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Transient absorption–dispersion properties of four-level atomic system via elliptically polarized probe light and magnetic field

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ABSTRACT

A novel four-level atomic system which interacted by an elliptically polarized probe field and a control laser field in the presence of external magnetic field is proposed. Here, we are interested in the transient properties of a weak probe field due to its potential application on quantum computing and quantum communication. It is shown that the external magnetic field and relative phase between two electric field components of the probe field can influence the probe absorption and dispersion.

1. Introduction

The research on the electromagnetically induced transparency (EIT) has attracted a great deal of interest in the past few years. In the EIT medium, the strong coherent laser fields provide the atomic phase coherence that is responsible for transparency of the medium. In fact, EIT is a technique for eliminating the effect of a medium on propagation beam of the electromagnetic radiation [1–3]. So, in the EIT medium the weak probe field not only will not be absorbed but also a refractive index curve with very steep gradient will be appeared [4]. Recently, many studies have concentrated on the transient research related to the quantum coherence and interference phenomena [5–10]. Most of earlier studies with respect to the SGC focused on the steady state response of the medium. The effect of SGC in transient process in closed three-level λ-type and V-type systems with near degenerate levels in the case of weak probe field have investigated [11,12]. The transient behaviors of the probe absorption–dispersion and lasing without population have been discussed in an EIT medium [13]. In Ref. [14], the effect of spontaneously generated coherence (SGC) and incoherent pumping field on the transient behaviors of open and closed ladder-type atomic system is discussed. It is shown that the SGC effect made the open and closed system to be distinguished. In another research, comparison of steady and transient optical response between a four-level tripod system and a three-level lambda system was done [15]. The effect of incoherent pumping field on transient behavior of ladder-type atomic system is also investigated [16]. It is shown that the incoherent pumping field and SGC have essential role for superluminal light propagation in the medium. It is also shown that EIT four-level atomic system can be used as an optical switch [13], which is an important technique for quantum information network and communication [17]. The possibility of an optical switch via relative phase between applied fields is also investigated in a four-level EIT medium [18]. Recently, effect of quantum coherence on transient behaviors of solid state medium is also discussed [19,20].

In this paper, we propose a novel atomic configuration which in the presence of external magnetic field, interacted by an elliptically polarized probe light and a coupling laser filed. The transient behavior of mentioned atomic system is discussed and it is shown that the superluminal light propagation in the absence of absorption can be obtained by external magnetic field and relative phase between two electric components of the probe light. To the best of our knowledge, the effect of elliptically polarized probe light in the presence of external magnetic field on transient behaviors of inverted four-level Y-type atomic system is not presented.

2. Model and equation

We consider a four-level atomic system as depicted in Fig. 1. The two lower states $|1\rangle$ and $|2\rangle$ are the degenerate Zeeman sublevels corresponding respectively to the magnetic quantum numbers m=1 and m=−1 of a ground-state hyperfine level $F=1$. The two upper states $|3\rangle$, $|4\rangle$, are all the $m=0$ Zeeman sublevels, respectively, of different excited states and belong to hyperfine levels between which the electric dipole transitions are allowed. The medium is subject to a longitudinal magnetic field B that removes the degeneracy of the ground-state sublevels, where the magnetic field B shifts $m=\pm1$ levels by $\pm\Delta_B$. All the atoms are assumed to be optically pumped to the two ground-state levels $|1\rangle$ and $|2\rangle$, which therefore have the same incoherent populations equal to 1/2, i.e. $\rho_{11}=\rho_{22}\simeq 1/2$.

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An elliptically polarized control field with frequency ω_p and wave vector k_p is used to create electric dipole transitions from the exited state $\left|3\right\rangle$ to the ground states $\left|1\right\rangle$ and $\left|2\right\rangle$ simultaneously. A probe beam with electric field amplitude E_0 after passing through the QWP that has been rotated by angle θ becomes elliptically polarized. Thus the polarized probe beam can be decomposed into $E_p = E^+\sigma^+ + E^-\sigma^-$, where $E^+ = E_0/\sqrt{2}(\cos\theta + \sin\theta)e^{i\theta}$ and $E^- = E_0/\sqrt{2}(\cos\theta - \sin\theta)e^{-i\theta}$. Here, σ^+ and σ^- are the unit vectors of the right-hand circularly and the left-hand circularly polarized basis, respectively. The strength and phase difference of the two electric field components can be changed by QWP. Thus, the Rabi frequencies of the probe field become $\Omega_{p^+} = \Omega_p(\cos\theta + \sin\theta)e^{i\theta}$ and $\Omega_{p^-} = \Omega_p(\cos\theta - \sin\theta)e^{-i\theta}$. It is assumed that $\mu_{13} = \mu_{23} = \mu$ and $\Omega_p = \mu E_0/\sqrt{2}\hbar$. Electric dipole transition between states $\left|3\right\rangle$ and $\left|4\right\rangle$ is coupled by a control beam with carrier frequency ω_c and wave vector k_c.

In the interaction picture, the resulting 4×4 interaction Hamiltonian describing the atom–field interaction for the system under study can be written as:

$$H_{\text{int}} = 2\Delta_B\left|2\right\rangle\left\langle2\right| + (\Delta_B+\Delta_P)\left|3\right\rangle\left\langle3\right| + (\Delta_B+\Delta_P+\Delta_c)\left|4\right\rangle\left\langle4\right| + (\Omega_{P-}\left|3\right\rangle\left\langle1\right| + \Omega_{p+}\left|3\right\rangle\left\langle2\right| + \Omega_c\left|4\right\rangle\left\langle3\right|) + h.c \quad (1)$$

where the detuning parameters are defined as: $\Delta_p = \omega_{31} - \Delta_B - \omega_p = \omega_{32} + \Delta_B - \omega_p$, $\Delta_c = \omega_{43} - \omega_c$, where ω_{ij} is the frequency deference between level $\left|i\right\rangle$ and level $\left|j\right\rangle$. Δ_B is the Zeeman shift of levels $|1\rangle$ and $|2\rangle$ in the presence of the magnetic field and Δ_B is taken to zero for zero magnetic field. The density matrix equations of motion under the rotating wave approximation and in the rotating frame are:

$$\begin{aligned}
\frac{\partial\rho_{11}}{\partial t} &= \gamma_{31}\rho_{33} + i\Omega_{p-}\rho_{31} - i\Omega_{p-}\rho_{13},\\
\frac{\partial\rho_{22}}{\partial t} &= \gamma_{32}\rho_{33} + i\Omega_{p+}\rho_{32} - i\Omega_{p+}\rho_{23},\\
\frac{\partial\rho_{33}}{\partial t} &= -(\gamma_{31}+\gamma_{32})\rho_{33} + \gamma_{43}\rho_{44} + i\Omega_{p-}\rho_{13} - i\Omega_{p-}\rho_{31} + i\Omega_{p+}\rho_{23} - i\Omega_{p+}\rho_{32} + i\Omega_c\rho_{43} - i\Omega_c\rho_{34},\\
\frac{\partial\rho_{31}}{\partial t} &= -\left[i(\Delta_B+\Delta_p) + \frac{\gamma_{31}+\gamma_{32}}{2}\right]\rho_{31} + i\Omega_{p-}(\rho_{11}-\rho_{33}) + i\Omega_{p+}\rho_{21} + i\Omega_c\rho_{41},\\
\frac{\partial\rho_{44}}{\partial t} &= -\gamma_{43}\rho_{44} + i\Omega_c\rho_{34} - i\Omega_c\rho_{43},\\
\frac{\partial\rho_{21}}{\partial t} &= -2i\Delta_B\rho_{21} + i\Omega_{p+}\rho_{31} - i\Omega_{p-}\rho_{23},\\
\frac{\partial\rho_{32}}{\partial t} &= -\left[i(-\Delta_B+\Delta_p) + \frac{\gamma_{31}+\gamma_{32}}{2}\right]\rho_{32} + i\Omega_{p+}(\rho_{22}-\rho_{33}) + i\Omega_{p-}\rho_{12} + i\Omega_c\rho_{42},\\
\frac{\partial\rho_{41}}{\partial t} &= -\left[i(\Delta_B+\Delta_p+\Delta_c) + \frac{\gamma_{43}}{2}\right]\rho_{41} + i\Omega_c\rho_{31} - i\Omega_{p-}\rho_{43},\\
\frac{\partial\rho_{42}}{\partial t} &= -\left[i(-\Delta_B+\Delta_p+\Delta_c) + \frac{\gamma_{43}}{2}\right]\rho_{42} + i\Omega_c\rho_{32} - i\Omega_{p+}\rho_{43},\\
\frac{\partial\rho_{43}}{\partial t} &= -\left[i\Delta_c + \frac{\gamma_{31}+\gamma_{32}+\gamma_{43}}{2}\right]\rho_{43} + i\Omega_c(\rho_{33}-\rho_{44}) - i\Omega_{p-}\rho_{41} - i\Omega_{p+}\rho_{42}.
\end{aligned} \quad (2)$$

In the above equations, if we assume the cold atomic gas, the relaxation rates of coherence between the ground states $\left|1\right\rangle$ and $\left|2\right\rangle$ by collision and etc. are negligible thus can be safely omitted. The set of equations (2) can be solved numerically to obtain the transient and steady state response of the medium. In fact, response of the medium to the applied field is determined by the susceptibility χ_p, corresponding to two components of opposite circular polarization, for the $|3\rangle \leftrightarrow |1\rangle$ and $|3\rangle \leftrightarrow |2\rangle$ transitions, respectively, which are define as:

$$\chi_p = \frac{N\left|\mu\right|^2(\rho_{31}+\rho_{32})}{2\hbar\varepsilon_0\Omega_p} \propto (\rho_{31}+\rho_{32}) \quad (3)$$

where N is the atomic density number in the medium. Note that, the all parameters used in this paper are scaled by γ_{31}, which should be in the order of MHz for rubidium or sodium atoms. In this approach, when the Zeeman shift Δ_B is scaled by γ_{31}, then the magnetic field strength B should be in units of the combined constant $\gamma_c = \hbar g_F^{-1}\mu_B^{-1}\gamma_{31}$, where g_F is gyromagnetic factor and μ_B is the Bohr magneton. In the following numerical calculations we assume $\gamma_{31} = \gamma_{32} = \gamma$, $\gamma_{43} = 0.25\gamma$ and all the used parameters are scaled with γ.

3. Result and discussion

The numerical results for the transient and steady state of the absorption–dispersion with different corresponding parameters are shown in Figs. 2–6. In Fig. 2(a), with $\Delta_B = 0.0$, the effect of relative phase between two electric field components on absorption and dispersion properties is shown. If $\theta = 0$, an investigation shows that at time $t = 0$, the absorption immediately increases. Then it starts to oscillate with fast damping amplitude, and finally reaches to steady state value (solid line). By increasing the parameter θ to $\pi/6$, the absorption is decreased (dashed line) and finally for $\theta = \pi/3$, the probe absorption converts to the probe gain (dotted line). The transient behavior of dispersion is shown in Fig. 2(b). It is found that by increasing parameter θ, the dispersion value is enhanced. In this case the slope of dispersion is positive and group index correspond to the subluminal light propagation. It may be to emphasize that the dispersion in this system is positive for any value for relative phase. The effect of relative phase on transient absorption–dispersion behaviors for $\Delta_B = 2$ is displayed in Fig. 3(a) and (b). For $\theta = 0$ (solid line) and $\theta = \pi/6$ (dashed line) the absorption starts to increases as the time increases, while for $\theta = \pi/4$ (dotted line), the absorption starts to increase and finally reaches to the zero absorption at the steady state. In this case the medium become transparent to the weak probe field. Fig. 3(b) shows that for $\theta = 0$ (solid line) the dispersion is positive, and the light pulse