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Amplification without inversion, fast light and optical bistability in a duplicated two-level system

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ABSTRACT

The optical properties of a weak probe field in a duplicated two-level system are investigated in multi-photon resonance (MPR) condition and beyond it. It is shown that by changing the relative phase of applied fields, the absorption switches to the amplification without inversion in MPR condition. By applying the Floquet decomposition to the equations of motion beyond MPR condition, it is shown that the phase-dependent behavior is valid only in MPR condition. Moreover, it is demonstrated that the group velocity of light pulse can be controlled by the intensity of the applied fields and the gain-assisted superluminal light propagation (fast light) is obtained in this system. In addition, the optical bistability (OB) behavior of the system is studied beyond MPR condition. We apply an indirect incoherent pumping field to the system and it is found that the group velocity and OB behavior of the system can be controlled by the incoherent pumping rate.

1. Introduction

The study of the optical response of a medium is one of the most important fields in optics. Quantum coherence has a major role in determination of the optical properties of the systems and has various applications in optical physics [1]. It has been used to establish the Lasing without inversion (LWI) [2], electromagnetically induced transparency (EIT) [3], refractive index enhancement [4], optical bistability (OB) [5], and slow [6] and fast light [7]. In superluminal light propagation the group velocity of light pulse in a dispersive medium can exceed the speed of light in vacuum and can even be negative [8]. However, it does not violate Einstein's principle of special relativity. It is generally believed that complete information cannot be sent faster than the light speed in vacuum [9].

Recently the duplicated two-level (DTL) system has been extensively studied because of its interesting feature and potentiality of applications. The interaction of such a system with femtosecond coherent pulses has been studied by Delagnes and Bouchene and the efficient modulation of the medium gain for the probe field has been demonstrated due to the interference [10]. Slow light propagation through DTL system has been also studied and a new method based on Zeeman coherence oscillation for slow light has been presented in a transparency window [11]. Coherent control of the effective susceptibility through wave mixing has been studied in this system under MPR condition and a phase-dependent behavior due to a different quantum path associated with conjugate phase was presented [12]. The spatial interference of resonance fluorescence from two DTL atoms driven by two orthogonally polarized fields has been investigated in MPR condition. It was shown that the interference pattern can be recovered in fluorescence light of strongly driven atoms due to the effect of the relative phase of applied fields on the populations and atomic coherences [13]. Controllable OB and multistability behavior of a DTL atomic system has been studied and phase-dependent behavior has been obtained in MPR condition [14]. Recently the phase-control of the Goos–Hänchen shift using a DTL atomic medium has been reported in MPR condition [15].

It is well known that the optical properties of a closed-loop atomic system, under MPR condition, depend on the relative phase of applied fields [16]. This is due to the wave mixing of applied fields which is not generally allowed beyond MPR condition [17].

In this study, we investigate the optical properties of a DTL atomic system in MPR condition and beyond it. We obtain the amplification without inversion (AWI) under MPR condition and control it by the relative phase of applied field via the phase conjugation effect. Using the Floquet decomposition, the time-dependent differential equations of motion are solved beyond MPR condition. We find that in general the optical properties of the system are not phase-dependent. Moreover, the gain-assisted superluminal light propagation is obtained in this system. Moreover, the OB behavior of the system is calculated beyond MPR condition. Finally, by applying an indirect incoherent pumping

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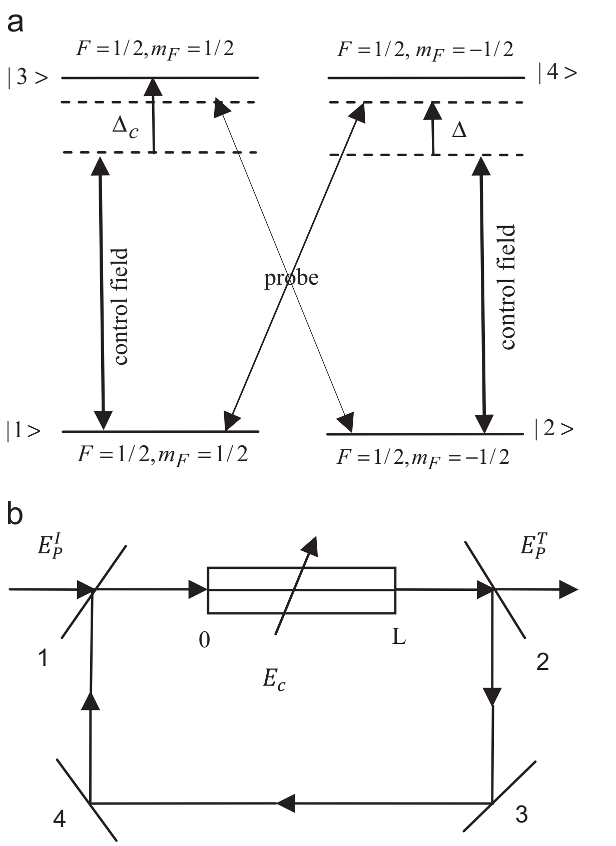

Fig. 1. (a) Schematic diagram of DTL system. (b) Unidirectional ring cavity with DTL sample of length L. E_p^I and E_p^T are the incident and transmitted fields, while $\vec{E}_p$ and $\vec{E}_c$ are the probe and control fields, respectively. For mirrors 1 and 2 it is assumed that $\overline{R}+\overline{T}=1$ and mirrors 3 and 4 have perfect reflectivity.

field to the system, it is demonstrated that the group velocity of light pulse as well as the OB behavior can be controlled by intensity of either coherent or incoherent pumping fields.

2. Theoretical analysis

2.1. Model and equations

We consider a DTL system with two degenerate ground states $|1\rangle$ and $|2\rangle$ and two degenerate excited states $|3\rangle$ and $|4\rangle$. The transitions $|1\rangle-|3\rangle$ and $|2\rangle-|4\rangle$ with identical m_F (with central resonance frequency $\omega_{31}=\omega_{24}$) are excited by a π-polarized control field $\vec{E}_c(t,y)=E_c\hat{e}_z\exp[-i(\omega_c t-k_c y)]+cc$ with Rabi frequency $\Omega_c=DE_c/\hbar$. A σ polarized probe field $\vec{E}_p(t,y)=E_p\hat{e}_x\exp[-i(\omega_p t-k_p y+\phi)]+cc$ with $\hat{e}_x=(\hat{e}_- -\hat{e}_+)/\sqrt{2}$ and Rabi frequency $\Omega_p=DE_p/\hbar$ is applied to the transitions $|1\rangle-|4\rangle$ and $|2\rangle-|3\rangle$ with different m_F as shown in Fig. 1(a). Here D denotes the dipole moment element of transitions. The parameter ϕ is the initial relative phase of applied fields. As a realistic example, we consider $F_{1/2}\rightarrow F_{1/2}$ transition (e.g. ${}^2S_{1/2}F_{1/2}\rightarrow {}^2P_{1/2}F_{1/2}$ transition of ^{6}Li at 671 nm) excited by two co-propagating, linearly polarized laser fields [11–13].

The density matrix equations of motion in the rotating wave approximation and in the rotating frame are given by

$$
\begin{aligned}
i\dot{\rho}_{11}&=[(\Omega_c\rho_{13}+\Omega_p\rho_{14}e^{-i\Phi(t,\vec{r})})-cc]+i\Gamma(\rho_{33}+2\rho_{44})/3\\
i\dot{\rho}_{22}&=[(-\Omega_c\rho_{24}+\Omega_p\rho_{23}e^{-i\Phi(t,\vec{r})})-cc]+i\Gamma(\rho_{44}+2\rho_{33})/3\\
i\dot{\rho}_{33}&=[-(\Omega_c\rho_{13}+\Omega_p\rho_{23}e^{-i\Phi(t,\vec{r})})-cc]-i\Gamma\rho_{33}\\
i\dot{\rho}_{44}&=[(\Omega_c\rho_{24}-\Omega_p\rho_{14}e^{-i\Phi(t,\vec{r})})-cc]-i\Gamma\rho_{44}\\
i\dot{\rho}_{31}&=\Omega_c(\rho_{33}-\rho_{11})+\Omega_p e^{-i\Phi(t,\vec{r})}(\rho_{34}-\rho_{21})+\overline{\Delta}_c^*\rho_{31}\\
i\dot{\rho}_{42}&=\Omega_c(\rho_{22}-\rho_{44})+\Omega_p e^{-i\Phi(t,\vec{r})}(\rho_{43}-\rho_{12})+\overline{\Delta}_c^*\rho_{42}\\
i\dot{\rho}_{12}&=-(\Omega_c\rho_{14}+\Omega_c^*\rho_{32})+(\Omega_p e^{-i\Phi(t,\vec{r})}\rho_{13}-\Omega_p^* e^{i\Phi(t,\vec{r})}\rho_{42})-i\Gamma_{zg}\rho_{12}\\
i\dot{\rho}_{34}&=-(\Omega_c\rho_{14}+\Omega_c^*\rho_{32})+(-\Omega_p e^{-i\Phi(t,\vec{r})}\rho_{24}+\Omega_p^* e^{i\Phi(t,\vec{r})}\rho_{31})-i\Gamma_{ze}\rho_{34}\\
i\dot{\rho}_{41}&=\Omega_c(\rho_{21}+\rho_{43})+\Omega_p e^{-i\Phi(t,\vec{r})}(\rho_{44}-\rho_{11})+\overline{\Delta}_c^*\rho_{41}\\
i\dot{\rho}_{32}&=-\Omega_c(\rho_{12}+\rho_{34})+\Omega_p e^{-i\Phi(t,\vec{r})}(\rho_{33}-\rho_{22})+\overline{\Delta}_c^*\rho_{32}
\end{aligned}
\tag{1}
$$

where $\overline{\Delta}_c=\Delta_c+i\Gamma_d$; $\Delta_c=\omega_{31}-\omega_c$, $\Phi(t,\vec{r})=\Delta t-(k_p\hat{e}_y-k_c\hat{e}_y)\cdot\vec{r}+\phi$ and $\Delta=\omega_p-\omega_c$. All the coherence except the ones between Zeeman levels relax with the rate Γ_d. In the absence of non-radiative dephasing processes, Γ_d reduces to $\Gamma/2$. The excited state Zeeman coherence ρ_{34} and the ground Zeeman coherence ρ_{12} relax with the rate Γ_{ze} and Γ_{zg}, respectively. In pure radiative dephasing (Γ_{ze}, Γ_{zg}) reduces to (Γ, 0) [12]. The decay rates from excited states to the ground states are assumed $\Gamma/3$ for identical m_F and $2\Gamma/3$ for different m_F. Eq. (1) can be simplified, due to the symmetry of the system, by a suitable change of variable. We define new variables as

$$
\begin{aligned}
&\rho_p=\rho_{32}+\rho_{41};\quad \rho_c=\rho_{31}-\rho_{42};\quad p_g=\rho_{11}+\rho_{22};\\
&p_e=\rho_{33}+\rho_{44};\ \rho_{zg}=\rho_{12}-\rho_{21};\quad \rho_{ze}=\rho_{34}-\rho_{43}.
\end{aligned}
\tag{2}
$$

Then Eq. (1) reduces to

$$
\begin{aligned}
i\dot{p}_g&=(\Omega_c\rho_c^*+\Omega_p e^{-i\Phi(t,\vec{r})}\rho_p^*-cc)+i\Gamma p_e-iR\,p_g\\
i\dot{\rho}_c&=\Omega_c(p_e-p_g)+\Omega_p e^{-i\Phi(t,\vec{r})}(\rho_{zg}+\rho_{ze})+\overline{\Delta}_c^*\rho_c-iR\,\rho_c\\
i\dot{\rho}_p&=-\Omega_c(\rho_{zg}+\rho_{ze})+\Omega_p e^{-i\Phi(t,\vec{r})}(p_e-p_g)+\overline{\Delta}_c^*\rho_p-iR\,\rho_p\\
i\dot{\rho}_{zg}&=(-\Omega_c\rho_p^*+\Omega_p e^{-i\Phi(t,\vec{r})}\rho_c^*+cc)-i\Gamma_{zg}\,\rho_{zg}\\
i\dot{\rho}_{ze}&=(-\Omega_c\rho_p^*+\Omega_p e^{-i\Phi(t,\vec{r})}\rho_c^*+cc)-i\Gamma_{ze}\,\rho_{ze}
\end{aligned}
\tag{3}
$$

Parameter R denotes the indirect incoherent pumping rate which is applied to the probe transitions.

2.2. Linear susceptibility and group velocity

The response of the system to the probe fields is determined by the susceptibility $\chi=\chi'+i\chi''$, which is defined as [18]

$$\chi(\omega_p)=\frac{2\alpha_0\Gamma_d}{k_p}\frac{\rho_p(\omega_p)}{\Omega_p\,e^{-i\varphi}} \tag{4}$$

where $\alpha_0=ND^2\omega_p/(2c\hbar\varepsilon_0\Gamma_d)$ and $k_p=\omega_p/c$. N is the atom number density in the medium. The real and imaginary parts of χ correspond to the dispersion and the absorption, respectively. The transition rate and dipole moment of the probe transition can be considered as $\Gamma=37$ MHz and $D=2.81\times10^{-29}$ cm, respectively. Then the atom density $N=4.36\times10^{11}$ atom/cm^3 and probe Rabi frequency $|\Omega_p|=0.01\,\Gamma$, lead to $2\alpha_0\Gamma_d/k_p\Omega_p\cong1$.

The group velocity of light pulse is determined by the slope of dispersion. We introduce the group index $n_g=c/v_g$, where the group velocity v_g is given by

$$v_g=\frac{c}{1+(1/2)\chi'(\omega_p)+(\omega_p/2)(\partial\chi'(\omega_p)/\partial\omega_p)}=\frac{c}{n_g}. \tag{5}$$

In a dispersive medium, the refractive index depends on the frequency and then the different frequency components of a light pulse experience the different phase velocities. Therefore the group velocity of light pulse in such a medium can exceed the velocity of light in vacuum which in general leads to the superluminal light propagation. In our notation the negative slope of