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Polaron effects on the optical absorption coefficients and refractive index changes in a square quantum well

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ABSTRACT

The linear and nonlinear optical absorption coefficients and refractive index changes are obtained by using the compact density-matrix approach and an iterative procedure. With typical semiconducting GaAs materials, the linear, third-order nonlinear, total optical absorption coefficients and the optical refractive index have been examined. We find that the polaron effect has an important influence on the linear, third-order nonlinear, and total absorption coefficients as well as the refractive index changes.

1. Introduction

It is well known that nonlinear optical properties such as optical absorption and refractive index changes have great influence on device applications, specially in high-speed electro-optical modulators [1], far infrared photodetectors [2], left-handed materials (LHM) [3] and semiconductor optical amplifiers [4]. Therefore, we have paid much attention to the nonlinear optical properties of low-dimensional systems for both theoretical and applied research. In 1987, Kan et al. studied the field effects on the refractive index and absorption coefficients in AlGaAs quantum well structures and their feasibility for electro-optic device applications [5]. Linear and nonlinear intersubband optical absorption coefficients and refractive index changes in a quantum box with finite confining potential were studied by Ünlü et al. [6]. The optical absorption and refractive index changes in a cylindrical quantum dot were studied by Liu and Xu [7]. Linear changes in the absorption and refractive index in a parabolic quantum well were studied by Chuang and Ahn [8]. In 1991, Kuhn et al. [9] discussed whether free carriers would induce changes in the absorption and refractive index for intersubband optical transitions in $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ quantum wells.

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Meanwhile, it is also well known that the electron–phonon interaction plays an important role in the physical properties of the polar crystals. Researches on the polaron effect on the quantum well, quantum wire, quantum dot systems show that the influence of the phonon could be enhanced and even become dominating as the dimensionality of the material reduces [10–12]. The electron–phonon interaction in a dielectric confined system was first studied by Lucas et al. [13]. Licari and Evrard [14] under the dielectric continuum model. Wendler [15] developed the framework of the theory of optical phonons and electron–phonon interaction for the spatially confined systems. Guo and Chen [16] presented the polaron effects on second-harmonic generation in quantum well within an electric field. Liu [17] discussed polaron effects on the third-order nonlinear optical susceptibility in quantum disk. Zhang and Guo [18] calculated the polaron effects on the optical rectification in asymmetrical semi-parabolic quantum wells. These electron–phonon interactions are also considered in calculating the electron scattering rate. Xie and Chen [11,19] investigated the influence of various phonon modes on the exciton ground-state property in a finite-height quantum well.

LO phonon should not be ignored when studying the quantum well systems. Because the LO phonon in ionic crystals involves the relative motion of positive and negative ions which follows polarization, it has a strong interaction with electromagnetic field [20–24]. As a result, when the electron–LO–phonon interaction is considered in the quantum well structures, the electronic properties and wave functions of the systems are changed significantly. Several works have studied about the polaron effects on the nonlinear optical properties. So, as far as we know, it is meaningful and important to calculate polaron effects on the optical absorption coefficients (ACs) and refractive index (RI) changes in a square quantum well (QW).

The outline of the paper is as follows: In Section 2, the eigenfunctions and eigenenergies of electron states are obtained by considering the polaron effects and using the effective mass approximation. And the ACs and RI changes are derived by adopting the compact density-matrix approach and the iterative method. 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 in an infinitely deep symmetric square potential well made of GaAs. The Hamiltonian of the system can be written as

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

where

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

is the electron part, here $V(z)$ is the potential, the z axis is perpendicular to the well layers,

$$V(z) = \begin{cases} 0, & 0 \leqslant z \leqslant 1, \\ \infty, & \text{elsewhere} \end{cases} \tag{3}$$

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

is the phonon part, and H_{e-ph} stands for the Hamiltonian of electron–LO–phonon interaction, which is give by [25]

$$H_{e-ph} = \sum_q \left(V_q e^{iq_\parallel r_\parallel + iq_z z} a_q + V_q^* e^{-iq_\parallel r_\parallel - iq_z z} a_q^+ \right), \tag{5}$$

where

$$|V_q|^2 = \frac{4\pi\alpha_e(\hbar\omega_{LO})^2}{AL_w(q_\parallel^2 + q_z^2)} \left(\frac{\hbar}{2m * \omega_{LO}} \right)^{1/2}, \tag{6}$$