Adiabatically driven electron dynamics in a resonant photonic band gap: Optical switching of a Bragg periodic semiconductor

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The adiabatic driving of the resonant electron dynamics in a one-dimensional resonant photonic band gap is proposed as an optical mechanism for nonlinear ultrafast switching. Pulsed excitation inside the photonic gap results in an ultrafast suppression and recovery of the gap. This behavior results from the adiabatic carrier dynamics due to rapid radiative damping inside the band gap.

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The time scale of the optical response in nano-optical systems near resonance is limited by the response time of the structured material and the duration of the excitation pulse. If all intrinsic relaxation processes in the material are fast compared to the duration of the excitation pulse, the optical pulse adiabatically drives the material variables and determines their temporal response.[1] In this Paper, we theoretically analyze and quantitatively explain this principle for pulse shaping and optical switching in a half-wavelength (i.e., spacing $\lambda/2$) periodic semiconductor structure, recently observed experimentally in Ref. 2. The analysis of the nonlinear reflection experiments[2] in pump-probe geometry, is carried out on the basis of the coupled semiconductor Maxwell-Bloch equations, recently used to explain the transmission of short single pulses through multiple quantum well Bragg structures.[3]

In multiple quantum well structures (MQW), with spacing great enough to eliminate direct Coulomb interaction between the quantum wells (QWs), the excitonic resonances inside the different QWs couple radiatively.[4–6] If the QWs are in Bragg periodicity, a super-radiant mode develops leading to a broad resonant photonic band gap[3,7–13] which for a large number of QWs results in the band gap of a one-dimensional photonic crystal.[14,15] Long-lived and short-lived polariton modes in such Bragg (and anti-Bragg) structures have been discussed.[16] Also the influence of defects in MQW photonic crystals and their optical properties have been studied.[17] Typical bandwidths are on the order of 10–20 meV, compared to 1–2 meV for the spectral width of a switching pulse. The resonant band gap itself is similar to a passive dielectric band gap of a Bragg reflector caused by multiple reflection at the periodic surfaces and interference effects (analytic solutions are known from atomic systems[18]). However, in contrast to passive dielectrics, the excitonic resonance which forms the band gap, can be directly influenced by the strength of the light field because of strong optical nonlinearities due to Coulomb many body and other interaction effects, and Pauli blocking. Such nonlinearities may lead to exciton saturation resulting in a breakdown of the band gap.[19]

In this Paper, we show that a strong laser pulse propagates—besides reflection—without strong reshaping if its spectrum is completely inside the optical band gap. This pulse suppresses the photonic band gap for the time of its duration, thus allowing for a femtosecond switching mechanism. This behavior is caused by Pauli blocking and Coulomb nonlinearities of the carrier density which adiabatically follows the light pulse. In contrast, if the pulse spectrum is energetically above the photonic band gap, the gap does not recover for nanoseconds.

The semiconductor Bragg-structure studied is depicted in Fig. 1 of Ref. 3. It contains $N=200$ (In,Ga)As QWs with a width L embedded in bulk GaAs. The QWs are equally spaced with a distance of $\lambda/2$ (corresponding to the exciton resonance). Plane waves propagating perpendicular to the QWs are assumed and the reflected and transmitted signals are calculated by numerically solving the semiconductor Maxwell-Bloch equations (SMBE)[19,20] using the finite-difference-time-domain method (FDTD).[21,22] The

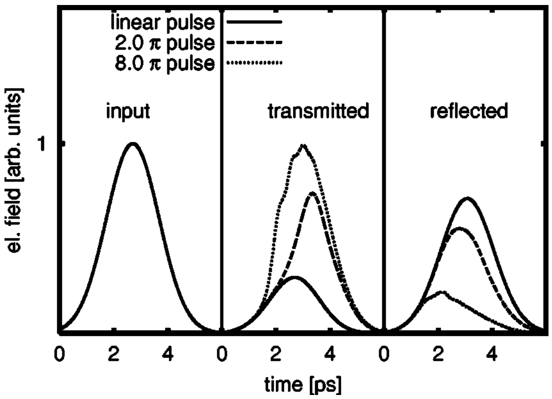

FIG. 1. Reflected and transmitted pulse shapes for increasing intensity. With increasing intensity the transmission increases and envelope modulations due to Rabi oscillations occur. All pulses are normalized to the respective input pulses maxima.

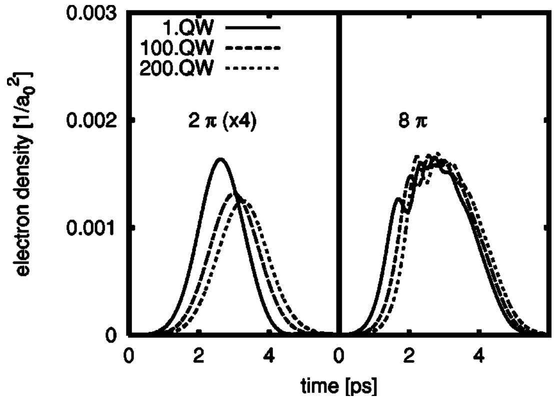

FIG. 2. Electron density in the first, 100th, and last (200th) QW for different incident field strengths. For nonlinear excitation, the system dynamics occur simultaneously with the pulse envelope. For strong excitation (8π), the populations exhibit Rabi oscillations.

parameters[23] used in the calculation are chosen to reflect the experiment.

Through the wave equation $[\partial_z^2-(1/c^2)\partial_t^2]E(z,t)=\mu_0\partial_t^2P_{\mathrm{dyn}}(z,t)$ the electric field E is coupled to the optical polarization P_{dyn}. Here, c is the speed of light in the background semiconductor material and μ_0 the permeability. The time-dependent polarization inside the semiconductor QWs at $z=z_n$ is expanded in a two-dimensional Bloch basis:[19] $P_{\mathrm{dyn}}(z,t)=A^{-1}\sum_{n=1}^{N}\sum_k\delta(z-z_n)d_{cv}p_k^n(t)+\mathrm{c.c.}$ The interband dipole transition element is denoted by d_{cv} and A is the area of a QW. Because of the small width of the QWs (typically less than 10 nm) in comparison to the large wavelength of the propagating wave (more than 200 nm) the quantum-confined envelope functions are approximated by delta functions $\delta(z-z_n)$.[7] The actual well width of $L=8.5$ nm only enters as an effective length in the FDTD algorithm. The equations of motion in Hartree-Fock approximation[24,27–29] for the electron coherence p_k^n and the electron/hole occupation $f_k^{e/h,n}$ in the nth well including the Coulomb-renormalized energies and fields are given in Refs. 3,19. These equations contain the dynamically Coulomb-renormalized optical field at the position of the nth QW. This field must be computed self-consistently from the wave equation and is therefore influenced by all other QWs in the sample.

First, we investigate the propagation of spectrally narrow [full width at half-maximum (FWHM) 1.6 meV $\triangleq$ 1.14 ps] Gaussian pulses with increasing intensities and calculate the reflected and transmitted signal. To classify the strength of the pulse-induced nonlinearity, one can compare the peak Rabi frequency $\Omega_0=E_0d_{cv}/\hbar$ of the time dependent Rabi frequency of the pulse $\Omega_0e^{-t^2/\tau^2}$ with the width Δ of the photonic band gap. For the investigated sample, the width of the band gap is found to be 15 meV. For comparison, a pulse with 3 meV peak Rabi frequency corresponds to a pulse area $\Theta=\int_{-\infty}^{\infty}dt\,\Omega_0e^{-t^2/\tau^2}$ of 1π (resulting in full inversion of a noninteracting two level system). Figure 1 shows the transmitted and reflected intensities for different pulse areas. Figure 1 (left) shows the normalized electric field envelope at the sample entrance as a function of time and is given for comparison with the transmitted (Fig. 1, middle) and the reflected fields (Fig. 1, right). With increasing input pulse area, the transmitted pulse exhibits pulse shortening and develops an asymmetric shape. For large input areas (8π), the transmitted pulse resembles more or less the input field. The reflected signal is weakened with increasing pulse area and the trailing edge is flattened.

In order to understand the observed dynamics, Fig. 2 depicts the electron density inside different QWs during the pulse propagation. As can be seen, the 2π and 8π pulses induce a temporal density dynamics which directly follows the pulse envelope (Fig. 1). Such dynamics are expected from a pulse with a temporal duration longer than the response time of the photonic lattice because the polarization and density dynamics are adiabatically driven by the pulse.[25] The lattice response time is given by the inverse half-width at half-maximum (HWHM) of the band gap (100 fs) and is much shorter than the applied pulse duration of 1.6 ps. For intensities greater than 5π (peak Rabi frequency larger than the lattice bandwidth) weak Rabi oscillations occur in the nonlinear material response and the dynamics of the density can no longer be adiabatically driven by the pulse envelope. During the action of the pulse, Pauli blocking of the Coulomb renormalized field[19] reduces the strength of the excitonic resonance, thus weakening the radiative coupling between the QWs. In consequence, the photonic band gap collapses. After the pulse, the band gap recovers.

To discuss whether this effect can be utilized for ultrafast switching of a second pulse, we investigate the influence of the induced carrier dynamics on the photonic band gap[2] by simulating a pump-probe setup for cross-linearly polarized light pulses. A weak, spectrally broad (FWHM 14.4 meV $\triangleq$ 126 fs) probe pulse experiences the nonlinear band gap dynamics induced by a strong pump pulse at different time delays. The investigated signal S_τ is chosen to be the ratio of the energy of the reflected probe pulse (E_{ref}) to the incident probe pulse (E_{probe}) energy computed for different pump-probe delays τ. A suppression of the photonic band gap by the pump induced density dynamics is shown by a drop in the reflectivity of the weak probe pulse (enlarged transmission). In addition, different detunings of the pump pulse with respect to the resonance are investigated: excitation below

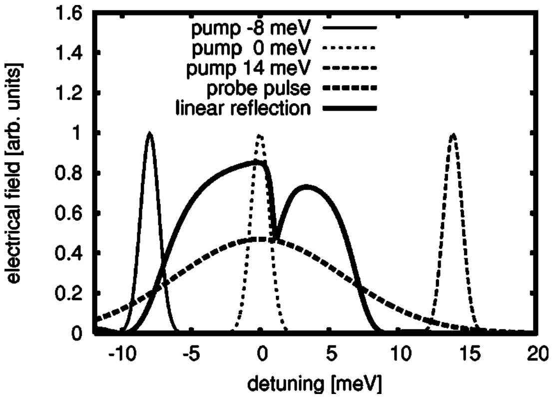

FIG. 3. Spectra of pump pulses located at different energies with respect to the excitonic resonance are used to investigate the influence of the induced carrier dynamics on a weak probe pulse.

(−8 meV), inside (0 meV), and above (14 meV) the photonic band gap (Fig. 3).

In Fig. 4 (top), the integrated reflected probe intensities are shown as a function of the delay τ between pump and probe pulses. Pump pulses with the relatively large detuning −8 meV below the center of the band gap do not significantly influence the reflection of the sample. However, for excitation inside the photonic band gap (0 meV), the reflectivity drops noticeably and recovers on the time scale of the pump pulse due to the transient bleaching of the exciton resonance. For an excitation 14 meV above the photonic band gap (near the semiconductor band edge), electron-hole populations are excited due to the overlap of the pump pulse with the interband absorption spectrum. Due to the lack of the super-radiant coupling of the unbound interband transitions, their phase coherence is lost and the process cannot be reversed during the switch off of the optical pulse. Therefore, the optical band gap does not recover on the time scale of the pulse.[26] The magnitude of the nonlinear band gap suppression of 15% depends on the intensity and shape of the pump pulse. For stronger pulses (in the order of 10π) complete suppression can be realized.

Next we show that the obtained theoretical results are in compliance with reflection measurements on MQW samples[2] (Fig. 4, bottom). The experiments were conducted on a $N=200$ $In_{0.04}Ga_{0.96}As/GaAs$ wedged MQW structure (DBR28) with a pump-probe setup in reflection geometry. The observed integrated reflection is not influenced by excitation below the band gap. If excited in or above the band gap, a significant drop in reflectivity is observed. This drop recovers instantaneously if the sample is excited inside the band gap whereas it stays at a low level for excitation above the band gap. All these effects are reproduced in every spectral excitation regime by our theoretical approach (Fig. 4, top).

In conclusion, our calculations show that a spectrally narrow laser pulse tuned into the photonic band gap of a Bragg-

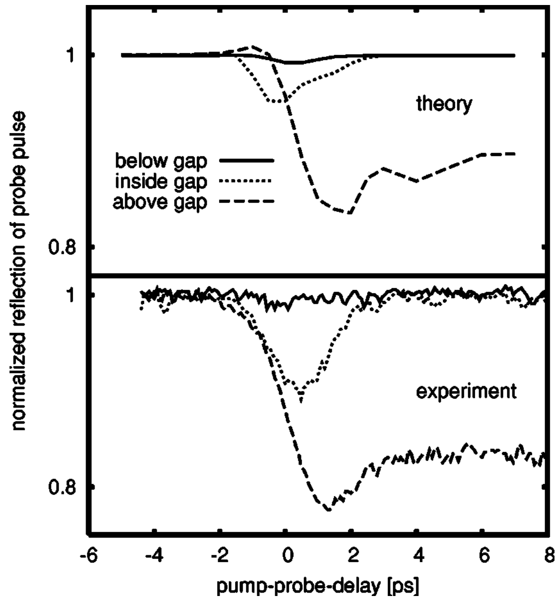

FIG. 4. Integrated probe pulse reflection: A pump pulse (1π) inside or above the photonic band gap suppresses the photonic band gap. The gap recovers on the time scale of the pump pulse when excited inside the photonic band gap. For excitation above the gap it does not recover for nanoseconds. Top, theoretical calculations. Bottom, measurements (Ref. 2) with a 4 μJ, FWHM 1.6 ps pulse.

periodic MQW structure induces carrier dynamics which instantaneously follow the pulse envelope. This behavior results from the strong radiative coupling in the sample. During the pulse, the gap is temporally weakened due to the Pauli blocking of the Coulomb renormalized field at the excitonic resonance forming gap. The band gap recovery due to the strong radiative decay takes place on the time scale of the pump pulse as long as the excitation is spectrally inside the photonic band gap. As a potential application, the observed effect could be utilized for ultrafast optical switching with switching times down to the response time of the lattice (100 fs).

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