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Linear and nonlinear optical absorption coefficients and refractive index changes associated with intersubband transitions in a quantum disk with flat cylindrical geometry

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ABSTRACT

The linear and nonlinear optical absorption coefficients and changes in the refractive index in GaAs/AlGaAs quantum disk in the form of a flat cylinder are investigated theoretically in the presence of a static magnetic and a laser field within the framework of the compact-density matrix approach. It is found that the absorption coefficients and the refractive index changes depend not only on the optical wave intensity but also on the strength of the static magnetic field. The intersubband relaxation time, also, has an important influence on the linear and nonlinear optical properties of a quantum disk.

1. Introduction

With recent sophisticated developments in modern material fabrication technology, it has now become possible to produce quasi-zero dimensional systems, so-called quantum dots or "artificial atoms", that confine electrons in all three spatial directions. Just like all the branches of science, both experimentalist and theorist are working on the study of various properties of quantum dots including spectrum of one two and three quantum dots [1], electronic properties [2], spin-orbit interaction [3,4], study of impurity states [5,6] etc. The nonlinear effects in these structures are much stronger than the bulk materials characterized by a small energy separation between subband levels, large values of electric dipole transition matrix elements and the possibility of achieving resonance conditions, and hence show strong coupling to even weak external fields [7–9]. In recent years the nonlinear properties of quantum dots associated with intersubband optical transitions semiconductor quantum dots have attracted considerable attention owing to their unusual electronic and optical properties and possible practical applications. The nonlinear optical properties of quantum dot have the potential for device applications such as far-infrared laser amplifiers [10,11], far-infrared photodetectors [12–15], high-speed electrooptical modulators [16–19], semiconductor optical amplifiers [20], optical memories [21], optical switches [22,23] and other extensive applications in optics communication are based on the theoretical studies of optical absorption and refractive index changes of quantum dots.

Efros and Efros [24] considered the optical properties of quantum dot, for the first time, in a spherical quantum dot with indefinitely high walls. The analytical dependencies of threshold frequencies of absorption on quantum dot radius and the appropriate selection rules by quantum numbers were obtained for transitions from one state to another. Subsequently, a great deal of work has been done on the optical behaviors related to linear and nonlinear optical properties of semiconductor quantum dots system. Various results demonstrate the large optical nonlinearities as compared to the bulk material in external electromagnetic fields. Rezaei et al. studied the intersubband optical absorption coefficient changes and refractive index changes in a two-dimensional quantum dot system [25,26] under the influence of uniform magnetic field, Lu et al. investigated linear and nonlinear optical absorption coefficients and refractive index changes in a two-electron quantum dot with a parabolic potential, Gaussian potential and Woods-Saxon potential [27–29]. Lahon et al. [30] studied the influence of elliptically polarized laser field on linear and non-linear properties of quantum dot. Xie and Liang [31] investigated the optical properties of a donor impurity in a two-dimensional quantum pseudodot and found that the optical

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properties of a donor impurity in a two-dimensional pseudoharmonic quantum dot were strongly affected by the zero point of the pseudoharmonic potential, the chemical potential of the electron gas and the Coulomb interaction. Sahin [32,33] carried out the study of third-order nonlinear optical properties of a one and two-electron spherical quantum dot with and without a hydrogenic impurity. Shao et al. [34] studied the third-harmonic generation coefficient for cylinder quantum dots under the influence of an applied electric field using the compact density-matrix approach and iterative method. Very recently, Kirak and Altinok [35] investigated in detail the influence of an external electric field on the binding energies of the ground state and excited states with the third-harmonic-generation coefficient for a spherical quantum dot with parabolic confinement. The numerical results demonstrated that the third-harmonic-generation coefficient very sensitively depends on the magnitude of the electric field and the radius of the quantum dots. In the numerical simulation [36,37], the size of quantum dot has influence on absorption and refraction index change in the cylindrical quantum dot and parabolic cylinder quantum dot. Therefore, studies in this field are still important for both theoretical research and practical applications.

In this paper, we have investigated the intersubband optical absorption coefficients and refractive index changes in a quantum dot having quantum disk geometry, with a parabolic potential in the radial direction and presence of two interfaces along the cylinder axis. We assume a uniform magnetic field applied along the cylinder axis. The detailed studies of the effects of incident optical intensity and a static magnetic field on the optical properties of the quantum disk are made. The paper is organized as follows: in Section 2, we describe the model and theoretical framework. The Hamiltonian and the relevant eigenenergies and eigenfunctions, obtained using the effective mass approximation are presented analytically. The analytical expressions for the linear and nonlinear optical absorption coefficients and refractive index changes, obtained using the density matrix approach are also presented in Section 2. The numerical results and detailed discussions are given in Section 3. Finally, a brief conclusion is made in Section 4 followed by references. Nevertheless, to the best of our knowledge, there is no study on the intersubband optical absorption coefficients and refractive index changes in a disk-shaped quantum dot with a flat cylindrical dimension.

2. Theory and model

We consider the motion of a single conduction band electron confined in a GaAs/Al_xGa_{1-x} quantum dot having quantum-disk geometry, assumed in the form of a flat cylinder where the radial dimensions are larger than axial one. Within the quantum dot framework of effective mass approximation, the Hamiltonian of the system, in the presence of a static magnetic field $\vec{B}$ along the z-direction, is given by

$$H=\frac{1}{2m^*}\left(\vec{p}-e\vec{A}\right)^2+V_{conf}(\vec{r}) \tag{1}$$

where m^* and e are the electron effective mass and charge, respectively, c is the speed of light, $\vec{A}$ is the vector potential of static magnetic field and $V_{conf}(\vec{r})$ is the confinement potential. We assume that the confinement along the radial direction of quantum dot is essentially electrostatic, we model it by a parabolic potential of the form $\frac{1}{2}m^*\omega_0^2\,r^2$, where $r=\sqrt{x^2+y^2}$ is the radius in the x–y plane and ω_0 is the confinement frequency of harmonic oscillator. Along the z-axis, taken as the cylinder axis, we assume the presence of two interfaces located at $z=\pm d/2$. We assume that only the lowest electronic subband in the z-direction is occupied and that there is no coupling between the z direction and the (x,y) plane and the potential is $V(z)$ along z-axis. The symmetry of the problem is such that it is our advantage to use cylindrical coordinates (r,θ,z) and to choose the vector potential in the symmetric gauge, $A_r=A_z=0$, $A_\theta=Br/2$. However, we shall just take into account the electronic intersubband transitions and hence study the linear and nonlinear absorption coefficient and refractive index changes associated with the intersubband transitions in a parabolic potential.

The time-independent the Schrödinger equation in plane polar coordinate system has the following form

$$\left\{-\frac{\hbar^2}{2m^*}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}+\frac{\partial^2}{\partial z^2}\right]-\frac{i}{2}\frac{\hbar eB}{m^*}\frac{\partial}{\partial\theta}+\frac{1}{8m^*}e^2B^2r^2+V(r,\theta,z)\right\}\psi(r,\theta,z)=E\psi(r,\theta,z) \tag{2}$$

in which E and $\psi(r,\theta,z)$are the energies and wavefunctions of the system.

Substituting for $V(r,\theta,z)=\frac{1}{2}m^*\omega_0^2r^2+V(z)$; cyclotron frequency, $\omega_c=\frac{eB}{m^*}$and renormalized cyclotron frequency or total confinement frequency, $\omega^2={\omega_c}^2+4\omega_0^2$, we have

$$\left\{-\frac{\hbar^2}{2m^*}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}+\frac{\partial^2}{\partial z^2}\right]-\frac{i}{2}\hbar\omega_c\frac{\partial}{\partial\theta}+\frac{1}{8}m^*\omega^2r^2+V(z)\right\}\psi(r,\theta,z)=(E_r+E_z)\psi(r,\theta,z) \tag{3}$$

The potential $V(z)$ describes the potential barriers located at $z=\pm d/2$ and is given by

$$V(z)=\begin{cases}0 & for\ |z|<d/2\\ \infty & for\ |z|\geq d/2\end{cases} \tag{4}$$

Let us present a wave function of an electron as

$$\psi(r,\theta,z)=\frac{1}{\sqrt{2\pi}}e^{im\theta}R(r)\eta(z) \tag{5}$$

where $m=0,\pm1,\pm2,\ldots$ because of the single-valuedness of the wave function. If we use the notation $\beta=\frac{m^*\omega}{2\hbar}r^2$ and $k=E_r/\hbar\omega-(m\omega_c/2\omega)$, the equation for the radial part of the wave function $R(r)$ becomes

$$\beta\frac{d^2R}{d\beta^2}+\frac{dR}{d\beta}+\left(k-\frac{1}{4}\beta-\frac{m^2}{4\beta}\right)R=0 \tag{6}$$

Assuming

$$R(\beta)=e^{-\beta/2}\beta^{|m|/2}\kappa(\beta) \tag{7}$$

Then $\kappa(\beta)$ will satisfy the Kummer's equation

$$\beta\frac{d^2\kappa}{d\beta^2}+(|m|+1-\beta)\frac{d\kappa}{d\beta}+\left(k-\frac{1}{2}(|m|+1)\right)\kappa=0 \tag{8}$$

whose solution is the confluent hypergeometric function [39]

$$\kappa(\beta)=F[(|m|+1)/2-k,|m|+1,\beta] \tag{9}$$

where F is given by series

$$F[a,b,x]=1+\frac{a}{b}\frac{x}{1!}+\frac{a(a+1)}{b(b+1)}\frac{x^2}{2!}+\ldots$$

If the wavefunction is finite everywhere in the (x,y) plane, $k-(|m|+1)/2$ must be a non-negative integer$n$, i.e., $k-(|m|+1)/2=n$ where $n=0,1,2,\ldots$.

The energy levels along radial direction are thus given by

$$E_{nm}^{(r)}=\hbar\sqrt{{\omega_c}^2+4\omega_0^2}\left[n+\frac{1}{2}(|m|+1)\right]+\frac{1}{2}m\hbar\omega_c \tag{10}$$