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Rashba spin-orbit coupling effects on the optical properties of double quantum wire under magnetic field

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ABSTRACT

We investigate the effects of Rashba spin-orbit interaction on the optical absorption coefficients and refractive index changes associated with transitions between the first two lower-lying electronic levels in double quantum wire. The wire system represented by a symmetric, double quartic-well confinement potential is subjected to a perpendicular magnetic field. The analytical expressions of the linear and third-order nonlinear optical absorption coefficients and refractive index changes are obtained by using the compact-density matrix formalism and iterative scheme. Optical properties are investigated as a function of structural parameter, magnetic field, Rashba spin-orbit interaction and photon energies. Numerical results reveal that competing effects between spin-orbit interaction and magnetic field modify strongly the optical properties and can be altered by these parameters.

1. Introduction

The examination of the physical properties of low-dimensional semiconductor structures (quantum well, quantum wire, quantum dot etc.), formed by restricting the motion of charge carriers in the bulk structures, offers significant contributions to the evolving product technology of today [1]. Limiting the movement direction of the charge carriers causes the formation of discrete energy spectrum which affects significantly the optical properties of the system [2,3]. Investigation of the nonlinear properties of low-dimensional systems has attracted immense activity because of having high potentiality for optoelectronic device applications such as the far-infrared laser amplifiers, photodetectors and high-speed electro-optical modulators [4–8].

Advances in nanofabrication techniques render possible the fabrication of low-dimensional systems with different shape and size. Therefore, the double structures (double quantum well, double quantum wire), which can be used to explain the many physical phenomena such as tunneling and doublet splitting, have become remarkable systems as well as low-dimensional single structures in the last two decades. Several experimental [9,10] and theoretical [11–15] studies have surveyed the effects of external fields on the different physical characteristics (such as electronic structure, mobility, conductivity, magnetoresistance, spectrum of impurity states etc.) of double quantum wire structure which is created with the

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separation of two identical narrow quantum wires by a potential barrier. However, as far as we know, less effort has been paid on the nonlinear optical properties of double quantum structures.

On the other hand, there is increasing interest in the use the electron spin rather than its charge for information processing and storage. Achieving a control on the spin manipulations stands as a promising tool in realization of new devices with characteristics of faster, smaller and more powerful than those of existing [16–19]. Rashba spin-orbit interaction, which arises due to the asymmetry associated with the confinement potential [20], is considered as a possibility to control and manipulate the electron spins. The effect of Rashba spin-orbit coupling can be tuned by changing the gate voltages and strength of which can be determined from the characteristic beating pattern of the Shubnikov-de Haas oscillations in the magnetoresistence of two-dimensional electron gas [21,22]. The effects of external fields and spin-orbit coupling on the electronic and transport properties in low-dimensional systems have been researched in some theoretical and experimental studies [23–31].

Moreover, in recent years optical properties of single quantum nanostructures have been studied extensively by many researchers, both in experimental and theoretical way [32–40]. Peter et al. have surveyed the effects of electric field strength on the total absorption and refractive index changes of a shallow hydrogenic impurity in an InAs/GaAs quantum wire [41]. Optical properties of a quantum wire under an external magnetic field and Rashba spin-orbit interaction have been investigated by Khordad [42] whereas the influence of external electric field and magnetic field on the optical absorption and refractive index changes of quantum wire in the presence of Rashba spin-orbit interaction has been studied by Kumar et al. [43]. Simultaneous effects of in-plane magnetic field and spin-orbit interaction on the linear and the nonlinear optical properties of a quantum wire have been researched by Gisi et al. [44]. To the best of our knowledge, despite much attention has been paid on the investigation of optical properties of single quantum wires with spin-orbit coupling, double wire system has not been studied, yet.

In this work, we focus on a relatively less studied scenario where the optical properties of double quantum wire are surveyed by considering Rashba spin-orbit interaction and external perpendicular magnetic field. The organization of this work is as follows. Firstly in Section 2, we briefly describe the system and present the analytical expressions. Section 3 is devoted to a summary of numerical results and Section 4 gives a short concluding of our findings.

2. Theory and formalism

We consider a quasi-one-dimensional double quantum wire subjected to a perpendicular magnetic field as shown in Fig. 1 of Ref. [31]. The system is imagined to be confined in the x-direction by a double-well potential [45,46] that is given as

$$V(x) = \frac{1}{4}\lambda\left(x^2 - \frac{\mu^2}{\lambda}\right)^2, \tag{1}$$

where λ and μ are positive, adjustable structural parameters which using to control the height of the barrier between wells and the width of wells. The double quantum wire system is assumed to lie on the xy-plane and the electrons can move freely along the y-direction. The orientation of applied magnetic field is chosen to be in the z-direction, $\overrightarrow{B} = (0, 0, B)$. So, the vector potential corresponding to this field can be chosen as $\overrightarrow{A} = (0, Bx, 0)$ in the Landau gauge. Accordingly, the single-particle Hamiltonian for a quasi-one-dimensional double quantum wire with the Rashba spin-orbit coupling is

$$H = \frac{1}{2m^*}\left[p_x^2 + \left(p_y + eBx\right)^2\right]\sigma_0 + V(x)\sigma_0 + \frac{1}{2}g^*\mu_B B\sigma_z + H_R. \tag{2}$$

Here, the first term is kinetic contribution, where m^* is the effective mass of electron, p_x and p_y are components of electron momentum, e is the electron charge and σ_0 is 2×2 unit matrix. Contributions of confinement potential and magnetic field are expressed via the second and the third terms, respectively. Here, g^* effective Lande g-factor, μ_B Bohr magneton and σ_z stands for the z-component of Pauli spin matrix. The last term, H_R, describes Rashba spin-orbit interaction that is given by

$$H_R = \frac{\alpha_R}{\hbar}\left[\sigma_x\left(p_y + eBx\right) - \sigma_y p_x\right]. \tag{3}$$

Here α_R is the Rashba spin-orbit coupling factor that can be varied by gate electric field, and σ_x and σ_y are the x- and y-components of Pauli spin matrix, respectively.

Translational invariance along the y-direction make it possible to write the energy eigenfunctions of Hamiltonian in terms of plane-waves as follows

$$\Psi(x, y) = \phi(x)\exp(ik_y y), \tag{4}$$

where k_y is good quantum number of the system and it represents the wave numbers of the plane-wave. Therefore, Hamiltonian can be written as: