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The second, third harmonic generations and nonlinear optical rectification of the Mathieu quantum dot with the external electric, magnetic and laser field

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ABSTRACT

In this study, the nonlinear optical properties of the $In_xGa_{1-x}As/GaAs$ Mathieu quantum dot (MQD) are investigated for the first time, focusing on the nonlinear optical rectification (NOR), second harmonic generation (SHG), and third harmonic generation (THG). The effects of external fields such as the electric field, magnetic field, and laser radiation field on the nonlinear optical properties of MQD are examined, along with structural parameters such as quantum dot depth and width determined by the indium concentration. The motivation of the study is to explain the NOR, SHG, and THG characteristics of MQD in response to changes in external fields and structural factors. To investigate the effects of the laser field, the time-dependent part of the laser field is transferred to the potential energy term of the wave equation using the Kramers–Henneberger (KH) and dipole approximations, creating a laser-dressed potential. Then, the effective potential wave equation is solved using the tridiagonal matrix method. The effects of external fields and structural parameters of MQD on the NOR, SHG, and THG coefficients are discussed in detail. The optimality of the structure for device design and applications considering MQD is revealed, and alternative parameter analysis is conducted for this optimality.

1. Introduction

The quantum confinement effects in semiconductors have been extensively studied both experimentally and theoretically, and it has been shown that they have significant impacts on the electronic properties, such as absorption–emission and subband energies-binding energies, as well as on the optical and statistical properties. Low-dimensional structures such as quantum wells (QWs) (confinement in one dimension), quantum wires (QWWs) (confinement in two dimensions), and quantum dots (QDs) (confinement in three dimensions) can be obtained with the advancement of growth techniques, which restrict the motion of particles in semiconductor materials. This situation provides a good motivation to explore different confinement potentials theoretically. It has been calculated that the binding energies and oscillator strengths of the particles are larger than those in bulk materials. Furthermore, as the size decreases, it has been observed that the resonant frequencies in quantum dots shift towards the blue region. Along with the changes in linear optics, the low-dimensional effects of particles in small-sized materials lead to nonlinear optical (NLO) responses that involve new physical phenomena by enhancing their interaction with intense optical fields. NLO effects have enabled various applications, including optical switches and ultrafast laser pulse generation [1–5]. In optoelectronic technology, quantum dots (QDs), where particles are confined in all three dimensions, have garnered greater attention compared to other low-dimensional structures. The quantum effects are more pronounced in QDs because the electron wavelength is comparable to the confinement length [6]. The three-dimensional confinement of QDs leads to the formation of inter-layer optical transitions of dipole matrix elements. Therefore, QDs exhibit more pronounced nonlinear effects compared to quantum wires and wells [7,8]. Additionally, these structures have various advantages, such as improved thermal stability [9], insensitivity to back reflection [10], lower threshold current density [11], and ultra-narrow spectral linewidth, thanks to their atom-like discrete state density [12]. Similar to other low-dimensional structures, the form of the confinement potential of particles in quantum dots has a significant impact on the optical performance of the structure [13]. Hence, effective potentials for QDs can be considered in different forms such as parabolic, triangular, spherical, and double-ring [14–18]. Some experimental studies suggest that the most suitable quantum dot profiles for encompassing electrons should be well-like structures [19]. In line with these suggestions, the Mathieu functions have applications

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