Physica B 458 (2015) 58–62

Contents lists available at ScienceDirect

Physica B

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

Controlling light pulse in triangular quantum well nanostructure via quantum interference

Faramarz Ebadpour [a], Ali Golestani [b,*], Ahad Darkhosh [c]

[a] Department of Physics, Marand Branch, Islamic Azad University, Marand, Iran
[b] Research Institute for Applied Physics and Astronomy, University of Tabriz, Tabriz, Iran
[c] Physics Department, Ataturk University, Erzurum, Turkey

ARTICLE INFO

Article history:
Received 21 October 2014
Received in revised form
1 November 2014
Accepted 4 November 2014
Available online 7 November 2014

Keywords:
Triangular quantum well
Refractive index
Absorption coefficient
Quantum interference

ABSTRACT

We study numerically the optical properties of the intersubband transitions in AlGaAs/GaAs triangular quantum well nanostructure. The Schrödinger equation is being solved numerically for this structure using homemade codes. Afterward the refractive index and the absorption coefficient are calculated for general triangular quantum well using the density matrix formalism. The density matrix equations are being solved numerically for calculation of linear susceptibility. The effect of quantum interference between spontaneous emission decays on the refractive index, absorption coefficient and group velocity is studied for purposed triangular quantum well nanostructure. The result shows the linear optical properties and group index can be controlled via quantum interference between spontaneous emission decays.

1. Introduction

Recently great attention has been paid to the semiconductor nanostructures for their applications in optoelectronics devices such as optical modulators and detectors [1–3]. Therefore, the electronic structures, optical properties of quantum wells have been commonly studied by using various calculation methods [4–6]. The GaAs-based devices potentially have great advantages such as high electron mobility, high thermal stability, low noise and wide temperature operating range [7,8]. Thus the GaAs-based structures are suitable for the implementation of devices such as emitters and detectors.

In recent years, many enhanced linear and nonlinear phenomena have been observed base on electromagnetically induced transparency (EIT) in cold atoms [9–14]. The advantages of EIT and its potential applications has led to many interesting optical phenomena such as Kerr nonlinearity [15–17], optical bistability [18,19], four-wave mixing (FWM) [20–22] and electron localization [23,24]. While the fundamental aspects of EIT investigated in cold atoms, for practical applications, such as optical telecommunication, we need to use it on solid-state material. The quantum interference effects of electromagnetic fields with intersubband transitions in quantum wells and dots have led to the observation of interesting effects such as EIT [25–27] and tunneling induced transparency (TIT) [28,29]. In these studies, atomic-like theoretical approaches have been used for the description of the electron dynamics of the intersubband transitions.

In several articles, slow and subluminal light propagation in semiconductor systems have been theoretically and experimentally demonstrated [30–37]. The dispersion and absorption properties of the semiconductor quantum wells are studied [38–40]. The effect of electric field on the linear and the nonlinear optical intersubband absorption coefficients in quantum well systems are calculated [41–44]. Ahn and et al. calculated the linear and nonlinear optical intersubband absorption coefficients for general asymmetric quantum well systems using the density matrix formalism. They studied the electric field dependence of the linear and the third order nonlinear intersubband optical absorption coefficients of a semiconductor quantum well [45]. Also the linear and the third order nonlinear absorption coefficients and refractive index changes in the quantum well with confinement potential are investigated theoretically [46–48]. In these studies, mostly the influence of the applied electric field on the refractive index and the absorption coefficient are investigated. In addition, the relative phase dependent [49,50] and the Fano interference [39,51] on controlling of light propagation are studied in quantum well systems.

In this paper, we will study the impact of quantum interference on the refractive index changes and absorption coefficient. Recently, we investigated these properties in square coupled quantum wells numerically [36] and now, we want to examine the

* Corresponding author.
E-mail addresses: f.ebadpour@marandiau.ac.ir (F. Ebadpour), aligolestani.sh@gmail.com (A. Golestani).

http://dx.doi.org/10.1016/j.physb.2014.11.004
0921-4526/

controllability of optical properties in triangular quantum well. We consider a triangular potential in our calculations and then analyze the effect of the quantum interference on optical properties in purposed triangular quantum well nanostructure.

This paper is organized as follows: in Section 2, we introduce the typical AlGaAs/GaAs triangular quantum well and calculate the linear susceptibility by the density matrix formalism. Then the refractive index changes and absorption coefficient by the calculated linear susceptibility are obtained. The numerical results are discussed in Section 3, and the conclusion could be found in Section 4.

2. The electronic structure and equations

We consider a four-subband triangular quantum well structure as shown in Fig. 1. The schematic of energy levels diagram of a AlGaAs/GaAs triangular quantum well is displayed. This structure consists of GaAs layer with thickness of 30 nm that is sandwiched between two layers of AlGaAs barrier with thickness of 15 nm. Dependence of bandgap on alloy composition for As-based ternary semiconductors as function of mole percentages is $1.424+1.247x$, $0<x<0.45$ and $1.424+1.087x+0.438x^2$, $x>0.45$ [36]. The transition energy for transitions ($|1\rangle \rightarrow |4\rangle$), ($|2\rangle \rightarrow |4\rangle$) and ($|2\rangle \rightarrow |3\rangle$) are 120, 73 and 39 meV, respectively.

In order to study the optical properties of the purposed triangular quantum well structure, we have to solve the Schrödinger equation. The Schrödinger equation for a conduction-band electronic structure is given by

$$\frac{\hbar^2}{2m^*}\nabla^2\psi(z)+V(z)\psi(z)=E\psi(z) \tag{1}$$

where E and $\psi(\vec{r})$ are the energy eigenvalue and the wave function, respectively. Both of them will be obtained by Finite Difference Method (FDM) solution for Schrödinger equation which is related to transition frequencies $\hbar\omega_{ji}=\left(E_j-E_i\right)$. Also we have considered the effective potential as $V(z)=q\mathcal{E}z$, where $\mathcal{E}$ is constant electric field. By using numerical wave function, we can define the electronic transition dipole moment which is $\mu_{ji}=\left\langle\phi_j(z)\middle|ez\middle|\phi_i(z)\right\rangle$. We develop homemade codes to calculate the dipole moments.

As mentioned above four subbands are considered in the conduction band of this asymmetric quantum well which is consists of a ground subband $|1\rangle$, two intermediate subband ($|2\rangle$ and $|3\rangle$) and an upper subband $|4\rangle$. In this four subband triangular quantum well structure, the intersubband dipole moments of the relevant transitions are defined by $\mu_{ij}(i,j=1-4\&i\neq j)$ where μ_{ij} denotes the dipole moment for the transition between subbands $|i\rangle$ and $|j\rangle$. The transition ($|1\rangle \rightarrow |4\rangle$) is coupled by a weak probe laser field. Also the transitions ($|2\rangle \rightarrow |4\rangle$) and ($|2\rangle \rightarrow |3\rangle$) are coupled by the strong control lasers. The corresponding Rabi frequency of the probe and control fields are $\Omega_P=\varepsilon_P\mu_{14}/2\hbar$, $\Omega_{C1}=\varepsilon_{C1}\mu_{24}/2\hbar$ and $\Omega_{C2}=\varepsilon_{C2}\mu_{23}/2\hbar$ respectively, where ε_P, ε_{C1} and ε_{C2} are the amplitudes of probe and control laser fields. The configuration and interaction of these fields with quantum well system is shown in Fig. 1.

The total Hamiltonian for this system includes the free energy and interaction terms state as

$$H=H_0+H_1, \tag{2}$$

where

$$H_0=\hbar\omega_1|1\rangle\langle 1|+\hbar\omega_2|2\rangle\langle 2|+\hbar\omega_3|3\rangle\langle 3|+\hbar\omega_4|4\rangle\langle 4| \tag{3}$$

and

$$H_1=-\hbar\Omega_P e^{-i\nu_P t}|4\rangle\langle 1|-\hbar\Omega_{C1}e^{-i\nu_{C1}t}|4\rangle\langle 2|-\hbar\Omega_{C2}e^{-i\nu_{C2}t}|3\rangle\langle 2| + C.C. \tag{4}$$

Here, H_0 is the free energy term and H_1 denotes interaction Hamiltonian of the system with the probe, control laser fields.

The dynamical behavior of the system is governed by the density matrix equation of motion,

$$\frac{d\rho}{dt}=-\frac{i}{\hbar}[H,\rho] \tag{5}$$

The density matrix equations of motion in the rotating wave approximation and in rotating frame are [52]

$$\begin{aligned}
\dot{\rho}_{11}&=\gamma_1\rho_{44}+i\Omega_P(\rho_{41}-\rho_{14})\\
\dot{\rho}_{22}&=\gamma_4\rho_{44}+\gamma_3\rho_{33}+i\Omega_{C2}\rho_{32}-i\Omega_{C2}\rho_{23}\\
&\quad+i\Omega_{C1}(\rho_{42}-\rho_{24})+\eta\sqrt{\gamma_3\gamma_4}(\rho_{34}e^{i\phi}+\rho_{43}e^{-i\phi})\\
\dot{\rho}_{33}&=-\gamma_3\rho_{33}+i\Omega_P\rho_{41}+i\Omega_{C2}(\rho_{23}-\rho_{32})\\
&\quad-\frac{\eta}{2}\sqrt{\gamma_3\gamma_4}(\rho_{34}e^{i\phi}+\rho_{43}e^{-i\phi})\\
\dot{\rho}_{21}&=-i(\Delta_P-\Delta_{C1})\rho_{21}+i\Omega_{C2}\rho_{31}-i\Omega_P\rho_{24}+i\Omega_{C1}\rho_{41}\\
\dot{\rho}_{31}&=\left(\frac{1}{2}\gamma_3-i(\Delta_P+\Delta_{C2}-\Delta_{C1})\right)\\
&\quad\rho_{31}+i\Omega_{C2}\rho_{21}-i\Omega_P\rho_{34}-\frac{\eta}{2}\sqrt{\gamma_3\gamma_4}\rho_{41}e^{-i\phi}\\
\dot{\rho}_{41}&=-\left(\frac{(\gamma_1+\gamma_4)}{2}+i\Delta_P\right)\rho_{41}+i\Omega_{C1}\rho_{21}\\
&\quad+i\Omega_P\left(\rho_{11}-\rho_{44}\right)-\frac{\eta}{2}\sqrt{\gamma_3\gamma_4}\rho_{31}e^{i\phi}\\
\dot{\rho}_{32}&=-\left(\frac{1}{2}\gamma_3+i\Delta_{C2}\right)\rho_{32}-i\Omega_{C1}\rho_{34}+i\Omega_{C2}\left(\rho_{22}-\rho_{33}\right)\\
&\quad-\frac{\eta}{2}\sqrt{\gamma_3\gamma_4}\rho_{42}e^{-i\phi}\\
\dot{\rho}_{42}&=-\left(\frac{(\gamma_1+\gamma_4)}{2}+i\Delta_{C1}\right)\rho_{42}+i\Omega_P\rho_{12}\\
&\quad+i\Omega_{C1}\left(\rho_{22}-\rho_{44}\right)-i\Omega_{C2}\rho_{43}-\frac{\eta}{2}\sqrt{\gamma_3\gamma_4}\rho_{32}e^{i\phi}\\
\dot{\rho}_{43}&=\left(\frac{(\gamma_1+\gamma_3+\gamma_4)}{2}-i(\Delta_{C2}-\Delta_{C1})\right)\\
&\quad\rho_{43}+i\Omega_P\rho_{13}+i\Omega_{C1}\rho_{23}-i\Omega_{C2}\rho_{42}\\
&\quad-\frac{\eta}{2}\sqrt{\gamma_3\gamma_4}(\rho_{33}+\rho_{44})e^{i\phi}\\
\rho_{11}&+\rho_{22}+\rho_{33}+\rho_{44}=1
\end{aligned} \tag{6}$$

The linear response of the triangular quantum well system to the applied fields is determined by the nonlinear susceptibility $\chi^{(1)}$, which depends on coherence term $\rho_{14}^{(1)}$.

$$\chi^{(1)}=\frac{2N\left|\mu_{14}\right|^2}{\varepsilon_0\hbar\Omega_P}\rho_{14}^{(1)} \tag{7}$$

Here, N is the sheet electron density in the medium. In order to obtain the linear susceptibility, solving the steady state solution of the density matrix equations is required. Here, the density matrix elements are expanded as $\rho_{ij}=\rho_{ij}^{(0)}+\rho_{ij}^{(1)}+\rho_{ij}^{(2)}+...$, the zeroth order solution of ρ_{11} will be identical, i.e. $\rho_{11}^{(0)}=1$, and other zeroth elements are set to be zero. In next section, the density matrix equations for an AlGaAs/GaAs triangular quantum well are numerically solved.