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Pulsed four-wave mixing in intersubband transitions of a symmetric semiconductor quantum well

Sofia Evangelou, Emmanuel Paspalakis *

Materials Science Department, School of Natural Sciences, University of Patras, Patras 265 04, Greece

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Abstract

We study theoretically the phenomenon of pulsed four-wave mixing in intersubband transitions of a symmetric semiconductor double quantum well structure. In the theoretical model we consider two quantum well subbands that are coupled by a strong pump electromagnetic pulse and a weak probe electromagnetic pulse and take into account the effects of electron–electron interactions. For the description of the system dynamics we use the density matrix equations obtained from the effective nonlinear Bloch equations. These equations are solved numerically for a specific double GaAs/AlGaAs quantum well structure. We show that the time-integrated four-wave mixing spectrum depends strongly on the frequency and the intensity of the pump field, on the time-delay between the two electromagnetic pulses and on the electron sheet density.
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Keywords: Four-wave mixing; Two-subband system; Intersubband transitions; Semiconductor quantum well; Electron sheet density; Electromagnetic pulse

1. Introduction

In the last fifteen years the nonlinear optical properties of intersubband transitions in semiconductor quantum wells have attracted significant attention, especially in the case that the effects of electron–electron interactions are taken into account. Some of the nonlinear optical effects that have been studied theoretically are saturation effects and optical rectification [1,2], second harmonic generation [3] and third harmonic generation [4] in asymmetric semiconductor quantum wells. Also, linear and nonlinear optical effects up to fifth order [5], the four-wave mixing (FWM) [6,7] and the pump-probe optical response [8] in symmetric semiconductor quantum wells have been analyzed. Other nonlinear optical effects that have been considered are gain without inversion [9], optical bistability [10], ultrashort pulse propagation [11], high-order harmonic generation [12,13] and controlled electron dynamics in a two subband system [14–19] in symmetric semiconductor quantum wells. The effects of electron–electron interactions in nonlinear optical properties of intersubband transitions in semiconductor quantum wells have been also studied experimentally [20–25].

In this work we study theoretically the FWM effect [26,27] in intersubband transitions of a symmetric double quantum well structure and especially the case of pulsed FWM [28]. In the theoretical model we consider two quantum well subbands that are coupled by a strong pulsed pump electromagnetic field with fixed frequency and a weak pulsed probe electromagnetic field with varying frequency. We consider the interaction of the two-subband system with Gaussian shape electromagnetic fields. For the description of the system dynamics

* Corresponding author.
E-mail address: paspalak@upatras.gr (E. Paspalakis).

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we use the density matrix equations obtained from the effective nonlinear Bloch equations [8], that allow us to take into account the effects of electron–electron interactions. We write the proper differential equations of the density matrix elements for the several nonlinear optical processes. These equations are solved numerically for a specific double GaAs/AlGaAs quantum well structure. We show that both the shape and the maximum values of the time-integrated FWM spectrum are dependent on the frequency and intensity of the pump field, on the time-delay between the two electromagnetic pulses and on the electron sheet density.

We note that the interaction of a two-subband system with a strong and a weak electromagnetic field has been also studied by Olaya-Castro et al. [8], using the same theoretical approach as we use here. However, in their work the FWM effect was not studied. The FWM effect in intersubband transitions of semiconductor quantum wells, taking into account the electron–electron interactions, was studied by Nottelmann et al. [6] and most recently by our group [7]. In addition, recent studies have considered the effect of FWM in intersubband transitions of four-subband systems in coupled semiconductor quantum wells [29,30]. In the work by Nottelmann et al. [6] the quantum well structure interacts with two ultrashort electromagnetic pulses while in the previous work of our group [7] the quantum well system interacts with rectangular shape electromagnetic fields. We stress that both the assumptions and the theoretical methodology that we use here are rather different from Ref. [6], and it is similar to that of Ref. [7].

The article is organized as follows. In the next section we present the equations of the density matrix elements for the several nonlinear optical processes for a two-subband system that interacts with a weak probe field and a strong pump field. In Section 3 we solve numerically the density matrix equations for a specific GaAs/AlGaAs quantum well structure and study the phenomenon of pulsed FWM. We present results for the time-integrated FWM spectrum for different frequencies and intensities of the strong electromagnetic field, for different electron sheet densities and for different pulse delays. Finally, in Section 4 we summarize our findings.

2. Theoretical model and density matrix equations

We consider a symmetric double GaAs/AlGaAs quantum well structure. It is assumed that only the lower two 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 second subband minimum, so the excited subband is initially empty. This can be succeeded by a proper choice of the electron sheet density. The quantum well system interacts with two electromagnetic fields, and the total electric field is written as

$$E(t) = \mathcal{E}_a f_a(t)\cos(\omega_a t) + \mathcal{E}_b f_b(t)\cos(\omega_b t). \tag{1}$$

Here, $\mathcal{E}_a$, $\mathcal{E}_b$ are the electric field amplitudes, ω_a, ω_b are the angular frequencies and $f_a(t)$, $f_b(t)$ are the pulse shapes of the electromagnetic fields. The field with frequency ω_a is called the pump field and is a strong field with fixed frequency, while the field with frequency ω_b is called the probe field and is a weak field with varying frequency.

In our theoretical analysis we do not consider any propagation effects, and analyze the system purely with the density matrix equations. We take that the pump field is a strong field and its interaction with the quantum well system will be treated to all orders while the probe field is a weak field and its interaction with the quantum well system will be treated to first order. Starting from the effective nonlinear Bloch equations [8], we obtain the following differential equations for the density matrix elements, under the rotating wave approximation:

$$\dot{\sigma}_{01}^{(-\omega_a)}(t) = i\Delta_a\sigma_{01}^{(-\omega_a)}(t) - i(\gamma-\beta)w^{(0)}(t)\sigma_{01}^{(-\omega_a)}(t) + i\Omega_a f_a(t)w^{(0)}(t) - \frac{\sigma_{01}^{(-\omega_a)}(t)}{T_2}, \tag{2}$$

$$\dot{w}^{(0)}(t) = 2i\Omega_a f_a(t)\sigma_{01}^{(-\omega_a)}(t) - 2i\Omega_a f_a(t)\sigma_{10}^{(\omega_a)}(t) - \frac{w^{(0)}(t)+1}{T_1}, \tag{3}$$

$$\dot{\sigma}_{10}^{(\omega_b)}(t) = -i(\Delta_a-\delta)\sigma_{10}^{(\omega_b)}(t) - i\Omega_a f_a(t)w^{(\delta)}(t) - i\Omega_b f_b(t)w^{(0)}(t) + i(\gamma-\beta)w^{(0)}(t)\sigma_{10}^{(\omega_b)}(t) + i(\gamma-\beta)w^{(\delta)}(t)\sigma_{10}^{(\omega_a)}(t) - \frac{\sigma_{10}^{(\omega_b)}(t)}{T_2}, \tag{4}$$

$$\dot{\sigma}_{01}^{(\omega_b-2\omega_a)}(t) = i(\Delta_a+\delta)\sigma_{01}^{(\omega_b-2\omega_a)}(t) - i(\gamma-\beta)w^{(0)}(t)\sigma_{01}^{(\omega_b-2\omega_a)}(t) + i\Omega_a f_a(t)w^{(\delta)}(t) - i(\gamma-\beta)w^{(\delta)}(t)\sigma_{01}^{(-\omega_a)}(t) - \frac{\sigma_{01}^{(\omega_b-2\omega_a)}(t)}{T_2}, \tag{5}$$

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