MAGNETOOPTICS OF MASSLESS DIRAC FERMIONS: GIANT OPTICAL NONLINEARITY AND LANDAU LEVEL LASING

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Graphene and surfaces of topological insulators such as Bi_2Se_3 have low-energy electron states with chiral symmetry and gapless linear spectrum near the Dirac point. These states attracted a lot of interest, although the main effort was directed at studying their topological and electronic properties. We show that systems with massless Dirac electrons possess a giant mid/far-infrared optical nonlinearity, perhaps the highest among known materials. The nonlinearity is greatly enhanced by applying a strong magnetic field $B \sim 1\text{-}10$ T due to large dipole matrix elements and unique selection rules associated with inter-Landau level transitions. Strong optical nonlinearity enables efficient generation of coherent THz or mid-infrared radiation through resonant difference-frequency generation, four-wave mixing, and stimulated Raman scattering. Figure 1 shows an example of a four-wave mixing process which can be used, for example, to generate a coherent THz radiation at low frequency ω_{LF} . Another interesting application is the generation of mid/far-infrared polarization-entangled light at frequencies $\omega_{(+,-)}$ as shown in Fig. 1. Unique optical properties of Dirac fermions enable schemes with a high signal to noise ratio and high generation rate of entangled photons. They also open an interesting possibility of detection and control of electron states near the Dirac point by means of nonlinear optics.

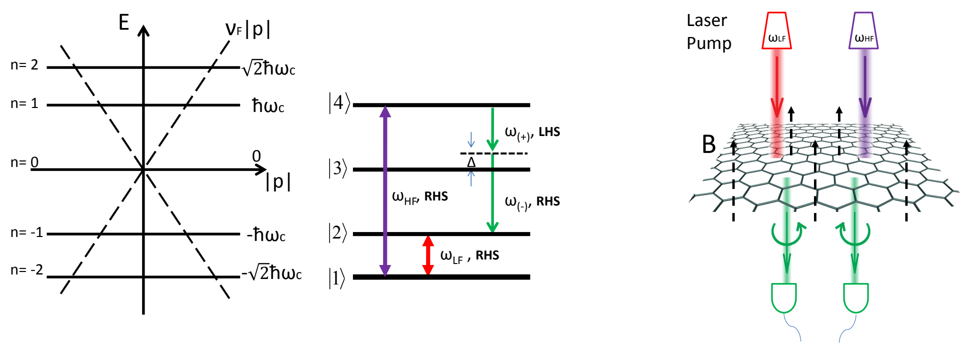

Fig. 1. Left: Landau levels near the Dirac point superimposed on the linear electron dispersion without the magnetic field. Center: A scheme of the four-wave mixing process in the four-level system of Landau levels with energy quantum numbers n = -2, -1, 0, 1 that were renamed as states 1,2,3, and 4 for convenience of notation. Right: Geometry of the entangled photon generation. Two pump fields at frequencies ω_{LF} and ω_{HF} normally incident on a sheet of graphene placed in a magnetic field B generate entangled photons at frequencies $\omega_{(+,-)}$ with opposite sense of the circular polarization.

We also prove the general feasibility and demonstrate the design of a continuous-wave THz laser operating between Landau levels in graphene placed on a polar substrate. Steady state population inversion under a continuous wave optical pumping becomes possible due to surface-phonon mediated relaxation of carriers.

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