High-order THz-sideband generation in semiconductors

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Abstract. The optical sideband generation in semiconductors under intense THz lasers presents flat wide-band spectra with the cutoff determined by the maximum energy-gain of electron-hole pairs in quantum trajectories under the THz field. The approximation based on the quantum trajectory picture agrees well with the numerical simulations.

Keywords: Terahertz, Sideband generation, Quantum trajectory
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INTRODUCTION

Semiconductors under intense THz lasers possess a wealth of physical effects such as the dynamical localization [1], dynamical Franz-Keldysh effect [2], and excitonic stabilization [3]. In this contribution, We will discuss the high-order sideband spectra of semiconductors under intense THz lasers, which resembles on several aspects the high-order harmonic generation by atoms under super-intense optical lasers [4]. The sideband spectra present flat wide-band plateaux, which can be well understood in the quantum trajectory theory developed in atomic physics to understand the plateau spectra of high harmonic generation [4]. The sideband generation by excitons, however, differs fundamentally from the harmonic generation in atomic systems, since the former starts from the creation of elementary excitations in solids and hence has tunable excitation energy while the latter involves atoms with fixed binding energy. Thus the THz-sideband spectroscopy is expected to provide more flexibility in studying the quantum trajectory, a central notion in many basic physics problems such as the quantum tunneling in macro-magnets. The high-order THz-sideband generation could also be useful in many electro-optical applications such as wide-band optical multiplexers, optical pulses with ultra-high repetition rate, and optical communication with THz bandwidth.

FORMALISM

The dynamics of electron-hole pairs excited by an optical field $\mathbf{E}(t)$ in semiconductors under an intense THz field [expressed by a vector potential $\mathbf{A}(t)$] can be described by the inhomogeneous Schrödinger equation

$$i\partial_t \psi = H(t)\psi + \mathbf{d}\cdot\mathbf{E}(t), \qquad (1)$$

with the Hamiltonian given (in the Rydberg unit system) by

$$H = [\mathbf{p}-\mathbf{A}(t)]^2 + E_g - 2/r, \qquad (2)$$

where $\mathbf{d}$ is the interband dipole matrix element in the semiconductor and E_g is the bandgap. The sideband generation is determined by the optical polarization $\mathbf{P}(t) = -\mathbf{d}^*\psi(0,t)$. By solving Eq. (1) numerically, the sideband generation spectrum can be readily calculated [3]. For an input optical field $\mathbf{E}(t) = \mathbf{E}_p(t)e^{-i\Omega t}$ and a THz field with angular frequency ω, the sideband intensity of the $2N$th order with output frequency $\Omega + 2N\omega$ is $I_{2N} \propto P_{2N}^2$ (the odd order sidebands are vanishing due to the inversion symmetry of the system), where

$$\mathbf{P}_{2N} = i\int \mathbf{d}^*\mathbf{d}\cdot\mathbf{E}_p(t-\tau)\theta(\tau)e^{iS(\mathbf{p},t,\tau)}dtd\tau d\mathbf{p}/(2\pi)^3 \qquad (3)$$

with the action

$$S(\mathbf{p},t,\tau) \equiv -\int_{t-\tau}^{t} H(t'')dt'' + (\Omega - E_g)\tau + 2N\omega t, \qquad (4)$$

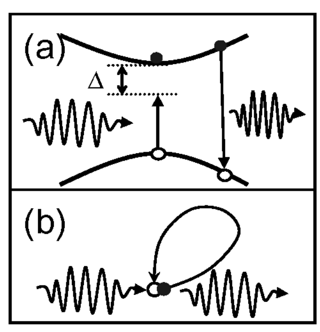

FIGURE 1. Schematics for the THz-sideband generation in semiconductors. (b) Schematic illustration of quantum trajectories in the THz-sideband generation.

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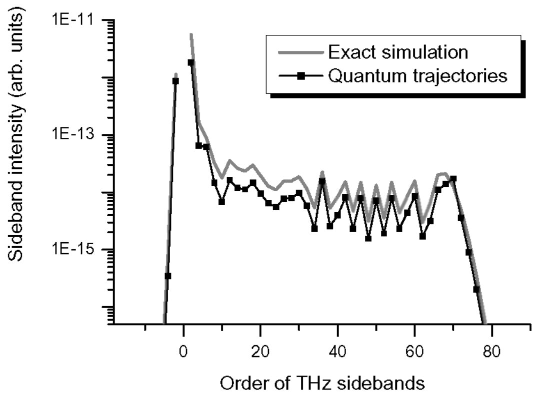

FIGURE 2. THz-sideband generation spectra in bulk GaAs driven by a THz field with $\omega = 5$ meV and $F = 35$ kV/cm, calculated with the exact numerical simulation and the quantum trajectory approximation, respectively. The input optical field has such frequency that $\Omega - E_g = -32$ meV.

giving the phase accumulation along an arbitrary path in the phase space characterized by the momentum $\mathbf{p}$, the delay time (τ) between the excitation and recombination of excitons, and the recombination time (t).

When the THz driving field is strong, the motion amplitude of the electron-hole pairs is much larger than the wavepacket diffusion (the quantum fluctuation), so the quantum dynamics can be well approximated as trajectories constrained by the classical kinetic equations plus the Gaussian quantum fluctuation, i.e., the action can be approximated as [4]

$$S(\mathbf{p},t,\tau) \approx S(\mathbf{p}_0,t_0,\tau_0) + \frac{1}{2}\delta(\mathbf{p},t,\tau)\cdot\partial^2_{\mathbf{p},t,\tau}S\cdot\delta(\mathbf{p},t,\tau).$$

For simplicity, we will neglect the Coulomb interaction between the electron and the hole, which is a well-justified approximation when the energy-gain from the THz field is much larger than the exciton binding energy. Thus the trajectory parameters can be easily determined by the saddle-point equations [4]

$$\partial_\tau S = 0 \;\Rightarrow\; [\mathbf{p}-\mathbf{A}(t-\tau)]^2 = \Omega - E_g \equiv -\Delta, \tag{5}$$

$$\partial_t S = 0 \;\Rightarrow\; [\mathbf{p}-\mathbf{A}(t)]^2 - [\mathbf{p}-\mathbf{A}(t-\tau)]^2 = 2N\omega, \tag{6}$$

$$\partial_{\mathbf{p}} S = 0 \;\Rightarrow\; \mathbf{p}\tau - \int_{t-\tau}^{t}\mathbf{A}(t')dt' = 2\int_{t-\tau}^{t}\dot{\mathbf{r}}(t')dt' = 0, \tag{7}$$

which correspond respectively to the energy conservation at excitation, the energy conservation at sideband generation, and the condition that the electron and the hole should be at the same position at the recombination time, as schematically illustrated in Fig. 1. Such trajectories are quoted as "quantum" since in general no classical solution may exist which requires $\mathbf{p}$, t, and τ be real numbers. Let $A(t) = -(F/\omega)\sin(\omega t)$, it can be easily seen that the energy-gain from the THz field by the electron-hole pair in the quantum trajectories is bounded by $E_{\max} \approx 3.2U_p + \Delta$ [4] (where the ponderomotive energy $U_p \equiv F^2\omega^{-2}/2$), and hence the sideband generation will be cut off at $2N\omega \approx E_{\max}$, similar to the cutoff effect in the high-order harmonic generation [4].

RESULTS

Figure 2 presents a typical example of THz-sideband generation spectra in semiconductors. For the parameter used, the ponderomotive energy U_p is about 98 meV, much larger than the THz laser frequency ($\omega = 5$ meV) and the exciton binding energy ($\sim$4 meV) in GaAs, so the sideband generation is well described by the quantum trajectories, as can be seen from the good agreement between the trajectory approximation and the exact numerical simulation. The spectrum presents a plateau as wide as close to 70 times the fundamental frequency. The cut-off is well consistent with the calculation of the maximum energy gain $E_{\max} \approx 68\omega$. Such a flat wide-band sideband spectrum is of potential application in optical pulses with ultra-high repetition rate. Since the exciton as an elementary excitation can be excited by optical pulses at selected time and frequency, the quantum trajectories can be controlled with much more flexibility than in atomic physics, which may lead to further physical insight and to novel electro-optical applications.

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