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

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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

$$d_t\rho(\mathbf{k})=e\mathbf{E}(t)\cdot\nabla_{\mathbf{k}}\rho(\mathbf{k})/\hbar-\Gamma^{out}(\mathbf{k})\rho(\mathbf{k})+\Gamma^{in}(\mathbf{k})[1-\rho(\mathbf{k})], \quad (1)$$

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

$$\Gamma^{out}(\mathbf{k})=2\pi/\hbar\sum_{j,\mathbf{q}}|g_{\mathbf{kq}j}|^2\rho(\mathbf{q})[(n_j+1)\delta(\varepsilon(\mathbf{q})-\varepsilon(\mathbf{k})-\hbar\omega_j) +n_j\delta(\varepsilon(\mathbf{q})-\varepsilon(\mathbf{k})+\hbar\omega_j)]. \quad (2)$$

Here j denotes phonon mode, $g_{\mathbf{kq}j}$ electron-phonon interaction strength, n_j phonon population, $\hbar\omega_j$ phonon energy, and $\varepsilon(\mathbf{k})=\hbar v_F|\mathbf{k}|$ the carrier energy, where v_F is the Fermi velocity. The scattering-in rate $\Gamma^{in}(\mathbf{k})$ is similar to Eq. (2) but with $\rho(\mathbf{q})\leftrightarrow 1-\rho(\mathbf{q})$ and $n_j+1\leftrightarrow n_j$. We include transverse and longitudinal Γ modes, with $\hbar\omega_\Gamma$=196 meV, $|g_{\mathbf{kq}\Gamma}|^2$ = 0.081 eV^2, as well as K modes, with $\hbar\omega_K$=160 meV, $|g_{\mathbf{kq}K}|^2$=[1-cosθ]·0.0994 eV^2, where θ 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.

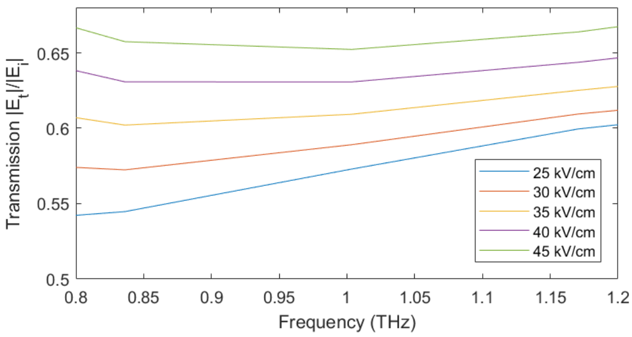

Figure 1: Calculated THz field transmission, seen to increase with increasing incident field amplitude.

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

References

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