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Detection of Rabi oscillations in a two-dimensional electron gas under ultrafast intersubband excitation

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Abstract
We investigate the coherent nonlinear response of a 2D electron gas under ultrafast mid-IR excitation. Laser-induced Rabi oscillations result in population redistribution between resonantly excited subband levels. We calculate temporal redistributions using non-Markovian balance equations, taking into account population relaxation and dephasing of the intersubband polarization. Detection schemes, based on terahertz emission of radiation from non-symmetric quantum wells, as well as a two-colour pump probe method, are discussed for signatures of intersubband Rabi oscillations.

1. Introduction

Advances in ultrafast pulse generation in the mid-infrared (mid-IR) spectral region [1] have offered the possibility to probe coherent intersubband dynamics of 2D electrons in modulation-doped semiconductor quantum well (QW) structures. With dephasing times ranging from tens up to a few hundred femtoseconds in the low-density regime and at low temperatures [2], windows for coherent manipulations to take place are short. Such manipulations are possible however, as recently demonstrated in [3] for relatively low pulse energies, and further discussed in [4]. Depending on pulse power and sample area excited, it is estimated that intersubband Rabi oscillations, with on the order of 10^6 electrons, are feasible. Detection of such oscillations using a cross-correlation absorption method has been analysed [4] using non-Markovian balance equations, taking into account different mechanisms of relaxation and dephasing, both homogeneous and inhomogeneous. In this paper, we discuss further detection schemes based on (i) THz emission from a non-symmetric QW and (ii) two-colour pump probe spectroscopy in a three-level QW.

We have performed calculations based on the following approximations. In order to minimize the role played by electron–electron scattering and Coloumb renormalization of the intersubband resonance, we limit our discussion to the low-density regime with typical carrier concentrations of $n_{2D} \lesssim 10^{10}$ cm^{-2}. Due to the reduced availability of phase space for electron–electron scattering (which dominates dephasing processes [3] resulting in homogeneous broadening of transitions), a constant dephasing rate is included within a non-Markovian memory kernel. We assume band parabolicity throughout and neglect bandgap renormalization—effects which dominate at much higher carrier concentrations than those considered here. With interlevel energies much larger than LO-phonon energies, phonon emission times are reduced and included here in a phenomenonlogical approximation.

2. Theory

The coherent response of a single QW under ultrafast resonant, or near-resonant excitation, is described by balance equations for the level populations averaged over the period of the mid-IR pulse. The contributions of population relaxation and dephasing are included in the framework of τ-approximation. We consider an electric field, $E_t \equiv [E\exp(-\mathrm{i}\omega t) + \mathrm{c.c.}]w_t$, polarized in the growth direction, driving intersubband transitions of electrons between levels with energies ε_1 and ε_2. The pulse has a secant temporal profile, w_t, with duration τ_p (FWHM). The redistribution of electrons between subband levels with population densities n_{1t} and n_{2t} is described by the population difference $\Delta n_t = n_{1t} - n_{2t}$, which is governed by the non-Markovian balance equation [4]

$$\frac{\mathrm{d}\Delta n_t}{\mathrm{d}t} + \nu_r w_t \int_{-\infty}^{t} \frac{\mathrm{d}t'}{\tau_p} w_{t'}\,\mathrm{e}^{-(t-t')/\tau_2} \cos[\Delta\omega(t-t')]\Delta n_{t'} + \frac{\Delta n_t - n_{2D}}{\tau_1} = 0. \tag{1}$$

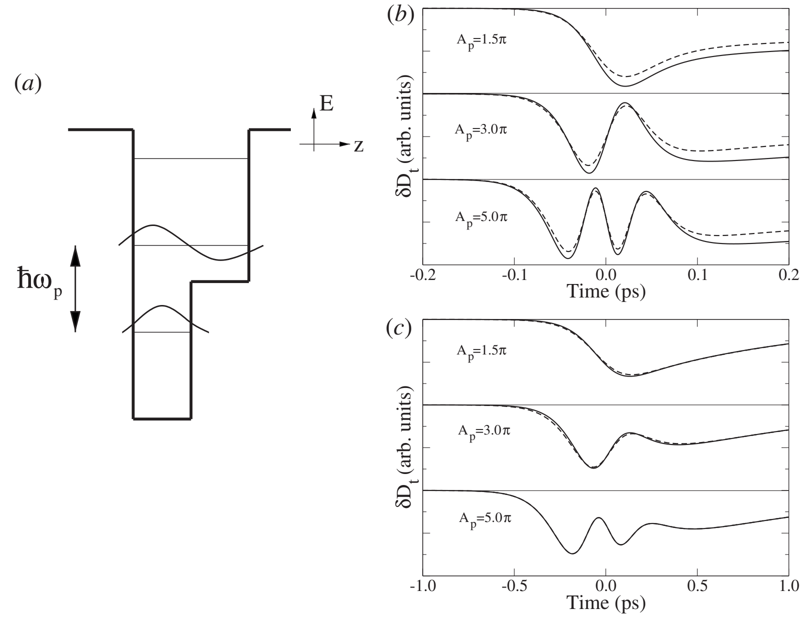

Figure 1. (*a*) Schematic conduction band diagram showing wavefunctions in a non-symmetric QW. The resonant pump pulse (with $\tau_p = 0.1$ ps) is tuned to the transition energy of the lowest two subbands. The evolution of the induced dipoles for pump areas $A_p = 1.5\pi, 3.0\pi, 5.0\pi$ are shown in (*b*). The effects of a detuning of $\hbar\Delta\omega = 6$ meV are shown as the dashed curves. (*c*) Same as in (*b*) only with longer pulse duration, $\tau_p = 0.5$ ps, such that the energy densities are reduced by a factor of five with respect to those in (*b*).

The initial condition is given by $\Delta n_{t\to-\infty} = n_{2\mathrm{D}}$, where $n_{2\mathrm{D}}$ is the concentration of electrons in the QW. Here we introduced the phototransition frequency $\nu_r = (2ev_{12}E/\hbar\omega)^2\tau_p$ expressed through the intersubband velocity matrix element v_{12}. With the carrier concentration $n_{2\mathrm{D}}$ fixed, the degree of interlevel redistribution is determined by the interplay of dephasing (τ_2), interlevel relaxation due to LO-phonon emission (τ_1), pulse area, $A_p = \sqrt{\nu_r\tau_p}\int_{-\infty}^{\infty} \mathrm{d}t\, w_t$ and detuning from resonance, $\hbar\Delta\omega = \hbar\omega - \varepsilon_{21}$.

In order to couple to the intersubband dipole, we consider a 45° prism integrated onto the sample. Consequently, in our results below, we quote pulse parameters taking into account that around 33% of the pulse power couples to the transition. We note that typical pulse lengths corresponding to the parameters considered are around 15–25 μm. As this value exceeds characteristic kinetic lengths associated with the dynamics, we can neglect in-plane inhomogeneities in the problem.

3. Results

We turn now to the detection scheme based on the oscillating dipole moments associated with Rabi oscillations in a non-symmetric quantum well (figure 1(*a*)). Due to the asymmetry of the QW along the growth direction, the dipole moments of the two levels, d_1 and d_2, differ such that the total induced dipole moment can be written as

$$D_t = n_{1t}d_1 + n_{2t}d_2 \propto (1 - d_2/d_1)\Delta n_t. \qquad (2)$$

Thus the THz radiation emitted from such induced charge oscillations should follow the temporal pattern of the Rabi oscillating population. Our calculations below are based on typical parameters for a GaAs QW with an energy level splitting of $\hbar\omega = 100$ meV [3, 4]. We include constant dephasing ($\tau_2 = 0.32$ ps) and LO-phonon emission times ($\tau_1 = 1.0$ ps), corresponding to a two-level system homogeneously broadened by 4 meV.

In figure 1(*b*), we plot the dipole response for pulses with areas of $A_p = 1.5\pi, 3.0\pi, 5.0\pi$ and $\tau_p = 0.1$ ps, corresponding to free space pulse energy densities of 1.17, 4.70 and 13.05 μJ cm^{-2}, respectively. The effects of a small detuning, $\hbar\Delta\omega = 6$ meV, of the pulse from resonance are evidenced by the slight suppression of the oscillations. The calculations are repeated for $A_p = 1.5\pi, 3.0\pi, 5.0\pi$ with $\tau_p = 0.5$ ps, and results plotted in figure 1(*c*). The energy densities for these pulses are 0.23, 0.94 and 2.61 μJ cm^{-2}, respectively. With the longer pulse duration, the Rabi oscillations are suppressed but still visible even with 6 meV detuning as before. We note that the concentration excited is typically of the same order as excited under interband excitation [6], so that a visible intensity of THz radiation should be expected.

A direct observation of intersubband Rabi oscillations is possible based on a two-colour detection method which allows for the time-resolved detection of the photoexcited electrons. The method, based on a similar scheme for the interband case [5], requires the use of an additional weak probe pulse which is tuned to the 1–3 or 2–3 transition (figure 2(*a*)). The linear response to the probe pulse, $\left[E_{pr}^{(k)}\exp(-\mathrm{i}\omega_{pr}t) + \mathrm{c.c.}\right]w_t^{(pr)}$, is described by the induced current density $I_t^{(k)}\exp(-\mathrm{i}\omega_{pr}t)$ + c.c. with the time-dependent amplitude

$$I_t^{(k)} = \frac{2e^2E_{pr}^{(k)}}{\hbar\omega_{pr}}|v_{3k}|^2\int_{-\infty}^{0}\mathrm{d}t'\,w_{t+t'}\,\mathrm{e}^{t'/\tau_2+\mathrm{i}(\varepsilon_{3k}-\hbar\omega_{pr})t'/\hbar}\Delta n_{k,t+t'}, \qquad (3)$$

which is written in the resonant approximation, $|\varepsilon_{3k} - \hbar\omega_{pr}| \ll \hbar\omega_{pr}$. Here $k = 1, 2$ corresponds to the detection of ground (excited) population, ε_{3k} is the splitting between level 3 and

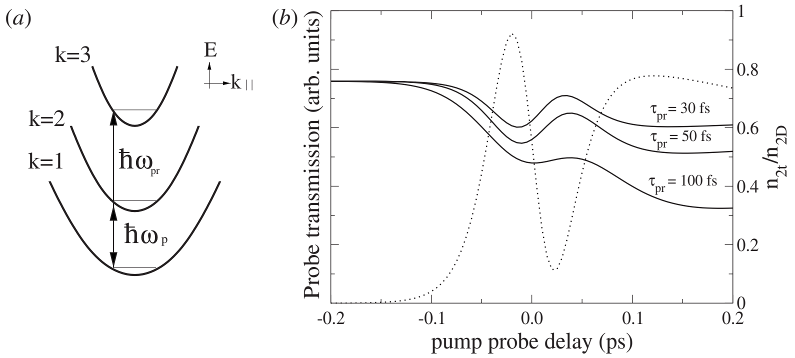

Figure 2. (a) Energy (E) versus in-plane wavevector ($k_\parallel$) for the two-colour detection scheme. Rabi oscillations are driven by a pump pulse with duration $\tau_p = 0.1$ ps tuned to the $1 \rightarrow 2$ transition. The probe transmission of pulses with the same area, variable duration τ_{pr}, is shown in (b) as a function of pump probe delay. The population in level 2 is shown as the dotted curve.

the two lower states ($\varepsilon_{32} \sim 150$ meV, $\varepsilon_{31} \sim 250$ meV), with v_{3k} the corresponding matrix element. The absorbed power is written as

$$\mathcal{P}_t^{(k)} = \frac{\left(2eE_{pr}^{(k)}\right)^2}{\hbar\omega_{pr}} |v_{3k}|^2 w_t^{(pr)} \int_{-\infty}^{0} \mathrm{d}t' w_{t'} \times \mathrm{e}^{t'/\tau_2} \cos \Delta\omega_k t' \Delta n_{k,t+t'}, \tag{4}$$

where $\hbar\Delta\omega_k = \hbar\omega_p - \varepsilon_{3k}$ and n_{kt} is determined by equation (1). For a pump probe delay of τ_d, equation (4) effectively gives a measure of the population of the kth level at that time. In figure 2(b), we plot the probe transmission as a function of the pump probe delay. In this case the $k = 2$ level is probed, resonantly exciting electrons to the $k = 3$ level. Calculations are carried out with a variety of probe pulse times with identical pulse areas. The strong pump pulse with $A_p = 3\pi$ ($\tau_p = 0.1$ ps with energy density of 4.7 μJ cm^{-2}) drives the coherent oscillations between $k = 1$ and $k = 2$. The signature of the Rabi flops in the oscillating transmission becomes clear as the probe pulse is made shorter, thereby enhancing the time resolution.

In conclusion, we have shown the signatures that one might observe from Rabi oscillating populations in a low-density quasi-2D electron gas, where dephasing rates are constant and many-body effects are neglected to first approximation. Moreover, we find that signatures remain for pulse durations comparable with relaxation times, thus offering the possibility to further reduce the pulse intensities required.

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