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Consideration of electromanetically induced transparency of four level atoms in quantum cavity with fully quantum approach

Saeideh Ghaempanah, Hassan Ranjbar Askari*, Zahra Raki

Department of Physics, Faculty of Science, Vali-e-AsrUniversity, Rafsanjan, Iran

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ABSTRACT

In this paper, an M type four level system in full quantum approach was considered. To investigate of the Electromagnetically Induced Transparency (EIT) in this system under radiation of one quantized probe field and two quantized control field, the relation between polarization and electric field, and the time evaluation equations of the density matrix were used. And finally the real and imaginary parts of susceptibility coefficients (χ) for an M type four level system in full quantum approach were obtained. Then, by plotting $Re(\chi)$ and $Im(\chi)$, the effect of parameters of system such as the amplitude of the control field, number of photon, detuning and decay rate on EIT in full quantum approach were investigated.

1. Introduction

Because of the remarkable influences of optical properties of low-dimensional systems in microelectronic and optoelectronic devices, it have become interesting fields to research. Quantum dots, quantum wire and quantum well are known as Small solid state devices, which can confine a few electrons in three, two and one spatial dimensions, respectively [1,2]. Due to this spatial confinement, energy states of quantum dots, quantum wire and quantum well are discrete. QDs have electronic and optical properties so that these particular properties can lead to interesting applications in optoelectronic devices [3–5]. Many concepts, such as spontaneous emission, coherence, quantum interference, entanglement, etc., that are the basis of optical phenomena like electromagnetically induced transparency and photon blockade, were discovered in quantum optics [6,7].

These phenomenon are used in the storage and processing of information and data transfer and calculations have been made faster and more reliable by using of these concepts in quantum systems. One of the ways to recover and store photon quantum states is electromagnetically induced transparency [8,9]. In this phenomenon, by applying a strong control field to the system, destructive quantum interference between excitation pathways is created, and the probe field is not absorbed by the system [10,11]. This quantum interference will cause the opaque medium converts to transparent environment and maximum dispersion is created. Zhang et al. [12] have considered influence of laser propagating direction on electromagnetic induced transparency. Effect of thermal motion on the phenomenon of electromagnetically induced transparency are

* Corresponding author at: Department of Physics, Faculty of Science, Vali-e-Asr University, Vallayat Blvd., Rafsanjan, Iran.
E-mail addresses: sghaempanah@yahoo.com (S. Ghaempanah), hraskari@vru.ac.ir (H.R. Askari), raki.zahra@yahoo.com (Z. Raki).

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studied by Zhang et al. [13]. Effects of structural parameters and geometrical size of the strained quantum wells on electromagnetically induced transparency have been studied [14]. Wana et al. [15] have considered electromagnetically induced transparency in a planar complementary metamaterial and its sensing. Pavlovic et al. [16] have also studied electromagnetically induced transparency in a spherical quantum dot with hydrogenic impurity in a four level ladder configuration. Dispersion and absorption properties of the Y-type-four-level system with electromagnetically induced transparency have been studied by Hua et al. [17].

The effects of different parameters of light and matter on EIT in systems that contain one or more atoms (quantum dot) [18,19] inside the cavity with different levels and configurations [20] were checked. In recent years, EIT in Λtype three level systems by using of the full quantum approaches was investigated [21]. In the approach, Effects such as the interaction of an atom with a vacuum field were observed. Khademi and et al. to investigate the measurement of photons number and squeezing parameter of photon state in a quantum cavity used a full quantum approach [22]. In this paper, theory of EIT is studied in M-type four level system by using of the full quantum approach and effects of amplitude of the control fields, number of photon, detuning and decay rate are also investigated.

2. Theory of EIT

The phenomenon of EIT can be observed in systems with the number of levels more than two levels. Three dipole allowed transitions and three dipole forbidden transitions are required for a four level system. Some energy level structures of four level systems are: W type, M type and C type. In this paper, electromagnetically induced transparency in a four level M-type system was investigated. To view EIT, four level system interacts with three quantized electromagnetic fields (one probe field and two control fields), according to Fig. 1. The initial state of total system is $\left|a, n_p, n_{c_1}, n_{c_2}\right\rangle = \left|1\right\rangle$ so that n_p is the photon number of probe field and n_{c_1}, n_{c_2} are the photon numbers of two control fields. With interaction between atoms and probe fields, system absorbs a photon and changes to $\left|d, n_p-1, n_{c_1}, n_{c_2}\right\rangle = \left|4\right\rangle$ and then with interaction between atoms and two control fields and emission of coupling photon, system changes into $\left|c, n_p-1, n_{c_1}, n_{c_2}+1\right\rangle = \left|3\right\rangle$ or$\left|b, n_p-1, n_{c_1}+1, n_{c_2}\right\rangle = \left|2\right\rangle$. $\left|1\right\rangle$ Is a stable ground state, $\left|2\right\rangle$, $\left|3\right\rangle$ and $\left|4\right\rangle$ are excited. Υ_{12}, Υ_{13} and Υ_{14} are decay rates for states $\left|2\right\rangle$, $\left|3\right\rangle$and $\left|4\right\rangle$, respectability. $\hat{\sigma}_{nm} = |n\rangle\langle m|$, $(n, m = a, b, c, d)$ is the atomic transition operator from level $|m\rangle$ to $|n\rangle$. Transitions$\left|1\right\rangle \to \left|4\right\rangle$, $\left|2\right\rangle \to \left|4\right\rangle$ and $\left|3\right\rangle \to \left|4\right\rangle$ are allowed transitions and $\left|1\right\rangle \to \left|2\right\rangle$, $\left|1\right\rangle \to \left|3\right\rangle$ and $\left|2\right\rangle \to \left|3\right\rangle$ are forbidden transitions. The atomic transition σ_{14}which is observed with resonant frequency $\omega_{41} = (E_4 - E_1)/\hbar$ is driven by a quantized weak probe field with frequency $\omega_P$and amplitude of electric fieldE_P. The atomic transitions $\hat{\sigma}_{24}$and $\hat{\sigma}_{34}$ which are performed at resonant frequencies $\omega_{42} = (E_4 - E_2)/\hbar$and $\omega_{43} = (E_4 - E_3)/\hbar$ are driven by two strong control fields with frequency ω_{c_1} and $\omega_{c_2}$and amplitudes of electric field $E_{c_1}$and E_{c_2}, respectability. $\Delta_p = \omega_{41} - \omega_p$, $\Delta_{c_1} = \omega_{42} - \omega_{c_1}$ and $\Delta_{c_2} = \omega_{43} - \omega_{c_2}$ are detuned from resonance frequencies for a probe field and two control fields, respectively.

By using of dipole approximation, applied electric fields are written as [23]:

$$\vec{E}(r,t) = \sum_{j=p,c_1,c_2} g_j \left(\hat{a}_j e^{-i\omega_j t} + \hat{a}_j^{\dagger} e^{i\omega_j t}\right), \tag{1}$$

Where $\omega_j\,(j = p, c_1, c_2)$, $\hat{a}_j$ $\left(\hat{a}_j^{\dagger}\right)$, $g_j = \sqrt{\hbar\omega_j/2\varepsilon_\circ \upsilon}$ are frequencies, annihilation (creation) operators and amplitude of the electric field of probe and control lasers, respectively and $\upsilon$is the cavity volume.

The total Hamiltonian of system is given by:

$$\hat{H} = \hat{H}_{\circ A} + \hat{H}_{\circ F} + \hat{V}(t), \tag{2}$$

$\hat{H}_{\circ A} + \hat{H}_{\circ F}$ is the unperturbed part of Hamiltonian for the quantum system and $\hat{V}(t)$ is an interaction Hamiltonian which describes interaction of the four level system with the electromagnetic fields.

Where atom Hamiltonian $\hat{H}_{\circ A}$can be written as:

$$\hat{H}_{0A} = \sum_{n=(a,b,c,d)} E_n |n\rangle\langle n|, \tag{3}$$

Where $E_n$is eigenvalue corresponding to eigenkets $|n\rangle$of $\hat{H}_{\circ A}$.

$\hat{H}_{\circ F}$Is quantum fields Hamiltonian and is written as:

$$\hat{H}_{\circ F} = \sum_{j=(p\ ,c_1,c_2)} \hbar\omega_j \left(\hat{a}_j^{\dagger}\hat{a}_j + \frac{1}{2}\right), \tag{4}$$

Interaction of the quantum system with the electromagnetic fields is described by interaction Hamiltonian $\hat{V}(t)$as:

$$\hat{V}(t) = -\vec{\mu}\cdot\vec{E}, \tag{5}$$