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# Laser-induced nonlinear optical rectification in a two-dimensional quantum pseudodot system

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ABSTRACT

In this work, the effects of intense laser field on the nonlinear optical rectification in a two-dimensional quantum pseudodot system subjected to an uniform external magnetic field have been investigated theoretically. The non-resonant monochromatic intense laser field with circular polarization has been taken into account within the framework of high-frequency Floquet theory. Analytical expression for the coefficient of nonlinear optical rectification is deduced by using the compact-density matrix approach and iterative method. Numerical results show that the nonlinear optical rectification coefficient depends strongly on the magnitude of magnetic field, the chemical potential and zero point of the pseudoharmonic potential. Moreover, we have demonstrated that the strength of intense laser field alters the structure of confinement potential and affects remarkably the nonlinear optical rectification coefficients.

## 1. Introduction

During the last two decades, low-dimensional structures such as quantum wells, quantum wires and quantum dots (QDs) have attracted a great deal of interest due to their unusual optical properties for device applications in the infrared region [1–3]. Progress in semiconductor growth technology renders possible the fabrication of quantum dots with different size and geometry. Confinement of the motion of charge carriers gives rise to the formation of discrete electronic energy levels and brings about large optical nonlinearities in comparison with bulk semiconductor [4,5]. Several theoretical and experimental studies have been conducted to find out the electronic structure and optical properties of quantum dots with different shapes (spherical, cylindrical, ellipsoidal, lens shape and parabolic cylinder) by considering confinement potentials such as infinite, finite, Gaussian and parabolic [6].

Among the nonlinear optical properties, optical rectification, second-harmonic generation and electro-optic effect are the simplest and the lowest-order nonlinear processes usually stronger than the other optical nonlinearities particularly in quantum systems exhibiting an asymmetry [7–12]. Optical rectification coefficient (ORC) has been studied in several quantum systems [13,14]. Yu et al. researched the exciton effects on the nonlinear optical rectification in one-dimensional quantum dots [15]. Nonlinear optical rectification in cubical quantum dots has been studied by Zhang et al. [16]. The role of applied magnetic field on the nonlinear optical rectification of hydrogenic impurity in a disk-like parabolic quantum dot has been analyzed by Shojaei and coworkers [17].

Electronic and optical properties of nanostructures can be manipulated and controlled by external perturbations [18–20]. In this context, advent of strong coherent tunable laser sources has provided an opportunity to survey the response of quantum systems to external fields [21–24]. Many interesting physical phenomena associated with the intense laser field (ILF)-matter interaction has been reported [25–27]. Lima et al. have studied that dichotomy of the exciton wave function and transition from single to double quantum well potential in quantum wells under intense laser fields [28]. The effects of intense laser field on donor impurities in a cylindrical quantum dot under external electric field have been investigated by Kasapoğlu et al. [29]. Unified view of low- and high-frequency regimes of atomic ionization in intense laser fields have been examined by Miyagi and Someda [30]. Lahon et al. discussed the effect of elliptically polarized laser field on linear and non-linear properties of quantum dots [31]. It's well known that the geometry has a noticeable effect on the physical propertis of QDs. Across a wide number of studies, mostly the harmonic oscillator potential is considered due to being close to the molecular vibrational potential in QDs and more of an computational simplicity. Nevertheless, in comparison with a real molecular vibrational potential, this one could be interpreted as an unrealistic [32]. Therefore, QD can be described more properly via combination of dot and antidot potentials. Çetin has investigated the electronic structure of a two-

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dimensional pseudoharmonic quantum dot (2DPHQD) with the presence of a strong magnetic field together with an Aharonov-Bohm flux field [33]. Rezaei et al. have researched the optical rectification coefficient (ORC) of a two-dimensional quantum pseudodot system [4]. The effects of electromagnetically induced transparency in a two-dimensional quantum pseudodot system have been demonstrated by Jahromi et al [34]. Khordad has studied bound polaron in a quantum pseudodot considering Rashba spin-orbit interaction effect [35].

Though remarkable interest has been shown on the research of ILF effects on nonlinear optical properties of quantum dots, the nonlinear optical rectification in a two-dimensional quantum pseudodot system under ILF has not been investigated so far. In this paper, we focus on the laser-induced ORC in quantum dot subjected to an uniform external magnetic field where the laser field has been treated via laser-dressed potential approach. The paper is organized as follows: In Section 2, the theoretical framework is briefly given. Results are presented in Section 3 and finally the conclusions are given in Section 4.

## 2. Theory

Within the framework of the effective mass approximation, the Hamiltonian for an electron in a two-dimensional quantum pseudodot system subjected to an uniform magnetic field is given by

$$H = \frac{1}{2\,m^*}(\mathbf{p} + e\mathbf{A})^2 + V(r)\,. \tag{1}$$

Here, $m^*$ is the electron effective mass, $e$ is the absolute value of the elementary charge, $\mathbf{p}$ is the momentum operator, $\mathbf{A}(\hat{r}, \hat{\varphi}, \hat{z})$= $(0, Br/2, 0)$ is the vector potential corresponding to the magnetic field chosen along the $z$-direction. $V(r)$ is the confinement potential, constitutive of both dot and antidot harmonic potentials [33], and is given as

$$V(r) = V_0\left(\frac{r}{r_0} - \frac{r_0}{r}\right)^2 . \tag{2}$$

Here $V_0$ defines the chemical potential of the two-dimensional electron gas and $r_0$ is the zero-point of the pseudoharmonic potential.

In the present study, the adopted approach for the inclusion of ILF-effects onto the system is based upon a non-perturbative theory developed to elucidate the atomic behavior in intense high-frequency laser fields. Details of this approach are available in elsewhere [36–39]. Within the framework of the high-frequency Floquet theory, the particle feels only the time average of the rapidly oscillating confinement potential which implies

$$\langle V_d(\mathbf{r}, \alpha_0)\rangle = \frac{1}{T}\int_0^T V(\mathbf{r} + \boldsymbol{\alpha}(t))dt \tag{3}$$

where $T = 2\pi/\Omega$ is the period of a high-frequency, non-resonant intense laser field with angular frequency $\Omega$. The vector $\boldsymbol{\alpha}(t)$ is related to the vector potential of the radiation as $\boldsymbol{\alpha}(t) = \int^t \mathbf{A}(t')dt'$. In this work, we consider a non-resonant, monochromatic, circularly polarized intense laser field with corresponding vector potential $\mathbf{A}(t)$

$$\mathbf{A}(t) = A_0(-\hat{x}\sin\Omega t + \hat{y}\cos\Omega t) \tag{4}$$

which yields to $\boldsymbol{\alpha}(t)$ given as follows [38]:

$$\boldsymbol{\alpha}(t) = \alpha_0(\hat{x}\cos\Omega t + \hat{y}\sin\Omega t)\,, \tag{5}$$

where $\hat{x}$ and $\hat{y}$ are unit vectors orthogonal to the direction of propagation. The laser-dressing parameter defined as $\alpha_0 = eA_0/m^*\Omega$ represents the excursion amplitude of the particle in its quiver motion in the laser field and is a characteristic parameter determined by the intensity and frequency of the ILF [40].

Accordingly, by using Eqs. (2) and (3), the analytical expression for the laser-dressed form of pseudoharmonic potential seen by the electron is obtained as follows [41]:

$$\langle V_d(\mathbf{r}, \alpha_0)\rangle = V_0\left(\frac{r^2}{r_0^2} + \frac{\alpha_0^2}{r_0^2} - 2 + \frac{r_0^2}{|r^2 - \alpha_0^2|}\right). \tag{6}$$

We should note that, due to the singularities of the potential at $r = \alpha_0$, in our calculations we merely considered the interval $\alpha_0 < r < \infty$. Solution of Eq. (1) entail the use of cylindrical coordinates which reads to:

$$-\frac{\hbar^2}{2\,m^*}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial\varphi^2}\right]\Psi - i\frac{\hbar\omega_c}{2}\frac{\partial\Psi}{\partial\varphi} + \frac{m^*\omega_c^2 r^2}{8}\Psi + V(r)\Psi = E\Psi\,, \tag{7}$$

where $\omega_c = eB/m^*$ is the cyclotron frequency. By denoting the magnetic quantum number as $m$ and substituting the wave function $\Psi$ expressed as

$$\Psi(r, \varphi) = \frac{U(r)}{\sqrt{r}}\frac{e^{im\varphi}}{\sqrt{2\pi}}\,, \tag{8}$$

we get a one-dimensional radial equation. Setting the length and energy scales as the effective Bohr radius $a_0^*$ and effective Hartree energy $E_H^* = \hbar^2/m^* a_0^{*2}$, respectively leads to

$$-\frac{1}{2}\frac{d^2U(r)}{dr^2} + \left[\frac{(m^2 - 1/4)}{2r^2} + \frac{m\gamma}{2} + \frac{1}{2}\left(\frac{\gamma}{2}\right)^2 r^2 + V(r)/E_H^*\right]U(r) = EU(r)\,, \tag{9}$$

where the dimensionless measure of the magnetic field is chosen as $\gamma = \hbar\omega_c/E_H^*$. We should note that, treatment of intense laser radiation effect upon the system is performed via the replacement of the $V(r)$ term by its laser-dressed counterpart $\langle V_d(\mathbf{r}, \alpha_0)\rangle$. Finite element method has been utilized for the calculation of eigenenergies and corresponding wave functions [42,43].

In order to calculate the second-order optical rectification coefficient, we assume that the system is illuminated by an optical light field with frequency $\omega$ along the radial direction [20,44]. The electric field vector of this optical wave is

$$E(t) = \tilde{E}e^{i\omega t} + \tilde{E}^* e^{-i\omega t}\,. \tag{10}$$

Because of the time-dependent interaction, the time-evolution of the matrix elements of one-electron density operator obeys the following Liouville quantum equation [15]

$$\frac{\partial\hat{\rho}_{ij}}{\partial t} = \frac{1}{i\hbar}[\hat{H}_0 - \hat{M}E(t), \hat{\rho}\,]_{ij} - \Gamma_{ij}(\hat{\rho} - \hat{\rho}^{(0)})_{ij}\,, \tag{11}$$

where $\hat{\rho}$ is the density matrix of one-electron state and $\hat{\rho}^{(0)}$ is the unperturbed density matrix operator. $\hat{H}_0$ is the Hamiltonian of the system in the absence of electromagnetic field, $-\hat{M}E(t) = -e\hat{r}E(t)$ is the perturbation term and $\Gamma_{ij}$ is the relaxation rate caused the damping processes. Eq. (11) can be solved by means of the standard iterative method [45]:

$$\hat{\rho}(t) = \sum_{n=0}^{\infty}\hat{\rho}^{(n)} \tag{12}$$

with

$$\frac{\partial\hat{\rho}_{ij}^{(n+1)}}{\partial t} = \frac{1}{i\hbar}\left\{[\hat{H}_0, \hat{\rho}^{(n+1)}]_{ij} - i\hbar\Gamma_{ij}\hat{\rho}^{(n+1)}\right\} - \frac{1}{i\hbar}[e\hat{r}, \hat{\rho}^{(n)}]_{ij}E(t)\,. \tag{13}$$

In addition, the electronic polarization of the system because of the electric field, up to the third order in $\tilde{E}$, can be expressed as