangle$. In the rotating wave, slowly varying envelope and mean field approximations, the density-matrix motion equations of the system can be derived as follows

$$\dot{\rho}_{11} = -\Lambda\rho_{11} + (\Lambda + 2\gamma_{31})\rho_{33} + 2\gamma_{21}\rho_{22} + i(\Omega\rho_{21} - \Omega^*\rho_{12}) + ig(\rho_{31} - \rho_{13}) - s\rho_{11} + r_1 \quad (1a)$$

$$\dot{\rho}_{22} = -2\gamma_{21}\rho_{22} + 2\gamma_{42}\rho_{44} + i(\Omega^*\rho_{12} - \Omega\rho_{21}) - s\rho_{22} + r_2 \quad (1b)$$

$$\dot{\rho}_{33} = \Lambda\rho_{11} - (\Lambda + 2\gamma_{31} + 2\gamma_{34})\rho_{33} + ig(\rho_{13} - \rho_{31}) - s\rho_{33} \quad (1c)$$

$$\dot{\rho}_{44} = 2\gamma_{34}\rho_{33} - 2\gamma_{42}\rho_{44} - s\rho_{44} \quad (1d)$$

$$\dot{\rho}_{12} = i\Omega(\rho_{22} - \rho_{11}) - (\Lambda/2 + \gamma_{21} + i\Delta_1)\rho_{12} + ig\rho_{32} \quad (1e)$$

$$\dot{\rho}_{13} = ig(\rho_{33} - \rho_{11}) - (\Lambda + \gamma_{31} + \gamma_{34} + i\Delta_2)\rho_{13} + i\Omega\rho_{23} \quad (1f)$$

$$\dot{\rho}_{23} = i\Omega^*\rho_{13} - ig\rho_{21} - [\Lambda/2 + \gamma_{31} + \gamma_{34} + \gamma_{21} + i(\Delta_2 - \Delta_1)]\rho_{23} \quad (1g)$$

along with the equations for the complex conjugates. Here ρ_{ij} is the atomic polarization between states $|i\rangle$ and $|j\rangle$, ρ_{jj} ($j = 1-4$) is the population of the state $|j\rangle$. In Eqs. (1), r_1 (r_2) is the atomic injection rate for level $|1\rangle$ ($|2\rangle$), and s is the atomic exit rate from the cavity. Δ_1 ($= \omega_{21} - \omega_d$) and Δ_2 ($= \omega_{31} - \omega_p$) express the detuning of the driving and probe field

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from their relevant atomic transition, respectively. For convenience of calculation, assumed that g in Eqs. (1) is real. The gain coefficient of the probe field is proportional to $\mathrm{Im}\rho_{13}$. If $\mathrm{Im}\rho_{13} > 0$, the system exhibits gain for the probe field; if $\mathrm{Im}\rho_{13} < 0$, the probe field is attenuated. Furthermore, the dispersion is determined by $\mathrm{Re}\rho_{13}$, $\mathrm{Re}\rho_{13} > 0$ corresponds to the red shift of the frequency of the probe field; $\mathrm{Re}\rho_{13} < 0$ shows the blue shift[11]. The refractive index of medium is proportional to $\mathrm{Re}\rho_{13}$.

Now it is considered that the influence of phase fluctuation of the driving field on the open four-level atomic system. For this we assume that phase fluctuation of the driving field is independent and free. Let $\phi(t)$ represents the phase fluctuation of the driving field, i. e.,

$$\Omega = \Omega_0 \exp\left[\mathrm{i}\phi(t)\right] \tag{2}$$

The phase is characterized by the following random equation of motion[12]

$$\dot{\phi}(t) = u(t) \tag{3}$$

with zero average, i. e., $\langle u(t)\rangle = 0$. Here $u(t)$ is a δ-correlated Langevin-noise term, whose diffusion coefficient gives the linewidth $2R_L$ of the driving field, i. e.,

$$\langle u(t)u(t)'\rangle = 2R_L\delta(t-t') \tag{4}$$

Eqs. (1) are therefore stochastic equations with multiplicative white noise, which gives rise to noise-induced drift terms that alter the semiclassical evolution of the system. In order to clarify the influence of the finite linewidth, we redefine the variables and as follows

$$\rho_{12} = \rho_{12}'\exp\left[\mathrm{i}\phi(t)\right], \rho_{32} = \rho_{32}'\exp\left[\mathrm{i}\phi(t)\right] \tag{5}$$

For the new variables, the corresponding equations of motion read

$$\dot{\rho}_{12}' = i\Omega_0(\rho_{22}-\rho_{11}) - (\Lambda/2+\gamma_{21}+ i\Delta_1)\rho_{12}' - iu(t)\rho_{12}' + ig\rho_{32}' \tag{6a}$$

$$\dot{\rho}_{23}' = i\Omega_0\rho_{13} - ig\rho_{21}' - [\Lambda/2+\gamma_{31}+\gamma_{34}+\gamma_{21}+ i(\Delta_2-\Delta_1)]\rho_{23}' + iu(t)\rho_{23}' \tag{6b}$$

In this case, the density-matrix equations (1a)-(1d), (6a), (1f) and (6b) should be averaged over the randomly fluctuating phase. Dropping both the primes from the quantities ρ_{12}' and ρ_{32}', assuming a small probe field strength, derive the semiclassical set of equations for the stochastic averaged values of the populations $\langle\rho_{jj}\rangle$ (j = 1-4) and the polarization $\langle\rho_{12}\rangle$ correct to the zeroth order of the probe field, and for the averaged values of the polarizations ρ_{13} and ρ_{23} correct to the first order of the probe field

$$\langle\dot{\rho}_{11}\rangle = -(\Lambda+s)\langle\rho_{11}\rangle + (\Lambda+2\gamma_{31})\langle\rho_{33}\rangle + 2\gamma_{21}\langle\rho_{22}\rangle + i\bar{\Omega}(\langle\rho_{21}\rangle - \langle\rho_{12}\rangle) + i\bar{g}(\langle\rho_{31}\rangle - \langle\rho_{13}\rangle) + r_1 \tag{7a}$$

$$\langle\dot{\rho}_{22}\rangle = -(2\gamma_{21}+s)\langle\rho_{22}\rangle + 2\gamma_{42}\langle\rho_{44}\rangle + i\bar{\Omega}(\langle\rho_{12}\rangle - \langle\rho_{21}\rangle) + r_2 \tag{7b}$$

$$\langle\dot{\rho}_{33}\rangle = \Lambda\langle\rho_{11}\rangle - (\Lambda+2\gamma_{31}+2\gamma_{34}+s)\langle\rho_{33}\rangle + i\bar{g}(\langle\rho_{13}\rangle - \langle\rho_{31}\rangle) \tag{7c}$$

$$\langle\dot{\rho}_{44}\rangle = 2\gamma_{34}\langle\rho_{33}\rangle - (2\gamma_{42}+s)\langle\rho_{44}\rangle \tag{7d}$$

$$\langle\dot{\rho}_{12}\rangle = i\bar{\Omega}(\langle\rho_{22}\rangle - \langle\rho_{11}\rangle) - (\Lambda/2+\gamma_{21}+R_L+i\Delta_1)\langle\rho_{12}\rangle \tag{7e}$$

$$\langle\dot{\rho}_{13}\rangle = i\bar{g}(\langle\rho_{33}\rangle - \langle\rho_{11}\rangle) - (\Lambda+\gamma_{31}+\gamma_{34}+i\Delta_2)\langle\rho_{13}\rangle + i\bar{\Omega}\langle\rho_{23}\rangle \tag{7f}$$

$$\langle\dot{\rho}_{23}\rangle = i\bar{\Omega}\langle\rho_{13}\rangle - i\bar{g}\langle\rho_{21}\rangle - [\Lambda/2+\gamma_{31}+\gamma_{34}+ \gamma_{21}+R_L+i(\Delta_2-\Delta_1)]\langle\rho_{23}\rangle \tag{7g}$$

In transforming Eqs. (1) into Eqs. (7), used the relations $i\langle u(t)\rho_{lj}(t)\rangle = R_L\langle\rho_{lj}\rangle$, where the value of lj is 12 or 32. Comparing Eqs. (1) and (7), find that the phase fluctuation in the driving field modifies the off-diagonal decay rates $\Lambda/2+\gamma_{21}$ and $\Lambda/2+\gamma_{31}+\gamma_{32}+\gamma_{21}$ to $\Lambda/2+\gamma_{21}+R_L$ and $\Lambda/2+\gamma_{31}+\gamma_{32}+\gamma_{21}+R_L$, respectively. In other words, because of the phase fluctuation of the driving field, the off-diagonal decay rates now have additional diffusion terms along with the usual rates. For the steady state, always make $r_1+r_2=s$ to keep $\langle\rho_{11}\rangle+\langle\rho_{22}\rangle+\langle\rho_{33}\rangle+\langle\rho_{44}\rangle=1$. Setting all the time derivatives equal to zero for Eqs. (7), obtain the steady state solutions for population differences $P_{21}\equiv\langle\rho_{22}\rangle-\langle\rho_{11}\rangle$ and $P_{31}\equiv\langle\rho_{33}\rangle-\langle\rho_{11}\rangle$, the imaginary and the real parts of polarization $\langle\rho_{13}\rangle$

$$P_{21} = -(\beta_2\beta_9 + r_1\beta_8)/\beta_{10} \tag{8a}$$

$$P_{31} = (\beta_2\beta_3 + r_1\beta_4/\beta_{10} \tag{8b}$$

$$\mathrm{Im}\langle\rho_{13}\rangle = -\bar{g}[\bar{\Omega}^2(\alpha_3\alpha_5-\alpha_4\alpha_6)P_{21}/\alpha_7 - \alpha_3P_{31}]/\alpha_8 \tag{8c}$$

$$\mathrm{Re}\langle\rho_{13}\rangle = \bar{g}[-\bar{\Omega}^2(\alpha_4\alpha_5+\alpha_3\alpha_6)P_{21}/\alpha_7 + \alpha_4P_{31}]/\alpha_8 \tag{8d}$$

Detailed expressions for α_i (i = 1-8) and β_j (j = 1-10) in the Eqs. (8) are as follows

$$\alpha_1 = (\Delta_2-\Delta_1)^2 + k_2^2, \alpha_2 = k_3^2 + \Delta_1^2$$

$$\alpha_3 = k_1 + \bar{\Omega}^2 k_2/\alpha_1, \alpha_4 = \Delta_2 - \bar{\Omega}^2(\Delta_2-\Delta_1)/\alpha_1$$

$$\alpha_5 = k_2k_3 + (\Delta_2-\Delta_1)\Delta_1, \alpha_6 = (\Delta_2-\Delta_1)k_3 - \Delta_1k_2$$

$$\alpha_7 = \alpha_1\alpha_2, \alpha_8 = \alpha_3^2 + \alpha_4^2$$

$$\beta_1 = 2\gamma_{42}+s, \beta_2 = 2\gamma_{42}+r_2$$

$$\beta_3 = 2\bar{\Omega}^2k_3/\alpha_2 + 2\gamma_{21}, \beta_4 = \beta_1+\beta_3$$

$$\beta_5 = k_4/(\Lambda-k_4), \beta_6 = 6\gamma_{42}+2\gamma_{21}+s$$

$$\beta_7 = 2\gamma_{31}+2\gamma_{21}-s, \beta_8 = 2\gamma_{42}+\beta_5\beta_6$$

$$\beta_9 = k_5+\beta_5\beta_7, \beta_{10} = \beta_3\beta_8 - \beta_4\beta_9$$

Here $k_1 = \Lambda+\gamma_{31}+\gamma_{34}$, $k_2 = \Lambda/2+\gamma_{31}+\gamma_{34}+\gamma_{21}+R_L$, $k_3 = \Lambda/2+\gamma_{21}+R_L$, $k_4 = \Lambda+2\gamma_{31}+2\gamma_{34}+s$, $k_5 = \Lambda+2\gamma_{31}$.

For $\Delta_1 \backslash \Delta_2 = 0$, Re$\langle\rho_{13}\rangle$ is always equal to zero that is getten the verification from Eq. (8d). In the limit of $\bar{\Omega} \gg s$, r_1, r_2, Λ, R_L, γ_{ij} $(i, j = 1\text{-}4)$ and $\bar{g}$, the steady state solution of Im$\langle\rho_{13}\rangle$ is

$$\mathrm{Im}\langle\rho_{13}\rangle = \bar{g}\frac{\Lambda(\beta_1 k_6 + 2\gamma_{34} r_1) - k_7(k_7 + 2R_L)\beta_1}{\bar{\Omega}^2[(4k_4 + \Lambda)\beta_1 + 2\Lambda(\gamma_{34} + \gamma_{42})]} \quad (9)$$

Here $k_6 = 2\gamma_{21} - 2\gamma_{31} - 4\gamma_{34} - 3\gamma_2$, $k_7 = 2\gamma_{31} + 2\gamma_{34} + s$.

The weak probe laser is amplified if the incoherent pumping rate Λ between states $|3\rangle$ and $|3\rangle$ satisfies

$$\Lambda > k_7(k_7 + 2R_L)\beta_1/(\beta_1/k_6 + 2\gamma_{34} r_1) \quad (10)$$

and

$$\gamma_{21} > \gamma_{31} + 2\gamma_{34} + 1.5r_2 - r_1\gamma_{34}/\beta_1 \quad (11)$$

The steady state population difference between states $|3\rangle$ and $|1\rangle$ ($|2\rangle$) is

$$P_{31} = P_{21} = \frac{(k_4 - \Lambda)(s + 2\gamma_{42})}{(2k_4 + \Lambda)(s + 2\gamma_{42}) + 4\gamma_{34}\Lambda} < 0 \quad (12)$$

Thus population inversion cannot happen in any atomic state basis for the resonant excitations. If the inequalities (10) and (11) are satisfied, Im$\langle\rho_{13}\rangle > 0$, the model system exhibits gain without population inversion in any states basis. It is obvious that the inequalities (10) and (11) can be satisfied by real atomic systems.

In the following section, it will investigate the effects of finite linewidth on the gain, dispersion and population difference from different respects by using the numerical calculation results from Eqs. (8).

2 Discussions and results

Values of parameters are $\Lambda = 8$, $\bar{\Omega} = 17$, $\gamma_{21} = 6$, $\gamma_{34} = 0.25$, $\gamma_{31} = 1$, $\gamma_{42} = 5$, $s = 0$, $c = r_1/r_2 = 4$, $\Delta_1 = 1$, $\Delta_2 = 4$ in Fig. 2 (All parameter values are normalized to γ_{31} in the paper). Fig. 2 reveals that: 1) with the linewith increasing, the gain, dispersion and population difference P_{31} decrease monotonously. P_{31} is always negative, i. e., population inversion cannot arise, and this means that variation of the linewidth cannot change

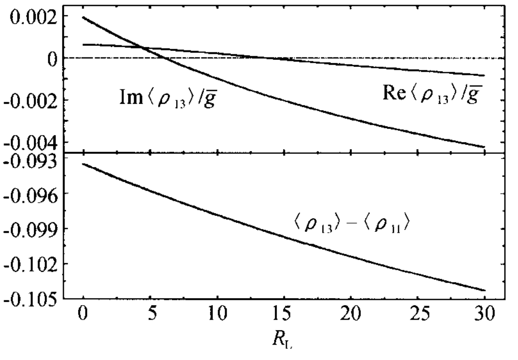

Fig. 2 Im$\langle\rho_{13}\rangle/\bar{g}$, Re$\langle\rho_{13}\rangle/\bar{g}$, and P_{31} vs R_L

the properties of the inversionless lasing of the system, nevertheless a closed four-level atomic system[13] where only a single driving laser is required can induce a change from a noninversion laser ($P_{31} < 0$ and Im$\langle\rho_{13}\rangle/\bar{g} > 0$) to a conventional laser ($P_{31} > 0$ and Im$\langle\rho_{13}\rangle/\bar{g} > 0$). 2) Im$\langle\rho_{13}\rangle/\bar{g}$ changes from positive to negative as R_L increases, this means that the probe field changes from gain to absorption. 3) Re$\langle\rho_{13}\rangle/\bar{g}$ also changes from positive to negative as R_L increases, this represents that the frequency of the probe field changes from blue shift to red shift. However, the frequency of the amplified probe field only appears the red shift, because Re$\langle\rho_{13}\rangle/\bar{g}$ is always positive when the probe field exhibits gain without population inversion. Comparing the open four-level atomic system with the open three-level model[14], the frequency of the amplified probe field in the open three-level model changes from blue shift to red shift.

It is considered the four-level system is open. Comparing with the closed system, the presence of the injection and exit rates in the open system will obviously affect the quantum coherence and interference (QCI) those in atomic system lead to LWI. Shown in Fig. 3 and Fig. 4 is the calculated atomic polarization $\langle\rho_{13}\rangle$ and the population difference P31 plotted versus the exit rate and the ratio of atomic injection rate, respectively, with the same parameters values as those in Fig. 2. Fig. 3 shows that: 1) with s increasing, the dispersive response Re$\langle\rho_{13}\rangle$ increases monotonically, but the gain and population difference P_{31} decreases monotonically. The population difference is always negative and the gain appears only at small s. Concerning the gain, the conclusion is much different from the one on the open three-level atomic system[14]. 2) With R_L increasing, the gain, dispersion and population difference decrease, and these are the same as the conclusions obtained from Fig. 2. However, effects of the finite linewidth R_L on the gain, dispersion and population difference is very weak when the exit rate is small. It is seen in Fig. 4 that: 1) With c increasing, the gain and dispersion increase monotonically at small c and reach the saturation values at moderate c, respectively, but the population difference decreases monotonically at small c because the atomic injection rate for the level $|1\rangle$ increases. 2) With R_L increasing, effects of R_L on the gain, dispersion and population difference whose versus c

are plotted are in agreement with the results obtained from Fig. 2.

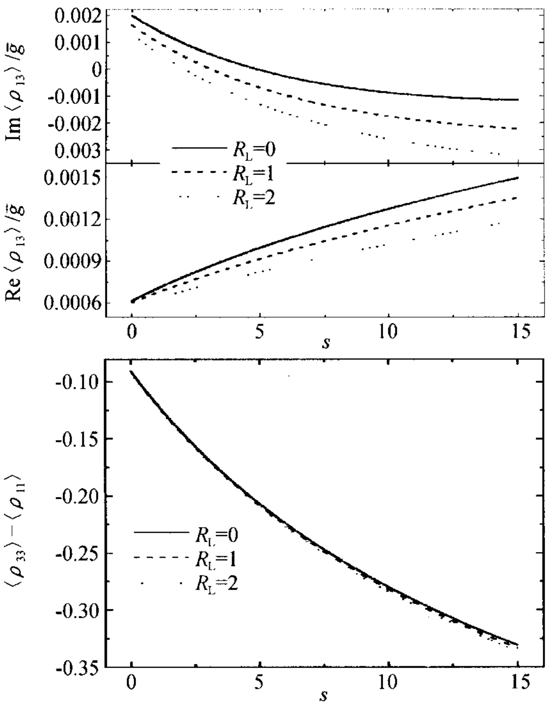

Fig. 3 $\mathrm{Im}\langle\rho_{13}\rangle/\bar{g}$, $\mathrm{Re}\langle\rho_{13}\rangle/\bar{g}$, and P_{31} vs s

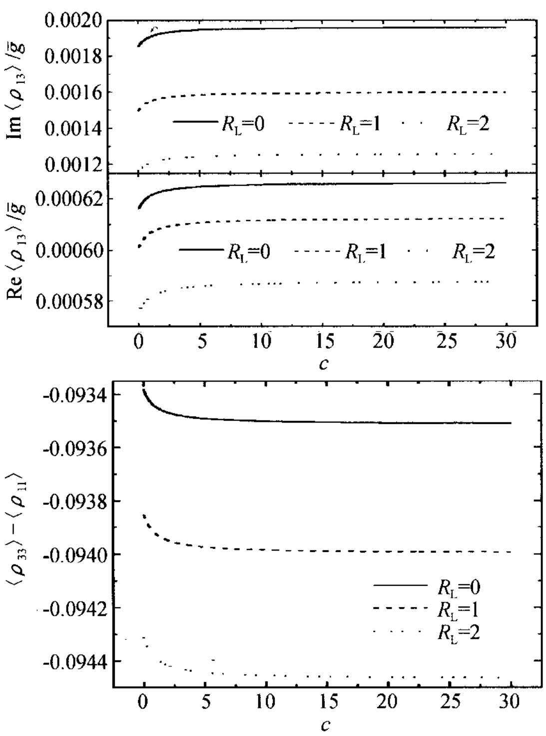

Fig. 4 $\mathrm{Im}\langle\rho_{13}\rangle/\bar{g}$, $\mathrm{Re}\langle\rho_{13}\rangle/\bar{g}$, and P_{31} vs c

For the sake of the further research influence of the finite linewidth R_L on the gain, dispersion and population difference, present numerical calculations about the dependence of the gain, dispersion and population difference on the strengths of coherent pumping as shown in Fig. 5 with the same parameters values as those in Fig. 2. Fig. 5 reveals that: 1) The gain is maximized at a moderate $\bar{\Omega}$ value ($10<\bar{\Omega}<20$). For large $\bar{\Omega}$, the gain approaches the value given by Eq. (9). That the maximum gain occurs at an intermediate can be understood as follows: for small $\bar{\Omega}$, the induced coherence $\langle\rho_{23}\rangle$ is weak, which leads to a small $\mathrm{Im}\langle\rho_{13}\rangle$ value from Eq. (7f) for the steady state; for very large $\bar{\Omega}$, the dynamic atomic response is dominated by the fast Rabi cycling between levels $|1\rangle$ and $|2\rangle$, the probability for the occurrence of the transition $|1\rangle\rightarrow|3\rangle$ is therefore reduced. The frequency of the amplified probe field only appears the red shift, because $\mathrm{Re}\langle\rho_{13}\rangle/\bar{g}$ is always positive when the probe field exhibits gain without population inversion. 2) With R_L increasing, the gain, dispersion and population difference decrease correspondingly, and these are in agreement with the results obtained from Fig. 2. The influence of R_L upon the gain at the moderate $\bar{\Omega}$ is more obvious. Increasing R_L reduces the magnitude of the gain and requires a larger $\bar{\Omega}$ value for the onset of the gain.

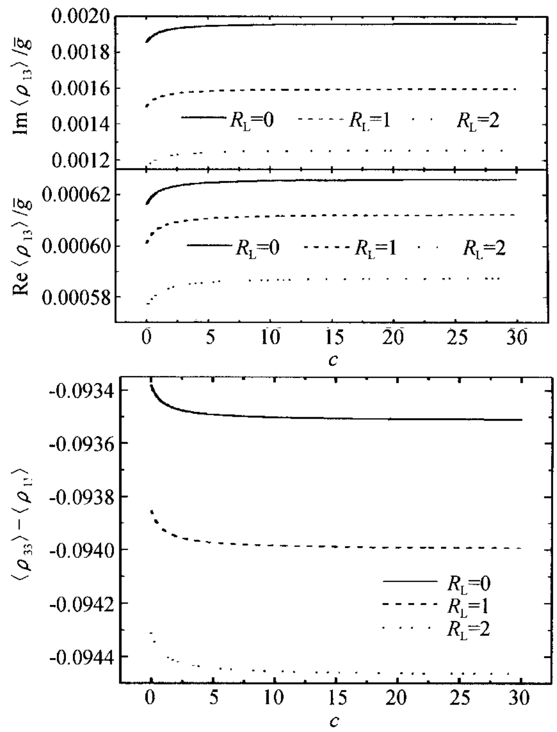

Fig. 5 $\mathrm{Im}\langle\rho_{13}\rangle/\bar{g}$, $\mathrm{Re}\langle\rho_{13}\rangle/\bar{g}$, and P_{31} vs $\bar{\Omega}$

The effects of R_L on the gain, dispersion and population difference have also been analyzed by using the numerical simulation when $\langle\rho_{13}\rangle$ and P_{31} versus function of Λ. The analysis shows that: increasing R_L reduces the gain and requires a larger Λ value to reach the gain threshold. The influence of R_L on the gain, dispersion and population difference accords with the conclusions obtained from Fig. 2.

Fig . 6 illustrates curves of Im $\langle \rho_{13} \rangle / \bar{g}$ and $\mathrm{Re}\langle \rho_{13} \rangle / \bar{g}$ versus the probe field detuning Δ_2 with the same parameters values as those in Fig. 2 except for $\Delta_1 = 0$. The variation of Δ_2 has no effect on P_{31} because the population difference has nothing to do with the detuning Δ_2 from Eq. (8b). The gain decreases with R_L increasing. If the linewidth is increased, the enhancement of refractive index is much less than for zero linewidth. When R_L is larger, such as $R_L = 2$, the system can still get a high dispersion (refractive index) without absorption. The result is much different from the one given by Gong et al[15] for a closed V-type, three-level system, that it, due to the finite linewidth produced by the phase diffusion of the driving field, the system cannot generate a large refractive index along with zero absorption when $R_L = 1$. For a sufficiently large R_L, the gain disappears, as shown by the curve for $R_L = 6.5$. At the moment, the open four-level system cannot generate a large refractive index along with zero absorption, yet.

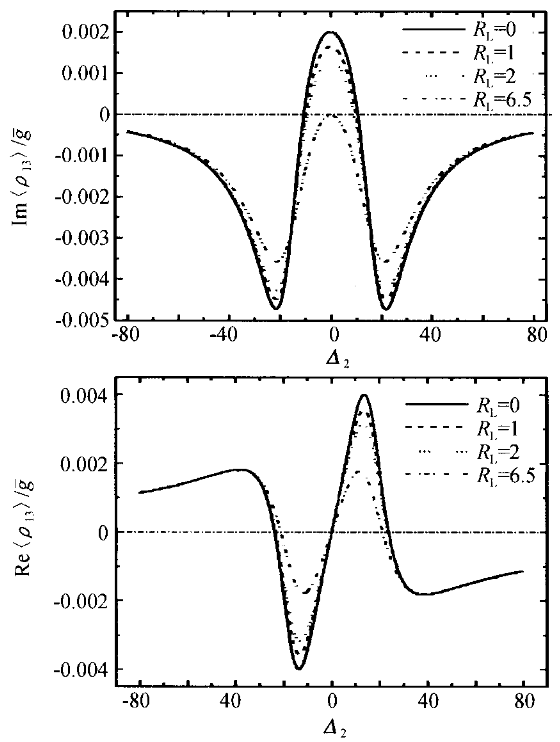

Fig. 6 $\mathrm{Im}\langle \rho_{13} \rangle / \bar{g}$ and $\mathrm{Re}\langle \rho_{13} \rangle / \bar{g}$, vs Δ_2

3 Conclusions

In the paper, it investigated for an open four level LWI system the steady-state behavior due to the effects of phase fluctuation. It is found that: 1) The finite linewidth appears due to the phase-fluctuation of driving field. With R_L increasing, the gain and population difference decrease, and P_{31} is always negative; 2) variation of the linewidth cannot change the property of the inversionless lasing of the system and this is much different from that obtained in a closed four-level atomic system[13]; 3) When the exit rate is small, effects of the finite linewidth R_L on the gain, dispersion and population difference is very weak; 4) Increasing R_L reduces the magnitude of the gain and requires a larger $\bar{\Omega}$ value for the onset of the gain; 5) When R_L is larger, such as $R_L = 2$, the system can still get a high refractive index without absorption. The system just cannot generate a large refractive index along zero absorption for a sufficiently large R_L, such as $R_L = 6.5$. The result is different from that obtained from a closed V-type, three-level atomic system[15].

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驱动场相位涨落对开放四能级系统的影响

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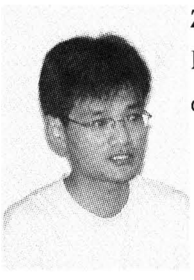
摘　要　考虑驱动场相位存在涨落,给出了开放四能级系统的稳态解析解,通过它分析了该系统由于驱动场相位涨落引起的有限线宽对增益、色散和粒子数差的影响.分析显示:线宽的变化不能改变无反转激光系统的特性;线宽的增大必须提高抽运阈值;相对来说退出速率很小时,线宽对增益、色散和粒子数差的影响较弱;当线宽不为零时该系统仍能获得无吸收高色散.

关键词　无反转激光;开放系统;相位涨落;非相干抽运速率



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