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Influence of the position of a donor impurity on the second-order nonlinear optical susceptibility in a cylindrical quantum dot

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The second-order nonlinear optical susceptibility in a cylindrical quantum dot (CQD) of $GaAs/Ga_{0.6}Al_{0.4}As$ with a donor impurity inside under the influence of a uniform magnetic field applied in the axial direction of the cylinder is studied theoretically. Using the variational method, the energies and the wave functions of the $1S-like$, $2P_{-}-like$, and $2P_{+}-like$ impurity states were found when it moves inside of the CQD. It was found that there is a degeneration of the energy of the impurity for the $2P_{-}-like$ and $2P_{+}-like$ states in the absence of magnetic field, producing two resonant peaks for the second-harmonic generation (SHG) for any position of the impurity. This degeneration is split only when a magnetic field is applied, indicating a Zeeman effect in the system. Thus the variation of the intensity of the magnetic field allows tuning the condition of resonance of two photons. It was also found that the increase in the radial position of the impurity produces an increase in the intensity of the peaks of the optical rectification (OR) and SHG coefficients, therefore a variation of the position of the impurity in a CQD allows modulating the intensity of the second-order nonlinear optical response.

1. Introduction

The advances in the technologies of growth of materials have allowed producing low-dimensional semiconductor quantum systems with different forms and sizes [1–3]. This has stimulated research on the optical and electronic properties of these nanostructured systems, which are of great interest for their potential applications in electronic and optoelectronic devices. The nonlinear optical effects, such as optical rectification (OR), second-harmonic generation (SHG), third-harmonic generation (THG), optical absorption, changes in the index of refraction, Raman dispersion, and optical Kerr effect, are used in far-infrared laser amplifiers [4], photo detectors [5], solar cells [6], etc. It has been found that the second-order nonlinear optical susceptibility is null unless the quantum system exhibits some type of asymmetry. This asymmetry can be produced: i) by means of the use of advanced technology of the growth of materials, which allows obtaining nanostructures with an asymmetric confinement potential [7], ii) by the application of a static electric field to a structurally symmetric system [8], and iii) by the variation of the position of an impurity in nanostructures [9]. The

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importance of the second-order nonlinear optical responses lies in their applications; for example the OR is used for the generation and detection of short pulses of electromagnetic radiation at terahertz (THz) frequencies [10]. In the biological and medical sciences, SHG optical microscopy [11–13] is used, because some live tissues behave like nonlinear materials and allow obtaining noninvasive images in living beings.

The essential difference between quantum dots (QDs) and other low-dimensional systems lies in the complete quantization of the energy spectrum of the charge carriers located in them. Due to this, QDs have properties identical to real atoms in many respects, and for that reason they are called “artificial atoms” [14]. Other properties of QDs are the occurrence of optical transitions between sub-bands and large values of the matrix elements of the dipolar optical transition between the sub-bands of the QDs. These characteristics increase the contribution of the nonlinear parts in the dielectric constants and in the optical properties [15]. The optical and electronic properties of the low-dimensional semiconductor devices exhibit variations because of the presence of impurities. An impurity produces significant changes in the energy sub-bands of the nanostructures, allowing controlled optical transitions. A controlled optical transition is of utmost importance for the fabrication of optoelectronic devices with properties of emission or tunable transmission and ultra-narrow spectral bandwidths. Furthermore, the relation between the optical transition energy and the quantum confinement makes the tuning of the resonance frequency possible [16]. Several research articles have been published on the optical response of low-dimensional systems with impurities. Khordad et al. [17] studied the influence of an impurity on the binding energy and the optical properties of lenticular QDs and found that the coefficients of absorption and the changes in the index of refraction decrease and move toward the highest energies when impurities are present in the nanostructure. Damiri and Askari [18] investigated the effect of impurities on the coefficient of absorption and the change of the index of refraction in a spherical QD, and their results show that upon varying the position of the impurity from the center of the QD, the frequency of absorption is smaller. Bejan [19] investigated the OR related to an impurity in a QD with an asymmetrical confinement potential under the influence of an electric field, finding that: (i) the binding energy of the ground state greatly varies with the position of the impurity and increases or decreases with the applied field; (ii) the OR spectra are sensitive to the position of the impurity and the intensity of the electric field; (iii) the changes in the position of the impurity inside of the QD and the value of the electric field can induce a red or blue shift of the resonant peaks.

In the present paper, a theoretical study of the calculation of the second-order nonlinear optical response generated by the interaction between a classical monochromatic optical field and a CQD of $GaAs/Ga_{0.6}Al_{0.4}As$ with a donor impurity inside it under the influence of a uniform magnetic field applied in the axial direction of the cylinder is presented. The effect of the magnetic field and the position of the impurity within the CQD on the optical rectification and the generation of the second harmonic is analyzed.

2. Theory

The system under study consists of a donor impurity confined in ta CQD in the presence of a uniform magnetic field $\boldsymbol{B}$ oriented in the axial direction of the CQD (Fig. 1).

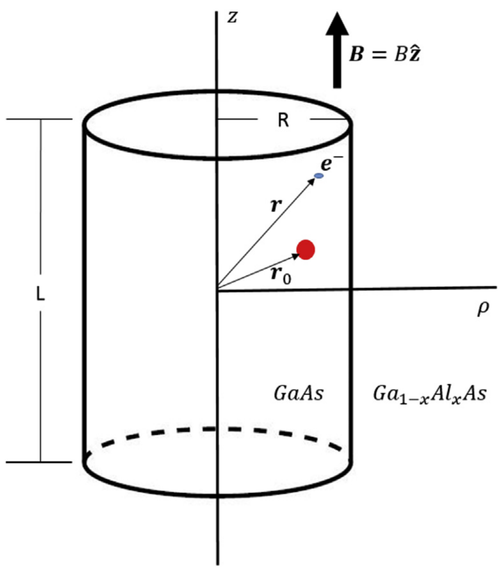

Fig. 1. Schematic representation of the cylindrical quantum dot under study.