Electromagnetically induced transparency and controllable group velocity in a five-level atomic system

Lihui Jin (金黎慧), Shangqing Gong (龚尚庆), Yueping Niu (钮月萍), and Shiqi Jin (金石琦)

State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800

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The optical properties of a five-level atomic system composed of a Λ-type four-level atomic and a tripod four-level atomic systems are investigated. It is found that the behaviors of electromagnetically induced transparency (EIT) and group velocity can be controlled by choosing appropriate parameters with the interacting dark resonances. In particular, when all the fields are on resonance, the slow light at the symmetric transparency windows with a much broader EIT width is obtained by tuning the intensity of the coupling field in comparison with its sub-system, which provides potential applications in quantum storage and retrieval of light.

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In recent years, a great deal of attention has been paid to the phenomenon of electromagnetically induced transparency (EIT)[1] in multi-level atomic systems interacting with two or more electromagnetic fields. The origin of this effect may be traced back to a so-called dark resonance[2] arising from the quantum superposition states that are decoupled from coherent and dissipative interactions. It has triggered the discovery of many related phenomena, such as lasing without inversion (LWI), coherent population trapping (CPT). As a further application it was pointed out that an otherwise opaque medium is rendered transparently to the probe laser field and a large variation in linear dispersion within the transparency window is created, which can lead to a slowing down of the group velocity of light[3,4]. For example, the group velocity of light pulse can be reduced to 17 m/s in a cooled sodium Bose-Einstein condensate gas. The potential applications based on slow light have been shown to be very promising in quantum storage and retrieval of light[5], high sensitivity magnetometer[6], and optical delay lines[7], etc..

Recently, two four-level systems have been proposed[8,9] and some corresponding experimental results have already existed[10,11]. Actually, the former addresses in a Λ-type system, where one lower state has the structure of two fold closely spaced levels coupled by a microwave field. In such a system, which is equivalent to two Λ sub-systems, the existence of two distinct dark resonances is clear at hand. The interaction of the double dark resonances leads to the phenomenon of double EIT. Hence, the optical properties of the EIT, such as width, position, and the group velocity of the probe field, can be manipulated by adjusting the interaction of double dark resonances[12]. The latter, namely the tripod system with three coherent laser fields, can not only exhibit double EIT and control group velocity but also be used for efficient nonlinear generation of new laser fields.

Motivated by Refs. [8—12], in this paper we introduce a five-level atomic system composed of these four-level systems to further explore the EIT characteristics, the group velocity of the probe field, etc.. We find that due to the additional control field, some new optical properties can appear compared with its sub-systems. For example, this system provides strong manipulation of EIT and group velocity via the interaction of the dark resonances by choosing various parameters. In particular, when all the fields are on resonance, we may obtain slow light at the symmetric transparency windows with a much broader EIT width by tuning the intensity of the coupling field in comparison with its sub-system, which provides potential applications in quantum storage and retrieval of light.

This system is illustrated in Fig. 1. Levels $|a\rangle$, $|b\rangle$, $|c\rangle$, and $|d\rangle$ are in a Λ-type system with two fold levels and level $|e\rangle$ together with levels $|a\rangle$, $|b\rangle$, and $|c\rangle$ forms the tripod configuration. So, this composite system consists of two sub-systems, i.e., one four-level Λ-type system and the other tripod system. In the interaction picture the density-matrix equations of motion for off-diagonal matrix elements of the atomic density operator in the rotating-wave approximation can be written as

$$\dot{\rho}_{\rm ab} = i\rho_{\rm eb}\Omega_2 + i(\rho_{\rm bb} - \rho_{\rm aa})\Omega_{\rm p} + i\rho_{\rm cb}\Omega_1 - \Gamma_{\rm ab}\rho_{\rm ab}, \quad (1)$$

$$\dot{\rho}_{\rm eb} = i\rho_{\rm ab}\Omega_2 - i\rho_{\rm ea}\Omega_{\rm p} - \Gamma_{\rm eb}\rho_{\rm eb}, \quad (2)$$

$$\dot{\rho}_{\rm cb} = i\rho_{\rm ab}\Omega_1 + i\rho_{\rm db}\Omega_3 - i\rho_{\rm ca}\Omega_{\rm p} - \Gamma_{\rm cb}\rho_{\rm cb}, \quad (3)$$

$$\dot{\rho}_{\rm db} = i\rho_{\rm cb}\Omega_3 - i\rho_{\rm da}\Omega_{\rm p} - \Gamma_{\rm db}\rho_{\rm db}, \quad (4)$$

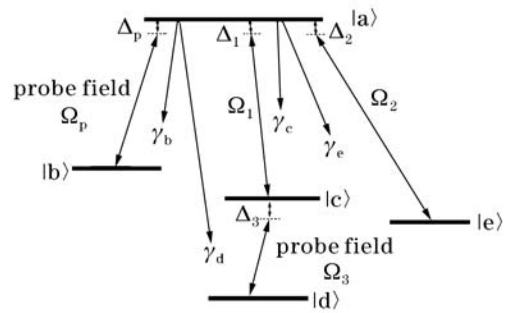

Fig. 1. Schematic diagram of the composite system consisting of two sub-systems. One is the four-level Λ-type atomic system, the other is the tripod four-level system.

where Ω_i (i = p, 1, 2, 3) are the Rabi frequencies of the probe, coupling, and control fields with frequencies ω_i exciting transitions $|a\rangle$ to $|j\rangle$ (j = b, c, e) and $|c\rangle$ to $|d\rangle$, respectively. Here, $\Gamma_{ab} = \gamma_{ab} + i\Delta_p$, $\Gamma_{nb} = \gamma_{nb} + i(\Delta_p - \Delta_k)$ (n = c, e; $k = 1, 2$), and $\Gamma_{db} = \gamma_{db} + i(\Delta_p - \Delta_1 - \Delta_3)$, where $\Delta_m = \omega_{aj} - \omega_m$ (m = p, 1, 2), and $\Delta_3 = \omega_{cd} - \omega_3$ denote the corresponding atomic detunings for these transitions. The relaxation rate of the respective coherence is denoted by γ_{tb} (t = a, c, d, e).

We assume that all atoms are initially prepared in the ground state $|b\rangle$, i.e., $\rho_{bb}(0) = 1$, and solving Eqs. (1)—(4) under the condition that the intensity of the probe field is weak. The steady state linear susceptibility can be expressed as

$$\chi = \frac{i\eta\Gamma_{cb}}{\Gamma_{ab}\Gamma_{cb} + \Omega_1^2}\left[1 + \frac{\Omega_1^2}{\Gamma_{cb}}\frac{\Omega_3^2}{\Gamma_{ab}(\Gamma_{cb}\Gamma_{db} + \Omega_3^2) + \Omega_1^2\Gamma_{ab}}\right]$$

$$\times\left[1 - \frac{\Omega_2^2(\Gamma_{cb}\Gamma_{db} + \Omega_3^2)}{(\Gamma_{cb}\Gamma_{db} + \Omega_3^2)(\Gamma_{db}\Gamma_{eb} + \Omega_2^2) + \Omega_1^2\Gamma_{db}\Gamma_{eb}}\right], \quad (5)$$

where, $\eta = \gamma_b 3N\lambda_p^3/(8\pi^2)$, λ_p is the wavelength of the probe field, and N is the number density of atoms. Equation (5) gives some ideas of how the coupling and control fields affect the absorption and dispersion properties of the probe field, which gives rise to the EIT. When $\Omega_2 = 0$, we get the susceptibility expression for the four-level Λ-type system[10] from Eq. (5) whose second bracket on the right-hand side (RHS) disappears. On the other hand, when $\Omega_3 = 0$, the first bracket on the RHS of Eq. (5) disappears, then the susceptibility expression reduces to the form of the tripod system[11]. Simple calculations show that the real and imaginary parts of the susceptibility, which are related to the dispersion and absorption, can be equal to zero at the detuning

$$(\Delta_p)_{1,2} = \Delta_1 + \frac{\Delta_3}{2} \pm \sqrt{\left(\frac{\Delta_3}{2}\right)^2 + \Omega_3^2}, \quad (6a)$$

$$(\Delta_p)_3 = \Delta_2, \quad (6b)$$

corresponding to the three transparency conditions. It can be shown obviously from Eq. (6) that in contrast to the sub-systems, the transparency properties can be controlled by the detunings of the coupling fields, as well as the detuning and intensity of the control field. Therefore, it is instructive to discuss the properties for this composite EIT system, such as width, position, and number, etc..

In order to explicitly show the properties of EIT for this composite system, in the case of infinitely long-lived lower-level coherence, we present numerical simulations in Fig. 2, where we plot the real (dotted lines) and imaginary (solid lines) parts of the susceptibility χ as a function of Δ_p/γ in the units of η/γ. The fixed parameters are $\gamma_b = \gamma_c = \gamma_d = \gamma_e = \gamma$, $\gamma_{ab} = (\gamma_b + \gamma_c + \gamma_d + \gamma_e)/2$, $\Omega_1 = \gamma$, and $\Delta_1 = 0$. The combined effects of these two sub-systems can be seen in Fig. 2(a), where we keep $\Omega_2 = \gamma$, $\Omega_3 = 0.2\gamma$, and $\Delta_2 = \Delta_3 = 0$, which shows the phenomenon of EIT with three transparency windows. In this situation, the shape of the absorption is symmetric. Due to the interaction of the dark resonances, the properties of EIT can be controlled by appropriately selecting the field amplitudes and detunings for the coupling control fields, which is shown in Figs. 2(b) and (c). We keep $\Omega_2 = \Omega_3 = 0.2\gamma$, $\Delta_2 = 0.8\gamma$, and $\Delta_3 = \gamma$ in Fig. 2(b). In this case the feature turns from two sharp absorption lines into two sharp transparency peaks and a wide transparency line close to the point of three-photon resonance in the three-level Λ-type system, which changes the position and width of EIT. Under the condition of $\Omega_2 = \gamma$, $\Omega_3 = 0.2\gamma$, $\Delta_2 = 0.2\gamma$, and $\Delta_3 = 0$, there is a merging of the three EIT peaks into two peaks and a loss of symmetry in the resulting two EIT peaks in Fig. 2(c). Hence, adjusting the coupling and control fields can lead to control the optical properties of the EIT such as width, position, and numbers more effectively, which is difficult to achieve with either of sub-systems alone.

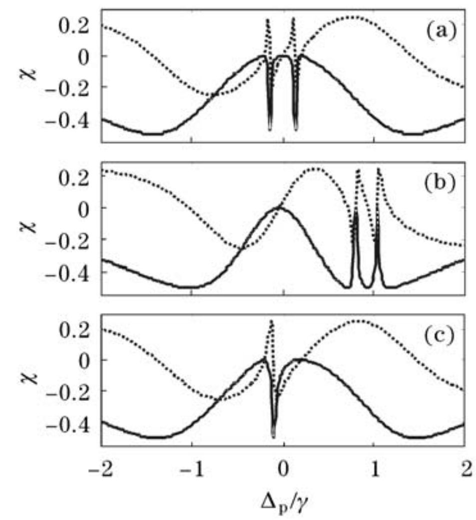

Fig. 2. Imaginary (solid lines) and real (dotted lines) parts of the line susceptibility χ of the probe field in the units of η/γ for the system of Fig. 1. Parameters are $\gamma_b = \gamma_c = \gamma_d = \gamma_e = \gamma$, $\gamma_{ab} = (\gamma_b + \gamma_c + \gamma_d + \gamma_e)/2$, $\Omega_1 = \gamma$, and $\Delta_1 = 0$. (a) $\Omega_2 = \gamma$, $\Omega_3 = 0.2\gamma$, and $\Delta_2 = \Delta_3 = 0$; (b) $\Omega_2 = \Omega_3 = 0.2\gamma$, $\Delta_2 = 0.8\gamma$, and $\Delta_3 = \gamma$; (c) $\Omega_2 = \gamma$, $\Omega_3 = 0.2\gamma$, $\Delta_2 = 0.2\gamma$, and $\Delta_3 = 0$.

The group velocities of the probe field at the transparency windows in this system are our focus for further consideration. The relation between the group velocity and the susceptibility is $v_g = c/[1 + \frac{1}{2}\chi' + \frac{\nu_p}{2}\frac{\partial\chi'}{\partial\nu_p}]$, where c is the speed of light in vacuum, ν_p is the angle frequency of the probe field, and χ' is the real part of the susceptibility.

According to Eqs. (5) and (6), when the coupling fields are both on resonantce, i.e., $\Delta_1 = \Delta_2 = 0$, the group velocities at three different transparency windows can be derived as

$$(v_g)_{1,2} \approx \frac{c\Omega_1^2}{\nu_p\eta}\left(1 + \frac{\Delta_3\left(\Delta_3 \pm \sqrt{\Delta_3^2 + 4\Omega_3^2}\right)}{4\Omega_3^2 + \Delta_3\left(\Delta_3 \pm \sqrt{\Delta_3^2 + 4\Omega_3^2}\right)}\right), \quad (7a)$$

$$(v_g)_3 \approx \frac{2c\Omega_2^2}{\eta\nu_p}, \quad (7b)$$

where $\frac{\eta\nu_p}{\Omega_1^2} \gg 1$ is used. Here the subscripts correspond to the ones on the left-hand side (LHS) of Eq. (6). It is seen clearly from Eqs. (6) and (7) that two of the group velocities $(v_g)_{1,2}$ correspond to the result in the four-level Λ-type system[12], and the rest group velocity $(v_g)_3$ in the tripod system[9]. Then we find that when the control field is resonant with the corresponding transition frequency, i.e., $\Delta_3 = 0$, there is no change for the Eq. (7b). However, the expression of the group velocities Eq. (7a) is simplified as

$$(v_g^0)_1 = (v_g^0)_2 \approx \frac{c\Omega_1^2}{\nu_p\eta}, \quad (8)$$

corresponding to the symmetric transparency condition in Fig. 2(a), where the superscripts correspond to the resonant condition. Two different group velocities become equal and are proportional to the square of the intensity of one coupling field Ω_1 but independent of the other coupling field Ω_2 and the control field Ω_3. Subsequently, we also find that when $\Delta_2 = \pm\Omega_3$ is satisfied, $(\Delta_p)_{1,2} = (\Delta_p)_3$. There is a merging of the three group velocities into two ones, which can be expressed by

$$\left(v_g^0\right)_a \approx \frac{c\Omega_1^2}{\nu_p\eta}, \quad (9a)$$

$$\left(v_g^0\right)_b \approx \frac{c(\Omega_1^2 + 2\Omega_2^2)}{2\nu_p\eta}. \quad (9b)$$

Here the subscripts correspond to the two asymmetry transparency windows in Fig. 2(c). Thus, through a proper choice of parameters, the composite system provides a more efficient way to manipulate the group velocity of the probe field than the sub-systems.

In the following, we study how these laser fields bring changes in the EIT width of the symmetric transparency windows under the condition of $\Delta_1 = \Delta_2 = \Delta_3 = 0$ in this system. We define the EIT width Γ_{EIT} as the full-width at half-maximum (FWHW) corresponding to the symmetric transparency windows, whose analytical expression is so complicated that we only give some numerical analysis. In Fig. 3, we show the relation between the EIT width Γ_{EIT} and the intensities of the control field Ω_3, the coupling field Ω_2 under the condition of $\Delta_1 = \Delta_2 = \Delta_3 = 0$. Other parameters are the same as those in Fig. 2(a). From the curve in Fig. 3, we can see that although the width of the symmetric transparency windows Γ_{EIT} increases gradually with the control field Ω_3[12], the EIT width Γ_{EIT} can be adjusted much broader by tuning the coupling field Ω_2 when we keep a small Ω_3. Therefore, this system also provides an efficient way to obtain slow light with broader EIT width than its sub-system, which has potential applications in quantum storage and retrieval of light.

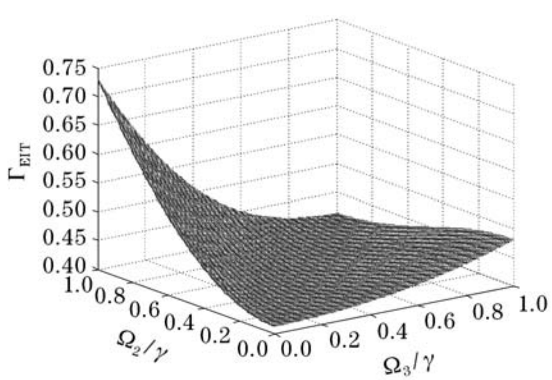

Fig. 3. The EIT width Γ_{EIT} at the symmetric transparency windows versus the intensities of the control field Ω_3 and the coupling field Ω_2 in the units of $\nu_p\eta/\gamma$. Other parameters are the same as those in Fig. 2(a).

In summary, we have studied the phenomenon of EIT and the group velocity in the five-level atomic system which is considered as a composition of two four-level sub-systems. We find that the additional control field leads to some new optical properties compared with its sub-systems. For example, the EIT and group velocity characteristics can be controlled efficiently by adjusting different parameters. In particular, when the coupling and control fields are on resonance, the slow group velocities at the symmetric transparency windows with a broader EIT width can be obtained by tuning the coupling field in comparison with its sub-system, which provides potential applications in quantum storage and retrieval of light. Furthermore, since the distance between the EIT peaks is determined by the applied microwave control field as shown in Fig. 2, the system might be used as a magnetometer. Such a closed five-level structure can be found in a real atomic system[13]. Therefore, the scheme gives a way to obtain slow light with a broader EIT width as well as controllable EIT and group velocity.

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