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High refractive index and lasing without inversion in an open four-level atomic system

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ABSTRACT

In this letter, a novel atomic scheme is proposed to study the transient evolution of the atomic response with applications to lasing with and without population inversion. We introduce an open four-level atomic medium and compare its transient properties with the corresponding closed system. The impact of cavity parameters i.e. the atomic exit rate from cavity and atomic injection rates on transient response of weak probe field of open system are investigated. It is realized that existence of cavity parameters leads to some interesting results such as large amplification, high refractive index without absorption as well as lasing with and without inversion. These results cannot be obtained in corresponding closed system, due to lack of atomic exit and injection rates. This extra controllability and flexibility, makes open four-level system much more practical than its counterpart closed one.

1. Introduction

The optical properties of atomic gases can be radically modified by quantum coherence and quantum interference. Quantum coherence and interference in an atomic medium can result in many appealing outcomes. A marvellous consequence of preparing an atomic system in a coherent superposition of states is the absorption elimination that leads to the lasing without inversion [1,2], enhancement of the refraction index [3,4] and electromagnetically induced transparency (EIT) [5–9]. Under the conditions of electromagnetically induced transparency (EIT) it is feasible to control the optical response and related absorption of weak laser light. This effect has been deeply studied in atomic physics [10,11]. EIT has many noteworthy usages in quantum optics, such as the multi-wave mixing [12–16], enhancement of Kerr nonlinearity [17–20] and optical bistability and multistability [21]. More interestingly, the EIT effect has been found applications in quantum information science, such as the photon information storing and releasing in an atomic assemble [22], correlated photon pairs generation [23] and even the entanglement of remote atomic assembles [24], which form the building blocks of the quantum communication and the quantum computation. In view of many proposals, the transient properties of the weak probe field via quantum interference such as transient-absorption, transient-dispersion, and transient-gain without inversion are widely investigated [24,25]. Zhu presented the condition required for observing the inversionless gain in the transient requirement for V [26] and Λ [27] schemes. The effect of SGC on transient process in the three-level system has also been investigated [28]. It is shown that EIT medium can be used as an absorptive optical switch [29], in which the transmission of highly absorptive medium is controlled dynamically by an additional signal (switching) light. Transient two-photon absorption property in a n-doped three-level semiconductor quantum well system is also investigated [30]. It is shown that the intensities and detunings of the optical fields can affect the two-photon absorption spectra dramatically, which can be used to suppress or enhance the two- photon absorption coefficient. Yang et al. [31] studied the transient and steady state absorption of a weak probe beam by means of a coupled double quantum well structure. However, almost all of these studies are considered with a closed system. An ideal level structure atomic system with appreciate interference and coherence features will bring great help to achieve more bright results. To the best of our knowledge, the transient properties of four-level open atomic media is never investigated, which motivates us to carry out this work. The presented scheme is based On Refs. [32,33], but our scheme is very different from those works. First, we investigate the transient evolution of the atomic response instead of steady-state response. Second, transient behavior in our scheme is realized by atomic exit rate and atomic injection rates which are characteristics of open

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systems and thus, is very different from other conventional closed schemes. Finally, we show new convenient ways to obtaining the high refractive index without absorption as well as lasing with and without absorption, which make our scheme much more practical than the other counterparts. Our paper is organized as follows: in Section 2, we present the model and equations. Numerical results and physical discussion are studied in Section 3. Section 4 presents some simple conclusions are given.

2. Model and equations

Fig. 1 denotes an open four-level atomic system coupled by a weak probe field, and two strong coupling fields. Levels $|1\rangle$ and $|3\rangle$ are coupled via a weak probe field with Rabi frequency of $\Omega_p = \vec{\wp}_{31}.\vec{E}_p/2\hbar$ (amplitude E_p and frequency ω_p). An strong driving field with Rabi frequency of $\Omega_c = \vec{\wp}_{32} \times \vec{E}_c/2\hbar$ (amplitude E_c and frequency ω_c) is applied to transition $|2\rangle \rightarrow |3\rangle$. A coherent pump field of Rabi-frequency of $\Omega_s = \vec{\wp}_{41} \times \vec{E}_s/2\hbar$ with amplitude E_s and frequency ω_s couples levels $|1\rangle$ and $|4\rangle$. $\vec{\wp}_{ij}$ denotes the corresponding electric dipole moment. The spontaneous decay rates from upper level $|4\rangle$(and $|3\rangle$) to level $|1\rangle$ and $|2\rangle$ are defined as γ_{41}, γ_{42} $(\gamma_{31}, \gamma_{32})$, respectively. J_1 and J_2 are the atomic injection rates for levels $|1\rangle$ and $|2\rangle$, respectively. The ratio of the atomic injection rates is $X = J_2/J_1$. The atomic exit rate from the cavity is defined by r_0. We also assume that the number of interacting atoms is constant, which means that $r_0 = J_1 + J_2$. Using the rotating-wave and the electric dipole approximations and in the interaction picture, the density matrix equations of motion of this system can be written as:

$$\dot{\rho}_{11} = \gamma_{31}\rho_{33} + \gamma_{41}\rho_{44} + i\Omega_p(\rho_{31} - \rho_{13}) + i\Omega_s(\rho_{41} - \rho_{14}) + J_1 - r_0\rho_{11},$$

$$\dot{\rho}_{22} = \gamma_{32}\rho_{33} + \gamma_{42}\rho_{44} + i\Omega_c(\rho_{32} - \rho_{23}) + J_2 - r_0\rho_{22},$$

$$\dot{\rho}_{33} = -(\gamma_{31} + \gamma_{32})\rho_{33} + i\Omega_p(\rho_{13} - \rho_{31}) + i\Omega_c(\rho_{23} - \rho_{32}) - r_0\rho_{33},$$

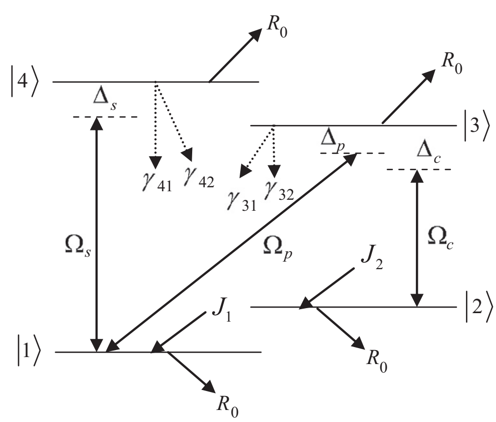

Fig. 1. The schematic of an open three-level ladder-type atomic system. The system will be a closed system if $r_0 = J_1 = J_2 = 0$.

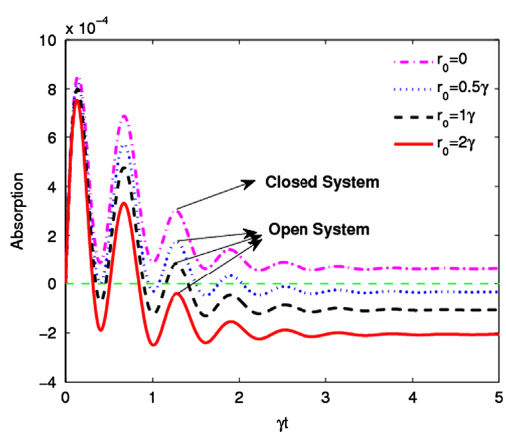

Fig. 2. Transient evolution of probe absorption for different values of r_0. The parameters values are $\gamma_{31} = \gamma_{32} = \gamma_{42} = \gamma_{42} = 3\gamma$, $\Omega_c = \Omega_s = 5\gamma$, $\Delta_p = 0.8\gamma, \Delta_s = 0$, $\Delta_c = \gamma$, $\Omega_p = 0.01\gamma$.

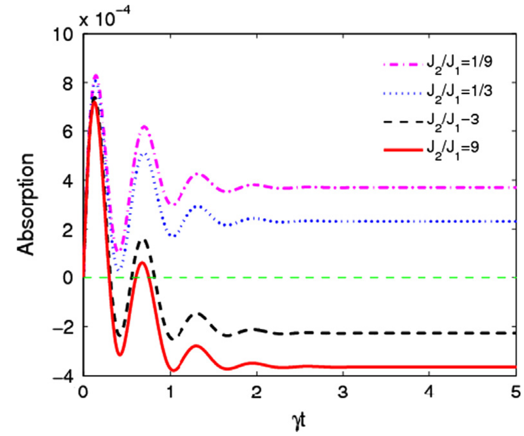

Fig. 3. Transient evolution of probe absorption for different values of X for open system. Here $r_0 = 2\gamma$ and the other parameters are the same as Fig. 2.

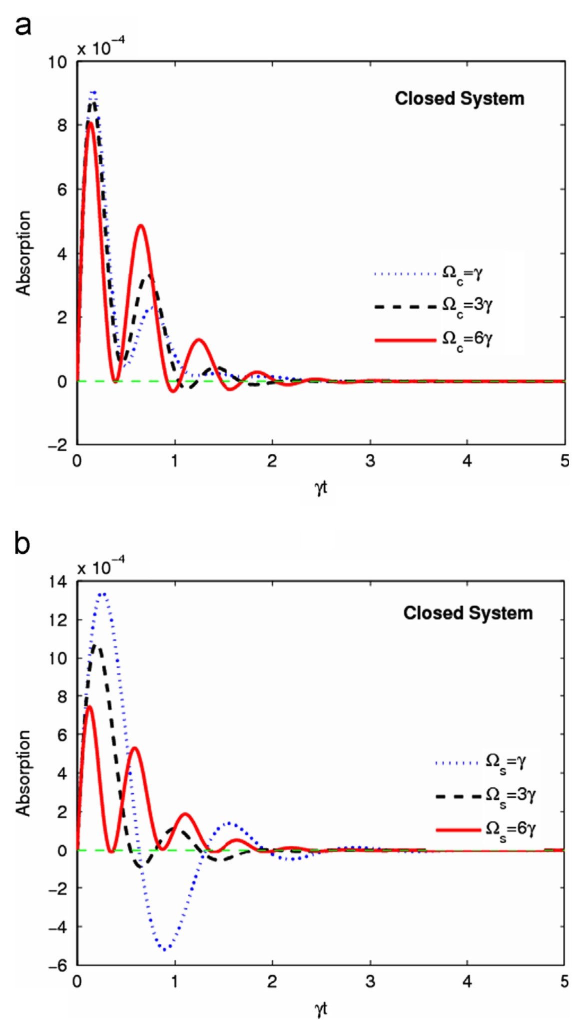

Fig. 4. Transient evolution of probe absorption for different values of (a) Ω_c, and Ω_s (b) for closed system. The parameters values are (a) $\Omega_s = 5\gamma$ and (b) $\Omega_c = 5\gamma$, $r_0 = J_1 = J_2 = 0$, $\Delta_p = \Delta_s = \Delta_c = 0$, the other parameters are the same as Fig. 2.