Nonlinear optics of massless Dirac fermions in graphene and topological insulators

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Massless chiral Dirac electrons in graphene and on the surface of 3D topological insulators such as Bi$_2$Se$_3$ demonstrate universal optical absorbance and strong optical nonlinearities. Although both systems constitute a centrosymmetric medium for in-plane electron excitations, their second-order nonlinear response becomes non-zero and in fact quite strong when its spatial dispersion is taken into account. In this case the anisotropy is induced by in-plane wave vectors of obliquely incident or in-plane propagating electromagnetic waves, as in Fig. 1. The spatial dispersion in momentum space is of course equivalent to the nonlocal response in real space. The magnitude of the second-order nonlinear conductivity grows rapidly with wavelength and exhibits strong enhancement at the Fermi edge; see Fig. 2. We outline main results of the quantum theory of the second-order nonlinear response and discuss its application to various nonlinear processes, such as second harmonic and difference frequency generation, parametric decay, and generation of entangled photon-plasmon states.

Fig. 1. A sketch of the second order nonlinear current generation in the graphene plane for obliquely incident light.

Fig. 2. Nonzero components of the second order nonlinear conductivity tensor for the process of second harmonic generation as a function of the fundamental frequency. The pump is incident at 45 degrees. The Fermi energy $E_F$ is 200 meV and the scattering rate is 100 fs. Note strong resonances when the fundamental frequency or its second harmonic are equal to 2 $E_F$.