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Polaron effects on the refractive index changes in cylindrical quantum dots with parabolic potential

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ABSTRACT

The effect of electron–LO–phonon interaction on refractive index changes (RICs) for cylindrical quantum dots (CQDs) with an applied electric field is theoretically investigated. Analytic forms of the linear and third-order nonlinear the RICs are obtained for a cylindrical QD by using compact-density-matrix approach and iterative method, and the numerical results are presented for a GaAs cylinder quantum dot. The results show that the RICs coefficient is greatly enhanced and the peak shift to the aspect of high energy when considering the influence of electron–LO–phonon interaction.

1. Introduction

Due to the remarkable advances in nanofabrication techniques in the past few years, the nonlinear optical phenomena of semiconduction quantum wells, quantum wires, quantum dots (QDs) and superlattices are of considerable interest because of their relevance for studying practical applications and as a probe for the electronic structure of mesoscopic media [1–13]. Sakiki et al. [2,12] were the first to present the concept of QDs, a great deal of work has been done on the optical behaviors related to linear and nonlinear optical properties of semiconductor QDs system. Because QDs can confine a few electrons in all spatial dimensions, their size, shape, and other properties can be controlled in experiments. With recent rapid advances of modern technology, in the theoretical investigation of these microstructures, it is well known that the electron–phonon interaction in QDs plays an important role in the physical properties of the polar crystals. Recently, Vartanian [14] investigated the hydrogenic impurity bound polaron in a cylindrical quantum dot in an electric field. Magna [15] presented A polaron model of the electronic transport in a nanotube quantum dot. Huangfu [16]

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discussed the bound polaron in a spherical quantum dot under an electric field. Samak [17] calculated the optical polaron in spherical quantum dot confinement. All the research results have already shown that the electron–phonon interaction becomes more and more important in electronic properties and optical properties with the decreasing of the dimension. Moreover, the electron–phonon interaction could modify the electronic properties and optical properties in low-dimensional systems obviously.

A parabolic potential is often considered to be a good representation of the potential in semiconductor structures. Recently, among the nonlinear optical properties, more attention has been paid to the nonlinear optical absorption and refraction index change based on an optical (intersubband) transitions in parabolic QDs [18–26]. In 2009, Xie [27] carried out research on the linear and nonlinear optical properties of an exciton in a spherical parabolic QD by using the matrix diagonalization technique, Sahin [28] investigated the third-order nonlinear optical properties of a one- and two-electron spherical quantum dot with and without a hydrogenic impurity. Chen et al. [29], Yuan et al. [30] and Yao et al. [31] investigated these absorption coefficients for an asymmetric double triangular quantum well, for an off-center hydrogenic donor confined by a spherical QD with a parabolic potential and for a cylindrical QD system, respectively. However, the polaron effects on the refractive index changes in cylindrical QDs with parabolic potential have not been researched in this area.

In our recent work, we study the polaron effects on the RICs in cylindrical QDs with a parabolic confinement potential. In order to simplify the polaron problem in multilayered heterostructures, we take the finite size of the QDs and the parabolic confinement potential into account and deal with only one bulk phonon mode. The results show that the RICs coefficient is greatly enhanced and the peak shifts to the aspect of higher energy when considering the influence of electron–phonon interaction.

This paper is organized as follows. In Section 2, we obtain the eigenenergies and eigenfunctions using the perturbation approximation, and the simple analytical formula for the RICs coefficient is derived by the compact density-matrix method and the iterative procedure. In Section 3 we provide the numerical results and discussions. Finally, a brief conclusion is given in Section 4.

2. Theory

Let us consider a polar semiconductor cylindrical quantum dots made of GaAs with radius R and height L, and the applied electric fields $\vec{F}$ in the z direction. The Hamiltonian of the system can be written as

$$H = H_e + H_{ph} + H_{e-ph}, \tag{1}$$

where

$$H_e = -\frac{\hbar^2}{2m^*}\nabla^2 + V(z) + V(\rho) - eFz, \tag{2}$$

is the electron part, here $V(\rho) = \frac{1}{2}m^*\omega_\rho^2\rho^2$ is the radial confining potential, $V(z)$ is the parabolic confining potential,

$$V(z) = \frac{1}{2}m^*\omega_0^2 z^2, -\infty < z < \infty, \tag{3}$$

and

$$H_{ph} = \sum_q \hbar\omega_{\mathrm{LO}} a_q^+ a_q, \tag{4}$$

is the phonon part, and H_{e-ph} stands for the Hamiltonian of electron–LO–phonon interaction, which is given by [14]

$$H_{e-ph} = \sum_q \left(V_q e^{iq\cdot r} a_q + V_q^* e^{-iq\cdot r} a_q^+\right), \tag{5}$$

where

$$V_q = -\frac{i\hbar\omega_{\mathrm{LO}}}{q}\left(\frac{4\pi\alpha_e}{\Omega}\right)^{1/2}\left(\frac{\hbar}{2m^*\omega_{\mathrm{LO}}}\right)^{1/4}, \tag{6}$$