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Effects of electromagnetic fields on the nonlinear optical properties of asymmetric double quantum well under intense laser field

U. Yesilgul [a], H. Sari [b], F. Ungan [a,*], J.C. Martínez-Orozco [c], R.L. Restrepo [d], M.E. Mora-Ramos [e], C.A. Duque [f], I. Sökmen [g]

[a] Faculty of Technology, Department of Optical Engineering, Cumhuriyet University, 58140 Sivas, Turkey
[b] Faculty of Education, Department of Primary, Cumhuriyet University, 58140 Sivas, Turkey
[c] Unidad Académica de Física, Universidad Autónoma de Zacatecas, Calzada Solidaridad esquina con Paseo a La Bufa S/N, C.P. 98060 Zacatecas, Zac., Mexico
[d] Universidad EIA, C.P. 055428 Envigado, Colombia
[e] Centro de Investigación en Ciencias – IICBA, Universidad Autónoma del Estado de Morelos, Ave. Universidad 1001, C.P. 62209 Cuernavaca, Morelos, Mexico
[f] Grupo de Materia Condensada-UdeA, Instituto de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia-UdeA, Calle 70 No. 52-21, Medellín, Colombia
[g] Faculty of Science, Department of Physics, Dokuz Eylül University, 35160 Buca, İzmir, Turkey

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ABSTRACT

In this study, the effects of electric and magnetic fields on the optical rectification and second and third harmonic generation in asymmetric double quantum well under the intense non-resonant laser field is theoretically investigated. We calculate the optical rectification and second and third harmonic generation within the compact density-matrix approach. The theoretical findings show that the influence of electric, magnetic, and intense laser fields leads to significant changes in the coefficients of nonlinear optical rectification, second and third harmonic generation.

1. Introduction

In recent years, the low-dimensional semiconductor nanostructures such as quantum wells (QWs), quantum well wires (QWWs), and quantum dots (QDs) are known as a good candidate for designing and fabricating the electronic and optoelectronic devices. Among these nanostructures, QWs with different shapes (square, parabolic, graded, V-shaped, inverse parabolic etc.) can be obtained by using the modern semiconductor growth techniques, such as the molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). The quantum confinement of charge carriers in these QWs leads to the formation of discrete energy subbands thus leads to drastic changes of electronic and optical properties. These structures are key components of many electronic and optoelectronic devices, because they can increase the strength of electro-optical interactions by confining the carriers into small regions. Therefore, the electrical and optical properties of these QWs have attracted great attention, both in practical applications and in theoretical research.

The nonlinear optical responses appearing in these semiconductor QWs have the potential for device applications in far-infrared laser amplifiers, high-speed electro-optical modulators, photodetectors, etc. Accordingly, the nonlinear optical properties of these QWs, in particular the nonlinear optical rectification (NOR) as well as second-order and third-order optical nonlinearities, have been widely studied by many authors [1–6]. In order to improve the properties of optical nonlinearities in semiconductor QWs, the researchers have brought forward and investigated many asymmetric structures [7–11]. Based on these research, the tunable asymmetries of the potential energy profile may lead to revealing promising nonlinear optical response. Mou et al. [7] studied third-harmonic generation (THG) coefficients in asymmetrical semi-exponential QWs. NOR in asymmetrical semi-parabolic QWs have been investigated by Karabulut et al. [8]. Yildirim and Tomak [9] explored THG in a QW with adjustable asymmetry under an electric field. Second harmonic generation (SHG) in an asymmetric rectangular QW under the hydrostatic pressure has been investigated by Karabulut et al. [10]. In addition, Wang et al. [11] studied the THG in special asymmetric QWs.

The optical processes in the semiconductor QWs are strongly affected by the external factors, such as non-resonant ILF, electric and magnetic fields, temperature, hydrostatic pressure, and noise. The influence of external electromagnetic fields on the electronic and optical properties of the quantum-confined systems has great relevance for potential technological applications. This is related to

* Corresponding author.
E-mail address: fungan@cumhuriyet.edu.tr (F. Ungan).

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the possibility of using such external probes to suitable tailoring of those properties. Consequently, many studies have addressed the investigation of the effects of external electromagnetic fields on such systems [12–22]. The electric-field-induced changes of the linear and nonlinear optical absorption in semi-parabolic QWs have been investigated by Zhang [12]. Mora-Ramos et al. [13] studied the intense laser field (ILF) effects on the electron-related linear and nonlinear optical properties in $GaAs/Ga_{1-x}Al_xAs$ QWs under electric and magnetic fields. The effects of ILF on the potential well and the corresponding bound states for electrons in a single semiconductor QW was reported by Lima et al. [14]. Sakiroglu et al. [15] presented theoretical calculations for the band structure of a semiconductor superlattice under non-resonant high-frequency ILF. The effects of the non-resonant laser radiation on the nonlinear optical properties of a square QW under the applied electric field have been investigated by Karabulut [16]. Ozturk [17] have discussed the nonlinear intersubband (ISB) transitions in asymmetric double quantum well (ADQW) as dependent on ILF. Furthermore, Shao et al. [18] investigated the THG coefficient for cylindrical quantum dots in a static magnetic field. Saha and Ghosh [19] reported a broad exploration of profiles of THG susceptibility of impurity doped QDs in the presence and absence of noise. The combined effects of hydrostatic pressure, temperature and Gaussian white noise on the profiles of electro-optic effect and third-order nonlinear optical susceptibility of impurity doped GaAs QDs have been studied by Ganguly et al. [20]. At this point, it is worth mentioning that the NOR in a GaAs-based DQW under electric and ILF was investigated in Ref. [21]. However, the influence of an external magnetic field, as well as the SHG and the THG were not considered there. Recently, we reported a study on the linear and nonlinear optical properties in an ADQW, in the simultaneous presence of ILF and static electric and magnetic fields [22]. We found that the ILF and external electromagnetic fields provide an important effect on the electronic and optical properties of ADQW, and the changes of the energy levels and the dipole moment matrix elements depend on the shape of the confinement potential.

In this paper, we investigate the effects of electric and magnetic fields on the NOR, SHG, and THG in $GaAs/Ga_{1-x}Al_xAs$ ADQW under the ILF. In this regard, the Schrödinger equation is solved numerically to find the wave functions and the energy eigenvalues of electrons in the conduction band. Then the results are used to obtain optical properties by compact density matrix approach. Thus, we calculated the changes of NOR, SHG, and THG with the external fields as a function of the incident photon energy. The organization of the paper is the following: In Section 2, details of the calculations are presented. The numerical results are presented and discussed in Section 3. Finally, Section 4 contains the main conclusions of the study.

2. Theory

Here, we are interested in the effects of ILF, electric and magnetic fields on electron states in a $GaAs/Ga_{1-x}Al_xAs$ ADQW grown along the z-axis. The method used in the present calculation is based upon on a non-perturbative theory developed to describe the atomic behavior in high-frequency ILFs. It has been described in details in Refs. [15,23,24]. For this reason, we will not enter into details here. Within the framework of the effective mass approximation, the electron Hamiltonian for the ADQW in the presence of magnetic field $\vec{B}$ applied perpendicular to the growth direction [i.e. $\vec{B}=(B,0,0)$], z-oriented static electric field $\vec{F}=(0,0,F)$, and ILF with linear polarization parallel to the growth direction is given by

$$H=\frac{1}{2m_e^*}\left[\vec{p}_e+\frac{e}{c}\vec{A}\right]^2+V(z,\alpha_0)+eFz, \tag{1}$$

where z represents the growth direction, m_e^* is the electron effective mass, $\vec{p}_e$ is electron momentum operator, e is the electron charge, c is the velocity of the light, $\vec{A}$ is the vector potential, and it is written as $\vec{A}=(0,-Bz,0)$, $\alpha_0=\frac{eF_0}{m_e^*\varpi^2}$ is the laser dressing parameter, F_0 is the field strength, ϖ is the non-resonant frequency of the laser field, and $V(\alpha_0,z)$ is the 'dressed' confinement potential which is given by the following expression [22]:

$$\begin{aligned}V_b(z,\alpha_0)=&V_0\Theta(-\alpha_0-z-L/2)\\&+\frac{V_0}{\pi}\arccos\left(\frac{L/2+z}{\alpha_0}\right)[1-\Theta(-\alpha_0-L/2-z)]\Theta(\alpha_0\\&-L/2-z)+V_0\Theta(-\alpha_0+z-L/2)\\&+\frac{V_0}{\pi}\arccos\left(\frac{L/2-z}{\alpha_0}\right)[1-\Theta(-\alpha_0-L/2+z)]\\&\Theta(\alpha_0-L/2+z)+V_0[1-\Theta(-\alpha_0-z)-\Theta(-\alpha_0+z)]\\&+\frac{V_0}{\pi}\left[\arccos\left(\frac{z}{\alpha_0}\right)[1-\Theta(-\alpha_0-z)]\Theta(\alpha_0-z)\right.\\&\left.+\arccos\left(\frac{-z}{\alpha_0}\right)[1-\Theta(-\alpha_0+z)]\Theta(\alpha_0+z)\right]\\&+V_0[1-\Theta(-\alpha_0-z)-\Theta(-\alpha_0-L_B+z)]\\&-\frac{V_0}{\pi}\left[\arccos\left(\frac{z}{\alpha_0}\right)[1-\Theta(-\alpha_0-z)]\Theta(\alpha_0-z)\right.\\&\left.+\arccos\left(\frac{L_B-z}{\alpha_0}\right)[1-\Theta(-\alpha_0-L_B+z)]\Theta(\alpha_0-L_B+z)\right],\end{aligned} \tag{2}$$

where Θ is the step function, V_0 is the confinement potential barrier height ($V_0(x)=0.6(1.155x+0.37x^2)eV$ and x is the aluminum concentration), L_B is the central barrier width of the ADQW, L_L (L_R) is the left (right) well width and $L=L_B+L_L+L_R$.

To understand the optical properties of the structure, we need to solve the eigenvalue problem of carriers in ADQWs. By solving the Eq. (1) (see Ref. [21] for details), we obtain the effective potential, the energy levels and their corresponding wave functions. After the energies and their corresponding wave functions are obtained, by using the compact density-matrix method and an iterative procedure, we are able to derive the expression of the optical rectification and second and third harmonic generation in the ADQW system. Firstly, we assume that the system is excited by an electromagnetic field with frequency ω and polarization along the growth direction. The electric field vector of the applied electromagnetic field can be written as

$$E(t)=\widetilde{E}^*e^{i\omega t}+\widetilde{E}e^{-i\omega t}. \tag{3}$$

Then the evolution of the one-electron density matrix $\hat{\rho}$ is given by the time-dependent Von Neumann equation

$$\frac{\partial\hat{\rho}_{ij}}{\partial t}=\frac{1}{i\hbar}[\widehat{H}_0-\widehat{M}E(t),\hat{\rho}]_{ij}-\Gamma_{ij}(\hat{\rho}-\hat{\rho}^{(0)})_{ij}, \tag{4}$$

where $\hat{\rho}^{(0)}$ is the unperturbed density matrix, $\widehat{H}_0$ is the Hamiltonian of the system in the absence of electromagnetic field, Γ_{ij} is the relaxation rate, and $\widehat{M}$ is the dipole moment operator. Eq. (4) is solved by the following standard iterative method [25]

$$\hat{\rho}(t)=\sum_{n=0}^{\infty}\hat{\rho}^{(n)} \tag{5}$$

with

$$\begin{aligned}\frac{\partial\hat{\rho}_{ij}^{(n+1)}}{\partial t}=&\frac{1}{i\hbar}\left\{[\widehat{H}_0,\hat{\rho}^{(n+1)}]_{ij}-i\hbar\Gamma_{ij}\hat{\rho}_{ij}^{(n+1)}\right\}\\&-\frac{1}{i\hbar}\left[\widehat{H}_0,\hat{\rho}^{(n+1)}\right]_{ij}E(t).\end{aligned} \tag{6}$$