Optik 126 (2015) 3807–3811

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Excitonic effects on linear and nonlinear optical absorption coefficients and refractive index changes in one-dimensional quantum dots with linear potential

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ARTICLE INFO

Article history:
Received 15 June 2014
Accepted 16 July 2015

Keywords:
Excitonic effects
Optical absorption
Refractive index changes
Linear potential

ABSTRACT

Excitonic effects on linear and nonlinear optical absorption coefficients (OAC) and refractive index changes (RIC) in one-dimensional quantum dots with linear potential are theoretically investigated within the framework of the compact-density-matrix approach and iterative method. It is found that linear and nonlinear OAC and RIC with excitonic effects in one-dimensional quantum dots are larger than that without excitonic effects. Besides, when excitonic effects are considered, our results show a remarkable dependence of linear and nonlinear OAC and RIC on linear potential.

1. Introduction

Optical and electronic properties in nano materials have been so intensively studied for many years owing to these unique properties that are beyond their bulk counterparts. Especially with the rapid advances in nanofabrication techniques such as molecular beam epitaxy and metal-organic chemical vapor deposition and their several variants such as chemical beam epitaxy and atomic layer epitaxy, it is possible to produce a variety of nano materials such as quantum wells, quantum wires, and quantum dots by controlling size, shape,chemical environment and composition, which further advances research on optical and electronic properties in nano materials. In the past few years linear and nonlinear optical properties associated with electronic transitions in nano materials such as quantum wells, quantum wires and quantum dots have been intensively investigated [1–10]. These properties have become the important physical foundation for many optoelectronic devices such as high-speed electro-optical modulators, far infrared photodetectors, semiconductor optical amplifiers [11–13]. Due to the existence of a strong quantum confinement effect, nonlinear optical effects in low-dimensional nano materials can be enhanced more dramatically over those in bulk materials, which is crucial for the evolution of the emerging nanoelectronics and has great influences on linear and nonlinear optical properties in low-dimensional nano materials. Therefore, linear and nonlinear optical properties in low-dimensional nano materials are studied by many researchers. Among nano materials, nonlinear optical properties about quantum dots have gained considerable attention due to their novel physical properties and potential applications. There are some experimental results obtained for nonlinear optical properties in quantum dots [14–16], which shows that quantum dots have very large nonlinear optical susceptibilities as compared with those in bulk semiconductors. In quantum dots, quantum size effects also lead to formation of atomic-like discrete energy levels and drastic changes of optical properties of quasi-zero-dimensional structures. In addition, in quantum dots, carriers are confined in three spatial dimensions, which substantially enhances the overlap between holes and electron clouds, and leads to enhancement of the coulomb binding energy and oscillator strength. Therefore, it is necessary to consider excitonic effects. Recently, excitonic effects on linear and nonlinear optics properties in quantum dots with different shapes and various confinement potentials are investigated by many researchers. In 2001, Wang et al. [17] investigated excitonic effects on the third-harmonic generation in disc-like quantum dots with parabolic potential, and studied the strong confinement and the weak confinement, with the result that the THG coefficient is greatly enhanced when excitonic effects are considered. Wang et al. [18] also studied linear and nonlinear optical absorptions considering excitonic effects in a parabolic quantum dot. Besides, in disc-like and spherical quantum dots, excitonic effects on linear and nonlinear optical properties are also studied by some researchers [19–21]. For example, Xie reported optical absorptions of an exciton in a disc-like quantum dot under an electric field [19]. Yakar et al. [20] reported excitonic effects on linear and nonlinear optical

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http://dx.doi.org/10.1016/j.ijleo.2015.07.108
0030-4026/

properties of spherical quantum dot with parabolic potential using algorithm and Hartree-Fock Roothaan method. Rezaei et al. [21] reported external electric field effect on optical rectification coefficient of an exciton in a spherical parabolic quantum dot. Besides, excitonic effects in one-dimensional quantum dots are reported by some authors and some interesting results are obtained. For instance, in 2005, Yu et al. [22] discussed exciton effects on nonlinear optical rectification in one-dimensional quantum dots with parabolic potential, with the conclusion that the optical rectification coefficient is greatly enhanced because of the quantum confinement of exciton. In 2008, excitonic effects on the nonlinear optical properties of semi-parabolic quantum dots within the framework of strong confinement approximation were studied by Karabulut et al. [23]. In 2010, excitonic effects on nonlinear intersubband optical properties of a semi-parabolic one-dimensional quantum dot in the strong confinement regime where the coulomb term is considered perturbation were reported by Razaei et al. [24], which presents new result that the peaks of linear and nonlinear optical coefficients with and without excitonic effects have not the same horizontal ordinate. However, excitonic effects on linear and nonlinear optical absorption coefficients and refractive index changes in one-dimensional quantum dots with linear potential have not been reported. In this paper, a detailed study will be given about this problem.

2. Theory

2.1. Energy eigenvalues and eigenfunctions of an exciton confined in one-dimensional quantum dots with linear potential

Let us consider an exciton confined in one-dimensional quantum dots with linear potential. Within the framework of effective mass approximation, the Hamiltonian of the system is given by

$$H=-\frac{\hbar^2}{2m_e^*}\frac{\partial^2}{\partial z_e^2}-\frac{\hbar^2}{2m_h^*}\frac{\partial^2}{\partial z_h^2}+V(z_e)+V(z_h)-\frac{e^2}{\varepsilon|z_e-z_h|}, \tag{1}$$

with

$$V(z_{e(h)})=\begin{cases}V_0 z_{e(h)} & z_{e(h)}\geq 0\\ \infty & z_{e(h)}<0\end{cases} \tag{2}$$

where z represents the growth direction of the one-dimensional quantum dot, $\hbar$ is Planck constant, m_e^* and m_h^* are the effective mass of the electron and the hole, respectively, and ε is the relative dielectric constant. V_0 is the coefficient of linear potential.

The Hamiltonian of the system can be changed into the following form:

$$H=H_c+H_r \tag{3}$$

with

$$H_c=-\frac{\hbar^2}{2M}\frac{\partial^2}{\partial Z^2}+2V_0 Z \tag{4}$$

and

$$H_r=-\frac{\hbar^2}{2\mu}\frac{\partial^2}{\partial z^2}+\frac{m_h-m_e}{M}2V_0 Z-\frac{e^2}{\varepsilon|z|} \tag{5}$$

where $M=m_e+m_h$ and $\mu=m_e{}^*m_h/m_e+m_h$ are the total mass and the reduced mass, respectively. H_c represents the center-of-mass motion, and H_r represents the relative motion. The energy eigenvalue and the eigenfunction of the Hamiltonian H_c of center-of-mass motion can be obtained as

$$\psi_n(Z)=N_c Ai(\xi),\quad \xi=\left(\frac{4MV_0}{\hbar^2}\right)^{1/3}Z-\left[\frac{M}{2\hbar^2V_0^2}\right]^{1/3}\epsilon_n \tag{6}$$

with

$$\epsilon_n=\left(\frac{4\hbar^2V_0^2}{2M}\right)^{1/3}\lambda_n \tag{7}$$

and

$$\lambda_1=2.338,\lambda_2=4.088,\lambda_3=5.521,\lambda_4=6.787,\cdots, \tag{8}$$

where $Ai(\xi)$ and N_c are the Airy function and the normalized constant,respectively. Let us set $F=(m_h-m_e/M)V_0$, which shows that the linear confinement potential with excitonic effects is $(m_h-m_e/M)(0.1625)$ times as large as that without excitonic effects. The Hamiltonian H_r of the relative motion satisfies the following equation:

$$\left[-\frac{\hbar^2}{2\mu}\frac{\partial^2}{\partial z^2}+Fz-\frac{e^2}{\varepsilon|z|}\right]\phi_n(z)=E_n\phi_n(z) \tag{9}$$

The Hamiltonian (5) contains two length scales. One is the size of the quantum dot, defined by

$$z_0=\left(\frac{\hbar^2}{\mu F}\right)^{1/3}. \tag{10}$$

The other length scale is the exciton effective Bohr radius

$$a_B^*=\frac{\varepsilon\hbar^2}{\mu e^2}. \tag{11}$$

The competition between the two length scales defines the strong-confinement regime, where $z_0\ll a_B^*$ and the weak-confinement regime, where $z_0\gg a_B^*$. Next we will discuss the strong-confinement regime. Eq. (9) can be solved analytically in the strong confinement regime where the Coulomb term is neglected. In this limit the energy eigenvalues and the energy eigenfunctions can be obtained as

$$\phi_n(z)=N_A i(\eta),\quad \eta=\left(\frac{2\mu F}{\hbar^2}\right)^{1/3}z-\left[\frac{2\mu}{\hbar^2F^2}\right]^{1/3}E_n \tag{12}$$

with

$$E_n=\left(\frac{\hbar^2F^2}{2\mu}\right)^{1/3}\lambda_n \tag{13}$$

and

$$\lambda_1=2.338,\lambda_2=4.088,\lambda_3=5.521,\lambda_4=6.787,\cdots. \tag{14}$$

From the equations above, in the strong confinement regime, an exciton has influences on the energy eigenvalues and the energy eigenfunctions through its reduced mass. In all confinement regimes, the energy eigenvalues and eigenfunctions of Eq. (9) can be obtained numerically using the fourth-order Runge-Kutta algorithm.

2.2. linear and nonlinear optical absorption coefficients and refractive index changes

In this section,we will give a brief derivation of linear and nonlinear optical absorption coefficients and refractive index changes by the compact density matrix method and the iterative procedure. Suppose our system is excited by an electromagnetic field. The electric field vector of the electromagnetic field is

$$E(t)=E_0\cos(\omega t)=\widetilde{E}\exp(-i\omega t)+\widetilde{E}\exp(i\omega t), \tag{15}$$