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Effects of external fields, dimension and pressure on the electromagnetically induced transparency of quantum dots

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ABSTRACT

Effects of external electric and magnetic fields, dimension and pressure on the electromagnetically induced transparency of a pumped-probe GaAs quantum dot are investigated. To study the electromagnetically induced transparency, the probe absorption and group velocity along with refractive index of the medium are discussed. It is found that electromagnetically induced transparency occurs in the system and its frequency, transparency window and group velocity of the probe field strongly depend on the external fields, pressure and the dot size. Significant effects of external factors on the quantum dot structures have the potential applications for implementation of electromagnetically induce transparency, slow lights, optical switches and quantum information storages.

1. Introduction

Great developments in nano-fabrication technology have made it now possible to design quantum dots (QDs). In such systems, few electrons are confined into a point-like structure and they can behave as artificial atoms. Consequently, they can be used to design electronic and optical devices [1–4].

The topic of light–matter interaction in semiconductor nanostructures has triggered a huge research effort both due to its importance in the fundamental understanding of these structures and in the many applications that depend on them [5]. For example, QDs have excellent linear and nonlinear optical properties mainly due to discrete energy states which result from three-dimensional confinement that making them good candidates for most optoelectronic applications [6–9]. The study of these interactions has experienced a pronounced development over the last few decades, both experimentally and theoretically. In these processes, progress has been made by advancing the foundations laid by pioneering observations, such as electromagnetically induced transparency (EIT) [10,11]. EIT in multi-level systems is based on quantum interference effects involving coherence between the states [12,13]. In this phenomenon, the medium is rendered transparent to a resonant probe laser field that couples one of the transitions by the application of a strong coupling field to the other transition, and 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 [14–18].

Up to now, the most theoretical and experimental works related to EIT are done in the atomic medium with different configurations [19]. The dispersive properties of the medium are significantly modified as has been recently demonstrated by the impressive reduction in the group velocity of a light pulse to only 17 m/s and the “freezing” of a light pulse in an atomic medium [20,21]. Controlling the group velocity of a light pulse is of great interest in optical communication and quantum information processing. Subluminal light propagation has potential applications in optical buffering, data synchronization, optical memories and optical signal processing. In a completely different context, superluminal group velocities have been considered in the problem of electromagnetic or matter wave packet tunnelling through potential barriers [22–24].

Although, a great deal of works has been done to study the EIT in atomic medium, QDs on the other hand have excellent benefits for investigation the EIT in these structures. For example, it is easier to isolate a definite number of QDs in comparison with atoms, or modify their properties by external agents such as external electric and magnetic fields, dimension, or even structural stress.

The purpose of this paper is to study the production and controlling the electromagnetically induced transparency in QDs and the variation of the optical properties in these pseudo-atomic systems. In particular, we study the absorption, dispersion and

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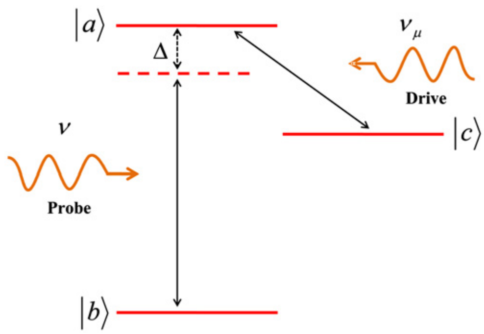

Fig. 1. The energy diagram of a three-level Λ-type atom interacting with two laser beams.

group velocity of the probe light pulse and their variation with external fields, pressure and dimension in these nanostructures. In contrast to the previous works which are based on the spin properties and coherency of the spin states in semiconductors [25–27], here we have focused on the sub-band states of QDs due to their strong dependence on the external agents and exhibition THz transitions. Observation of EIT and clear effects of external factors on this phenomena and group velocity of the laser pulse are proposed for design and fabrication of optical switches and light traps by QD structures.

2. Electromagnetically induced transparency

A three-level quantum mechanical system in which levels $|a\rangle$ and $|b\rangle$ are coupled by a probe field of amplitude $\mathcal{E}_p$, frequency ν, and level $|a\rangle$ is coupled to level $|c\rangle$ by a strong coherent field of amplitude $\mathcal{E}_\mu$ and frequency ν_μ is shown in Fig. 1. In the absence of the pump laser, one observes a standard absorption resonance profile, but under certain conditions, the addition of the pump laser prevents absorption in a narrow portion of the resonance profile, and the transmitted intensity as a function of the probe frequency has a narrow peak of induced transparency. The Hamiltonian of this three-level configuration, which is named Λ-configuration, in the rotating wave approximation, is obtained by a suitable extension of the Hamiltonian for a two-level system interacting with a single mode field and is given by [28]

$$H=H_0+H_I, \tag{1}$$

where H_0 and H_I represent the unperturbed and interaction parts of Hamiltonian, in which

$$H_0=\hbar\omega_a|a\rangle\langle a|+\hbar\omega_b|b\rangle\langle b|+\hbar\omega_c|c\rangle\langle c| \tag{2}$$

and

$$H_I=-\frac{1}{2}(\wp_{ab}\mathcal{E}_p\exp(-i\nu t)|a\rangle\langle b|)-\frac{\hbar}{2}\Omega_\mu \exp(-i\phi_\mu)\exp(-i\nu_\mu t)|a\rangle\langle c|)+H.c. \tag{3}$$

We have assumed that only $|a\rangle\leftrightarrow|c\rangle$ and $|a\rangle\leftrightarrow|b\rangle$ transitions are dipole allowed. The upper level is coupled to level $|c\rangle$ by a strong coherent field of frequency ν_μ, having complex Rabi frequency $\Omega_\mu\exp(-i\phi_\mu)$, where off-diagonal decay rates for ρ_{ab}, ρ_{ac} and ρ_{cb} are denoted by γ_1, γ_2 and γ_3, respectively.

Equations of motion for the density matrix elements are given by

$$\dot\rho_{ab}=-(i\omega_{ab}+\gamma_1)\rho_{ab}-\frac{i}{2}\frac{\wp_{ab}\mathcal{E}_p}{\hbar}\exp(-i\nu t)(\rho_{aa}-\rho_{bb}) +\frac{i}{2}\Omega_\mu\exp(-i\phi_\mu)\exp(-i\nu_\mu t)\rho_{cb}, \tag{4}$$

$$\dot\rho_{cb}=-(i\omega_{cb}+\gamma_3)\rho_{cb}-\frac{i}{2}\frac{\wp_{ab}\mathcal{E}_p}{\hbar}\exp(-i\nu t)\rho_{ca} +\frac{i}{2}\Omega_\mu\exp(i\phi_\mu)\exp(i\nu_\mu t)\rho_{ab}, \tag{5}$$

$$\dot\rho_{ac}=-(i\omega_{ac}+\gamma_2)\rho_{ac}+\frac{i}{2}\frac{\wp_{ab}\mathcal{E}_p}{\hbar}\exp(-i\nu t)\rho_{bc} -\frac{i}{2}\Omega_\mu\exp(-i\phi_\mu)\exp(-i\nu_\mu t)(\rho_{aa}-\rho_{cc}). \tag{6}$$

If the system is initially prepared in the ground state, $|b\rangle$, then the dispersion and absorption are determined by ρ_{ab}. So, we have used the following initial condition, which means that the system is in the ground state at $t=0$

$$\rho^0_{bb}=1,\quad \rho^0_{aa}=\rho^0_{cc}=0. \tag{7}$$

Substituting these values into Eqs. (4) and (5) and making use of the following relation:

$$\rho_{ab}=\frac{\epsilon_0\chi\mathcal{E}_p}{2\wp_{ab}}e^{-i\nu t}, \tag{8}$$

one can find the following expression of the real and imaginary parts of the complex susceptibility, $\chi=\chi_1+i\chi_2$:

$$\chi_1=\frac{N|\wp_{ab}|^2\Delta[\gamma_3(\gamma_3+\gamma_1)+\Delta^2-\gamma_1\gamma_3-\frac{1}{4}\Omega_\mu^2]}{\epsilon_0\hbar Z}, \tag{9}$$

$$\chi_2=\frac{N|\wp_{ab}|^2[\Delta^2(\gamma_3+\gamma_1)-\gamma_3(\Delta^2-\gamma_1\gamma_3-\frac{1}{4}\Omega_\mu^2)]}{\epsilon_0\hbar Z}, \tag{10}$$

where N is the density of three-level systems, $\wp_{ab}$ is the dipole moment, between levels $|a\rangle$ and $|b\rangle$ due to the probe field, $\Delta=\omega_{ab}-\omega_p$ is the detuning of the probe laser frequency, and

$$Z=(\Delta^2-\gamma_1\gamma_3-\left(\frac{1}{4}\right)\Omega_\mu^2)^2+\Delta^2(\gamma_3+\gamma_1)^2. \tag{11}$$

The imaginary part of susceptibility, $Im(\chi)$, determines the absorptive spectrum and the real part, $Re(\chi)$, is related to the refractive index, as follows:

$$\alpha(\omega_p)=k\,Im\,\chi(\omega_p), \tag{12}$$

$$n(\omega_p)=1+\frac{1}{2}Re\,\chi(\omega_p), \tag{13}$$

where $\alpha(\omega_p)$ is the absorption coefficient and $k=2\pi/\lambda$. Also, the group velocity of a light pulse can be determined by the slope of the dispersion. In dispersive medium, the frequency components of a light pulse experience different refractive indices, and the group velocity of a light pulse in such a material can exceed the speed of light in vacuum, leading to super-luminal light propagation. The group velocity of the probe light pulse (GVPLP), is given by the following equation [29]:

$$v_g=\frac{c}{n(\omega_p)+\omega_p\dfrac{dn}{d\omega_p}}. \tag{14}$$

Now, we introduce the group index (GI), $n_g=c/v_g-1$, to study the sub- and super-luminal properties of the medium. If $n_g>0$, then GVPLP is smaller than c and the propagation is subliminal, but if $n_g<0$, GVPLP is larger than c (even negative) and the propagation is superluminal [30].

The group velocity describes the speed of any feature of a wave that relies on different frequencies remaining in phase. For example, a pulse of finite width will contain a range of frequencies, and the center of the pulse will occur where they are all in phase, so it will move with this velocity.

Under the vacuum the group and phase velocities for all frequencies are the same, but in most materials, the group velocity depends not only on the refractive index but also on