Optical Materials 64 (2017) 540–547

Contents lists available at ScienceDirect

Optical Materials

journal homepage: www.elsevier.com/locate/optmat

Electromagnetically induced transparency in an asymmetric double quantum well under non-resonant, intense laser fields

E.C. Niculescu

Physics Department, "Politehnica" University of Bucharest, 313 Splaiul Independentei, RO-060042, Bucharest, Romania

ARTICLE INFO

Article history:
Received 8 September 2016
Received in revised form
6 December 2016
Accepted 3 January 2017

Keywords:
Electromagnetically induced transparency
Asymmetric double quantum well
Intense laser field
Transparency window

ABSTRACT

Electromagnetically induced transparency in an asymmetric double quantum well subjected to a non-resonant, intense laser field is theoretically investigated. We found that the energy levels configuration could be switched between a Λ-type and a ladder-type scheme by varying the non-resonant radiation intensity. This effect is due to the laser-induced electron tunneling between the wells and it allows a substantial flexibility in the manipulation of the optical properties. The dependence of the susceptibilities on the control field Rabi frequency, intensity of the nonresonant laser, and the control field detuning for both configurations are discussed and compared.

1. Introduction

During the last few decades there have been intensive investigations of physical phenomena based on quantum interference and coherence such as coherent population trapping [1], electromagnetically induced transparency (EIT) [2], lasing without inversion [3], enhancing Kerr nonlinearity [4], multiwave mixing [5], optical bistability and multistability [6,7]. Particularly, electromagnetically induced transparency, as a quantum effect that permits the propagation of light pulses through an otherwise opaque medium, has attracted considerable attention because it can lead to subluminal and superluminal group velocities [8–11]. Although up to now most of the theoretical and experimental works related to EIT were done in the atomic medium with different configurations [12–14] the possibility of observing efficient an EIT and slow light propagation in semiconductor quantum well structures is of particular significance. Quantum systems have properties similar to atomic vapors such as discrete energy levels but, due to the quantum-confinement effect, they have the advantages of high nonlinear optical coefficients and large electric dipole moments of intersubband transitions [15–18]. Moreover, in nanostructure-based devices the transition energies and electron wave-function symmetries can be engineered by external agents such as applied electric and magnetic fields, system size, or even structural stress [19–22].

Experimental realization of EIT in a semiconductor structure has been reported in Refs. [23–27]. Theoretical investigation of the optical properties and EIT in semiconducting nanostructures has also been a matter of some studies in the last few years. The optimization of the intraband electromagnetically induced transparency in strained InAs/GaAs quantum dot have been discussed in Refs. [28–30]. Raki et al. [31,32] have presented numerical simulations related to light polarization effects on the EIT in GaAs cylindrical quantum dot with a parabolic confining potential. Effects of the external magnetic fields on EIT in a quantum dot with a hydrogenic impurity have been recently examined by Rezaei et al. [33] and Pavlović and Stevanović [34].

Interesting effects are expected in multiple quantum structures. Yang et al. [35] analyzed the absorption-dispersive properties of a weak probe laser field based on the intersubband transitions in a triple semiconductor quantum well structure driven coherently by two control laser fields. They found that the dispersion can be changed between normal and anomalous by adjusting the relative phase between two coherent control fields. The studies of Villas-Boas et al. [36] and Hamedi et al. [37] related to a double quantum dot system have shown that the tunnel coupling has a major influence on enhancing the transmission coefficient of the probe beam.

In this paper we analyze the occurrence of the electromagnetically induced transparency effect in an asymmetric double

E-mail address: niculescu@physics.pub.ro.

http://dx.doi.org/10.1016/j.optmat.2017.01.005

quantum well subjected to an intense, non-resonant laser field (NLF). As the confining potential is very sensitive to this kind of external perturbation, the energy levels configuration could be switched between a Λ-type and a ladder-type scheme by a proper tailoring of the NLF intensity. Thus, the transparency window and group velocity of the probe field, under the EIT condition, are strongly dependent on the NLF strength, which becomes an important tool for manipulating the optical properties of the medium.

2. Theoretical framework

2.1. Three-level system coupled to the near-resonant laser fields

Here we shall study the intersubband electromagnetically induced transparency in the three-level double quantum well under an intense, **non-resonant** laser field. In order to obtain the EIT mechanism in a three-level system, it is required to have two dipole allowed transitions and one dipole forbidden transition. As we will prove in the following, an asymmetric DQW with a thick central barrier behaves such as a Λ-type (ladder-type) configuration at smaller (higher) non-resonant laser intensities. In the Λ configuration - see Fig. 1(a) - the transition $1\rightarrow 2$ is a dipole-forbidden one. A near-resonant electromagnetic field of frequency ω_c and the strength $\vec{E}_c$, termed the control field, is applied on the allowed $2\rightarrow 3$ transition which is observed at the resonant frequency $\omega_{23} = (E_3 - E_2)/\hbar$.

The $1\rightarrow 3$ allowed transition, having the resonant frequency $\omega_{13} = (E_3 - E_1)/\hbar$, is driven by a weak laser radiation (the probe field) of frequency ω_p and the strength $\vec{E}_p$. The probe and control lasers are detuned from the resonance frequencies by $\Delta_p = \omega_{13} - \omega_p$ and $\Delta_c = \omega_{23} - \omega_c$, respectively. In the ladder configuration (Fig. 1(b)) the probe field drives the transition $1\rightarrow 2$ and $\Delta_p = \omega_{12} - \omega_p$, whereas the control field is applied on the $2\rightarrow 3$ transition.

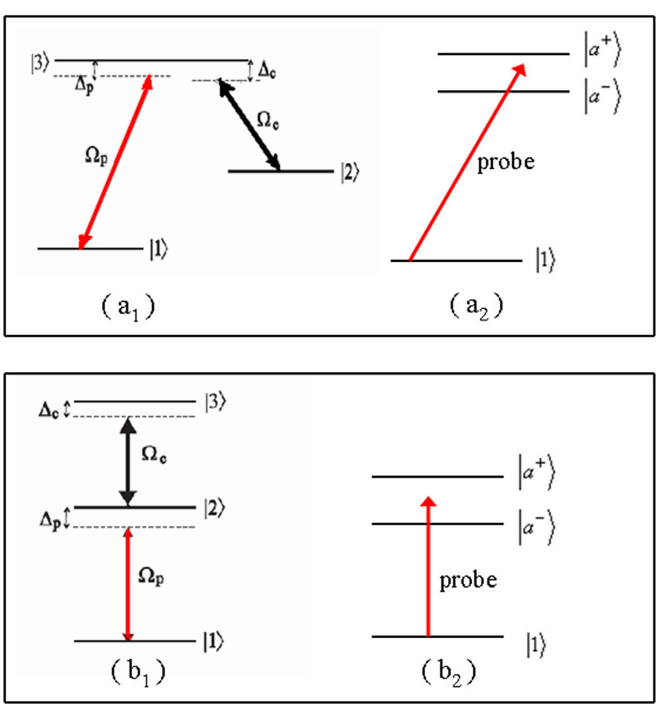

Fig. 1. Energy diagram of a Λ- type (upper) and a ladder-type (lower) three level system. (a_1) and (b_1): bare states; (a_2) and (b_2): dressed states.

The interaction between the material and the electromagnetic field can be described within the rotating wave approximation [38–41]. To briefly summarize the outcome of such a procedure, we note that the total Hamiltonian H can be written as a sum of the unperturbed part of Hamiltonian H_0 of the bare system and the interaction Hamiltonian, $H_i(t)$, which describes the coupling of the system to the electromagnetic fields. The interaction Hamiltonian is given by

$$H_i(t) = -\vec{\mu}\cdot\vec{E} \tag{1}$$

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

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

Within the dipole approximation $H_i(t)$ is often expressed in terms of the Rabi frequencies Ω_p and Ω_c defined as

$$\Omega_p = \frac{\vec{\mu}_{p1}\cdot\vec{E}_p}{2\hbar}, \tag{3a}$$

$$\Omega_c = \frac{\vec{\mu}_{32}\cdot\vec{E}_c}{2\hbar}. \tag{3b}$$

Here $\vec{\mu}_{p1}$ and $\vec{\mu}_{32}$ are the dipole moment matrix elements associated with the transition driven by the probe laser and the control laser, respectively. Introducing the rotating-wave approximation [40], we can represent the Hamiltonian of the three-level atom interacting with the applied laser pulses as:

$$H = -\hbar\begin{bmatrix} 0 & 0 & \Omega_p \\ 0 & -(\Delta_p - \Delta_c) & \Omega_c \\ \Omega_p & \Omega_c & -\Delta_p \end{bmatrix}. \tag{4a}$$

for the Λ-configuration and

$$H = -\hbar\begin{bmatrix} 0 & \Omega_p & 0 \\ \Omega_p & -\Delta_p & \Omega_c \\ 0 & \Omega_c & -(\Delta_p + \Delta_c) \end{bmatrix} \tag{4b}$$

for a ladder-type structure, respectively.

An alternative and equivalent picture is to consider the dressed rather than the bare states. In this view [40] the eigenstates of the Hamiltonian H can be expressed in terms of the “mixing angles” θ and ϕ, which depend on the Rabi frequencies as well as on the Δ_p and Δ_c detunings. For the Λ configuration, the dressed eigenstates can then be written [40] in terms of the bare states as:

$$\begin{aligned} |a^+\rangle &= \sin\theta\cos\phi|1\rangle - \sin\phi|3\rangle + \cos\theta\cos\phi|2\rangle \\ |a^-\rangle &= \sin\theta\sin\phi|1\rangle + \cos\phi|3\rangle + \cos\theta\sin\phi|2\rangle \\ |a^0\rangle &= \cos\theta|1\rangle - \sin\theta|2\rangle \end{aligned} \tag{5}$$

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

$$tg\theta = \frac{\Omega_p}{\Omega_c}, tg2\phi = 2\frac{\sqrt{\Omega_p^2 + \Omega_c^2}}{\Delta_p}. \tag{6}$$

Note that the state $|a^0\rangle$ has no contribution from the bare state $|3\rangle$. As a result, it represents the dark state because for a system in this state there is no possibility of excitation to $|3\rangle$ and