Non-equilibrium plasmons with gain in graphene

J. M. Hamm, A. F. Page, F. Ballout, O. Hess

Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom
joachim.hamm@imperial.ac.uk

Abstract

In calculating the gain spectra of photo-inverted graphene self-consistently from the exact complex-frequency dispersion curves, we provide evidence that graphene can, under realistic conditions, support plasmons with gain [1]. As the dispersion crosses through regimes where the plasmons couple to the particle/hole plasma via stimulated emission and absorption processes, it acquires an imaginary part that represents the gain and loss spectrum (see fig. 1b).
Based on a comprehensive theory for the non-equilibrium polarizability, we systematically study the influence of doping, collision loss and temperature on both the plasmon dispersion and the gain/loss spectrum. While doping and temperature affect the shape of the emission spectrum, collision loss leads to a reduction of gain proportional to the collision rate. The frequency dispersion curves, in turn, are robust against collision loss and temperature but are distinctly affected by doping. When the imbalance in the particle/hole chemical potentials reaches a critical value, the plasmon dispersion passes through a singularity and undergoes a sudden change. Our results show that plasmon amplification is possible at under assumption of realistic collision loss and temperature.
Carrier inversion does not only enable plasmon amplification via stimulated emission but also leads to spontaneous emission of plasmons. To investigate this incoherent channel, we extract the spontaneous plasmon emission spectra and associated carrier recombination rates directly from the complex-frequency dispersion and by application of Fermi's golden rule. We find that the emission spectra are weakly dependent on the collision rate, but strongly influenced by doping and temperature. Our results suggest that spontaneous plasmon emission is a significant channel for particle/hole recombination in photo-excited graphene, with rates that exceed those previously reported [2] by a factor of 5. In the light of these results, it appears evident that spontaneous plasmon emission plays an important role for the relaxation of the photo-excited plasma back to equilibrium, as observed in pump-probe and tr-ARPES experiments.

References

[1] A. Freddie Page, Fouad Ballout, Ortwin Hess, Joachim M. Hamm, arXiv:1412.3042 (2014).
[2] Farhan Rana, Jared Wang Strait, Christina Haining Manolatou, Phys. Rev. B 84(4), 045437 (2011).

Figures

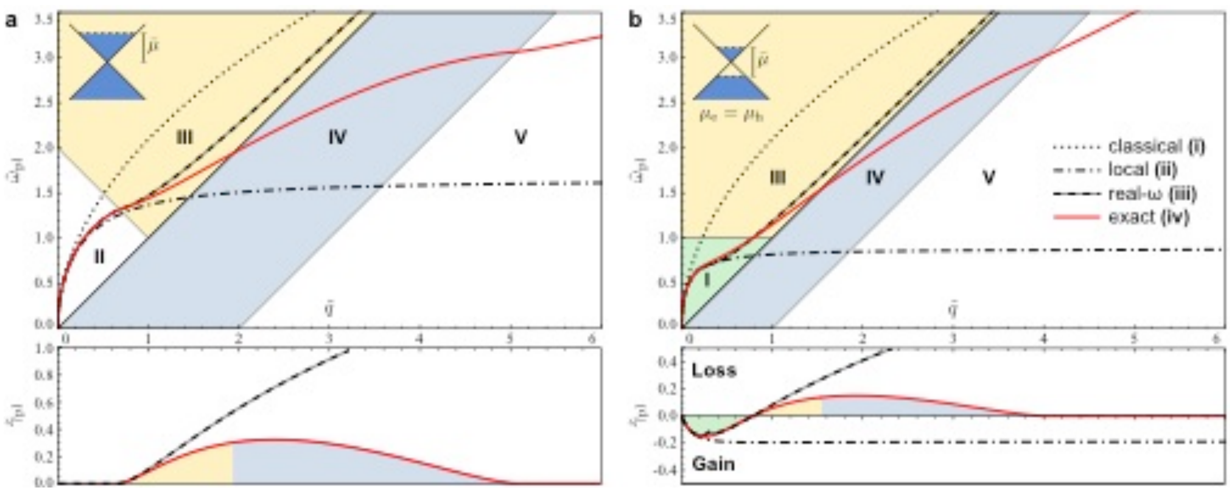

Figure 1: Plasmon frequency dispersion (top panel) and decay rate (bottom panel) for (a) the equilibrium case and (b) the photo-inverted intrinsic case. The exact complex-frequency dispersion (solid red lines) is shown together with the dispersion in the real-frequency approximation (dashed black lines), in the classical Drude limit (dotted black lines) and using the optical conductivity (dash-dotted black lines).