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Large index of refraction without absorption via decay-induced coherence in a three-level V system

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Abstract. We study the effects of quantum interference from spontaneous emission on the dispersion-absorption properties in a three-level V-type atomic system with two near-degenerate excited levels. We found that due to the quantum interference between two spontaneous decay channels, large index of refraction without absorption always can be obtained just by choosing proper values of the relative phase between the two applied fields.

PACS. 42.50.Gy Effects of atomic coherence on propagation, absorption, and amplification of light; electromagnetically induced transparency and absorption – 42.50.Hz Strong-field excitation of optical transitions in quantum systems; multiphoton processes; dynamic Stark shift

1 Introduction

It is now well-known that spontaneous decay can produce quantum interference. This decay-induced coherence happens in two cases. One occurs when a single excited state decays to a closely spaced lower doublet (the Λ-configuration). And the other appears when a closely spaced excited doublet decays to a single ground state (the V-configuration). During the past few years, much work has been done on the quantum interference effects arising from spontaneous emission in the V-configuration. It has been shown that the decay-induced coherence in a V-configuration can give rise to many unusual properties, such as quantum beats [1,2], dark lines in the spectrum [3,4], dark periods [5,6], very narrow resonances [3,7], lasing with or without population inversion [8–10]. The existence of the decay-induced quantum interference effect depends on the nonorthogonality of the two dipole matrix elements, which can be obtained from the mixing of the levels arising from internal fields [11] or external fields [12–14].

In this paper, we study the effects of quantum interference from spontaneous emission on the refractive properties in a V-type three-level atomic system with two near-degenerate excited levels. As is known, the usual dispersion-absorption relation tell us that the absorption of the light will be large at the same detuning at which the resonant index of refraction is large. While it is found that quantum coherence and interference in atomic systems can lead to enhancement of the index of refraction accompanied by vanishing absorption [15–19]. In reference [15], Scully and co-workers constructed a three-level system, where atoms are prepared to a coherent superposition of an excited state doublet by a strong driving field, when an incoherent field is applied, large resonance index of refraction with vanishing absorption can be obtained. In these previous works, the dispersion depends on the detunings, the atomic decay rates and the pumping rates as well as the Rabi frequencies, but not related to the relative phase between the applied fields. In the present paper, we show that, in a V-type three-level atomic system with two near-degenerate excited levels, due to the decay-induced coherence, large refractive index without absorption can be obtained by controlling the relative phase between the applied fields. We show that the relationship between the dispersion and absorption exhibits interesting features: whatever the parameters (spontaneous decay rates, Rabi frequency of the coupling field, detunings of the two fields) are taken, large index of refraction without absorption always can be obtained just by choosing proper values of the relative phase between the two applied fields. This unique characteristic of the dispersion-absorption relation caused by the decay-induced coherence cannot be realized in a conventional three-level V system.

2 The system and the density-matrix equations

The three-level V-type atomic system considered in this paper is shown in Figure 1. $|3\rangle$ and $|2\rangle$ are two closely-lying excited levels, $2\gamma_{31}$ and $2\gamma_{21}$ are the spontaneous

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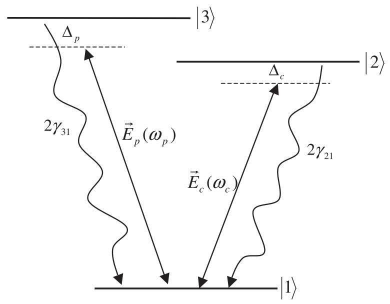

Fig. 1. A three-level V-type atomic system with two closely-lying excited levels, driven by two coherent fields.

emission rates from levels $|3\rangle$ and $|2\rangle$ to the ground level $|1\rangle$, respectively. A strong coherent coupling field with amplitude (frequency) $E_c(\omega_c)$ is used to drive the transition $|2\rangle \leftrightarrow |1\rangle$, and a weak coherent field with amplitude (frequency) $E_p(\omega_p)$ is used to probe the transition $|1\rangle \leftrightarrow |3\rangle$. $\Delta_c = \omega_{21} - \omega_c$, $\Delta_p = \omega_{31} - \omega_p$ are detunings of the corresponding fields. We suppose that the two dipole moments $\vec{d}_{13}$ and $\vec{d}_{12}$ are nonorthogonal so that the decay-induced coherence can take place; and we properly arrange the orientation of the fields polarizations so that $\vec{E}_c \perp \vec{d}_{13}$ and $\vec{E}_p \perp \vec{d}_{12}$, then one field acts on only one transition. That is to say, in our scheme, the two dipole moments are required neither be orthogonal, nor be parallel or antiparallel.

In such a system, the spontaneous emission from $|3\rangle$ to $|1\rangle$ can strongly affect the neighboring transition $|2\rangle$–$|1\rangle$, the interference due to spontaneous emission can arise. We have investigated the transient properties in such a configuration [20], and found that the decay-induced interference can dramatically change the transient behavior of the probe field, the transient absorption can be eliminated just by properly choosing the relative phase of the applied fields. In this paper, we will focus on the effects of decay-induced coherence on the refractive properties in such a scheme.

From reference [20] we have known that the existence of the decay-induced coherence make the system become quite sensitive to phases of the probe and the coupling fields. We use ϕ_p and ϕ_c to denote the phases of the probe and the coupling fields, respectively, and following the same method in reference [20], we derive the density-matrix equations of motion in the rotating-wave approximation and the dipole approximation as follows (for the detailed process please see Ref. [20]):

$$\begin{aligned}
\dot{\sigma}_{22} &= -2\gamma_{21}\sigma_{22} + iG_c\left(\sigma_{12} - \sigma_{21}\right) \\
&\quad - \eta\sqrt{\gamma_{31}\gamma_{21}}\left(e^{-i\Phi}\sigma_{23} + e^{i\Phi}\sigma_{32}\right) \\
\dot{\sigma}_{33} &= -2\gamma_{31}\sigma_{33} + iG_p\left(\sigma_{13} - \sigma_{31}\right) \\
&\quad - \eta\sqrt{\gamma_{31}\gamma_{21}}\left(e^{-i\Phi}\sigma_{23} + e^{i\Phi}\sigma_{32}\right) \\
\dot{\sigma}_{12} &= \left(-\gamma_{21} + i\Delta_c\right)\sigma_{12} + iG_c\left(\sigma_{22} - \sigma_{11}\right) + iG_p\sigma_{32} \\
&\quad - \eta\sqrt{\gamma_{31}\gamma_{21}}e^{-i\Phi}\sigma_{13} \\
\dot{\sigma}_{13} &= \left(-\gamma_{31} + i\Delta_p\right)\sigma_{13} + iG_c\sigma_{23} + iG_p\left(\sigma_{33} - \sigma_{11}\right) \\
&\quad - \eta\sqrt{\gamma_{31}\gamma_{21}}e^{i\Phi}\sigma_{12} \\
\dot{\sigma}_{23} &= -\left(\gamma_{21} + \gamma_{31}\right)\sigma_{23} + i\left(\Delta_p - \Delta_c\right)\sigma_{23} + iG_c\sigma_{13} \\
&\quad - iG_p\sigma_{21} - \eta\sqrt{\gamma_{31}\gamma_{21}}e^{i\Phi}\left(\sigma_{22} + \sigma_{33}\right) \\
\sigma_{ij} &= \sigma_{ji}^*, \qquad \sigma_{11} + \sigma_{22} + \sigma_{33} = 1. \qquad (1)
\end{aligned}$$

In the above equations, the parameter η is defined as $\eta = \vec{d}_{13} \cdot \vec{d}_{12} \,/\, |\vec{d}_{13}||\vec{d}_{12}| = \cos\theta$. θ is the angle between the two dipole moments. Those terms with $\eta\sqrt{\gamma_{31}\gamma_{21}}$ represent the quantum interference effect resulting from the cross-coupling between spontaneous emissions $|3\rangle \to |1\rangle$ and $|2\rangle \to |1\rangle$, i.e., the decay-induced coherence, which is nonzero when $\theta \neq \pi/2$. The parameter G_c, G_p are the effective Rabi frequencies of the coupling and the probe fields, and after the canonical transformation [20] they have been treated as real parameters; considering the linearly polarized electric fields with the restriction of $\vec{E}_c \cdot \vec{d}_{13} = 0$ and $\vec{E}_p \cdot \vec{d}_{12} = 0$, they are given by $G_c = |\vec{E}_c||\vec{d}_{12}|\sin\theta/2\hbar$ and $G_p = |\vec{E}_p||\vec{d}_{13}|\sin\theta/2\hbar$. The parameter Φ is defined as $\Phi = \phi_p - \phi_c$, which is the relative phase between the two applied fields.

3 Numerical analysis

As is known, the indexes of refraction and absorption for the probe field are governed by the real and imaginary parts of the complex polarization σ_{13}, which can be obtained from equations (1). In what follows, we assume that γ_{21}, G_c, G_p, Δ_c, Δ_p are in units of γ_{31}.

In Figures 2 and 3, with $\gamma_{21} = \gamma_{31}$, $\Delta_c = 0$, we plot $\mathrm{Re}(\sigma_{13})$ (solid curve, represents index of refraction) and $\mathrm{Im}(\sigma_{13})$ (dashed curve, represents absorption) versus the probe detuning Δ_p. We first consider the situation that no decay-induced coherence is included, i.e., $\eta = 0$, as shown in Figure 2. In Figure 2a, we take a smaller Rabi frequency of the coupling field $G_c = 3\gamma_{31}$, and in Figure 2b we take a larger Rabi frequency of the coupling field $G_c = 15\gamma_{31}$. It is shown that, when there is no decay-induced coherence ($\eta = 0$), the higher refractive index is always accompanied by nonzero absorption; with the increasing of the Rabi frequency of the coupling field, both $\mathrm{Im}(\sigma_{13})$ and $\mathrm{Re}(\sigma_{13})$ vanish at the same detuning $\Delta_p = 0$ (as shown in Fig. 2b), but large index of refraction with zero absorption still can not be obtained.

Figure 3 depicts the absorption and dispersion properties of the probe field under the case that the decay-induced coherence is included, where $\theta = \pi/4$, $G_c = 3\gamma_{31}\sin\theta$, $G_p = 0.1\gamma_{31}\sin\theta$. We consider several different values of the relative phase Φ: (a) $\Phi = 0$, (b) $\Phi = \pi$, (c) $\Phi = \pi/2$. It can be found that no matter what values the relative phase are taken, the largest index of refraction always corresponds to zero absorption, shown as the points A, B, C in Figures 3a, 3b and 3c, respectively. With different values of the relative phase, the large index of refraction with zero absorption is located at

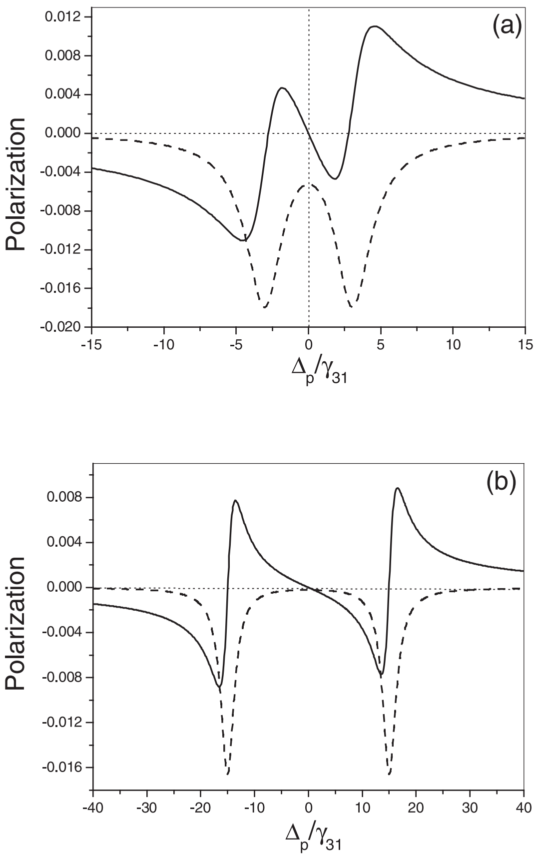

Fig. 2. $\mathrm{Re}(\sigma_{13})$ (solid curve, represents index of refraction) and $\mathrm{Im}(\sigma_{13})$ (dashed curve, represents absorption) versus the probe detuning Δ_p, the decay-induced coherence is not included ($\eta = 0$). Other parameters are: $\gamma_{21} = \gamma_{31}$, $\Delta_c = 0$, $G_p = 0.1\gamma_{31}$, (a) $G_c = 3\gamma_{31}$, (b) $G_c = 15\gamma_{31}$.

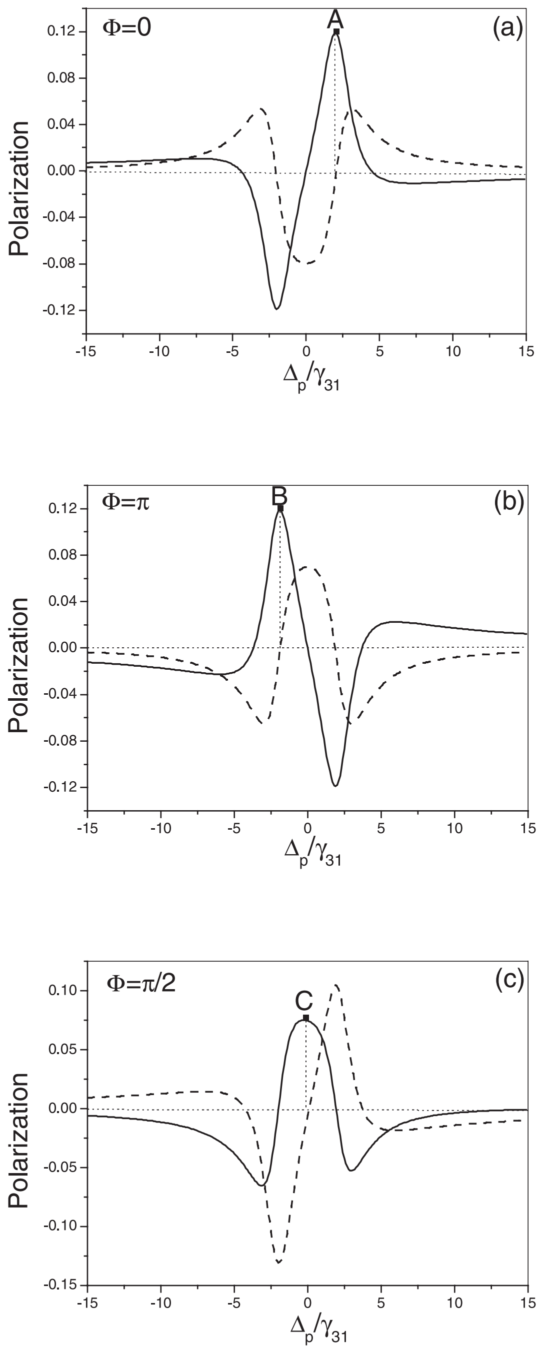

Fig. 3. $\mathrm{Re}(\sigma_{13})$ (solid curve) and $\mathrm{Im}(\sigma_{13})$ (dashed curve) versus the probe detuning Δ_p, the decay-induced coherence is included ($\eta \neq 0$). The parameters are: $\gamma_{21} = \gamma_{31}$, $\Delta_c = 0$, $\theta = \pi/4$, $G_p = 0.1\gamma_{31}\sin\theta$, $G_c = 3\gamma_{31}\sin\theta$, (a) $\Phi = 0$, (b) $\Phi = \pi$, (c) $\Phi = \pi/2$.

different detunings. When $\Phi = 0$ (Fig. 3a), the large index of refraction with zero absorption is located at $\Delta_p = G_c$, which corresponds to one of the dressed-state sublevels. As is known, under the action of the coherent field G_c, the ground level $|1\rangle$ will be split into two dressed sublevels: $|-\rangle=(|1\rangle-|2\rangle)/\sqrt{2}$, $|+\rangle=(|1\rangle+|2\rangle)/\sqrt{2}$, the eigenvalues of the two sublevels are $-G_c$ and G_c, respectively. When $\Phi = \pi$ (Fig. 3b), the large index of refraction with zero absorption is located at $\Delta_p = -G_c$, which corresponds to another sublevel of the dressed-state. When $\Phi = \pi/2$ (Fig. 3c), the large index of refraction with zero absorption is located at $\Delta_p = 0$.

In order to get a deeper insight into the dependence of the dispersion-absorption relation on the relative phase Φ, in Figure 4, we plot $\mathrm{Re}(\sigma_{13})$ (solid curve) and $\mathrm{Im}(\sigma_{13})$ (dashed curve) versus the relative phase Φ at different values of the probe detunings: $\Delta_p = 0$, $\Delta_p = \pm G_c$ (eigenvalues of the two dressed-state sublevels), and $\Delta_p = 5\gamma_{31}$ (arbitrary value), other parameters are the same as in Figure 3. An interesting and useful characteristic can be found in these figures: no matter what the probe detunings are, for the fixed detuning, the largest index of refraction always corresponds to zero absorption; with different detunings, the large index of refraction with zero absorption always can be obtained by choosing the proper values of the relative phase Φ. For example, when $\Delta_p = 0$, the large index of refraction with zero absorption can be obtained by choosing $\Phi = \pi/2 + 2k\pi$ (points A_1, A_2 in Fig. 4a); when $\Delta_p = +G_c$, the large index of refraction with zero absorption can be obtained by choosing $\Phi = 2k\pi$ (points B_1, B_2, B_3 in Fig. 4b); when $\Delta_p = -G_c$, the large index of refraction with zero absorption can be obtained by choosing

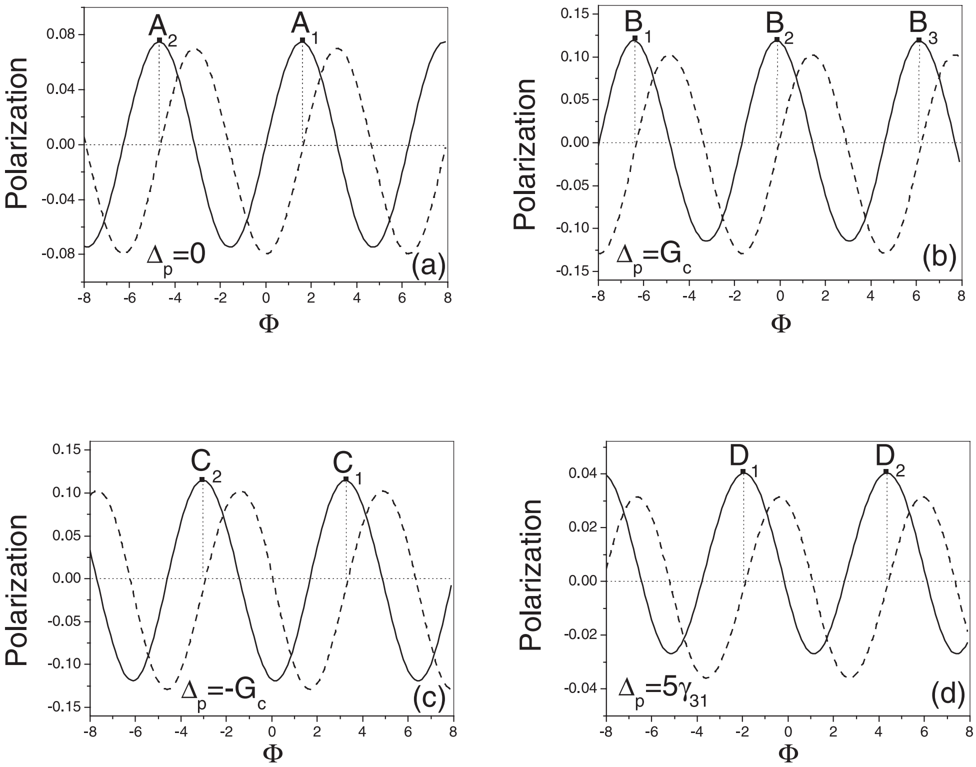

Fig. 4. $\mathrm{Re}(\sigma_{13})$ (solid curve) and $\mathrm{Im}(\sigma_{13})$ (dashed curve) versus the relative phase Φ at different values of the probe detunings: (a) $\Delta_p = 0$, (b) $\Delta_p = +G_c$, (c) $\Delta_p = -G_c$, (d) $\Delta_p = 5\gamma_{31}$, other parameters are the same as in Figure 3.

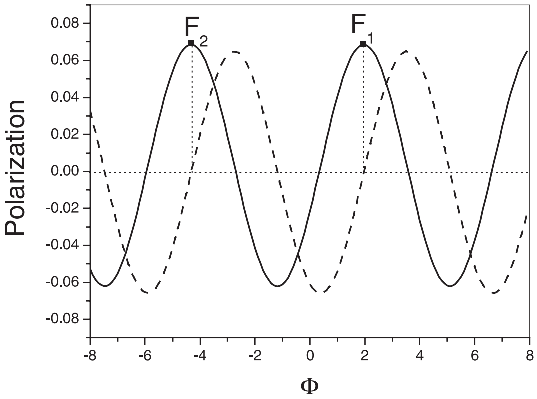

Fig. 5. $\mathrm{Re}(\sigma_{13})$ (solid curve) and $\mathrm{Im}(\sigma_{13})$ (dashed curve) versus the relative phase Φ. The parameters are: $\gamma_{21} = 5\gamma_{31}$, $\Delta_c = 15\gamma_{31}$, $\Delta_p = 6\gamma_{31}$, $\theta = \pi/6$, $G_c = 20\gamma_{31}\sin\theta$, $G_p = 0.1\gamma_{31}\sin\theta$.

$\Phi = (2k+1)\pi$ (points C_1, C_2 in Fig. 4c); when $\Delta_p = 5\gamma_{31}$, the large index of refraction with zero absorption can be obtained by choosing $\Phi \approx -3\pi/5 + 2k\pi$ (points D_1, D_2 in Fig. 4d), where $k = 0, \pm1, \pm2...$

Above discussions are under the case that the spontaneous decay rates are equal ($\gamma_{21} = \gamma_{31}$), the coupling Rabi frequency is not very large ($G_c = 3\gamma_{31}\sin\theta$), the coupling field is in resonance ($\Delta_c = 0$). In Figure 5, we plot $\mathrm{Re}(\sigma_{13})$ (solid curve) and $\mathrm{Im}(\sigma_{13})$ (dashed curve) versus the relative phase Φ by taking another set of quite different parameters: the spontaneous decay rates are disparity ($\gamma_{21} = 5\gamma_{31}$), the coupling field is much more stronger ($G_c = 20\gamma_{31}\sin\theta$), the coupling and probe fields are both tuned far away from resonance ($\Delta_c = 15\gamma_{31}$, $\Delta_p = 6\gamma_{31}$), and $\theta = \pi/6$. It shows that despite of the variation of the parameters, the largest index of refraction still corresponds to zero absorption (see points F_1, F_2), and the large index of refraction with zero absorption still can be obtained by choosing the proper values of the relative phase Φ.

4 Conclusions

In summary, we have investigated the effects of decay-induced coherence on the dispersion-absorption properties in a V-type three-level atomic system with two closely-lying excited levels. We show that due to the quantum interference between two spontaneous decay channels, the dispersion-absorption properties can be related to the relative phase between the two applied fields, and the large index of refraction without absorption always can be obtained just by choosing proper values of the relative phase. It should be noted that in this system, no incoherent pump is needed for achieving large index of refraction with zero absorption. Such a system is very useful for realizing ultra-high index of refraction without absorption, which plays an important role for dispersion compensation in optical communication.

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