Coherent Intersubband Excitations on a Picosecond Time Scale

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***Abstract*—Coherent light-matter interaction in asymmetric quantum well structures is investigated with picosecond time resolution. Coupling two excited subbands by a strong mid-infrared pulse is found to result in an increased transparency of the fundamental e1-e2 transition, and a transient absorption between higher subbands is observed. In a V-type subband system oscillations due to quantum coherence are discussed on a picosecond time scale.**

***Index Terms*—Coherent effects, intersubband transitions, time resolved spectroscopy**

I. Introduction

There is a long tradition in the investigation of matter-wave interference effects in atomic vapors with their long dephasing times. Such experiments are much more difficult in solids due to their considerably shorter dephasing times. Intersubband transitions in quantum wells (QW) appear to be a system suitable for such experiments due to their high transition moments which result in relatively high Rabi frequencies Ω at moderate intensities.

Time and frequency resolved studies of intersubband transitions are not only a versatile method to investigate the population dynamics of the subband system, but they give also access to coherent interaction processes. First experiments on electromagnetically induced transparency (EIT) and gain without inversion were reported in [1,2].

In this paper time and frequency resolved data are presented which show quantum interference in QW samples with three coupled subbands. In a cascade-type system, EIT and electromagnetically induced absorption are demonstrated, whereas oscillations in the time domain are detected in a V-type subband system.

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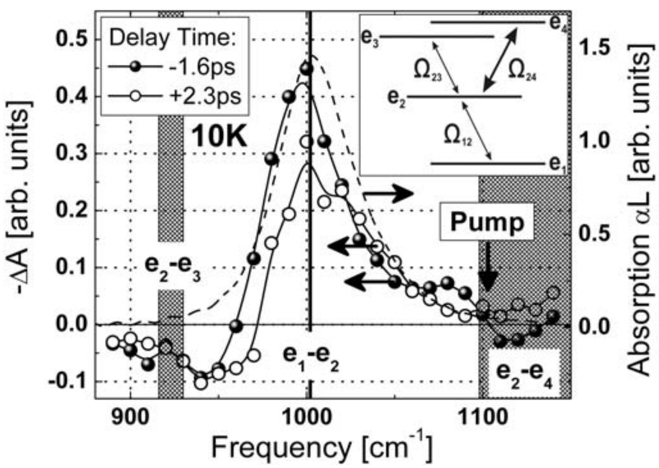

Fig. 1. Electromagnetically induced bleaching of the absorption due to excitation of e2-e4 at 1103 cm^{-1} outside the e1-e2 absorption band for two delay times. A strongly increased transparency is found at the e1-e2 transition frequency and an absorption arises at the e2-e3,e4 transition frequencies. The dashed line represents the FTIR spectrum. Inset: Cascade-type system with subbands coupled by Rabi frequencies Ω_{ij}.

II. EIT and Electromagnetically Induced Absorption

Experiments are performed with two independently tunable mid-infrared pulses of 2ps duration and a spectral width of ~15 cm^{-1}. The sample used is an asymmetric GaAs/AlGaAs multiple QW structure with 4 bound states. The QWs are n-doped resulting in a carrier concentration of 2.6×10^{17} cm^{-3} in the wells. The e1-e2 transition is observed at 1002 cm^{-1}, whereas the e2-e3 and the e2-e4 transitions are calculated to be at 923 cm^{-1} and 1133 cm^{-1}, respectively.

Fig. 1 shows the absorption change ΔA of the sample due to excitation by an infrared pulse at 1103 cm^{-1} (corresponding to the e2-e4 transition). The ΔA spectra are measured by a second tunable pulse at the delay times t_D=-1.6ps and t_D=2.3ps. Despite the fact, that the excitation frequency is far from the absorption band of the e1-e2 transition, we detect a strong bleaching of that transition, i. e. we observe EIT. At the frequency positions of the e2-e3 and the e2-e4 transitions an increased absorption appears. It should be noted that the ΔA peak values of these signals are found at slightly shorter delay times than that of population bleaching which is observed by resonant excitation at the e1-e2 transition at 1002 cm^{-1}. Such a behavior is typical for coherent interactions.

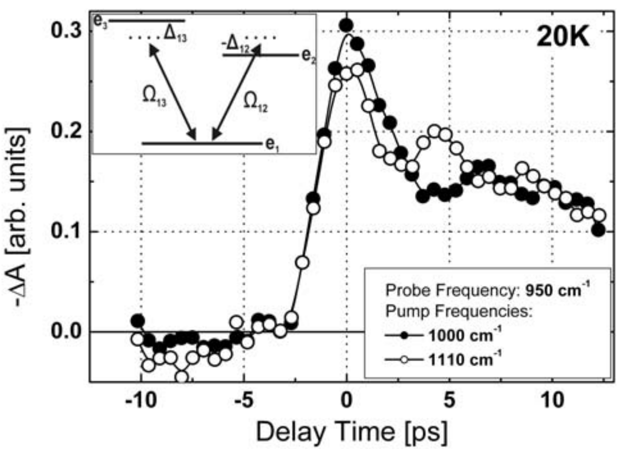

Fig. 2. Absorption change as a function of time due to excitation at 1000 cm^{-1} and 1110 cm^{-1}, respectively. The change in absorption is monitored by a probe pulse at 950 cm^{-1}. Oscillations due to quantum interference are clearly observed. Inset: V-type subband system excited off resonance.

III. Quantum Oscillations on a ps-Time Scale

A second asymmetric GaAs/AlGaAs multiple QW sample exhibiting a V-type subband structure [3] is used to study coherent excitations on a picosecond time scale. The wells are heavily n-doped leading to a carrier concentration of 10^{18} cm^{-3}. The sample shows two strong intersubband absorption bands centered at 936 cm^{-1} and 1153 cm^{-1} corresponding to the e1-e2 and e1-e3 transition, respectively (see inset of Fig. 2).

Fig. 2 shows time resolved data for an excitation by 2ps pulses at frequencies of 1000 cm^{-1} and 1110 cm^{-1}, respectively, between the two intersubband transition frequencies. The pump pulse interacts simultaneously with the e1-e2 and the e1-e3 transitions with the corresponding Rabi frequencies Ω_{12} and Ω_{13}. The excitation of the sample is probed by a second pulse of 2 ps duration at 950 cm^{-1}, close to the e1-e2 transition. Two effects contribute to the observed absorption change: i) incoherent population changes, and ii) coherent quantum interferences due to Rabi frequencies in the order of 5 meV. The depopulation of the excited subbands gives rise to a slowly decaying component, which is delayed by a reabsorption of hot phonons. The oscillations superimposed on the signals cannot be explained by an incoherent process; they reflect quantum interferences in the three level system.

To confirm the coherent nature of the oscillations, density matrix calculations were performed for that three level system using the Maxwell Bloch equations. Fig. 3 shows the results of the simulations for the population ρ_{nn} of the three states and for the coherences $\mathrm{Im}(\rho_{ij})$ of the e1-e2 and e1-e3 transitions as a function of time. The high frequency oscillations denoted by the black areas cannot be resolved in our experiments, however, the oscillations of the envelopes reproduce nicely the experimental data.

IV. Conclusion

Experiments with two independently tunable mid-infrared pulses on asymmetric QW structures show signatures in the

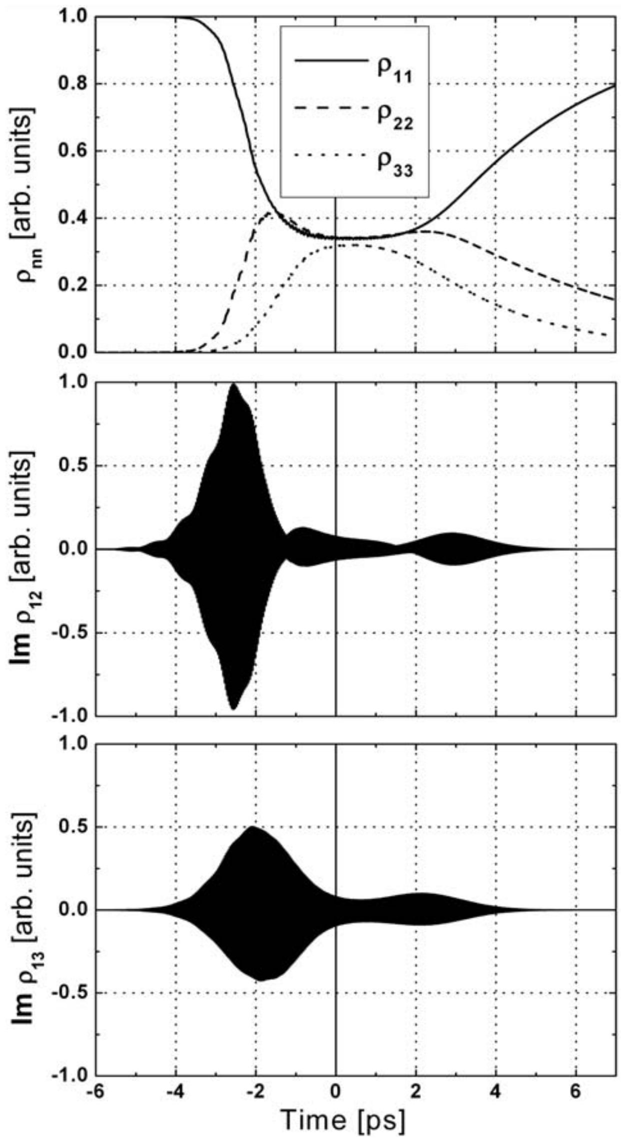

Fig. 3. Simulation of the investigated three level system by a density matrix model. The time dependence of the subband populations of level 1,2, and 3 (at the top) and the coherences $\mathrm{Im}(\rho_{ij})$ (two lower graphs) are shown for ν_{pump}=1000 cm^{-1} and ν_{probe}=950 cm^{-1}. The coherences represent the polarizations which give rise to oscillations.

frequency as well as in the time domain which clearly indicate the presence of coherent matter-wave excitations. The time resolution is not sufficient to monitor field oscillations occurring on a femtosecond time scale, but there are oscillations in the envelope of the polarization field amplitude, which are observable on a ps time scale.

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