A Theoretical Study of Strong Probe Field Effects in Nonlinear Optical Processes in Asymmetric Semiconductor Nanostructures

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SCOPE OF THIS WORK: A basic problem in coherent light-matter interaction is the effect of a strong probe electromagnetic field in nonlinear optical phenomena in a driven quantum transition [1]. This leads to the effect of saturation in nonlinear optical processes. Similar phenomena was studied almost twenty years ago in the nonlinear optical response of intersubband transitions of semiconductor quantum wells, giving specific emphasis to asymmetric quantum well structures [2]. In that work [2] the formulae for strong probe field effects in nonlinear optical rectification and nonlinear optical absorption in asymmetric quantum structures were derived. These formulae were used recently for the study of nonlinear optical rectification and nonlinear optical absorption in various semiconductor nanostructures [3-5].

In this work we revisit the problem of strong probe field driving of an asymmetric semiconductor nanostructure, apply the proper form of the rotating wave approximation for asymmetric quantum systems [6,7], and derive again the formulae for nonlinear optical rectification and nonlinear optical absorption. The derived formulae are different from those obtained in ref. [2], and the formulae of ref. [2] are only recovered in a specific limit. The differences between our formulae and that of ref. [2] are presented for a specific example of an asymmetric semiconductor quantum well.

NONLINEAR OPTICAL COEFFICIENTS OF REF. [2]

$$\chi_0^{(2)}(\omega)=\frac{2(\mu_{22}-\mu_{11})\,\mu_{12}^2 N_e T_1 T_2}{\varepsilon_0\hbar^2}\,\frac{1}{1+(\omega_{21}-\omega)^2T_2^2+\mu_{12}^2E^2T_1T_2/\hbar^2},$$

$$\alpha(\omega)=\frac{\omega_{21}\mu_{12}^2N_eT_2}{nc\varepsilon_0\hbar}\,\frac{1}{1+(\omega_{21}-\omega)^2T_2^2+\mu_{12}^2E^2T_1T_2/\hbar^2}.$$

NONLINEAR OPTICAL COEFFICIENTS OF OUR WORK

$$\chi_0^{(2)}(\omega)=\frac{2(\mu_{22}-\mu_{11})\,\bar{\mu}_{12}^2 N_e T_1 T_2}{\varepsilon_0\hbar^2}\,\frac{1}{1+(\omega_{21}-\omega)^2T_2^2+\bar{\mu}_{12}^2E^2T_1T_2/\hbar^2},$$

$$\alpha(\omega)=\frac{\omega_{21}\mu_{12}\bar{\mu}_{12}N_eT_2}{nc\varepsilon_0\hbar}\,\frac{\left|J_2(q)-J_0(q)\right|}{1+(\omega_{21}-\omega)^2T_2^2+\bar{\mu}_{12}^2E^2T_1T_2/\hbar^2}.$$

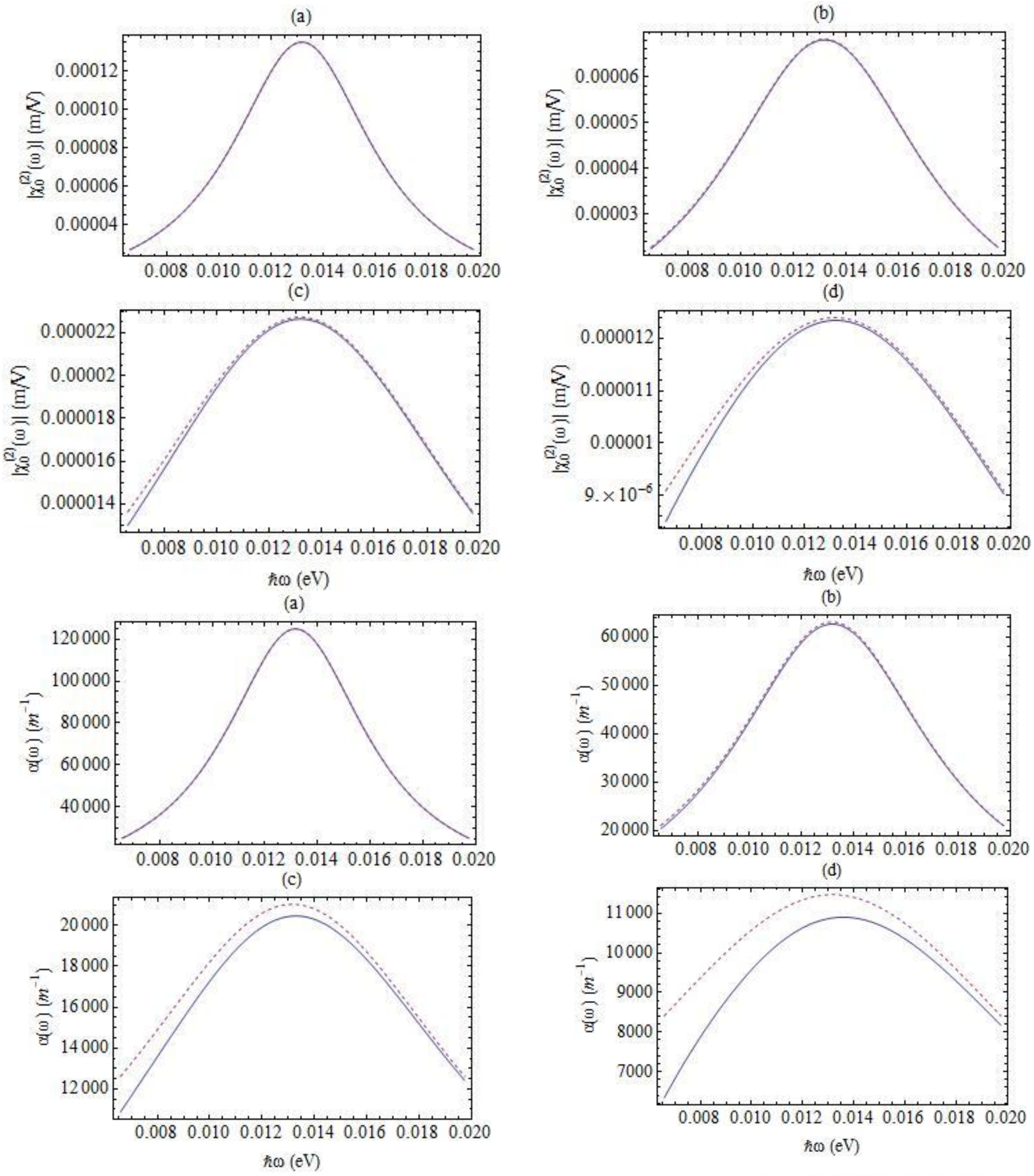
$$\bar{\mu}_{12}=\mu_{12}\left|J_0(q)+J_2(q)\right|,$$

$$q=\frac{\left|\mu_{22}-\mu_{11}\right|E}{\hbar\omega},\quad \mu_{ij}=e\langle i|z|j\rangle.$$

- E is the electric field amplitude and ω is the frequency of the electromagnetic field that is applied to the quantum well.
- ω_{21} is the frequency difference of the two states of the quantum well that contribute in the dynamics.
- The relaxation processes in the system are described phenomenologically by the population decay time T_1 and the dephasing time T_2. Also, N_e is the volume electron density and n the index of refraction of the quantum well material.

QUANTUM WELL STRUCTURE UNDER STUDY: We consider a GaAs/AlGaAs quantum well with semi-parabolic confinement potential with characteristic frequency ω_0. This is a model that has been studied in various papers, see for example ref. [8]. A benefit of this system is that the electric dipole matrix elements and the frequency difference of the quantum states can be calculated analytically. For this system we take $T_1 = 1$ ps, $T_2 = 0.2$ ps, n = 3.2, $N_e = 3\times10^{22}$ m^{-3}, $m_e^* = 0.067m_e$ and $\omega_0 = 10^{13}$ s^{-1}.

FIGURES: The nonlinear optical rectification coefficient (four upper figures) and the nonlinear absorption coefficient (four lower figures) for the transition from the ground state to the first excited state of the quantum well for different values of the applied electromagnetic field intensity: (a) $I = 250$ W/cm^2, (b) $I = 2.5\times10^4$ W/cm^2, (c) $I = 1.25\times10^5$ W/cm^2 and (d) $I = 2.5\times10^5$ W/cm^2. We display with solid curve our results and with dashed curve the results of ref. [2].



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