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Ultrashort Pulse Interaction with Intersubband Transitions of Semiconductor Quantum Wells

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Abstract. We study coherent ultrashort pulse propagation in a two-subband system in a symmetric semiconductor quantum well structure, performing calculations beyond the rotating wave approximation and the slowly varying envelope approximation and taking into account the effects of electron-electron interactions. The interaction of the quantum well structure with the electromagnetic fields is studied with modified, nonlinear, Bloch equations. These equations are combined with the full-wave Maxwell equations for the study of pulse propagation. We present results for the pulse propagation and the population inversion dynamics in the quantum well structure for different electron sheet densities.

1. Introduction

In recent years, Rabi flopping and coherent propagation of ultrashort electromagnetic pulses have been studied both theoretically and experimentally when intersubband transitions of semiconductor quantum wells interact with electromagnetic fields [1, 2, 3, 4, 5, 6, 7, 8, 9]. In some of these studies the Rabi flopping [2, 3, 8] and the coherent propagation of ultrashort far-infrared electromagnetic pulses [4, 5, 7] that interact with a two-subband system in a symmetric semiconductor quantum well structure, taking into account the effects of electron-electron interactions, have been presented. All these studies have shown that at certain electron densities the electron-electron interactions make the intersubband transitions to behave quite differently from atomic transitions.

Here, we revisit the problem of coherent ultrashort pulse propagation in a two-subband system in a symmetric semiconductor quantum well structure, performing calculations beyond the rotating wave approximation (RWA) and the slowly varying envelope approximation (SVEA) and taking into account the effects of electron-electron interactions. The interaction of the quantum well structure with the electromagnetic fields is studied with modified, nonlinear, Bloch equations [10]. These equations are combined with the full-wave Maxwell equations for the study of pulse propagation, so the coupled Maxwell-nonlinear Bloch equations are solved computationally beyond the RWA and SVEA. In order to analyze the impact of propagation on self-induced transparency effects [11, 6], we present results for a hyperbolic secant envelope electromagnetic pulses with initial 2π pulse area.

2. Coupled Maxwell-Nonlinear Bloch Equations

The system under study is a symmetric double semiconductor quantum well and is presented in Fig. 1. We assume that only the two lower energy subbands, $n = 0$ for the lowest subband and $n = 1$ for the excited subband, contribute to the system dynamics. The Fermi level is below the $n = 1$ subband minimum, so the excited subband is initially empty. This is succeeded by a proper choice of the electron sheet density. The two subbands are coupled by a time- and spatially-dependent electric field polarized along the x-direction $E_x(z,t)$, which is taken at the entrance of the medium as $E_x(z = 0,t) = E\text{sech}[1.76(t - t_0)/t_p] \cos[\omega(t - t_0)]$, where E is the maximum electric field amplitude, ω is the central carrier frequency, t_p is the full-width at half-maximum of the pulse intensity envelope of the electromagnetic pulse, and t_0 is the pulse delay. We consider the propagation properties of an ultrashort pulse $E_x(z,t)$ along the z-axis in multiple double symmetric quantum wells. The propagation of the electric field $E_x(z,t)$ is determined by the Maxwell-wave equations

$$\frac{\partial E_x}{\partial t} = -\frac{1}{\varepsilon}\frac{\partial H_y}{\partial z} - \frac{1}{\varepsilon}\frac{\partial P_x}{\partial t}\,, \tag{1}$$

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu_r}\frac{\partial E_x}{\partial z}\,, \tag{2}$$

where $H_y(z,t)$ is the magnetic field along the y-direction, ε is the relative dielectric constant and μ_r is the magnetic permeability in the medium.

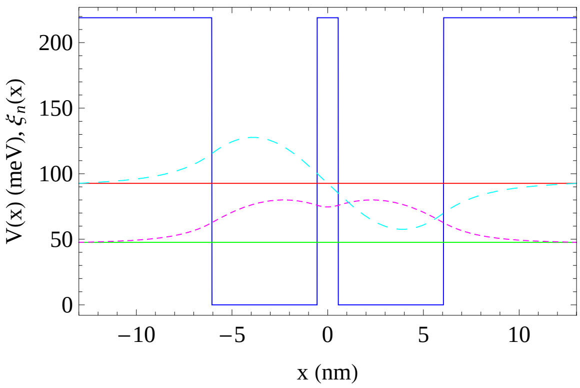

Figure 1. The confinement potential of the quantum well structure under study (blue solid curve) and the energies of the lower (green lower line) and upper states (red upper line). The envelope wavefunctions for the ground (dotted curve) and first excited (dashed curve) subbands.

Olaya-Castro *et al.* [10] showed that the quantum well dynamics is described by the following effective nonlinear Bloch equations

$$\frac{\partial S_1}{\partial t} = [\omega_{10} - \gamma S_3]S_2 - \frac{S_1}{T_2}\,, \tag{3}$$

$$\frac{\partial S_2}{\partial t} = -[\omega_{10} - \gamma S_3]S_1 + 2[\frac{\mu E_x}{\hbar} - \beta S_1]S_3 - \frac{S_2}{T_2}\,, \tag{4}$$

$$\frac{\partial S_3}{\partial t} = -2[\frac{\mu E_x}{\hbar} - \beta S_1]S_2 - \frac{S_3 + 1}{T_1}\,. \tag{5}$$

Here, $S_3(z,t)$ is the mean population inversion per electron (difference of the occupation probabilities in the upper and lower subbands) and the macroscopic polarization of the medium is given by $P_x(z,t) = -N_v \mu S_1(z,t)$, where N_v is the electron volume density of the quantum well. Also, $\mu = ex_{01}$ is the electric dipole matrix element between the two subbands and the parameters $\omega_{10}, \beta, \gamma$ are given by

$$\omega_{10} = \frac{E_1 - E_0}{\hbar} + \frac{\pi e^2}{\hbar \varepsilon} N \frac{L_{1111} - L_{0000}}{2}, \tag{6}$$

$$\gamma = \frac{\pi e^2}{\hbar \varepsilon} N \left(L_{1001} - \frac{L_{1111} + L_{0000}}{2} \right), \tag{7}$$

$$\beta = \frac{\pi e^2}{\hbar \varepsilon} N L_{1100} \,. \tag{8}$$

Here, N is the electron sheet density, e is the electron charge, E_0, E_1 are the eigenvalues of energy for the ground and excited states in the well, respectively, and $L_{ijkl} = \int \int dx dx' \xi_i(x) \xi_j(x') |x - x'| \xi_k(x') \xi_l(x)$, with $i, j, k, l = 0, 1$. Also $\xi_i(x)$, is the envelope wavefunction for the i-th subband along the growth direction. Finally, T_1 describes the population decay time and T_2 the dephasing time.

3. Numerical Results

We consider a GaAs/AlGaAs double quantum well. The structure consists of two GaAs symmetric square wells of width 5.5 nm and height 219 meV. The wells are separated by a AlGaAs barrier of width 1.1 nm. This system has been studied in several previous works [3, 4, 5, 7, 8, 10]. The electron sheet density takes values between 10^9 cm^{-2} and 5×10^{11} cm^{-2}. These values ensure that the system is initially in the lowest subband, so the initial conditions can be taken $S_1(z, t = 0) = S_2(z, t = 0) = 0$, $S_3(z, t = 0) = -1$.

The relevant parameters are calculated to be $E_1 - E_0 = 44.955$ meV and $x_{01} = -3.29$ nm. Also, for electron sheet density $N = 2 \times 10^{11}$ cm^{-2}, we obtain $\pi e^2 N (L_{1111} - L_{0000})/2\varepsilon = 0.412$ meV, $\hbar\gamma = 0.095$ meV and $\hbar\beta = -1.56$ meV. In all calculations we include the population decay and dephasing rates with values $T_1 = 100$ ps and $T_2 = 10$ ps. Also, in all calculations the angular frequency of the field is at exact resonance with the modified frequency ω_{10}, i.e. $\omega = \omega_{10}$.

We consider a structure with 40 quantum wells, each one equally separated by the other by 20 nm. We also take $N_v = N/L$, where $L = 11$ nm. In the propagation homogenization of the structure is considered, similar to what was done in previous studies [4, 5, 7]. The solution of the coupled Maxwell-nonlinear Bloch equations is performed computationally, without applying the SVEA and the RWA, using a combination of the finite-difference time-domain method for the Maxwell equations and a predictor-corrector scheme for the nonlinear Bloch equations, similar to the approach proposed initially by Ziolkowski *et al.* [12].

Typical results are presented in Fig. 2, where the pulse propagation and the population inversion for a pulse with area 2π at the entrance of the medium are shown for three different electron sheet densities. We find that for short propagation distances the pulse changes and leads to strong population inversion, that is in contrast to the behavior expected for an ultrashort 2π pulse [8] which, if no propagation is applied it leads to transient excitation and final de-excitation of the quantum well. Then, for longer propagation distances, near the middle of the medium, the pulse changes and the expected behavior of excitation and de-excitation is found. Finally, for even longer distances, near the end of the medium, the pulse is absorbed and leads to partial population inversion. It is interesting that similar behavior is found for both weak electron sheet densities and for large sheet densities. Qualitatively similar results have been found for other pulse durations, e.g. $t_p = 0.15$ ps and $t_p = 0.05$ ps. In addition, similar behavior is found for an initially 4π pulse.

4. Summary

In this work, we have studied coherent ultrashort pulse propagation in a two-subband system in a symmetric semiconductor quantum well structure. We have performed numerical calculations

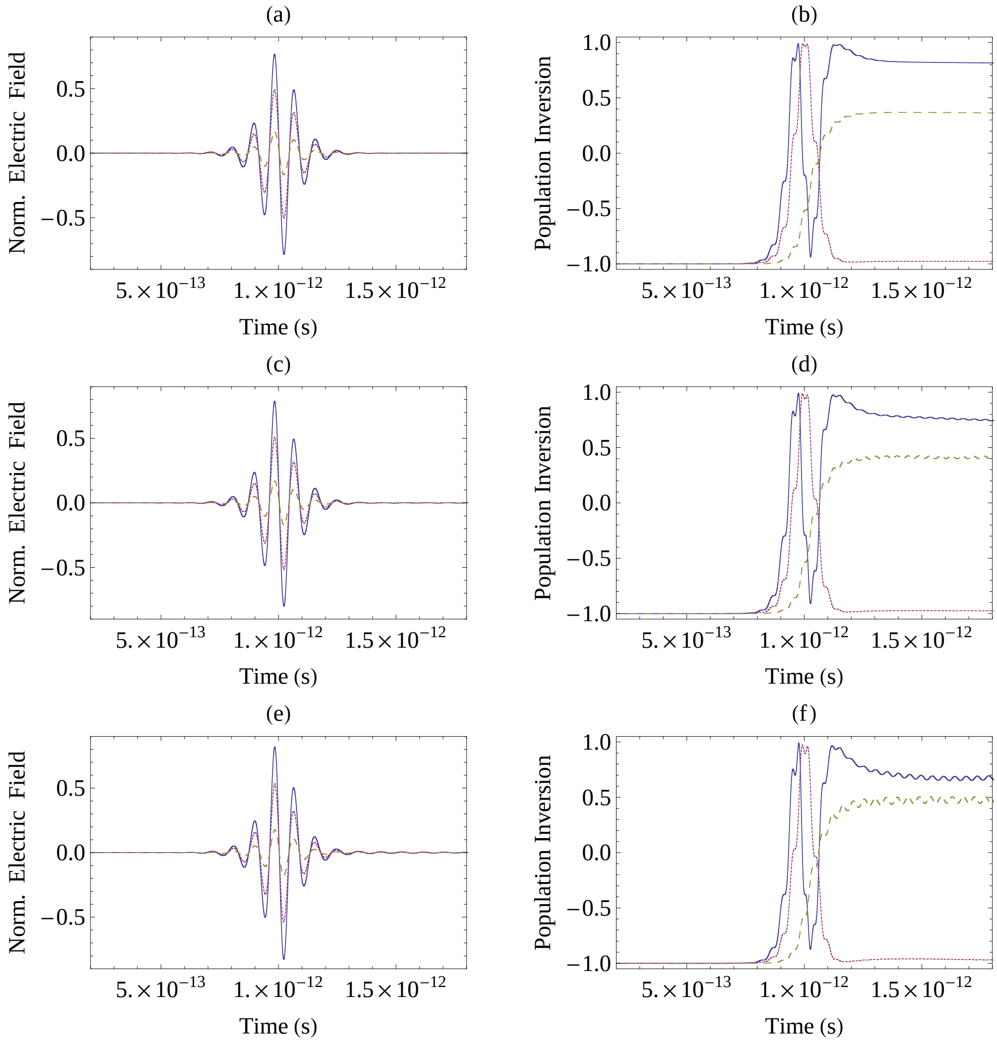

Figure 2. In (a), (c) and (e) we present the normalized electric field for an initially 2π pulse for $t_p = 0.1$ ps. In (b), (d) and (f) we present the respective population inversion. In (a), (b) $N = 10^9$ cm^{-2}, in (c), (d) $N = 2 \times 10^{11}$ cm^{-2} and in (e), (f) $N = 5 \times 10^{11}$ cm^{-2}. The solid curves are for $z = 20$ nm, the dotted curves are for $z = 320$ nm and the dashed curves are for $z = 640$ nm.

beyond the RWA and the SVEA, taking into account the effects of electron-electron interactions. The interaction of the quantum well structure with the electromagnetic fields was studied with nonlinear Bloch equations. These equations were combined with the full-wave Maxwell equations for the study of pulse propagation, and we presented results for the pulse propagation and the population inversion dynamics in the quantum well structure for different electron sheet densities.

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