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Group velocity of the light pulse in an open V-type system

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Abstract

We investigate the group velocity of the probe light pulse in an open V-type system with spontaneously generated coherence. We find that, not only varying the relative phase between the probe and driving pulses can but varying the atomic exit rate or incoherent pumping rate also can manipulate dramatically the group velocity, even make the pulse propagation switching from subluminal to superluminal; the subliminal propagation can be companied with gain or absorption, but the superluminal propagation is always companied with absorption.

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Keywords: Open system; Group velocity; Spontaneously generated coherence; Subluminal; Superluminal

1. Introduction

The group velocity of a light pulse passing through a medium can be much less than c, the velocity of light in the vacuum (subluminal propagation) or exceed c and even become negative (superluminal propagation). Recently, the phenomena of the subluminal and superluminal propagations have widely been investigated theoretically and experimentally [1–15]. For superluminal light, it has been shown that the real information is not carried at the group velocity and Einstein causality is preserved [6]. In view of many potential applications of ultraslow and superluminal light propagation, an interesting question is that whether one can have a controlling parameter in a single experiment for switching from subluminal to superluminal propagation. Some schemes have been presented for realized this goal. For example, Kang et al. [11] have shown that the group velocity of a light pulse propagating through a four-level system exhibiting electromagnetically induced transparency can be manipulated by a pump laser, Wang et al. [12] have pointed out that by adjusting the coherence of the pulse can make the propagation of a light pulse changing from superluminal to subluminal in a three-level system with two closely placed Raman gain peaks, Sahrai et al. [13] have demonstrated that tunable control of the group velocity of a weak probe pulse from subluminal to superluminal can be obtained by phase variation of one of the control fields in an extended V-type system with two extra control fields and an extra energy level. Agarwal et al. [14] have proclaimed that in a V-type system the variation of a coupling field connecting the two lower metastable states can leads

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to a weak pulse propagation changing from subluminal to superluminall, Bortmand-Arbir et al. [15] have analyzed the effect of the relative phase between the probe and driving pulses on the propagation of the probe pulse. In this paper, we study the group velocity of the probe light pulse in an open V-type atomic system with spontaneously generated coherence (SGC). We find that, when both the probe and driving light pulses are weak and have different center frequencies, not only varying the relative phase between the probe and driving light pulses can but varying the atomic exit rate or incoherent pumping rate also can manipulate notably the group velocity of the probe pulse, even make the propagation of the probe pulse switching from subluminal to superluminal.

2. Equations and steady solutions

The system considered here is shown in Fig. 1. The two closely spaced upper levels $|2\rangle$ and $|3\rangle$ decay spontaneously to the ground state $|1\rangle$ at the decay rates $2\gamma_2$ and $2\gamma_3$, respectively. The atomic injection rates for levels $|1\rangle$ and $|2\rangle$ are W_1 and W_2, respectively. The atomic exit rate from the cavity is r_0. An incoherent pump with a pumping rate $2R$ is applied between states $|1\rangle$ and $|3\rangle$. The probe light pulse with the frequency ω_p and Rabi frequency $G(=\vec{\mu}_{13}\cdot\vec{\varepsilon}_p/2\hbar)$ is applied between states $|1\rangle$ and $|3\rangle$. The excited state $|2\rangle$ is coupled to the ground state $|1\rangle$ through the driving light pulse with the frequency ω_c and Rabi frequency $\Omega=(\vec{\mu}_{12}\cdot\vec{\varepsilon}_c/2\hbar)$. $\vec{\mu}_{12}$ and $\vec{\mu}_{13}$ are the dipole matrix elements of the transitions $|2\rangle\to|1\rangle$ and $|3\rangle\to|1\rangle$, respectively. $\vec{\varepsilon}_p$ and $\vec{\varepsilon}_c$ are amplitudes of the probe and driving light fields, respectively. Due to the existence of SGC, the properties of system can be change by varying the relative phase of the applied fields [16–20]. We let

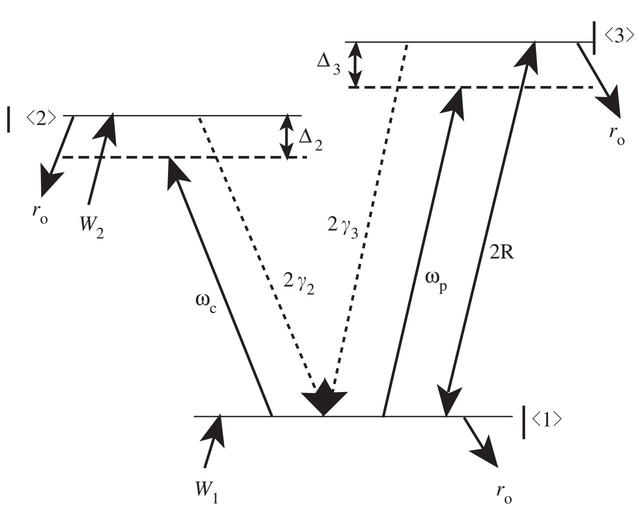

Fig. 1. Open V-type atomic system.

$\Omega=\Omega_c\exp(\mathrm{i}\phi_c)$ and $G=G_p\exp(\mathrm{i}\phi_p)$ (Ω_c and G_p are real parameters), then the relative phase between the probe and driving fields is $\phi=\phi_p-\phi_c$. In the rotating wave frame the density matrix equations of motion for the system can be written as following [20]:

$$
\begin{aligned}
\dot{\tilde{\rho}}_{11} &= 2\gamma_2\tilde{\rho}_{22}+2\gamma_3\tilde{\rho}_{33}\text{-}r_0\tilde{\rho}_{11}\text{-}\mathrm{i}(\Omega_c\tilde{\rho}_{12}-\Omega_c^*\tilde{\rho}_{21})\\
&\quad -\mathrm{i}(G_p\tilde{\rho}_{13}-G_p^*\tilde{\rho}_{31})+2R(\tilde{\rho}_{33}-\tilde{\rho}_{11})\\
&\quad +2p\sqrt{\gamma_2\gamma_3}(\mathrm{e}^{-\mathrm{i}\phi}\tilde{\rho}_{23}+\mathrm{e}^{\mathrm{i}\phi}\tilde{\rho}_{32})+W_1,\\
\dot{\tilde{\rho}}_{22} &= -(2\gamma_2+r_0)\tilde{\rho}_{22}-p\sqrt{\gamma_2\gamma_3}(\mathrm{e}^{-\mathrm{i}\phi}\tilde{\rho}_{23}+\mathrm{e}^{\mathrm{i}\phi}\tilde{\rho}_{32})\\
&\quad +\mathrm{i}(\Omega_c\tilde{\rho}_{12}-\Omega_c^*\tilde{\rho}_{21})+W_2,\\
\dot{\tilde{\rho}}_{33} &= 2R\tilde{\rho}_{11}-(2\gamma_3+2R+r_0)\tilde{\rho}_{33}-p\sqrt{\gamma_2\gamma_3}\\
&\quad \times(\mathrm{e}^{-\mathrm{i}\phi}\tilde{\rho}_{23}+\mathrm{e}^{\mathrm{i}\phi}\tilde{\rho}_{32})+\mathrm{i}(G_p\tilde{\rho}_{13}-G_p^*\tilde{\rho}_{31}),\\
\dot{\tilde{\rho}}_{23} &= -[\gamma_2+\gamma_3+R+r_0+\mathrm{i}(\Delta_3-\Delta_2)]\tilde{\rho}_{23}-p\sqrt{\gamma_2\gamma_3}\\
&\quad \times\mathrm{e}^{\mathrm{i}\phi}(\tilde{\rho}_{22}+\tilde{\rho}_{33})+\mathrm{i}\Omega_c\tilde{\rho}_{13}-\mathrm{i}G_p^*\tilde{\rho}_{21},\\
\dot{\tilde{\rho}}_{21} &= -(\gamma_2+R+r_0-\mathrm{i}\Delta_2)\tilde{\rho}_{21}-p\sqrt{\gamma_2\gamma_3}\mathrm{e}^{\mathrm{i}\phi}\tilde{\rho}_{31}\\
&\quad +\mathrm{i}\Omega_c(\tilde{\rho}_{11}-\tilde{\rho}_{22})-\mathrm{i}G_p\tilde{\rho}_{23},\\
\dot{\tilde{\rho}}_{31} &= -(\gamma_3+2R+r_0-\mathrm{i}\Delta_3)\tilde{\rho}_{31}-p\sqrt{\gamma_2\gamma_3}\mathrm{e}^{-\mathrm{i}\phi}\tilde{\rho}_{21}\\
&\quad +\mathrm{i}G_p(\tilde{\rho}_{11}-\tilde{\rho}_{33})-\mathrm{i}\Omega_c\tilde{\rho}_{32},
\end{aligned}
\tag{1}
$$

where $\Delta_3=(\omega_{31}-\omega_p)$ and $\Delta_2(=\omega_{21}-\omega_c)$ are the detunings of the probe and driving fields from their relevant atomic transitions, respectively. $p\sqrt{\gamma_2\gamma_3}$ accounts for SGC. $p\equiv\vec{\mu}_{12}\cdot\vec{\mu}_{13}/\left|\vec{\mu}_{12}\right|\left|\vec{\mu}_{13}\right|=\cos\theta$. When $p=0$, SGC effect is absent, and Eq. (1) reduce to the equations for an open V-type system without SGC [21,22].

The polarizations induced by the probe and driving fields are proportional to $\tilde{\rho}_{21}$ and $\tilde{\rho}_{31}$, respectively. Considering both probe field and driving field are weak fields, in the steady states we can obtain the linear analytical expressions of $\tilde{\rho}_{31}$ as following:

$$
\tilde{\rho}_{31}=\frac{(f_1W_1+f_2W_2)G_p+p\sqrt{\gamma_2\gamma_3}\mathrm{e}^{-\mathrm{i}\phi}(f_3W_1+f_4W_2)\Omega_c}{r_0(p^2\gamma_2\gamma_3+D_0+\mathrm{i}k_3)(4R_{23}^2p^2\gamma_2\gamma_3-R_{20}t_0m_6)}.
\tag{2}
$$

The coefficients $f_i(i=1,2,3,4)$, D_0, t_0, m_6, R_{23}, R_{20} are functions of the system parameters and their detail expressions are given in the appendix of Ref. [20]. In our notation, if Im $\tilde{\rho}_{31}<0$ (Im $\tilde{\rho}_{13}>0$), the probe field is amplified. If Im $\tilde{\rho}_{31}>0$ (Im $\tilde{\rho}_{13}<0$), the probe field is attenuated. The dispersion of the probe field is proportional to Re $\tilde{\rho}_{31}(=$ Re $\tilde{\rho}_{13})$. We can see that $\tilde{\rho}_{31}$ is composed of two parts: the first is proportional to the probe field which couples levels $|1\rangle$ and $|3\rangle$, and the second proportional to driving fields which couples levels $|1\rangle$ and $|2\rangle$. This second term is due to the coupling of the $|2\rangle\to|1\rangle$ and $|1\rangle\to|3\rangle$ transitions by SGC. In this system phase control is possible only when SGC is present. When both the probe and driving light pulses are weak and have different center frequencies, the