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Second and third harmonic generations of a quantum ring with Rashba and Dresselhaus spin-orbit couplings: Temperature and Zeeman effects

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ABSTRACT

In current article, the Zeeman effect is considered in the presence of simultaneous Rashba and Dresselhaus spin-orbit interactions (SOI) and under such circumstances the second and third harmonic generations (SHG and THG) of a GaAs quantum ring are investigated at finite temperature. The effective Hamiltonian is derived in cylindrical coordinate while the angular part is eliminated because of axial symmetry and the energy eigenvalues and eigenvectors of two lowest levels are obtained numerically. Eventually, the optical properties of such system are studied hiring compact density matrix approach. The results show that, an increase in the magnetic field, leads to blue shift in resonant peaks of both SHG and THG. Furthermore, by reducing the temperature, all the resonant peaks of both SHG and THG experience a red shift. Finally, the effect of the structure dimension is studied and results illustrate that variation of size leads to both red and blue shifts in resonant peaks.

1. Introduction

Intersubband optical transition in semiconductor quantum dots (QD) have become the most vital forefront field in opto-electronic devices based on size quantization within nano-scale systems and has grabbed a great deal of attention. In order to gain intersubband transition, the system needs to be illuminated by electromagnetic pulses. In such circumstances, the light interacts with the nonlinear medium and the system shows nonlinear optical behavior. Harmonic generation can be mentioned as one of the extremely fascinating outcomes of such interaction, which is a nonlinear process that two non-similar frequencies can combine, known as frequency doubling (Second Harmonic Generation), or the frequency can be tripled passing through nonlinear medium known as frequency tripling (Third Harmonic Generation). Experimentally, the harmonic generations can be induced with different methods. For example, the enhanced field gives rise to local second-harmonic (SH) generation at the tip surface [1], using filamented infrared femtosecond laser pulse [2], inducing via magnetization [3], nonadiabatic current generation by time-dependent electromagnetic pulse [4] and quasi-phasematching in GaAs [5], are some experimental methods. Therefore, it is easy to find a wide variety of works in literature that have investigated these features in various nanostructures [6–15].

As we know, most of the theoretical works on the intersubband optical transitions are done neglecting the spin of charge carrier. However, considering the spin and so the interaction of spin with a magnetic field caused by a Lorentz-transformed electric field (created via electron's motion within the electric field) known as spin-orbit interaction (SOI) can considerably influence the nonlinear optical properties of the system. Applied fields aside, a conduction band electron can also move in an electric field caused either due to the structural inversion asymmetry (SIA) or bulk inversion asymmetry (BIA). The SIA (such as heterointerface) generates Rashba SOI term and leads to precession of the spin of electron around the axis that is perpendicular to the velocity within the SO magnetic field plane. On the other hand, the Dresselhaus SOI is originated after the BIA and results in polar bonds due to the lack of inversion symmetry that generates electric fields between the atoms [16–19].

As the transitions depend on energy eigenvalues as well as the eigenstates of the system, in the presence of spin-orbit interactions, the nonlinear optical properties of QDs can be adjusted via application of external factors such as magnetic field (Zeeman effect) and temperature (since almost all the material parameters are strongly sensitive to temperature and it can be easily applied to the system) as well as the shape and size of the structure. By taking advantage of progress in nano-fabrication technology, scientists have been able to experimentally fabricate QDs of various geometrical shapes and sizes [20–26]. The quantum rings are significantly attractive among QDs in which it is possible to fix the magnitude of its dipole moment and as a result of ring geometry, the electron wave packets can take two different paths around the ring that leads to interference. Therefore, quantum rings with spin-orbit coupling have been studied intensively for different

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aspects [27–36]. For instance, just to mention several cases of a long list, the effect of Rashba and Dresselhaus SOIs on spontaneous flowing persistent current [37], electron spin states in a perpendicular magnetic field [38], elliptical deformation of confined electron density [39], electronic charge and spin density distribution with coulomb interaction [40] and persistent, oscillatory charge and spin currents driven by a two-component terahertz laser pulse [41]. Considering all the facts mentioned above, in the current work, simultaneous Rashba and Dresselhaus SO couplings are present and the SHG and THG of a GaAs quantum ring are investigated under the influence of external magnetic field as well as the temperature. The effective Hamiltonian of the system, the temperature dependency and also the SHG and THG relations are described in Section (2); The numerical results are discussed in Section (3) and in Section (4) conclusions of this work are presented briefly.

2. Model and theory

2.1. Effective Hamiltonian

We investigate a GaAs quantum ring considering simultaneous effects of Rashba and Dresselhaus SO couplings under the influence of temperature and applied magnetic field. The magnetic field, $\mathbf{B} = B\hat{e}_z$, is oriented along the z-axis. Since our geometry has axial symmetry, the best and more convenient choice is to introduce the model of the half cross-section through the cylindrical axis that you can see in Fig. 1.

For such problem, we hired effective mass approximation in order to obtain the energy eigenvalues and approximate the eigenfunctions of the system. Therefore, the Hamiltonian of the system can be written as [42,43]:

$$H = \left(\frac{\mathbf{P}^2}{2\,m^*} + V_0\right)\mathbf{I}_2 + \frac{1}{2}gB\mu_B\sigma_z + H_R + H_D \tag{1}$$

where $\mathbf{I}_2$ indicates a 2 × 2 identity matrix, $\mathbf{P} = -i\hbar\vec{\nabla} + e\mathbf{A}$ ($\mathbf{A}$ is the magnetic vector potential), m^* is the electron effective mass, g represents the Landé factor, μ_B is the Bohr magneton, $\sigma_i \quad (i = x,\, y,\, z)$ stands for the ith component of the Pauli matrices vector and V_0 is the confinement potential

$$V_0 = \begin{cases} 0 & \rightarrow \text{ inside the quantum ring} \\ \infty & \rightarrow \text{ outside the quantum ring} \end{cases} \tag{2}$$

In the Hamiltonian Eq. (1), the H_R and H_D denote the Rashba and Dresselhaus SO coupling terms respectively as [42–44]:

$$H_R = \frac{\alpha}{\hbar}(p_y\sigma_x - p_x\sigma_y) \tag{3}$$

$$H_D = \frac{\beta}{\hbar}(p_x\sigma_x - p_y\sigma_y) \tag{4}$$

that α and β are coupling constants. Finally, by assuming the symmetric gauge, $\mathbf{A} = \frac{Br}{2}\hat{e}_\varphi$, we can write the momentum operator in cylindrical coordinate as:

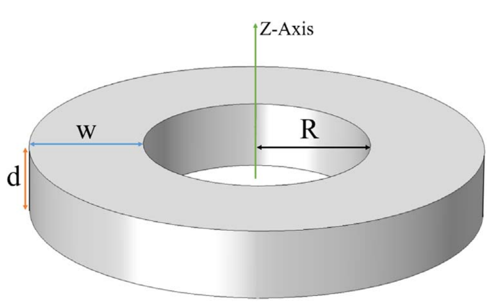

Fig. 1. The schematic view of the quantum ring.

$$\mathbf{P} = -i\hbar\frac{\partial}{\partial r}\hat{e}_r - i\frac{\hbar}{r}\left(\frac{\partial}{\partial\varphi} + i\frac{Ber^2}{2\hbar}\right)\hat{e}_\varphi - i\hbar\frac{\partial}{\partial z}\hat{e}_z \tag{5}$$

which will leads to the Rashba and Dresselhaus SO couplings by the form of:

$$H_R = i\alpha[-\sin(\varphi)\sigma_x + \cos(\varphi)\sigma_y]\frac{\partial}{\partial r} - i\frac{\alpha}{r}[\cos(\varphi)\sigma_x + \sin(\varphi)\sigma_y]\left(\frac{\partial}{\partial\varphi} + i\frac{Ber^2}{2\hbar}\right) \tag{6}$$

and

$$H_D = i\beta[-\cos(\varphi)\sigma_x + \sin(\varphi)\sigma_y]\frac{\partial}{\partial r} + i\frac{\beta}{r}[\sin(\varphi)\sigma_x + \cos(\varphi)\sigma_y]\left(\frac{\partial}{\partial\varphi} + i\frac{Ber^2}{2\hbar}\right) \tag{7}$$

Now, the Hamiltonian Eq. (1) can be illustrated as a 2 × 2 matrix that, in the operator form, its elements are written as:

$$H_{11} = -\frac{\hbar^2}{2\,m^*}\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - \frac{1}{r^2}\left(i\frac{\partial}{\partial\varphi} - \frac{m^*\omega_c r^2}{2\hbar}\right)^2 + \frac{\partial^2}{\partial z^2}\right] + V_0 + \frac{1}{2}gB\mu_B \tag{8}$$

$$H_{22} = -\frac{\hbar^2}{2\,m^*}\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - \frac{1}{r^2}\left(i\frac{\partial}{\partial\varphi} - \frac{m^*\omega_c r^2}{2\hbar}\right)^2 + \frac{\partial^2}{\partial z^2}\right] + V_0 - \frac{1}{2}gB\mu_B \tag{9}$$

$$H_{12} = [\alpha e^{-i\varphi} - i\beta e^{i\varphi}]\frac{\partial}{\partial r} + \frac{1}{r}[\beta e^{i\varphi} - i\alpha e^{-i\varphi}]\left(\frac{\partial}{\partial\varphi} + i\frac{m^*\omega_c r^2}{2\hbar}\right) \tag{10}$$

$$H_{21} = -[\alpha e^{i\varphi} + i\beta e^{-i\varphi}]\frac{\partial}{\partial r} - \frac{1}{r}[\beta e^{-i\varphi} + i\alpha e^{i\varphi}]\left(\frac{\partial}{\partial\varphi} + i\frac{m^*\omega_c r^2}{2\hbar}\right) = H_{12}^* \tag{11}$$

with $\omega_c = eB/m^*$ (cyclotron angular frequency). Because of the cylindrical symmetry, the angular part of the wave function can be presented as $\Phi_\varphi = e^{il\varphi}$, that l stands for the orbital angular momentum quantum number. Noting the relation, $\langle l'|H_{ij}|l\rangle \equiv \int_0^{2\pi} e^{-il'\varphi}H_{ij}e^{il\varphi}d\varphi$, we introduce a 4 × 4 Hamiltonian whose matrix components are derived considering the effects of the two lowest states ($l = 0{,}1$):

$$H = \begin{bmatrix} \langle 0|H_{11}|0\rangle & 0 & 0 & \langle 0|H_{12}|1\rangle \\ 0 & \langle 1|H_{11}|1\rangle & \langle 1|H_{12}|0\rangle & 0 \\ 0 & \langle 0|H_{21}|1\rangle & \langle 0|H_{22}|0\rangle & 0 \\ \langle 1|H_{21}|0\rangle & 0 & 0 & \langle 1|H_{22}|1\rangle \end{bmatrix} \tag{12}$$

with components written as:

$$\langle 0|H_{11}|0\rangle = -\frac{\hbar^2}{2\,m^*}\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}\right] + \frac{1}{8}m^*\omega_c^2 r^2 + V_0 + \frac{1}{2}g\mu_B B \tag{13}$$

$$\langle 1|H_{11}|1\rangle = -\frac{\hbar^2}{2\,m^*}\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2}\right] + \frac{\hbar^2}{2\,m^* r^2} + \frac{1}{2}\hbar\omega_c + \frac{1}{8}m^*\omega_c^2 r^2 + V_0 + \frac{1}{2}g\mu_B B \tag{14}$$

$$\langle 0|H_{22}|0\rangle = \langle 0|H_{11}|0\rangle - g\mu_B B \tag{15}$$

$$\langle 1|H_{22}|1\rangle = \langle 1|H_{11}|1\rangle - g\mu_B B \tag{16}$$

$$\langle 0|H_{12}|1\rangle = \alpha\left(\frac{m^*\omega_c r}{2\hbar} + \frac{1}{r} + \frac{\partial}{\partial r}\right) \tag{17}$$

$$\langle 1|H_{12}|0\rangle = -i\beta\left(\frac{\partial}{\partial r} - \frac{m^*\omega_c r}{2\hbar}\right) \tag{18}$$