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Giant Kerr nonlinearity in a four-level atomic medium

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ABSTRACT

The linear and nonlinear response of a driven four-level Λ-type atomic system with two fold lower-levels with three driving fields is investigated. It is found that the giant Kerr nonlinearity can be achieved just by tuning the intensity of coupling fields. Maximal Kerr nonlinearity with zero linear and nonlinear absorption enters the EIT window. Also it is found that the relative phase between applied fields can change the Kerr nonlinearity behavior.

1. Introduction

Quantum coherence and quantum interference in an atomic system have shown a number of important phenomena, such as lasing without inversion (LWI) [1,2], cancellation of spontaneous emission [3], subluminal and superluminal light propagation [4,5], coherent population trapping (CPT) [6] and electromagnetically induced transparency (EIT) [7–9]. For two past decades, much kind of nonlinear quantum optical phenomena based on quantum coherence and interference have been studied in atomic media. Refractive part of the third order susceptibility which is known as Kerr nonlinearity plays a crucial role in nonlinear optics. The giant Kerr nonlinearity with reduced linear absorption causes the nonlinear optics to be studied at low light levels [10,11]. There are several applications that highlight the significance of having giant Kerr nonlinearities. For example it is shown that the enhanced Kerr nonlinearity has an essential role to cross-phase modulation for generation of optical solitons [12]. In addition, many usages in quantum information process (QIP) such as quantum bit regeneration [13], long-distance quantum teleportation [14], and Bell-state measurement [15]. In recent years, several atomic configurations by different methods were proposed for giant Kerr nonlinearity [16–18]. In Ref. [16] Niu and Gong showed that spontaneously generated coherence (SGC) enhanced the Kerr nonlinearity with zero linear absorption in usual three-level atomic media. Yan et al. investigated the effect of SGC on a four level atomic system too [17]. Moreover, the effect of dark resonances on Kerr nonlinearity had been shown by Niu et al. [18]. They had found that in the edge of probe field detuning the Kerr nonlinearity can be enhanced with zero linear absorption. Recently, it is shown that the relative phase between applied fields with closed loop can dramatically influence the optical properties of atomic medium [19–21].

In this paper, a four-level atomic medium for a giant Kerr nonlinearity with zero linear absorption is proposed. The effect of driving fields and relative phase between applied fields on linear and nonlinear susceptibility is discussed. Also, the group velocity of light propagation is investigated. It is shown that the giant Kerr nonlinearity can be obtained in a subluminal light propagation which is desirable for slow light level applications.

The paper is organized as follows: model and equation of motion are presented in Section 2. Analytical solution of density matrix equation for first and third order susceptibility is given in Section 3. We present result and discussion in Section 3 and finally, the conclusion can be found in Section 4.

2. Model and equations

Consider a three-level Λ type system with two fold lower-levels driven by three strong coupling laser fields and a weak tunable probe field each laser field allows to have only one transition Fig. 1. A weak tunable probe field couples the upper level $|b\rangle$ to level $|a\rangle$, and two closely lying lower levels $|c\rangle$ and $|d\rangle$ are coupled to the upper level $|b\rangle$ by two coherent driving fields and the level $|c\rangle$ and $|d\rangle$ are coupled by a microwave field. The Hamiltonian of this system is given by $H=H_0+H_I$, where H_0 is the free energy component and H_I is the Hamiltonian of the interaction picture.

$$\begin{aligned} H_0 &= \hbar\omega_a|a\rangle\langle a| + \hbar\omega_b\left|b\right\rangle\left\langle b\right| + \hbar\omega_c|c\rangle\langle c| + \hbar\omega_d\left|d\right\rangle\left\langle d\right|. \\ H_I &= -\hbar\Omega_1\exp(-i\upsilon_1 t)\left|b\right\rangle\langle a| - \hbar\Omega_2\exp(-i\upsilon_2 t)\left|b\right\rangle\langle c| \\ &\quad -\hbar\Omega_3\exp(-i\upsilon_3 t)|c\rangle\left\langle d\right| - \hbar\Omega_4\exp(-i\upsilon_4 t)\left|b\right\rangle\left\langle d\right| + H.C. \end{aligned} \tag{1}$$

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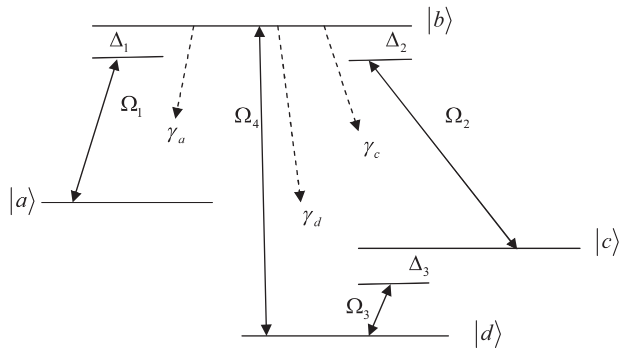

Fig. 1. Configuration of four level atomic system with two fold lower-levels.

where $\hbar\omega_i$ is the energy of state $|i\rangle$. The angular frequencies of the optical fields is υ_i and $\Omega_k = \varepsilon_k \wp_{ij}/\hbar\,(k=1,2,3), (i,j=c,b,d)$ are the corresponding Rabi frequencies where, ε_k is the amplitude of the laser fields and $\wp_{ij}$ denotes the electric dipole moments of $|i\rangle \to |j\rangle$ transition. The Rabi-frequency of the probe field is $\wp_{ba}$, where ε_p and μ_{ba} signify the amplitude of probe field and the electric dipole moment of $|a\rangle \to |b\rangle$ transition. The density-matrix approach for obtaining the dynamics of the whole system is used.

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] \tag{2}$$

Expanding Eq. (2) and after moving to an appropriate rotating wave, we can arrive to the density matrix equations of motion:

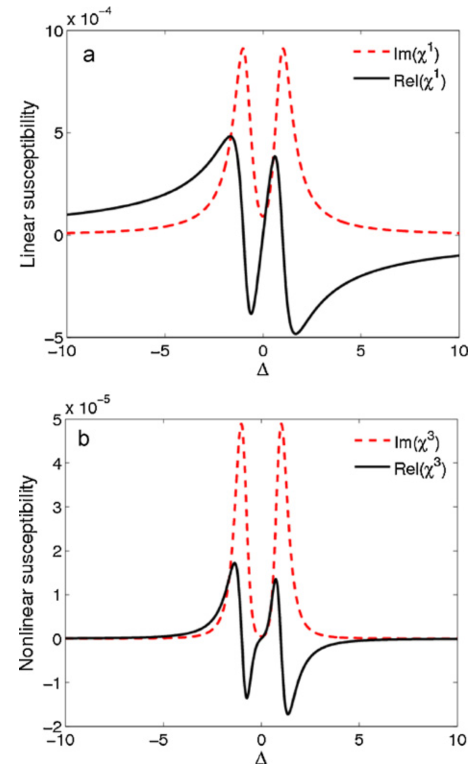

Fig. 3. Linear and nonlinear susceptibility versus probe field detuning. (a) Linear absorption (dashed line) and dispersion (solid line). (b) Nonlinear absorption (dashed line) and Kerr nonlinearity (solid line). $\Omega_2 = 1\gamma$ and other parameters are the same as Fig. 2.

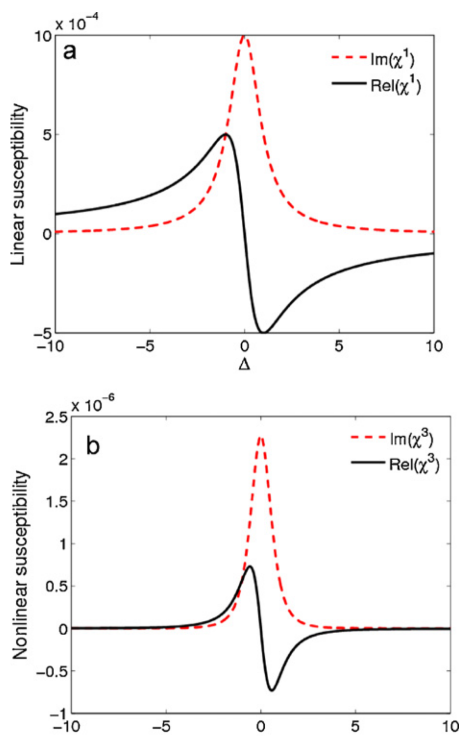

Fig. 2. Linear and nonlinear susceptibility versus probe field detuning. (a) Linear absorption (dashed line) and dispersion (solid line). (b) Nonlinear absorption (dashed line) and Kerr nonlinearity (solid line). The selected parameters are $\gamma_1 = 1\gamma$, $\gamma_2 = 0.1\gamma$, $\Omega_2 = \Omega_3 = \Omega_4 = 0.01\gamma$, $\gamma_a = 0.6\gamma$, $\gamma_c = 0.6\gamma$, $\gamma_d = 0.7\gamma$, $\Omega_p = 0.001$, $\varphi = 0$. $\gamma_{cd} = 0.1\gamma$, $\gamma_{bd} = 0.1\gamma$, $\gamma_{bc} = 0.1\gamma$ and $\Delta_2 = \Delta_3 = 0$.

$$\begin{aligned}
\dot{\tilde{\rho}}_{aa} &= -i(\Omega_1\tilde{\rho}_{ab} - \Omega_1^*\tilde{\rho}_{ba}) + \gamma_a\tilde{\rho}_{bb}.\\
\dot{\tilde{\rho}}_{bb} &= -i[-(\Omega_1\tilde{\rho}_{ab} - \Omega_1^*\tilde{\rho}_{ba}) + (\Omega_2^*\tilde{\rho}_{bc} - \Omega_2\tilde{\rho}_{cb}) + (\Omega_4^*\tilde{\rho}_{bd} - \Omega_4\tilde{\rho}_{db})] - (\gamma_a + \gamma_c + \gamma_d)\tilde{\rho}_{bb}.\\
\dot{\tilde{\rho}}_{cc} &= -i[(\Omega_3^*\exp(-i\varphi)\tilde{\rho}_{cd} - \Omega_3\exp(i\varphi)\tilde{\rho}_{dc}) - (\Omega_2^*\tilde{\rho}_{bc} - \Omega_2\tilde{\rho}_{cb}) + \gamma_c\tilde{\rho}_{bb},\\
\dot{\tilde{\rho}}_{dd} &= -i[(\Omega_4\tilde{\rho}_{db} - \Omega_4^*\tilde{\rho}_{bd}) - (\Omega_3^*\exp(-i\varphi)\tilde{\rho}_{cd} - \Omega_3\exp(i\varphi)\tilde{\rho}_{dc})] + \gamma_d\tilde{\rho}_{bb}.\\
\dot{\tilde{\rho}}_{ba} &= i\Omega_2\tilde{\rho}_{ca} + i\Omega_1(\tilde{\rho}_{aa} - \tilde{\rho}_{bb}) + i\Omega_4\tilde{\rho}_{da} - (\gamma_{ba} + i\Delta_1)\tilde{\rho}_{ba}.\\
\dot{\tilde{\rho}}_{ca} &= i\Omega_2^*\tilde{\rho}_{ba} - i\Omega_1\tilde{\rho}_{cb} + i\Omega_3\exp(i\varphi)\tilde{\rho}_{da} - (\gamma_{ca} + i\Delta)\tilde{\rho}_{ca}\\
\dot{\tilde{\rho}}_{da} &= -i\Omega_1\tilde{\rho}_{db} + i\Omega_3^*\exp(-i\varphi)\tilde{\rho}_{ca} + i\Omega_4^*\tilde{\rho}_{ba} - (\gamma_{da} + i(\Delta - \Delta_3))\tilde{\rho}_{da}.\\
\dot{\tilde{\rho}}_{bc} &= -i\Omega_2(\tilde{\rho}_{bb} - \tilde{\rho}_{cc}) + i\Omega_1\tilde{\rho}_{ac} - i\Omega_3^*\exp(-i\varphi)\tilde{\rho}_{bd} - (\gamma_{bc} + i\Delta_2)\tilde{\rho}_{bc} + i\Omega_4\tilde{\rho}_{dc}.\\
\dot{\tilde{\rho}}_{bd} &= i\Omega_2\tilde{\rho}_{cd} + i\Omega_1\tilde{\rho}_{ad} - i\Omega_3\exp(i\varphi)\tilde{\rho}_{bc} + i\Omega_4(\tilde{\rho}_{dd} - \tilde{\rho}_{bb}) - (\gamma_{bd} + i(\Delta_2 + \Delta_3))\tilde{\rho}_{bd}.\\
\dot{\tilde{\rho}}_{cd} &= i\Omega_2^*\tilde{\rho}_{bd} + i\Omega_3\exp(i\varphi)(\tilde{\rho}_{dd} - \tilde{\rho}_{cc}) - i\Omega_4\tilde{\rho}_{cb} - (\gamma_{cd} + i\Delta_3)\tilde{\rho}_{cd}.\\
\rho_{aa} &+ \rho_{bb} + \rho_{cc} + \rho_{dd} = 1.
\end{aligned} \tag{3}$$

where the detuning parameters are $\Delta_1 = \omega_{ba} - \upsilon_1$, $\Delta_2 = \omega_{bc} - \upsilon_2$, $\Delta_3 = \omega_{cd} - \upsilon_3$, corresponding to the frequency detuning of the probe field and the coherent control fields and we define $\Delta = \Delta_1 - \Delta_2$. Note that the driving fields of this system build a closed loop; therefore the relative phase between applied fields can impact the optical properties of the medium.

In order to derive linear and nonlinear part of susceptibilities, we have to solve our density matrix equation, in the steady state. We use the perturbation theory, in our approach, and the density matrix elements expand as: $\rho_{ij} = \rho_{ij}^{(0)} + \rho_{ij}^{(1)} + \rho_{ij}^{(2)} + \rho_{ij}^{(3)} + \ldots$. Because of this assumption that $\Omega_p \ll \Omega_1, \Omega_2, \Omega_3$, the zero$^{\text{th}}$ order solution will be $\rho_{ij}^{(0)} = 1$ and other elements are zero. Ultimately, we can get the expressions of the first and third order of matrix element ρ_{ba}:

$$\rho_{ba}^{(1)} = \frac{i\Omega_1(\Delta^2 + \Delta(\Delta_3 - 2i\wp_2) + i\Delta_3\wp_2 - \Omega_3^2 - \wp_2^2)}{A}, \tag{4}$$