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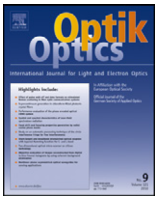

Transient properties in a resonant ladder-type atomic system with vacuum-induced coherence and incoherent pumping

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ABSTRACT

The transient absorption and population in a resonant ladder-type atomic system with or without an incoherent pumping field are theoretically investigated. We find that the vacuum-induced coherence and the relative phase between probe and coupling fields can clearly affect the transient absorption (gain) properties, but the steady-state value of the probe absorption (gain) is remarkably dependent on the incoherent pumping. And the steady population distribution is sensitive to the incoherent pumping and insensitive to the relative phase. Additionally, it is shown that the lasing with inversion can be reached with the incoherent pumping.

1. Introduction

The interference induced by a strong resonant coupling field makes an opaque atomic system transparent for a probe field. This phenomenon, which is termed as electromagnetically induced transparency (EIT), has been studied in all kinds of three-level atomic systems with ∧,∨ and ladder configurations [1,2]. Another way of generating quantum interference connects with relaxation processes such as spontaneous emission, i.e., vacuum-induced coherence (VIC), which is also known as spontaneously generated coherence (SGC). It is created by the interference of spontaneous emission of either a single excited level to two closely lying atomic levels (∧-type system) [3–5], or by two closely lying atomic levels to a single ground level (∨-type system) [6–8] with the same vacuum radiation field. In a ladder-type system [9–11], it can also be created in a nearly equispaced atomic levels case. A theoretical study was made of the steady-state intensity and squeezing properties of the fluorescent light from a three-level ladder system, which was subject to spontaneous emission decay to the electromagnetic-field vacuum [10]. And the quantum interference in two-photon excitation of a three-level ladder system interacting with squeezed vacuum was considered [12]. Ma et al. found that the population inversion can be enhanced on one of the optical transitions due to the VIC effect [13]. Fan et al. shown that lasing without inversion can be realized in an open ladder system without incoherent pumping [14]. Recently, Kumar and Singh presented a general theory of EIT in inhomogeneously broadened ladder system in which Doppler broadening of both one- and two-photon transitions can occur [15]. On the other hand, experimental investigations have been reported through EIT features in a three-level ladder system [16–20]. Besides, many theoretical and experimental works have focused on the transient research in order to understand the dynamical process [21–32], which is important due to its novel application in the optical switch. For example, Xu et al. discussed the effect of VIC on the transient process in a three-level ∧-type system [25]. With the nonresonant probe field, Xiao and Kim mainly compared the transient response between open and closed systems [29]. The dynamical behaviors of the dispersion and absorption in a three-level ∧-type system were investigated [31]. In the previous works, our group studied the effects of VIC on the stationary-state response in a multilevel atomic system [33–36]. In this paper, we investigate the transient absorption and population in a resonant ladder-type atomic system with VIC and incoherent pumping. It is well displayed that due to the effects of VIC and incoherent pumping, there

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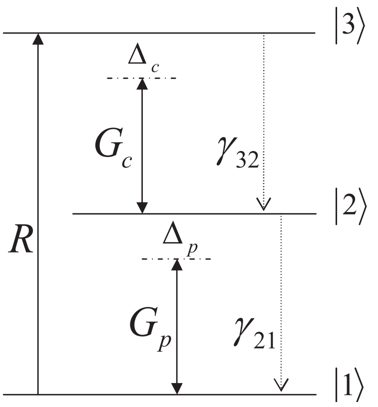

Fig. 1. The energy scheme of the three-level ladder-type atomic system.

appear some interesting transient properties in the ladder-type system.

2. Model and equations

A three-level ladder-type system is shown in Fig. 1, which has been experimentally studied [18] by the ^{87}Rb atom with $5S_{1/2}$, $5P_{3/2}$ and $4D_{5/2}$ behaving as the $|1\rangle$, $|2\rangle$ and $|3\rangle$ state labels, respectively. A weak probe field with frequency ω_p and Rabi frequency $G_p = \vec{\mu}_{12} \cdot \vec{\varepsilon}_p/\hbar$ is applied on the transition $|1\rangle \leftrightarrow |2\rangle$, and a strong coherent coupling field with frequency ω_c and Rabi frequency $G_c = \vec{\mu}_{23} \cdot \vec{\varepsilon}_c/\hbar$ drives the transition $|2\rangle \leftrightarrow |3\rangle$. An incoherent pumping field with rate $2R$ interacts with the transition $|1\rangle \leftrightarrow |3\rangle$. γ_{21} and γ_{32} are the spontaneous decay rates from the level |2> to the level |1> and from the level |3> to the level |2>, respectively.

In the interaction picture the density–matrix equations of motion in the dipole and rotating-wave approximations can be written as

$$\dot{\rho}_{11} = -2R\rho_{11} + 2\gamma_{21}\rho_{22} + iG_p(\rho_{21} - \rho_{12}) \tag{1}$$

$$\dot{\rho}_{33} = 2R\rho_{11} - 2\gamma_{32}\rho_{33} + iG_c(\rho_{23} - \rho_{32}) \tag{2}$$

$$\begin{aligned}\dot{\rho}_{12} = &-(R + \gamma_{21} + i\Delta_p)\rho_{12} + iG_p(\rho_{22} - \rho_{11}) - iG_c\rho_{13} \\ &+2\sqrt{\gamma_{32}\gamma_{21}} \cdot \eta \exp(i\Phi) \cdot \cos\theta \cdot \rho_{23}\end{aligned} \tag{3}$$

$$\dot{\rho}_{23} = -(\gamma_{32} + \gamma_{21} + i\Delta_c)\rho_{23} + iG_c(\rho_{33} - \rho_{22}) + iG_p\rho_{13} \tag{4}$$

$$\dot{\rho}_{13} = -[R + \gamma_{32} + i(\Delta_p + \Delta_c)]\rho_{13} - iG_c\rho_{12} + iG_p\rho_{23} \tag{5}$$

The above density–matrix elements additionally obey the normalization and Hermitian condition $\sum_{i=1}^{3}\rho_{ii} = 1$ and $\rho_{ij} = \rho_{ji}^*$. The detunings of the probe and coupling lasers are defined as $\Delta_p = \omega_{21} - \omega_p$ and $\Delta_c = \omega_{32} - \omega_c$, respectively. In the case of nearly equispaced levels, an additional term $2\sqrt{\gamma_{32}\gamma_{21}} \cdot \eta \exp(i\Phi) \cdot \cos\theta \cdot \rho_{23}$ of the optical Bloch equations represents the effect of VIC. Where $\Phi = \varphi_p - \varphi_c$ is the phase difference between the probe and the coupling fields, and θ is the angle between the two induced dipole moments $\vec{\mu}_{12}$ and $\vec{\mu}_{23}$. It is obviously that when $\eta = 1$, the VIC effect is included and its strength will vary with the value of θ; otherwise $\eta = 0$, the VIC effect is not included. As is well known, in the limit of a weak probe, the gain-absorption coefficient for the probe laser on transition $|1\rangle \leftrightarrow |2\rangle$ is proportional to the imaginary part of ρ_{12}, which can be obtained from Eqs. (1) to (5). In our notation, the system exhibits gain for the probe laser if $\mathrm{Im}(\rho_{12}) > 0$. Considering the case of two resonant transitions ($\Delta_p = \Delta_c = 0$), with the initial conditions $\rho_{11}(0) = \rho_{22}(0) = 0.5$ and other $\rho_{ij}(0) = 0(i,j = 1,2,3)$, the following discussions will be deployed based on the time-dependent numerical solutions of Eqs. (1)–(5).

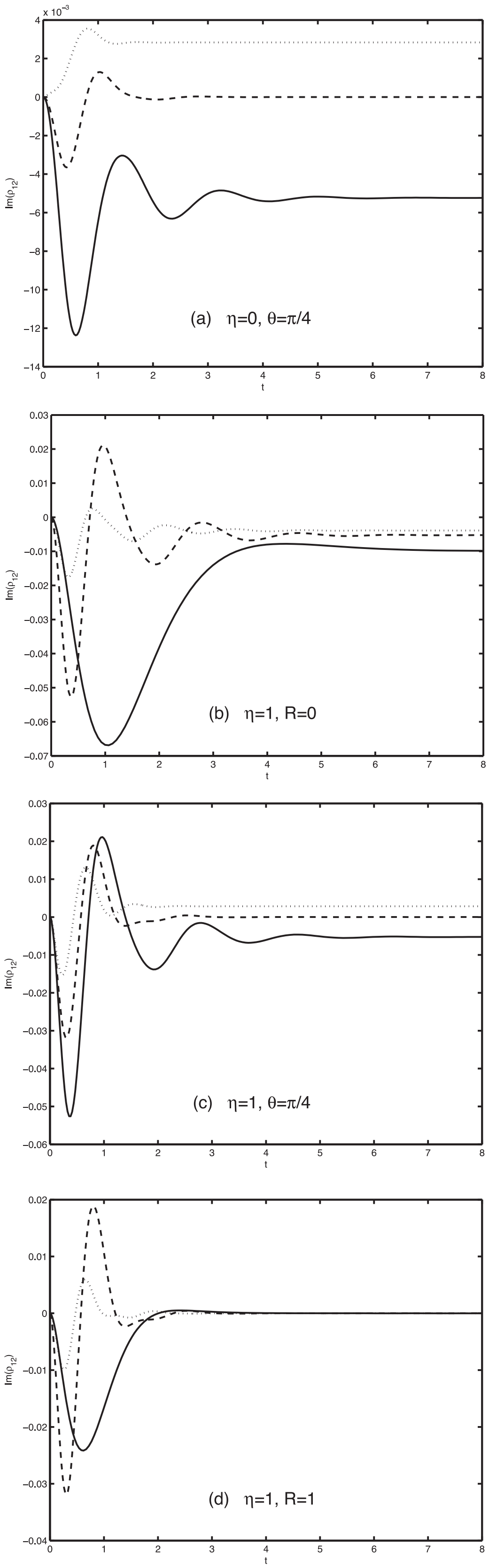

Fig. 2. Time evolution of the absorption coefficient $\mathrm{Im}(\rho_{12})$, where parameter values are $\gamma_{21} = 1$, $\gamma_{32} = 1$, $G_p = 0.1\sin\theta$, $G_c = 5\sin\theta$, $\Delta_p = 0$, $\Delta_c = 0$, $\Phi = 0$. (a) and (c) $R = 0$ (solid curve), $R = 1$ (dashed curve), $R = 3$ (dotted curve); (b) and (d) $\theta = \pi/20$ (solid curve), $\theta = \pi/4$ (dashed curve), $\theta = 9\pi/20$ (dotted curve).