Coherent Control of Intersubband Quantum Well Transitions with Ultrashort Electromagnetic Pulses

Emmanuel Paspalakis[1] and John Boviatsis[2]

[1]*Materials Science Department, School of Natural Sciences, University of Patras, Patras 26504, Greece*

[2]*Technological and Educational Institute of Patras, Megalou Alexandrou 1, 26334 Patras, Greece*

INTRODUCTION AND SCOPE OF THIS WORK: An important problem in the area of light interaction with intersubband quantum well transitions is the potential for controlled population transfer between two quantum well subbands [1-5]. This problem was first studied by Batista and Citrin [1,2] including the many-body effects arising from the macroscopic carrier density of the system. They showed that the inclusion of the electron-electron interactions makes the system behave quite differently from an atomic-like two-level system. To succeed high-efficiency population transfer in a two-subband *n*-type modulation-doped semiconductor quantum well, they used the interaction with specific chirped electromagnetic fields, i.e. fields with time-dependent frequency [1,2]. Different approaches for creating high-efficiency intersubband population transfer were also proposed by our group, where specific formulae for the electric field amplitude of the electromagnetic field that leads to high-efficiency population transfer were given [3,4]. We also showed that when a two-subband system interacts with a strong chirped electromagnetic pulse, high-efficiency population inversion is possible for several values of the chirp rate and the electric field amplitude [5].

In this work we study the interaction of ultrashort electromagnetic pulses with intersubband quantum well transitions, giving emphasis to the case of a few cycle and single cycle electromagnetic pulses. We numerically solve the nonlinear Bloch equations [3,6] for a specific double GaAs/AlGaAs quantum well structure, taking into account the ultrashort nature of the applied field, and show that high-efficiency population inversion is possible for specific pulse areas. The dependence of the efficiency of the population transfer on the electron sheet density is also explored.

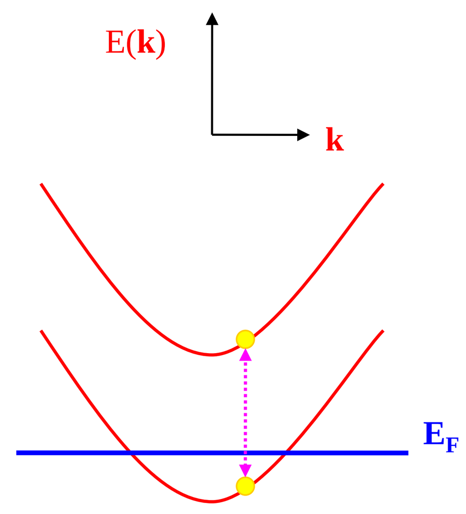
EFFECTIVE NONLINEAR OPTICAL BLOCH EQUATIONS FOR INTERSUBBAND TRANSITION DYNAMICS IN A SEMICONDUCTOR QUANTUM WELL

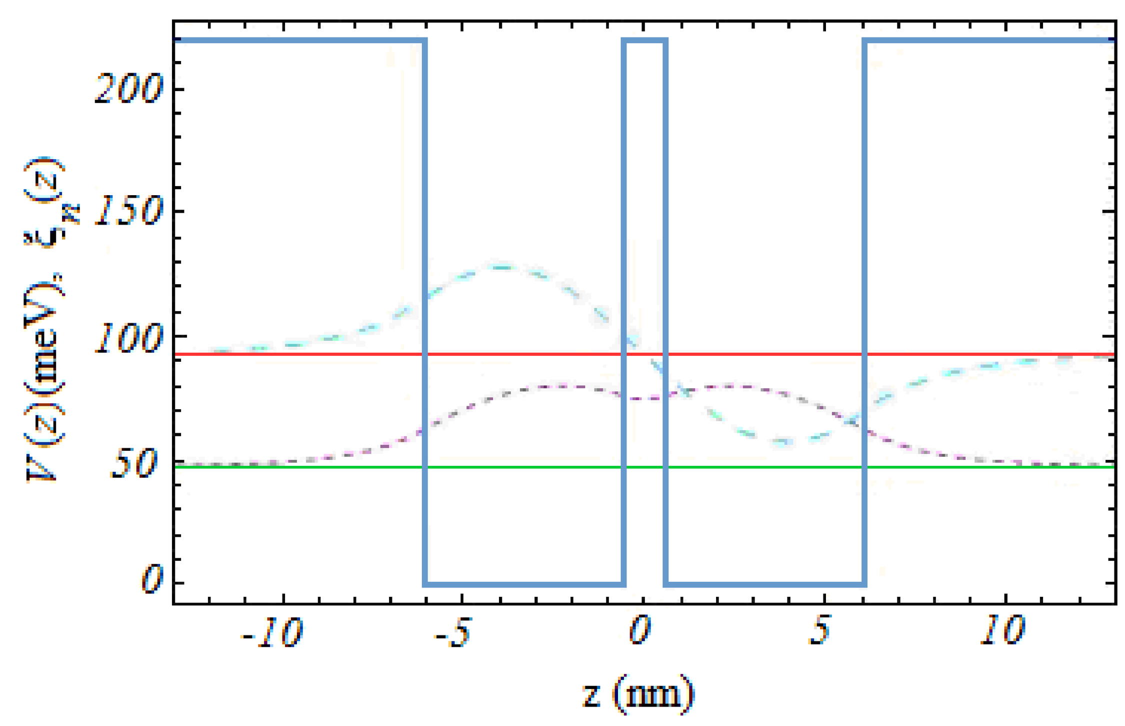
$$dS_1(t)/dt = [\omega_{10} - \gamma S_3(t)]S_2(t) - S_1(t)/T_2$$

$$dS_2(t)/dt = -[\omega_{10} - \gamma S_3(t)]S_1(t) + 2[\mu E(t)/\hbar - \beta S_1(t)]S_3(t) - S_2(t)/T_2$$

$$dS_3(t)/dt = -2[\mu E(t)/\hbar - \beta S_1(t)]S_2(t) - [S_3(t)+1]/T_1$$

- μ is the electric dipole matrix element between the two subbands. $E(t)$ is the total electric field applied to the quantum well structure.
- ω_{10}, β, γ are parameters defined by means of the envelope functions of the ground and excited states in the quantum well system and depend on electron sheet density.
- The relaxation processes are described phenomenologically by the population delay time T_1 and the dephasing time T_2.





Upper figures: Double symmetric semiconductor quantum well structure, energies and corresponding envelope functions (right). Lower subband (solid line) and upper subband (dashed line) are shown. Energy dispersion in the first two subbands are presented (left).

$$\omega_{10} = \frac{E_{10}}{\hbar} + \frac{\pi e^2 N}{2\hbar\varepsilon}(L_{1111} - L_{0000})$$

$$\gamma = \frac{\pi e^2 N}{2\hbar\varepsilon}(2L_{1001} - L_{1111} - L_{0000}), \quad \beta = \frac{\pi e^2 N}{\hbar\varepsilon} L_{1100}$$

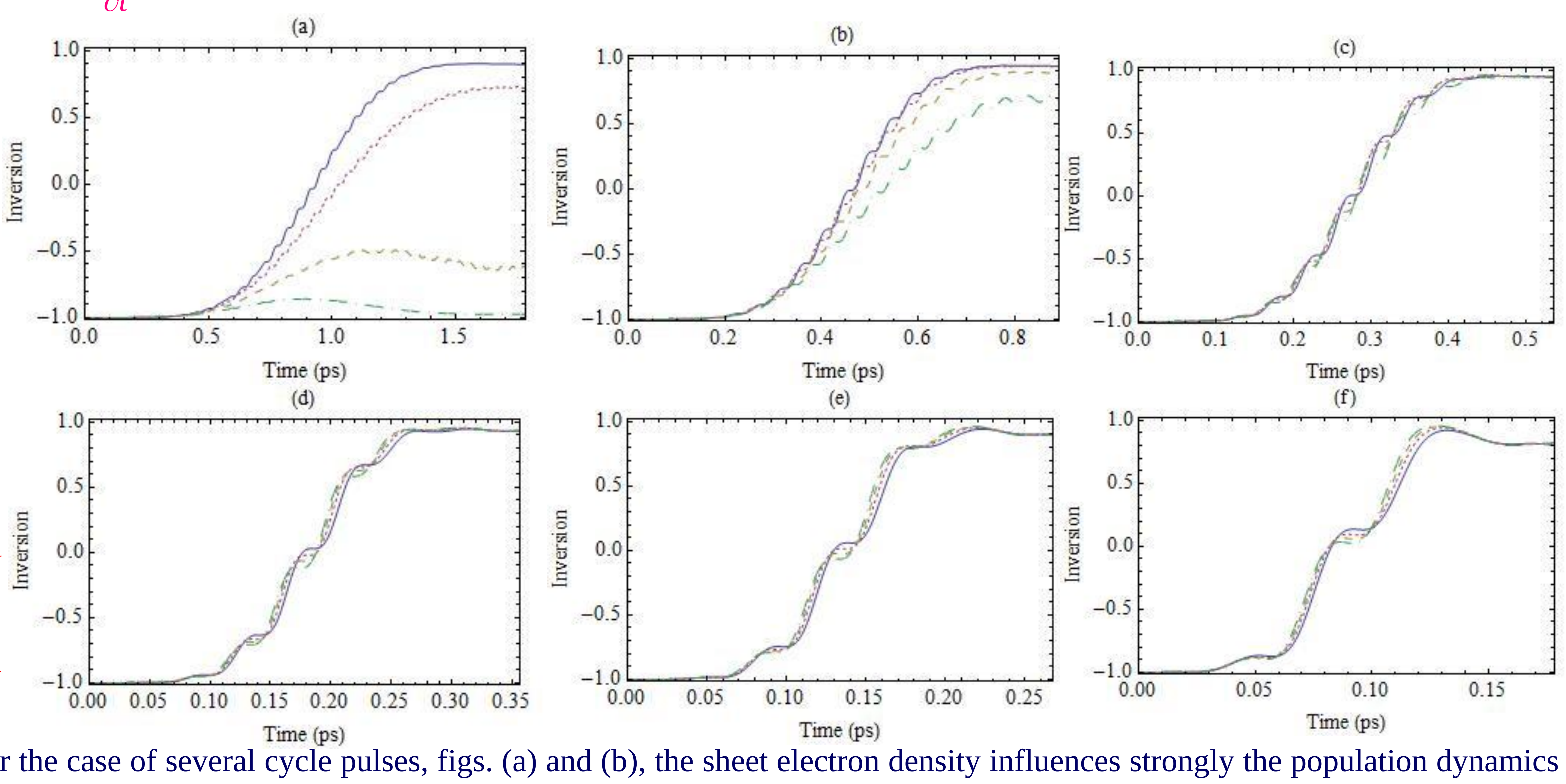
$$L_{ijkl} = \iint dz dz' \xi_i(z)\xi_j(z')|z-z'|\xi_k(z')\xi_l(z)$$

$$A(t) = A_0 \sin^2\left(\frac{\pi t}{2\tau_p}\right)\cos(\omega t + \varphi), \quad E(t) = -\frac{\partial A}{\partial t}$$

QUANTUM WELL STRUCTURE UNDER STUDY AND THEORETICAL PROCEDURE:

We consider a **GaAs/AlGaAs** double quantum well [3,6]. 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. For this system we take $T_1 = 60$ ps and $T_2 = 6$ ps. We study the interaction of the quantum well structure with a sin-squared electromagnetic pulse and calculate the dynamics of the population inversion for various pulse durations and electron sheet densities. For the structure under study we present results in the region $N = 10^9 - 7 \times 10^{11}$ cm^{-2}, such that the system can be initially taken in the ground subband.

- N is the **electron sheet density**
- The electric field is defined via the vector potential in order to correctly account for effects that happen with single and few cycle pulses [7]. The pulse duration is $\tau_p = 2\pi N_p/\omega$, with N_p the number of cycles that can be non-integer.



Right: The inversion $S_3(t)$ as a function of time. The excitation is on resonance, i.e. $\omega = \omega_{10}$, and the pulse area is π. (a) $N_p = 10$, (b) $N_p = 5$, (c) $N_p = 3$, (d) $N_p = 2$, (e) $N_p = 1.5$ and (f) $N_p = 1$. Solid curve $N = 10^9$ cm^{-2}, dotted curve $N = 3 \times 10^{11}$ cm^{-2} dashed curve $N = 5 \times 10^{11}$ cm^{-2} and dot-dashed curve $N = 7 \times 10^{11}$ cm^{-2}. Here, φ=0.

SUMMARY OF RESULTS: For the case of several cycle pulses, figs. (a) and (b), the sheet electron density influences strongly the population dynamics and as the electron density increases the population inversion strongly decreases. For the case of few cycle pulses, figs. (c)-(f), the electron sheet density influences only weakly the population dynamics and its influence decreases with the decrease of pulse duration. In this region very strong population inversion is succeeded for all the values of electron sheet density considered.

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