Can optical phonons explain intense terahertz field enhancement through monolayer graphene?

L. G. Helt
M. M. Dignam

Department of Physics, Engineering Physics and Astronomy, Queen’s University, Kingston, Ontario K7L 2G1, Canada
l.helt@queensu.ca

Terahertz (THz) investigations of graphene have revealed an increase in the transmission of THz fields through monolayer graphene with increasing THz field strength [1,2]. While it is clear that this is likely due to a combination of reduced photoconductivity and increased intraband scattering, the dynamics of their interplay is currently less well understood.

Building upon a tight-binding model treating the carrier-field interaction in the length gauge [3], in this work we include scattering at the microscopic, rather than phenomenological, level, and calculate scattering dynamics up to the second-order Born-Markov approximation. For simplicity, we take the Fermi level high enough that we can ignore holes and associated interband transitions. The resulting dynamical carrier equation is

$$d\rho(k) = eE(t) \cdot \nabla \rho(k) / \hbar - \Gamma^{\text{out}}(k) \rho(k) + \Gamma^{\text{in}}(k) [1 - \rho(k)],$$

where $\rho(k)$ is the electron population, $e$ the electron charge, $E(t)$ the THz field, and the scattering-out rate

$$\Gamma^{\text{out}}(k) = 2n/\hbar \sum_q |g_{kq}|^2 \rho(q)[\delta(\epsilon(q) - \epsilon(k) - \hbar \omega) + n_{\epsilon(k)} \delta(\epsilon(q) - \epsilon(k) + \hbar \omega)].$$

Here $j$ denotes phonon mode, $g_{kq}$ electron-phonon interaction strength, $n_{\epsilon}$ phonon population, $\hbar \omega$ phonon energy, and $\epsilon(k) = \hbar v_F |k|$ the carrier energy, where $v_F$ is the Fermi velocity. The scattering-in rate $\Gamma^{\text{in}}(k)$ is similar to Eq. (2) but with $\rho(q) \leftrightarrow 1 - \rho(q)$ and $n_{\epsilon} \leftrightarrow n_{\epsilon^*}$. We include transverse and longitudinal $\Gamma$ modes, with $\hbar \omega_{\Gamma} = 196$ meV, $|g_{kq}|^2 = 0.081$ eV², as well as K modes, with $\hbar \omega_{K} = 160$ meV, $|g_{kq}|^2 = [1 - \cos \theta]/0.0994$ eV², where $\theta$ is the angle between $k$ and $q$ [4].

We solve Eq. (1) numerically on a hexagonal 401x401-point grid in $k$. At room temperature, for incident x-polarized pulses with a carrier frequency of 1 THz and a Gaussian envelope of 1 ps, we obtain the transmitted fields (see Fig. 1). At these field strengths, transmission increases with increasing field amplitude, in qualitative agreement with experiments [1,2]. We understand this as arising from greater scattering rates, due to an increase in the number of states available to scatter into as carriers are driven to larger $|k|$. At low incident field amplitudes (not shown here), current clipping and absorption from small but finite electron-phonon scattering rates have opposite effects on THz field transmission, and the transmission trends are more complicated.

![Figure 1: Calculated THz field transmission, seen to increase with increasing incident field amplitude.](image)

In conclusion, we have performed calculations showing that electron-phonon scattering enhances THz transmission through doped graphene for large fields.

References