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Effects of electric field and structure on the electromagnetically induced transparency in double quantum dot

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ABSTRACT

We theoretically investigated the effects of electric field and structural parameters of the confining potential on the optical properties of a GaAs/AlGaAs double quantum dot related to the occurrence of the electromagnetically induced transparency phenomenon, using the compact density-matrix formalism and the effective mass approximation. The dependences of the absorption coefficient, refraction index and light group velocity on the Rabi frequency of the control field, intensity of the static electric field, asymmetry parameter of the potential and dot dimension are discussed in detail. It is found that electromagnetically induced transparency occurs in the system for intermediate field values and its transparency window for probe field absorption and sub- and super-luminal frequency interval of the probe field are blueshifted by the increment of the electric field strength and dot dimension but are redshifted by the augment of the asymmetry parameter of the potential.

1. Introduction

Electromagnetically induced transparency (EIT) is one of the most interesting effects of quantum optics as it allows the coherent control of the optical properties of materials and processes. In this phenomenon, an opaque medium of three-level atoms (or nanostructures) is rendered transparent in the presence of a pair of near-resonant fields. When the weak probe laser is turned on in the presence of a strong coupling laser, dressed states are produced as a coherent superposition of the bare initial states. The destructive interference in the absorption of the dressed states lowers the absorption at the resonant frequency of the probe laser. Also, a large variation in the linear dispersion within the transparency window is created, which can lead to a slowing down of the group velocity of light [1,2]. EIT has been observed in atoms [3,4], rare-earth-ion doped crystals [5], nitrogen-vacancy center in diamond [6], semiconductor quantum wells [7–9] and ultra-cold sodium vapors [10]. EIT may have wide applications in quantum information processing [11], optical memory [12] and optical switches [13,14].

Although, EIT in atomic medium was largely studied, quantum wells (QWs) and quantum dots (QDs) are excellent candidates for investigation of EIT in these structures. Quantum confinement of carriers inside the QDs or QWs results in the discretization of their energy levels, closely resembling an atomic structure. Also, it is easier to isolate a definite number of QWS or QDs in comparison with atoms, or modify their properties by external agents such as external electric and magnetic fields, or even structural parameters.

Many studies were devoted in the last years to the theoretical investigation of the EIT in QDs semiconductor nanostructures. Thereby, one founds papers about EIT and associated optical properties realized on cylindrical GaAs QD with parabolic confining potential [15,16], InAs hemispherical quantum dot with a wetting layer embedded in a GaAs barrier [17], spherical QD [18,19] or two-dimensional QD [20].

In the present work we investigate the effects of electric field and structural parameters of the confining potential on the optical properties of a GaAs double quantum dot (DQD) related to the realization of the electromagnetically induced transparency phenomenon. A method to create a system of two coupled dots is to deposit metal gates on top of a GaAs/AlGaAs heterostructure grown by molecular beam epitaxy, with a 2D electron gas below the surface. Applying a negative voltage to all gates depletes the electron gas underneath them and forms two quantum dots [21,22]. Such gate-defined DQD devices were the subject of experimental [21,23] and theoretical studies [24–32]. In our previous papers we studied the modulation of the optical properties of these structures by an intense laser field (ILF) [29], by the combined effects of ILF and a static electric field [30,31] or by the presence of a donor impurity under electric field [32].

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As GaAs/AlGaAs DQD is a good candidate for EIT occurrence in Λ-configuration, because among the lowest three levels the transition between the first two levels has an almost zero dipole moment, this will be the subject of the present paper. To our knowledge, EIT in the quantum double dot system under the influence of an electric field has not been investigated so far. The paper is organized as follows. In Section 2, we present our theoretical model and explain the general theory. In Section 3, the numerical results and detailed discussions are given. Finally, the conclusions are presented in Section 4.

2. Theory

In the framework of the effective mass approximation, a two-dimensional double dot QD under applied electric field is described by the Hamiltonian:

$$H_0 = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right) + V(x,y) \pm eFx \tag{1}$$

where m^* is the electronic effective mass in QD and e is the absolute value of the electron charge. The confinement potential of the double dot structure is:

$$V(x,y) = \frac{1}{2}m^*\frac{\omega_0^2}{D^{2+\delta}}\left|x-\frac{D}{2}\right|^{2+\delta}\left(x+\frac{D}{2}\right)^2 + \frac{1}{2}m^*\frac{\omega_0^2}{D^2}\left(y^4+2D|y|^3 + D^2y^2\right) = V_x(x)+V_y(y). \tag{2}$$

An analogous potential was proposed before by Selstø and Førre [24]. In Eq. (2), ω_0 defines the strength of the potential barrier between the wells and D is the inter-dot distance. The asymmetry of the quantum dot system is described by the parameter δ.

The eigenvalues $E = E_x + E_y$ and eigenfunctions $\Phi(x,y) = \psi(x)\phi(y)$ may be calculated numerically by solving two one-dimensional equations. The considered three states for EIT occurrence are: the ground state $|1\rangle \equiv \Phi_1(x,y) \equiv \psi_0(x)\phi_0(y)$, the first excited state $|2\rangle \equiv \Phi_2(x,y) \equiv \psi_1(x)\phi_0(y)$ and the second excited state $|3\rangle \equiv \Phi_3(x,y) \equiv \psi_2(x)\phi_0(y)$. As we will prove in the following, the highest energy state $|3\rangle$ has a nonzero coupling dipole moment to both $|1\rangle$ and $|2\rangle$ states, whereas the transition $1\to 2$ is a dipole-forbidden one. These characteristics define a three-level system in a Λ-type configuration, shown in Fig. 1.

In order to obtain the electromagnetically induced transparency, a pair of near-resonant fields is coupled to the Λ-system. So, an electromagnetic field of frequency ω_p and strength $\vec{E}_p$, termed the probe field, is applied on the allowed $1\to 3$ transition, which is observed at the resonant frequency $\omega_{31} = (E_3 - E_1)/\hbar$. The $3\to 2$ transition, having the resonant frequency $\omega_{32} = (E_3 - E_2)/\hbar$, is driven by the control field having the frequency ω_c and the strength $\vec{E}_c$. The probe and control lasers are detuned from the resonance frequencies by $\Delta_p = \omega_{31} - \omega_p$ and $\Delta_c = \omega_{32} - \omega_c$, respectively. The interaction Hamiltonian reads as:

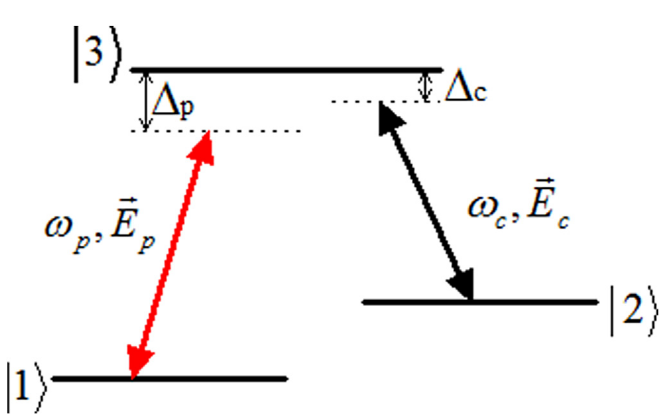

Fig. 1. Three energy levels in Λ-configuration for EIT occurrence.

$$H_{\text{int}}(t) = -\vec{\mu}\cdot\vec{E} \tag{3}$$

where $\vec{\mu} = -e\vec{r}$ is electric dipole moment operator and $\vec{E}$ is the electric field strength of the applied laser pulses:

$$\vec{E}(\vec{r},t) = \frac{\vec{E}_p}{2}\left[\exp(i\omega_p t)+\exp(-i\omega_p t)\right] + \frac{\vec{E}_c}{2}\left[\exp(i\omega_c t) + \exp(-i\omega_c t)\right]. \tag{4}$$

In the rotating-wave approximation [33], we can represent the Hamiltonian of the three-level system interacting with the applied laser pulses as:

$$H = H_0 + H_{\text{int}} = -\hbar\begin{bmatrix} 0 & 0 & \Omega_p \\ 0 & -(\Delta_p - \Delta_c) & \Omega_c \\ \Omega_p & \Omega_c & -\Delta_p \end{bmatrix}, \tag{5}$$

where Ω_p and Ω_c are half of the Rabi frequencies [33] and are defined as:

$$\Omega_p = \frac{\Omega_p^R}{2} = \frac{\vec{\mu}_{31}\cdot\vec{E}_p}{2\hbar}, \tag{6}$$

$$\Omega_c = \frac{\Omega_c^R}{2} = \frac{\vec{\mu}_{32}\cdot\vec{E}_c}{2\hbar}. \tag{7}$$

Here $\vec{\mu}_{31}$ and $\vec{\mu}_{32}$ are the dipole moment matrix elements associated with the transition driven by the probe laser and the control laser, respectively.

The Hamiltonian from Eq. (5) has a new set of eigenstates called dressed states [34] that depend on the bare states and on the "mixing angles" θ and φ:

$$\begin{aligned} |a^+\rangle &= \sin\theta\ \sin\phi\ |1\rangle - \cos\phi\ |3\rangle + \cos\theta\ \sin\phi\ |2\rangle \\ |a^-\rangle &= \sin\theta\ \cos\phi\ |1\rangle + \sin\phi\ |3\rangle + \cos\theta\ \cos\phi\ |2\rangle \\ |a^0\rangle &= \cos\theta\ |1\rangle - \sin\theta\ |2\rangle, \end{aligned} \tag{8}$$

where for the two photon resonance ($\Delta_p = \Delta_c$) the mixing angles are given by:

$$tg\theta = \frac{\Omega_p}{\Omega_c},\quad tg2\phi = \frac{2\sqrt{\Omega_p^2+\Omega_c^2}}{\Delta_p}. \tag{9}$$

The state $|a^0\rangle$ contains no amplitude from the bare state $|3\rangle$. For this reason $|a^0\rangle$ is also called a dark state because from this state there is no possibility of excitation to $|3\rangle$ and subsequent spontaneous emission. Therefore, the state $|a^0\rangle$ remains at its bare energy, whereas the pair of states $|a^+\rangle$ and $|a^-\rangle$ are shifted by an amount $\Delta E^\pm$ around E_3:

$$\Delta E^\pm = \frac{\hbar}{2}\left(\Delta_p \pm \sqrt{\Delta_p^2 + 4\Omega_p^2 + 4\Omega_c^2}\right). \tag{10}$$

The dynamics of the system is governed by the master equation for the density matrix: