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Effects of spontaneously induced coherence on absorption of a ladder-type atom*

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This paper investigates the effects of spontaneously induced coherence on absorption properties in a nearly equispaced three-level ladder-type system driven by two coherent fields. It find that the absorption properties of this system with the probe field applied on the lower transition can be significantly modified if this coherence is optimized. In the case of small spontaneous decay rate in the upper excited state, it finds that such coherence does not destroy the electromagnetically induced transparency (EIT). Nevertheless, the absorption peak on both sides of zero detuning and the linewidth of absorption line become larger and narrower than those in the case corresponding to the effects of spontaneously induced coherence; while in the case of large decay rate, it finds that, instead of EIT with low resonant absorption, a sharp absorption peak at resonance appears. That is, electromagnetically induced absorption in the nearly equispaced ladder-type system can occur due to such coherent effects.

Keywords: spontaneously induced coherence, a ladder-type atom, absorption
PACC: 4250

1. Introduction

Recently, there has been much interest in the study of the effects of spontaneously induced coherence. This kind of coherence is created by the interference of spontaneous emission of either a single excited level to two closed lying atomic levels (Λ-type atom),[1] or two close lying atomic levels to a common atomic level (V-type atom).[2] In a ladder-type system, it can be also created in the nearly equispaced atomic levels case.[3,4] In 1996, Xia *et al*[5] carried out the first experimental investigation of constructive and destructive interference effects in spontaneous emission. They observed that the fluorescence spectrum exhibited two-peak or three-peak features according to parallel or anti-parallel dipole moments. The observed variation of the number of peaks with the mutual polarization of the dipole moments gave compelling evidence for coherence in spontaneous emission. However, in a later paper it was reported that a repeat of the experiment had failed to observe the same features.[6] Wang *et al*[7] gave a theoretical investigation of this experiment and showed that the numbers of peaks depend on the excitation process. Nevertheless this experiment showed some interesting effects induced by spontaneous emission-induced coherence. The effects of spontaneously induced coherence on absorption or spontaneous emission spectra have been extensively investigated recently.[8−14] Menon and Agarwal have investigated the effects of spontaneously induced coherence on a Λ-type system with near-degenerate lower levels and found that such coherence preserves both electromagnetically induced transparency (EIT)[15,16] and coherent population trapping (CPT)[17] phenomena. However, it changes the time scales associated with the formation of the CPT state, and brings about quantitative changes in the line profiles of absorption and dispersion. Paspalakis *et al*[13] have studied the effects of spontaneously induced coherence in a closed V-type system. They found that absorption and dispersion of the atom can be significantly modified if this coherence is optimized and lasing with or without inversion, EIT, and enhancement of the index of refraction are all dependent on this coherence. In a ladder-type system, Ficek, Dalton and Knight[4] discussed the effects of spontaneously induced coherence on the steady-state intensity and squeezing properties of the fluorescent

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light. They found the unusual three-level squeezing properties near two-photon resonance. Recently, we investigated the effects of spontaneously induced coherence on the population inversion in a nearly equispaced three-level ladder-type system and found that not only the population inversion on one of the optical transitions can be greatly enhanced, but also the unexpected inversion on both of the optical transitions can occur due to the coherent effects.[18]

It is well known that when the probe absorption spectrum is characterized by a sharp dip at resonance, the phenomenon is called electromagnetically induced transparency (EIT). However, when the absorption spectrum is characterized by a sharp peak at resonance, the effect is then called electromagnetically induced absorption (EIA). Generally, EIA cannot be generated in conventional three-level atomic system. The authors of Refs.[19] and [20] proposed a simple theoretical model for EIA, which is a four-state N-figuration system (Λ-type plus an auxiliary level transition driven by a control field). They found that EIA can occur due to the effects of the coherent control field. In this paper, we investigate the effects of spontaneously induced coherence on absorption properties in a nearly equispaced ladder-type system driven by two coherent fields. We find that the absorption properties of this system can be significantly modified if this coherence is optimized. In the case of small spontaneous decay rate in the upper excited state, we find that such coherence does not destroy the EIT at resonance. However, the absorption peak on both sides of zero detuning and the linewidth of absorption line become larger and narrower than those in the case corresponding to the effects of spontaneously induced coherence. While in the case of large decay rate, we find that, instead of EIT with low resonant absorption, a sharp absorption peak at resonance appears. That is, EIA in the nearly equispaced ladder-type system can occur due to such coherent effects.

2. Model description and equations

We consider a three-level ladder-type system with nearly equispaced levels, as shown in Fig.1. A coupling field of frequency $\omega_{\rm b}$ with a real Rabi frequency Ω_2 ($=\boldsymbol{\mu}_{23}\cdot\boldsymbol{\varepsilon}_{\rm b}$) drives transition $|3\rangle \leftrightarrow |2\rangle$, a probe field of frequency $\omega_{\rm a}$ with a real Rabi frequency $\Omega_1 = (\boldsymbol{\mu}_{12}\cdot\boldsymbol{\varepsilon}_{\rm a})$ is applied to the transition $|2\rangle \leftrightarrow |1\rangle$. The excited state $|2\rangle$ ($|3\rangle$) exhibits spontaneous decay to the state $|1\rangle$ ($|2\rangle$) at the rate $\gamma_1(\gamma_2)$.

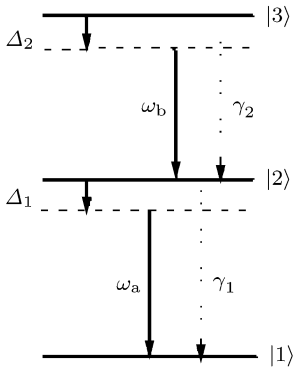


Fig.1. Three-level ladder-type atom interacting with the two coherent fields $\omega_{\rm a}$ (the probe laser field) and $\omega_{\rm b}$ (the coupling laser field). γ_1 and γ_2 are the decay rates, and Δ_1 and Δ_2 are the coherent field frequency detuning.

In such a case, the density-matrix equations in a rotating frame can be written as

$$\dot{\rho}_{33} = -2\gamma_2\rho_{33} - \mathrm{i}\Omega_2\rho_{32} + \mathrm{i}\Omega_2\rho_{23}, \tag{1}$$

$$\dot{\rho}_{22} = 2\gamma_2\rho_{33} - 2\gamma_1\rho_{22} - \mathrm{i}\Omega_1\rho_{21} + \mathrm{i}\Omega_1\rho_{12} + \mathrm{i}\Omega_2\rho_{32} - \mathrm{i}\Omega_2\rho_{23}, \tag{2}$$

$$\dot{\rho}_{11} = 2\gamma_1\rho_{22} + \mathrm{i}\Omega_1\rho_{21} - \mathrm{i}\Omega_1\rho_{12}, \tag{3}$$

$$\dot{\rho}_{32} = (\mathrm{i}\Delta_2 - \gamma_1 - \gamma_2)\rho_{32} - \mathrm{i}\Omega_2(\rho_{33} - \rho_{22}) - \mathrm{i}\Omega_1\rho_{31}, \tag{4}$$

$$\dot{\rho}_{21} = (\mathrm{i}\Delta_1 - \gamma_1)\rho_{21} + \mathrm{i}\Omega_2\rho_{31} - \mathrm{i}\Omega_1(\rho_{22} - \rho_{11}) + 2p\sqrt{\gamma_1\gamma_2}\rho_{32}, \tag{5}$$

$$\dot{\rho}_{31} = (\mathrm{i}\Delta_1 + \mathrm{i}\Delta_2 - \gamma_2)\rho_{31} + \mathrm{i}\Omega_2\rho_{21} - \mathrm{i}\Omega_1\rho_{32}, \tag{6}$$

constrained by

$$\rho_{11} + \rho_{22} + \rho_{33} = 1\,, \tag{7}$$

and

$$\rho_{mn} = \rho^*_{nm}\,. \tag{8}$$

Here Δ_1 ($=\omega_{21}-\omega_{\rm a}$) and Δ_2 ($=\omega_{32}-\omega_{\rm b}$) are the coherent field frequency detuning. The term $p\sqrt{\gamma_1\gamma_2}$ represents the effects of spontaneously induced coherence resulting from the cross coupling between the transitions $|3\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |1\rangle$. We should note that only for nearly equispaced levels, the effects of spontaneously induced coherence are important. As for non-equispaced levels, the rapid oscillations in ρ_{21} will average out any such effects.[3,4,11] The parameter p

denotes the alignment of the two matrix elements and is defined as $p = \boldsymbol{\mu}_{12} \cdot \boldsymbol{\mu}_{23} / |\boldsymbol{\mu}_{12} \cdot \boldsymbol{\mu}_{23}| = \cos\theta$, where θ is the angle between the two induced dipole moments $\boldsymbol{\mu}_{12}$ and $\boldsymbol{\mu}_{23}$. The parameter p plays a very important role in the creation of coherence as we will show later. If we consider linearly polarized electric fields with the restriction that $\boldsymbol{\mu}_{12} \cdot \boldsymbol{\varepsilon}_{\rm b} = 0$ and $\boldsymbol{\mu}_{23} \cdot \boldsymbol{\varepsilon}_{\rm a} = 0$, we can show that the Rabi frequencies are connected to the p parameter by the relation $\Omega_1 = \Omega_{10}\sqrt{1-p^2} = \Omega_{10}\sin\theta$ and $\Omega_2 = \Omega_{20}\sqrt{1-p^2} = \Omega_{20}\sin\theta$ with $\Omega_{20} = |\boldsymbol{\mu}_{23}|\,|\boldsymbol{\varepsilon}_{\rm b}|$ and $\Omega_{10} = |\boldsymbol{\mu}_{12}|\,|\boldsymbol{\varepsilon}_{\rm a}|$. It is obvious that if the two matrix elements μ_{12} and μ_{23} are orthogonal, then p=0 and no interference from spontaneous decay occurs. The steady-state solutions can then be found by setting the time derivatives to zero and reducing Eqs.(1)–(6) to a set of coupled 9×9 algebraic equations after splitting into real and imaginary parts. In numerical calculations, we will use computation package Maple and choose the parameters to be dimensionless (Ω/γ and γ=1, etc.).

3. Results

In the conventional ladder-type system (i.e., there is no term of spontaneously induced coherence) with the probe field applied on the lower transition, the introduction of spontaneous decay in the upper excited state can lead to crucial difference of the depth of EIT window.[21] For smaller spontaneous decay rate, a good EIT is present; while for large decay rate, only a poor EIT along with a low absorption exists. In the following, we will investigate the effects of spontaneously induced coherence on the EIT for these two cases and will show that the absorption properties of this system can be substantially modified if the coherence is optimized.

In Fig.2 for small spontaneous decay rate in the upper excited state, we present the absorption line (Fig.2(a)) and the dispersion line (Fig.2(b)) as a function of the probe field frequency detuning Δ_1 under different values of the parameter p, respectively. In this case, we choose the parameters $\Delta_2 = 0$,$\gamma_1 = \gamma$, $\gamma_2 = 0.02\gamma$, $\Omega_{10} = 2.5\gamma$, $\Omega_{20} = 5\gamma$. In Fig.2(a), the absorption spectra exhibit two absorption components, known as the Autler–Townes components[22] and this Autler–Townes absorption doublet can be related to the dressed states. Figure 2(a) shows that the absorption at resonance is nearly zero regardless of the parameter p. That is, such coherence does not destroy the EIT phenomena. However, the absorption line on both sides of zero detuning is substantially modified as the coherence is optimized. For example, in the case of p=0.99 as shown in Fig.2(a), the absorption peak is two times larger than that of p=0. At the same time, the linewidth of absorption line becomes very narrower than that in the previous case. In Fig.2(b), it can be seen, near the probe resonant frequency, that the dispersion becomes much steeper as the parameter p increases. The combination of low resonant absorption and much steeper positive dispersion can lead to a dramatic slowing down of the group velocity of light and consequently large time delay.[23]

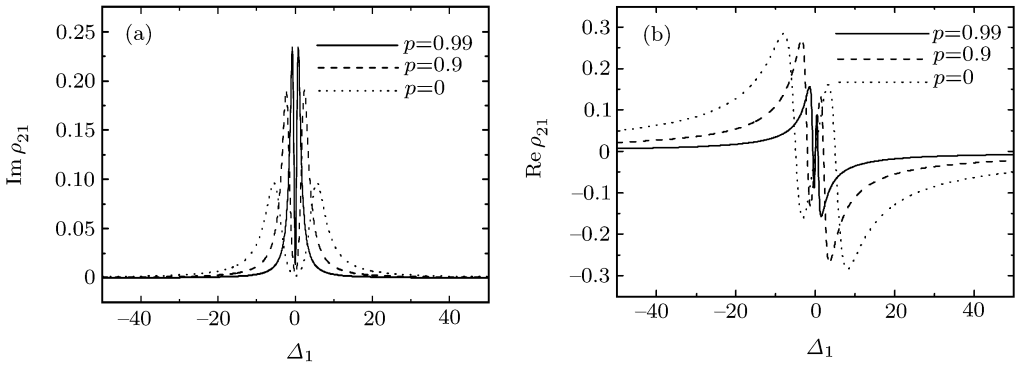


Fig.2. Plots for absorption Imρ_{21} (a) and dispersion Reρ_{21} (b) for the probe field as a function of the probe frequency detuning Δ_1 for different parameter p. Solid line, dashed line, dotted line correspond to p=0.99, 0.9, 0.0 respectively. The parameters are $\Delta_2 = 0$,$\gamma_1 = \gamma$, $\gamma_2 = 0.02\gamma$, $\Omega_{10} = 2.5\gamma$, $\Omega_{20} = 5\gamma$.

In Fig.3, we show the effects of spontaneously induced coherence on absorption as a function of the probe field detuning Δ_1 for different parameter p for large decay rate. In this case, the parameters are $\Delta_2 = 0$, $\gamma_1 = \gamma$, $\gamma_2 = \gamma$, $\Omega_{10} = 2.5\gamma$, $\Omega_{20} = 5\gamma$. It can be seen that the absorption is low in the absence of

spontaneously induced coherence (p=0) and the system approaches to transparency, although the EIT is poor, which is similar to Ref.[21]. However, after taking the coherent effects into account, the response of the system to the probe field can be completely altered if the coherence is optimized. For p=0.99 as shown by solid curves in Fig.3, a sharp absorption peak at resonance appears, which is of sub-natural width as discussed by our other partners. So, EIA can occur due to the effects of spontaneously induced coherence. The authors of Refs.[18] and [19] found that the appearance of EIA is the consequence of coherent transfer from the excited levels to the lower ones via spontaneous emission, while here in the nearly equispaced three-level ladder-type system the physical origin for generating EIA is obviously the existence of spontaneously induced coherence. In other words, spontaneously induced coherence leads to the EIA in the case of large decay rate. Also, we give an intuitive interpretation of the above absorption phenomena. When the effect

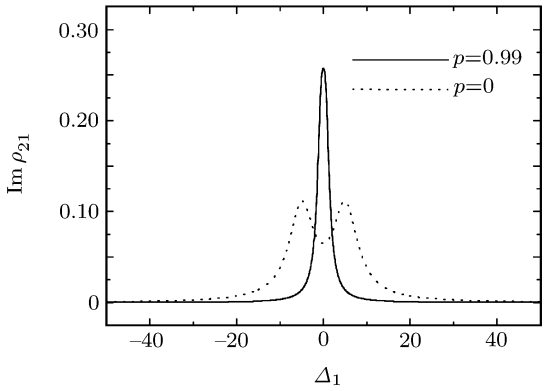


Fig.3. Plots for the absorption Imρ_{21} as a function of probe field detuning in the case of p=0 (dotted line), p=0.99 (solid line). The parameters are $\Delta_2 = 0$, $\gamma_1 = \gamma$, $\gamma_2 = \gamma$, $\Omega_{10} = 2.5\gamma$, $\Omega_{20} = 5\gamma$.

of spontaneously induced coherence is not taken into account, the system is populated in the dark state (called as CPT), which corresponds to EIT. After we take the effects into account, the CPT is destroyed, so instead of EIT, EIA occurs, which is similar to Ref.[24].

4. Conclusion

In summary, we investigated the effects of spontaneously induced coherence on absorption properties in the nearly equispaced ladder-type system driven by two coherent fields. We found that the absorption properties of this system with the probe field applied on the lower transition can be greatly modified after taking the coherent effects into account. In the case of small spontaneous decay rate in the upper excited state, we found that such coherence preserves the EIT phenomena at resonance. However, the absorption peak on both sides of zero detuning and the linewidth of absorption line become larger and narrower than those in the case corresponding to the effects of spontaneously induced coherence respectively. We also found that a zero resonant absorption accompanied by much steeper positive dispersion can occur in this case due to the coherent effects. In the case of large decay rate, instead of EIT resonances with low resonant absorption, we found that a sharp absorption peak at resonance appears due to the coherent effects. That is, EIA occurs due to the effects of spontaneously induced coherence. These results could be experimentally observed provided that the dipole elements for the two optical transitions in the ladder system are not orthogonal, which has been obtained from the mixing of the levels arising from internal fields.[5]

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