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Observation of Dynamical Franz-Keldysh Effect

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We observe the linear and non-linear optical properties of a semiconductor multiple quantum well under intense terahertz irradiation to reveal a Dynamical Franz-Keldysh Effect. It is characterized by increased sub-gap absorption and oscillations in the absorption above the gap which vary with applied THz field and frequency. We also observe non-linear mixing of near-bandgap light of frequency Ω_{NIR} with a strong Terahertz field of frequency ω_{THz} to produce optical sidebands at frequencies $\Omega_{\mathrm{NIR}} \pm 2n\omega_{\mathrm{THz}}$. We discuss our results as a function of THz field and frequency, and compare them to our theoretical model.

Strong electric fields have long been known to modify the near-bandgap optical absorption of semiconductor crystals. In the well-known Franz-Keldysh Effect (FKE), a strong DC field causes finite sub-gap absorption, plus oscillation of the absorption above the band edge [1, 2]. These effects are well-understood in both bulk and confined semiconductor systems (see, e.g. [3]). A strong electric field applied at THz frequencies is theoretically predicted to produce a Dynamical Franz-Keldysh Effect (DFKE) [4, 5]. The DFKE predicts increased sub-gap absorption and a Stark-like blue shift of the main absorption edge [5], as well as non-linear mixing between a weak near-bandgap NIR probe of frequency Ω_{NIR} and a strong THz field of frequency ω_{THz} to produce optical sidebands of frequencies $\Omega_{\mathrm{NIR}} \pm 2n\omega_{\mathrm{THz}}$ [4]. The DFKE is predicted to scale with the mean kinetic energy, E_{KE}, of a particle of mass m^* in a THz field of amplitude E_0 and frequency ω_{THz}, given by

$$E_{\mathrm{KE}} = \frac{e^2 E_0^2}{4m^* \omega_{\mathrm{THz}}^2} , \tag{1}$$

where e is the electronic charge. We can use this energy to define a parameter $\gamma = E_{\mathrm{KE}}/\hbar\omega_{\mathrm{THz}}$, to determine the DFKE regime, which occurs when $\gamma \approx 1$ (see Fig. 1).

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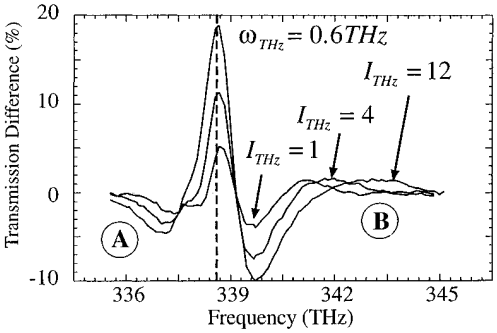

Fig. 1. Transmission difference spectra for three THz intensities at $\omega_{\mathrm{THz}} = 0.6$ THz. Note increased sub-gap absorption (A) and above-gap oscillation, varying with intensity (B). The dashed line marks the position of the heavy-hole exciton

Our sample is a MQW grown by molecular beam epitaxy on GaAs. It consists of 20 periods of 80 Å $In_{0.2}Ga_{0.8}As$ wells separated by 150 Å GaAs barriers. Since the energy of the MQW states is below the substrate band-gap, we can perform direct transmission spectroscopy without substrate removal. Strain lifts the valence-band degeneracy at $k = 0$, allowing us to focus on the heavy-hole exciton alone.

The transmission of a tunable CW Ti-Sapphire laser, focussed to a $\approx 200\,\mu$m spot on the sample, is measured with a conventional Si photodiode. Peak NIR intensity is $\approx 10\,\mathrm{W/cm^2}$. Linearly-polarized THz radiation, focussed to a 0.5 to 2.0 mm spot coincident with the NIR, is provided by the UCSB Free-Electron Laser (FEL), a source of intense, coherent radiation which is tunable from $\approx$0.12 to 4.8 THz ($\approx$0.5 to 20 meV). We measure NIR transmission spectra as a function of THz internsity and frequency. We also analyze the transmitted light with a double-grating monochromator to detect new frequency components. All measurements are performed with the sample in He vapor at $\approx$7 K.

Our theoretical calculations are a solution of the two-time Bethe-Salpeter equation for the electron–hole correlation function, including the AC field non-perturbatively via a non-equilibrium Green functions technique. The **k**-space trace of the correlation function yields the susceptibility describing the linear absorption and sideband generation.

Fig. 1 shows a typical series of difference spectra taken in the vicinity of the heavy-hole exciton with a THz field at 0.6 THz at several intensities. They were calculated by subtracting the high-field spectrum from the zero-field spectrum. In direct analogy to the DC FKE, we observe increased absorption below the exciton, as well as above-gap oscillations in the absorption with increasing period as a function of THz intensity. This period decreases with increasing THz frequency and fixed THz intensity, qualitatively scaling with E_{KE}.

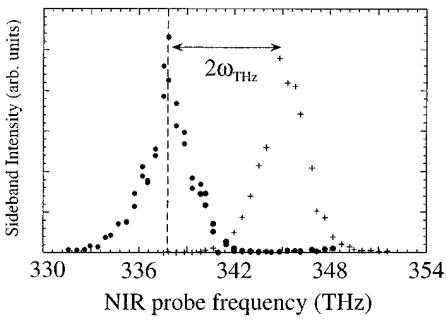

Fig. 2. Sideband intensity vs. NIR probe frequency at $\omega_{\mathrm{THz}} = 3.4$ THz for the $+2\omega_{\mathrm{THz}}$ (filled circles) and $-2\omega_{\mathrm{THz}}$ (crosses) sidebands. The horizontal arrow is exactly $2\omega_{\mathrm{THz}}$. The dashed line is the position of the heavy-hole exciton

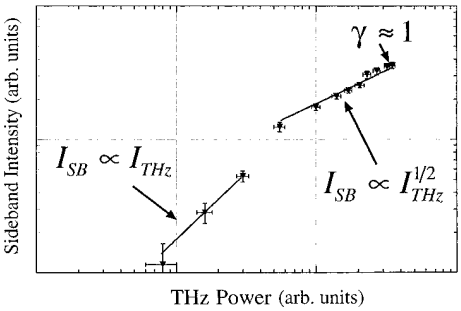

Fig. 3. A log–log plot of sideband intensity vs. THz intensity at $\omega_{\mathrm{THz}} = 0.6$ THz

Most striking is the appearance of optical sidebands on the probing NIR at even multiples of the frequency of the applied THz field. We observe sideband generation at frequencies from 0.6 THz to 3.4 THz. In agreement with theory, sideband generation only occurs when two conditions are satisfied: the energy of the NIR probe and the sideband are both above the band gap, and either one is near a resonance in the sample (e.g., the heavy-hole exciton). Sideband intensity as a function of NIR probe frequency is plotted for the +2 and −2 sidebands in Fig. 2. The peak in the +2 curve corresponds to the NIR *probe* tuned to resonance with the exciton, while the peak in the −2 curve corresponds to the *sideband* being in resonance with the exciton (thus, the two peaks are spaced by $2\omega_{\mathrm{THz}}$). At high THz frequencies, $\gamma < 1$, and the sideband generation behaves like a simple $\chi^{(3)}$ process: the sideband intensity is linear in NIR power and quadratic in THz power. At low THz frequencies, $\gamma \approx 1$, and the sideband intensity is linear in THz power at low powers, and goes as the square root of THz power at higher powers (see Fig. 3). This contradicts theory, which predicts quadratic power dependence at low powers, and linear power dependence at higher powers.

In conclusion, we have made the first observation of the Dynamical Franz-Keldysh Effect in a 2D MQW. Striking non-linear mixing data show much qualitative agreement with theory, although the high-field power dependence remains unexplained.

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