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Radiative coupling of intersubband transitions in GaAs/AlGaAs multiple quantum wells

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Abstract

Radiative coupling of resonantly excited intersubband transitions in GaAs/AlGaAs multiple quantum wells can have a strong impact on the coherent nonlinear optical response, as is shown by phase and amplitude resolved propagation studies of ultrashort electric field transients. Upon increasing the driving field amplitude, strong radiative coupling leads to a pronounced self-induced absorption, followed by a bleaching due to the onset of delayed Rabi oscillations. A many-particle theory including light propagation effects accounts fully for the experimental results.

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Obviously, for optical spectroscopy to yield information about the properties of a system it is necessary that the system couples to radiation. In most cases it is sufficient to consider this radiative coupling simply as a tool that does not influence the properties of the system. If the radiative coupling is strong, however, it can dominate the optical properties of the system. Here, we demonstrate the impact of radiative coupling on the *linear* and *nonlinear* response of intersubband (IS) transitions [1] in n-type modulation-doped multiple quantum wells (MQWs). The advantage of IS transitions is that the strength of the radiative coupling can be varied by changing the carrier density in otherwise identical structures, in contrast to, e.g., excitons, where the coupling strength is fixed.

We investigated two n-type modulation-doped MQW samples consisting each of 51 electronically uncoupled GaAs QWs of 10-nm width, separated by 20-nm-thick $Al_{0.35}Ga_{0.65}As$ barriers. Sample L has a low electron density of $5 \times 10^{10}\,cm^{-2}$ per QW and thus weak radiative coupling, sample H a high density of $1.2 \times 10^{12}\,cm^{-2}$ and thus strong radiative coupling. The samples were processed into prisms [Fig. 1(a)] to achieve a strong coupling of the p-polarized MIR pulse and the IS transition dipoles [2]. The incident field $E_{in}(t)$ enters through the side facet, travels through the whole stack of QWs and is totally reflected from the bottom surface of the prism. The reflected wave interacts a second time with the stack of QWs and $E_{out}(t)$ leaves the sample through the other side facet. Besides the strong coupling of the MIR pulse to the IS transition dipoles this geometry was chosen because it has only one output for the light. Thus $\int E_{in}(t)^2\,dt - \int E_{out}(t)^2\,dt$ is proportional to the optical power absorbed by the QWs.

The linear IS absorption spectra of the two samples presented in Fig. 1(b) show narrow absorption lines around 100 meV with almost the same linewidth. In sample L the linewidth of 4 meV is entirely due to homogeneous broadening with a T_2 time of 320 fs [3]. Contrary to expectation,

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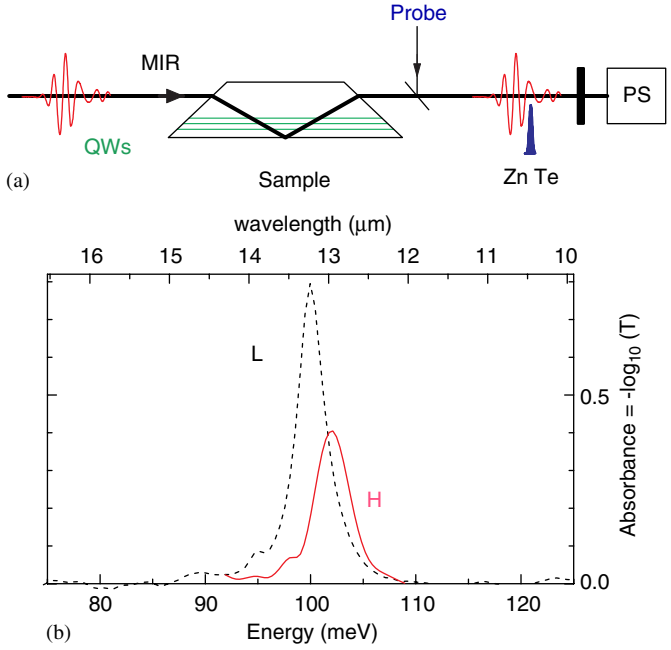

Fig. 1. (a) Schematic of the time-resolved nonlinear propagation experiment. (b) Measured linear IS absorption spectra of two multiple quantum well structures with electron densities of $5 \times 10^{10}\,\mathrm{cm}^{-2}$ (sample L, dotted line) and of $1.2 \times 10^{12}\,\mathrm{cm}^{-2}$ (sample H, solid line).

the absorption strength of sample H is even lower than that of sample L, despite sample H having 24-times higher electron density. This unexpected result is one of the effects of radiative coupling. One way to describe absorption is by considering the electric field $E_r(t)$ reemitted by the system in response to the incident field $E_{\mathrm{in}}(t)$. The transmitted field $E_{\mathrm{out}}(t)$ is the sum of incident and reemitted fields: $E_{\mathrm{out}}(t) = E_{\mathrm{in}}(t) + E_r(t)$. Energy is absorbed by the system if $E_{\mathrm{out}}(t)$ has a smaller amplitude than $E_{\mathrm{in}}(t)$, i.e., if $E_r(t)$ has the opposite direction of $E_{\mathrm{in}}(t)$. In the case of strong radiative coupling one has to consider two things which can be neglected for weak radiative coupling: (i) The field acting on the system is not the incident field, but the local field. (ii) Absorption is always accompanied by reflection. For two-dimensional systems like MQWs the expressions for these fields are particularly simple [4,5]: the local field is equal to the transmitted field and the reflected field is equal to the reemitted field. For sample L (weak radiative coupling) the local field is nearly equal to the incident field and the reflection can be neglected. On the other hand, for sample H (strong radiative coupling) the local field is considerably smaller than the incident field and the reflected field is strong. The strong reflection and the small local fields lead to the comparatively small absorption in sample H.

The nonlinear optical properties of both samples are investigated in coherent propagation experiments [Fig. 1(a)] for different field strengths of the excitation pulses. A coherent IS excitation is created by mid-infrared pulses with a duration of 200 fs and a center frequency resonant to the $1 \leftrightarrow 2$ IS transition. These pulses are generated by optical

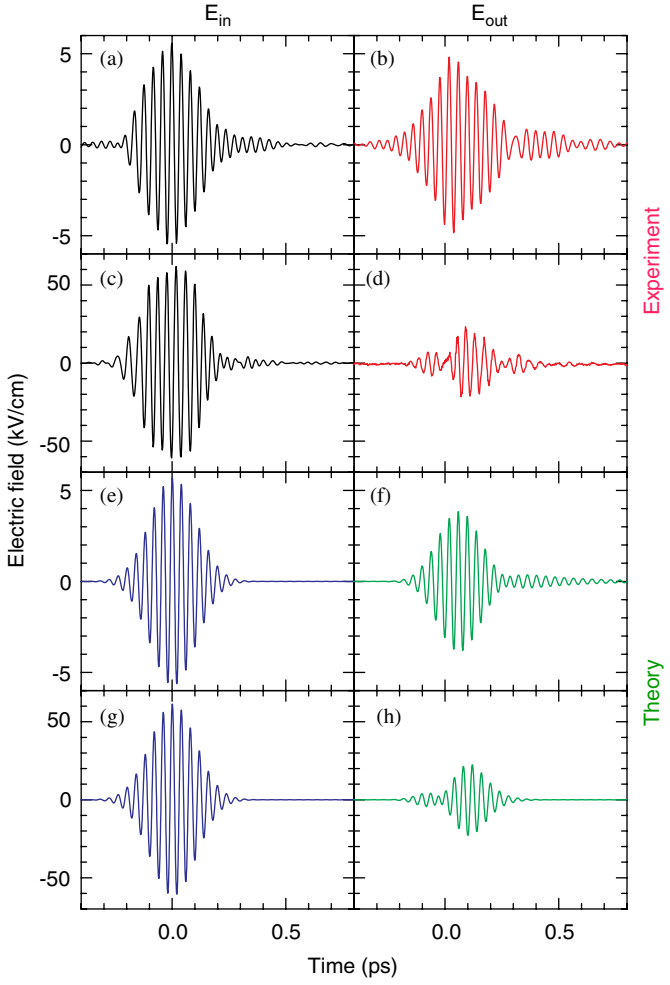

Fig. 2. Electric field transients measured before [(a) and (c)] and after [(b) and (d)] sample H (electron density of $n = 1.2 \times 10^{12}\,\mathrm{cm}^{-2}$ per QW) for different incident field amplitudes. (e)–(h) Both the shape and the amplitude of the theoretically calculated transients are in good agreement with the corresponding experimental counterparts (a)–(d).

rectification of intense 25-fs pulses at 800 nm in thin GaSe crystals [6]. The incident excitation pulse $E_{\mathrm{in}}(t)$ and the light transmitted through the sample $E_{\mathrm{out}}(t)$ are fully characterized by ultrafast electro-optic sampling [7].

Fig. 2 shows electric field transients $E_{\mathrm{in}}(t)$ incident on the sample and $E_{\mathrm{out}}(t)$ transmitted through sample H for different amplitudes of the input field [8], measured by electro-optic sampling. The field amplitude in Figs. 2(a) and (b) is low enough to show a linear response, namely a slightly lower amplitude of $E_{\mathrm{out}}(t)$ compared to $E_{\mathrm{in}}(t)$ during the pulse and a damped oscillation afterwards (free-induction decay). For intermediate amplitudes [Fig. 2(c)] one gets complex output transients [Fig. 2(d)], which show a surprisingly low amplitude compared to $E_{\mathrm{in}}(t)$.

From such measurements, we derive the energy transmission of the two samples, defined by $\int E_{\mathrm{out}}(t)^2\,\mathrm{d}t / \int E_{\mathrm{in}}(t)^2\,\mathrm{d}t$. In Fig. 3, these quantities are plotted as a function of the maximum amplitude of the incident electric field. For sample L (circles in Fig. 3), one finds