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The Effect of Electric Field on the Nonlinear Optical Properties in Asymmetric Parabolic Quantum Well Under Intense Laser Field

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Abstract. Within the framework of the compact-density matrix approach and iterative method, we study theoretically the effect of electric field on the nonlinear optical rectification (NOR) and second harmonic generation (SGH) in asymmetric parabolic quantum well (APQW) under the intense laser field (ILF). The numerical results show that the electric field, and ILF lead to significant changes in the coefficients of NOR, SGH.

Keywords: Nonlinear optics, intense laser field, electric field

Yoğun Lazer Alanı Altındaki Asimetrik Parabolik Kuantum Kuyusunun Doğrusal Olmayan Optiksel Özellikleri Üzerine Elektrik Alanın Etkisi

Özet. Bu çalışmada yoğun lazer alanı altındaki asimetrik parabolik kuantum kuyusunun doğrusal olmayan optiksel kırılma ve ikinci dereceden üretim katsayılarının üzerine elektrik alanın etkisi kompakt yoğunluk matrisi yaklaşımı çerçevesinde teorik olarak çalışılmıştır. Nümerik sonuçlar göstermektedir ki elektrik alan ve ILF, NOR, SGH katsayılarında önemli değişikliklere yol açar.

Anahtar Kelimeler: Lineer olmayan optik, yoğun lazer alanı, elektrik alanı

1. INTRODUCTION

The nonlinear optical properties in low-dimensional semiconductor quantum wells (QWs) can be used for practical applications in electronic and optoelectronic devices. The reason for this is that the properties of optical nonlinearities in low-dimensional semiconductor QWs quantum systems have been studied by many researchers in recent years. Among the nonlinear optical properties, more attention had been paid to the second-order nonlinear optical properties [1–10], such as NOR and SHG. For example, NOR in asymmetrical semi-parabolic QWs have been investigated by Karabulut et al. [1]. Rezai et al. investigated optical rectification coefficient associated with intersubband (ISB) transitions in a two-dimensional quantum pseudo dot system [2]. SHG coefficients in asymmetrical semi-exponential QWs are studied by Mou et al. [3]. Bondarenko et al. studied theoretically the influence of the Coulomb interaction on the SHG connected with ISB transitions in asymmetric QWs [4]. Karabulut et al. investigated SHG in an asymmetric rectangular QW under hydrostatic pressure [5]. NOR and the SHG in semi-parabolic and semi-inverse squared QWs are theoretically investigated by Hassanabadi et al. [6].

Research works on the effects of external electromagnetic fields on the electronic and optical properties of the quantum-confined systems are have been carried out in recent years [11-20]. Zhang presented the influences of electric field on the linear and nonlinear optical absorption in semi-parabolic QWs [11].

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Lima et al. studied the ILF effects the potential well and the corresponding bound states for electrons in a single semiconductor QW [12]. The ILF effects on the electron-related linear and nonlinear optical properties in QWs under applied electric and magnetic fields have been investigated by Mora-Ramos et al. [13]. The ILF effects on the band structure of semiconductor superlattice have been investigated by Sakiroglu et al. [14].

In this paper, we study theoretically the effect of electric field on NOR and SHG in $GaAs/Al_xGa_{1-x}As$ APQW under the ILF. The organization of the paper is as follows: Section 2 briefly presents the description of the theoretical model. In section 3 we discuss the corresponding results. Finally, section 4 contains the main conclusions of the study.

2. THEORY

Within the framework of the effective mass approximation, the Hamiltonian for the electron in the presence of an ILF (the laser-field polarization is along the z direction) is given by

$$H = -\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial z^2} + V_b(\alpha_o, z) + eFz \tag{1}$$

where z represents the growth direction, m* is effective mass, e is the electron charge, F is applied electric field in the z direction, α_0 is the laser dressing parameter, and $V_b(\alpha_o, z)$ is the 'dressed' confinement potential which is given by the following expression;

$$\begin{aligned} V_{b=} & \Big[V_L \Big(1-\Theta\Big[\alpha_o-\tfrac{L}{2}+z\Big]\Big) + \tfrac{V_L}{\pi}\,\mathrm{ArcCos}\Big[\tfrac{(z-\frac{L}{2})}{\alpha_o}\Big]\,\Theta\Big[\alpha_o+\tfrac{L}{2}-z\Big]\,\Theta\Big[\alpha_o- \\ & \tfrac{L}{2}+z\Big] + V_R\Big(1-\Theta\Big[\alpha_o+\tfrac{L}{2}-z\Big]\Big)\Big] + \tfrac{V_R}{2\pi}\Big[\mathrm{ArcCos}\Big[\tfrac{\frac{L}{2}-z}{\alpha_o}\Big]\,\Theta\Big[\alpha_o+\tfrac{L}{2}-z\Big]\,\Theta\Big[\alpha_o-\tfrac{L}{2}+z\Big]\Big(1-\Theta\Big[-\alpha_o+\tfrac{L}{2}-z\Big]-\Theta\Big[-\alpha_o- \\ & \tfrac{L}{2}+z\Big]\Big)\,k\Big((-Lc+z)^2+\tfrac{\alpha_o{}^2}{2}\Big) - \tfrac{1}{2\pi}\Theta\Big[\alpha_0+\tfrac{L}{2}-z\Big]\,\Theta\Big[\alpha_o+\tfrac{L}{2}-z\Big]\Big(k\Big(\tfrac{1}{2\pi}\Big((-Lc+z)^2+\tfrac{\alpha_o^2}{2}\Big)+\Big(-2(-Lc+z)+\tfrac{1}{2}\Big(- \\ & \tfrac{L}{2}+z\Big)\Big)\sqrt{-\Big(\tfrac{L}{2}-z\Big)^2+\alpha_o^2}+\Big((-Lc+z)^2+\alpha_o^2\Big)\mathrm{ArcSin}\Big[\tfrac{(\frac{L}{2}-z)}{\alpha_o}\Big]\Big)\Big)\Big] - \Big[\Theta[\alpha_o+\tfrac{L}{2}-z]\Theta[\alpha_o+\tfrac{L}{2}-z](k(\tfrac{1}{2\pi}\Big((-Lc+z)^2+\tfrac{\alpha_o^2}{2}\Big) - \\ & \Big(-2(-Lc+z)+\tfrac{1}{2}\Big(-\tfrac{L}{2}+z\Big)\Big)\sqrt{-\Big(\tfrac{L}{2}-z\Big)^2+\alpha_o^2}-((-Lc+z)^2+\alpha_o^2\,)\mathrm{ArcSin}[((\tfrac{L}{2}-z))/\alpha_o\,]))/2\pi\Big] \end{aligned} \tag{2}$$

where Θ is the step function, L is the quantum well width, V_L and V_R are the confinement potentials in the left-and right-hand sides, respectively.

The electronic energy eigenvalues and the corresponding wave functions in the APQW can be obtained by solving the Schrödinger equation. The time independent Schrödinger equation along the z direction is

$$H\psi(z) = E\psi(z),$$

with $\psi(z)$ represents the wave function of an electron.

We will derive the expressions of the NOR and SHG in the APQW system by using the compact density-matrix method and an iterative procedure. Firstly, we assume that the system is excited by an electromagnetic field with frequency ω ($E(t) = \tilde{E}e^{i\omega t} + \tilde{E}e^{-i\omega t}$) and the polarization along the growth direction z.

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

$$\frac{\partial \hat{\rho}_{ij}}{\partial t} = \frac{1}{i\hbar}\left[\hat{H}_0 - \hat{M}E(t), \hat{\rho}\right]_{ij} - \Gamma_{ij}\left(\hat{\rho} - \hat{\rho}^{(0)}\right)_{ij} \tag{3}$$

where $\hat{\rho}^{(0)}$, $\hat{H}_0$, Γ_{ij}, and $\hat{M}$ are the unperturbed density matrix, the Hamiltonian of the system in the absence of electromagnetic field and the relaxation rate, the dipole moment operator, respectively. Eq. (3) is calculated by the following standard iterative method [21]

$$\hat{\rho}(t) = \sum_{n=0}^{\infty} \hat{\rho}^{(n)} \tag{4}$$

with

$$\frac{\partial \hat{\rho}_{ij}^{(n+1)}}{\partial t} = \frac{1}{i\hbar}\left\{\left[\hat{H}_0, \hat{\rho}^{(n+1)}\right]_{ij} - i\hbar\Gamma_{ij}\hat{\rho}_{ij}^{(n+1)}\right\} - \frac{1}{i\hbar}\left[ez, \hat{\rho}^{(n)}\right]_{ij} E(t). \tag{5}$$

The electronic polarization response caused by the internal field E(t) will be given by

$$P(t) = \left(\varepsilon_0\chi_\omega^{(1)}\tilde{E}e^{i\omega t} + \varepsilon_0\chi_0^{(2)}\tilde{E}^2 + \varepsilon_0\chi_{2\omega}^{(2)}\tilde{E}^2 e^{2i\omega t} + \varepsilon_0\chi_\omega^{(3)}\tilde{E}^2\tilde{E}e^{i\omega t} + \varepsilon_0\chi_{3\omega}^{(3)}\tilde{E}^3 e^{3i\omega t} + cc\right) \tag{6}$$

where ε_0 is the permittivity of the free space, $\chi_\omega^{(1)}$ is the linear optical rectification, $\chi_0^{(2)}$ is NOR, $\chi_{2\omega}^{(2)}$ is SHG, $\chi_\omega^{(3)}$, and $\chi_{3\omega}^{(3)}$ are third-order and third-harmonic generation susceptibilities, respectively. The expressions for the NOR and SHG susceptibility can be derived as follows [22-24]

$$\chi_0^{(2)} = \frac{4e^3\rho_v}{\varepsilon_0\hbar^2}\mu_{01}^2\delta_{01}\frac{\omega_{10}^2(1+\Gamma_2/\Gamma_1) + (\omega^2+\Gamma_2^2)(\Gamma_2/\Gamma_1 - 1)}{\left[(\omega_{10}-\omega)^2+\Gamma_2^2\right]\left[(\omega_{10}+\omega)^2+\Gamma_2^2\right]}, \tag{7}$$

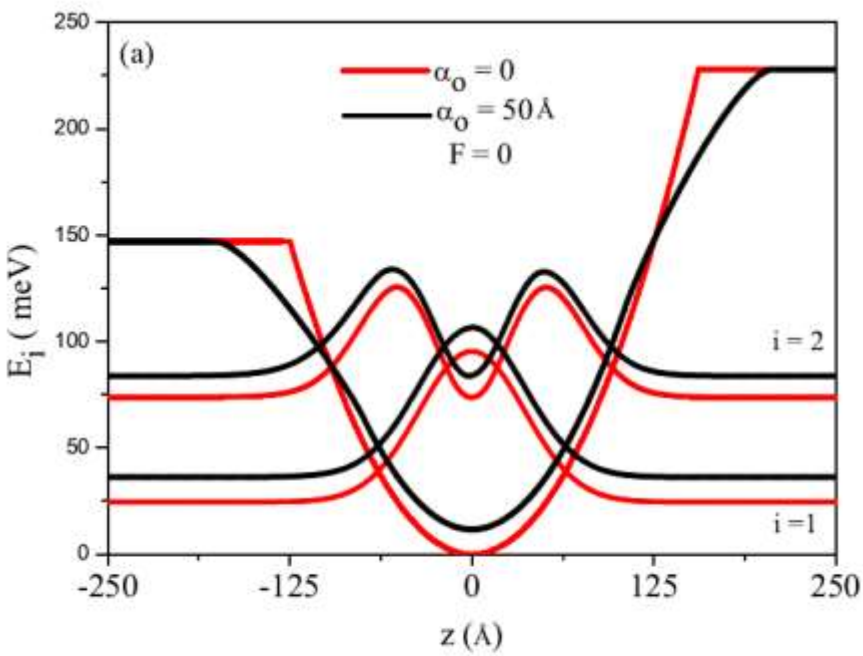
$$\chi_{2\omega}^{(2)} = \frac{e^3\rho_v}{\varepsilon_0\hbar^2}\frac{\mu_{01}\mu_{12}\mu_{20}}{(\omega-\omega_{10}-i\Gamma_3)(2\omega-\omega_{20}-i\Gamma_3)}, \tag{8}$$

Parameters used in these equations are defined as: ρ_v is the electronic density, $\mu_{ij} = \left|\langle\psi_i|z|\psi_j\rangle\right|$ $(i, j = 0,1,2,3)$ is the off-diagonal matrix element, $\delta_{10} = |\mu_{00} - \mu_{11}|$, $\omega_{ij} = (E_i - E_j)/\hbar$ is the transition frequency, and $\Gamma_k = 1/T_k$ with k = (1, 2, 3) are damping terms associated with the lifetime of the electrons involved in the transitions.

3. RESULTS AND DISCUSSION

In this work, we investigate the effect of electric fields on the NOR and SGH in $GaAs/Al_xGa_{1-x}As$ APQW under the ILF. In the values of the physical parameters used in our calculations are $m^* = 0.067m_0$ (m_0 is mass of the free electron), $L = 250$ Å, ($x = 0.3$, $V_R = 228\,meV$), (x=0.2, $V_L = 147\,meV$), $\rho_v = 1\times10^{23} m^{-3}$, $n_r = 3.2$, $T_1 = 1ps$, $T_2 = 0.2ps$, and $T_3 = 0.5ps$.

In Fig. 1(a) and (b), we show the changes of the confinement potential profile, the ground and the first excited state energies and squared wave function corresponding to the two energy levels considered, for different values of the ILF and electric field. As known, ILF creates an additional geometric confinement on the electronic states in the QW. Thus, the electronic structure and main optical properties of the system depend on ISB transitions by ILF. As seen in Fig.1 (a), as ILF increases the width of the well bottom decreases, while the top width increases. Therefore, E_1 and E_2 energy levels blue shifted with the ILF. As expected, with the increase of the electric field applied on the growth direction, the charge carriers are swept towards left-hand side of the structure, since the electric field leads to the creation of a deeper QW on left-hand side of the structure. As a result, these configurations are significant for the electronic structure and main optical properties of the system.



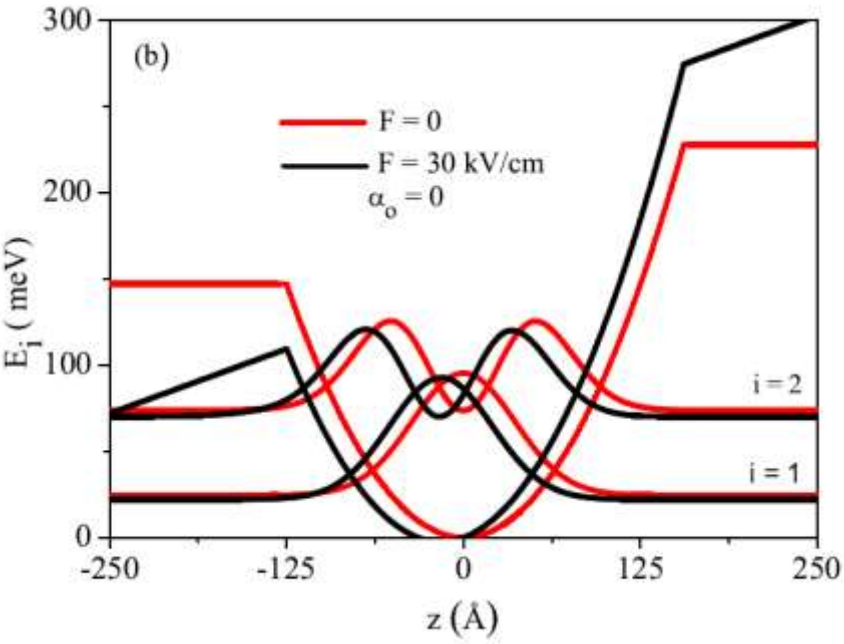


Fig. 1. The changes of the confinement potential profile, the ground and the first excited state energies and squared wave function corresponding to the two lowest energy levels considering two values of (a) ILF parameter, (b) electric field.

The variations of the NOR coefficients as a function of the incident photon energy for three different laser-dressing values (α_o= 0, 25, 50 Å) is given in Fig. 2 (a). A very important feature of this figure is that the magnitude of the changes in the resonant peaks of the NOR increases and also shifts towards lower energies with the increasing α_o. In Fig. 2(b), the variations of the NOR coefficients as a function of the incident photon energy for three different electric fields (F = 0, 15, 30 kV/cm) is shown. It is clearly seen from this figure that the magnitude of the changes in the resonant peaks of NOR is increased as the electric field increases. As seen these figures, we observe that the NOR experiences a red-shift that can be clearly explained because ω_{10} increases as a function of the α_o and electric field. On the other hand, as the applied ILF and electric field increases, the NOR maximum increasing, this is because the factor $\mu_{01}^2\omega_{10}\delta_{01}$ increases as the ILF and electric field increases. In fact the reason for this is that the dipole matrix element $\mu_{01}^2\delta_{01}$ increases faster than the ω_{10} rises.

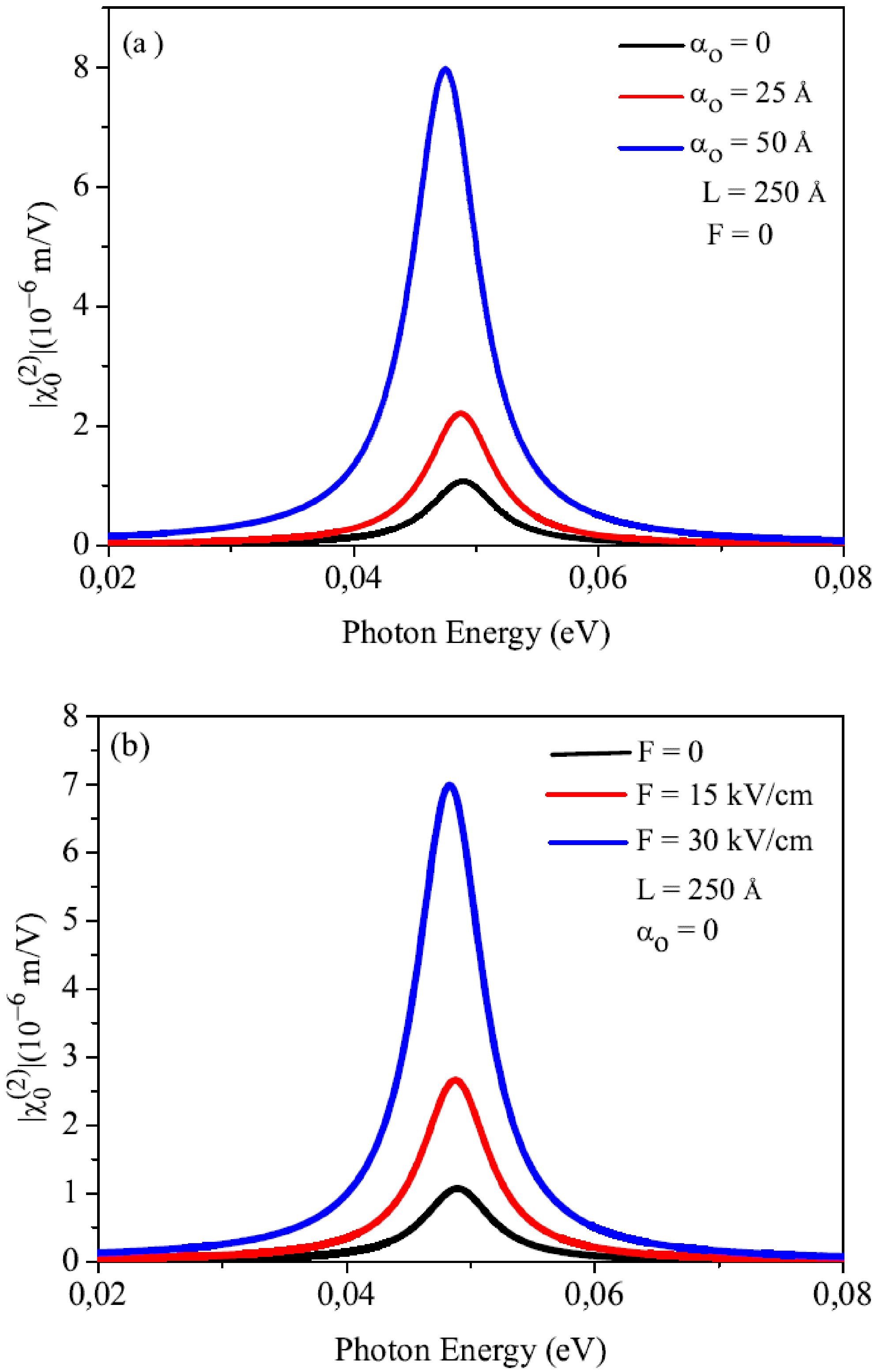


Fig. 2. The variations of the NOR coefficients as a function of the incident photon energy for three different values of (a) α_0, (b) electric field.

In figure 3 we report the computed SHG for the system, as a function of the incident photon energy, for several values of the applied α_o and electric field. As seen as these figures, the red-shift of the response with the increase of the α_o and electric field is again readily apparent. It can be noticed that the increasing α_o and electric field leads to an almost double resonant condition which favors the resolution of the SHG and the increase of the peak amplitude. The former depends on the ISB energy levels separation and the last is determined fundamentally by the wave-function behavior.

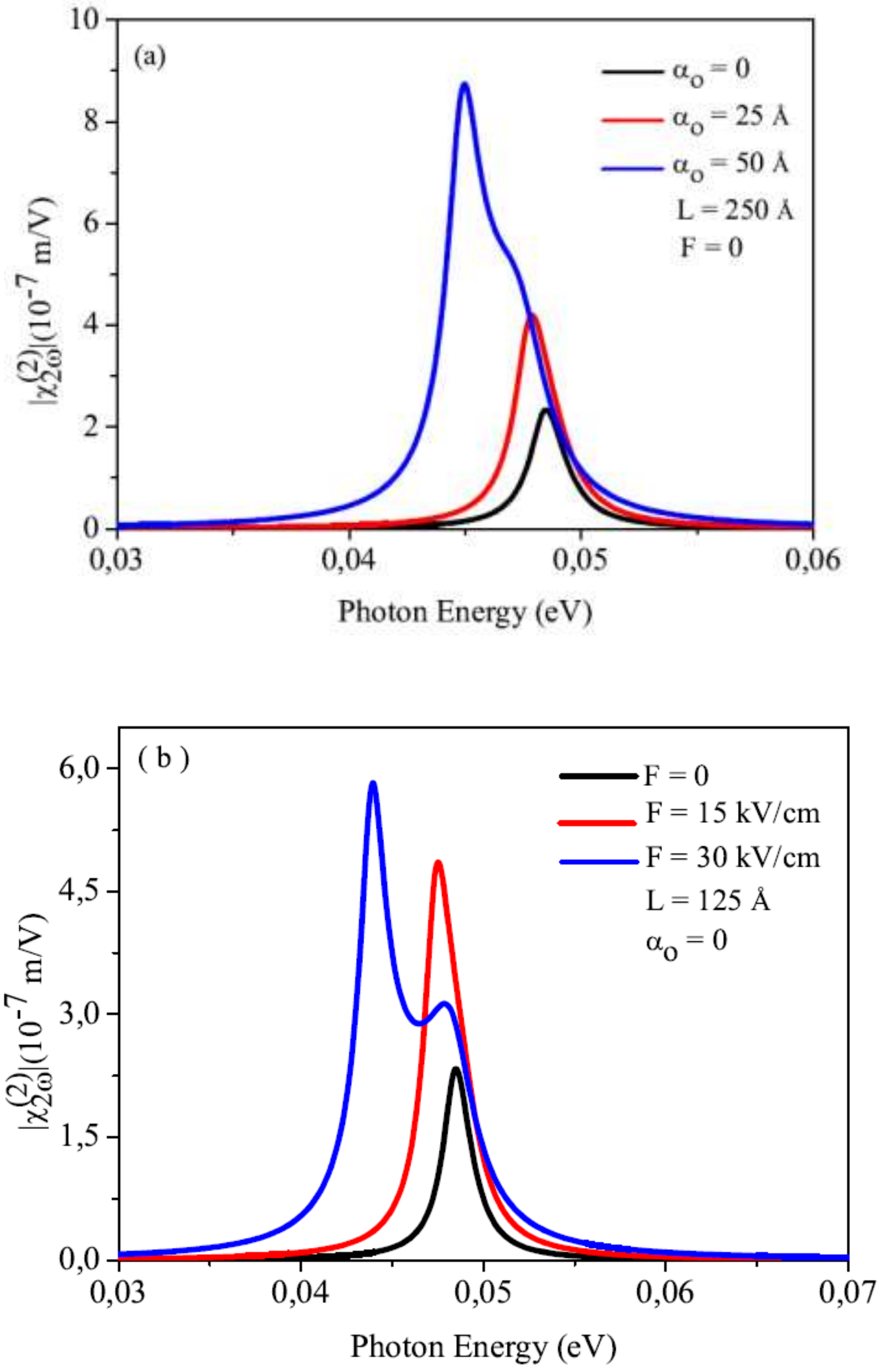


Fig. 3. Second Harmonic Generation (SHG) for an asymmetric parabolic quantum well as a function of the incident photon energy for three different values of (a) α_0, (b) electric field.

4. CONCLUSION

In this present work we have calculated the nonlinear optical rectification-NOR and the second harmonic generation-SHG for an asymmetric parabolic quantum well, considering the effects of ILF and electric field. Calculations have been made in the effective mass approximations and using the compact matrix density formalism. In general we can conclude that this asymmetric parabolic quantum well potential profile exhibits NOR and SHG an that these optical properties can be relatively easily controlled by the growth direction externally applied intense laser field and electric field. In particular we found that for the chosen configuration the harmonic generations are in the THz emission region that are suitable building blocks for THz communication application devices.

5. ACKNOWLEDGEMENTS

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