Nonlinear Terahertz Response of Graphene Plasmons

Mohammad M. Jadidi[1], Jacob C. König-Otto[2], Stephan Winnerl[2], Andrei B. Sushkov[1],
H. Dennis Drew[1], Thomas E. Murphy[1], and Martin Mittendorff[1]

[1] University of Maryland, College Park, MD 20742, USA

[2] Helmholtz-Zentrum Dresden-Rossendorf, PO Box 510119, D-01314 Dresden, Germany

mmjadidi@umd.edu

Abstract

Graphene ribbons support terhaertz (THz) plasmon resonances [1] with subwavelength electric field confinement on the graphene surface [2]. The extreme field localization at plasmon resonance greatly increases the light-graphene interaction, and can lead to a strong nonlinear optical response [2,3].

Here we present the first experimental study of the nonlinear response of graphene plasmon resonances and their energy relaxation dynamics. We observe a strong saturation of plasmon absorption in graphene ribbons, using THz pump-THz probe measurements with a free electron laser tuned at the plasmon frequency (9.4 THz). The observed nonlinearity is found to be two orders of magnitude higher than that of graphene with no plasmon resonance. We further present a thermal model for nonlinear plasmonic absorption in graphene ribbons that supports the experimental results. The thermal model suggests that red-shifting and broadening of the plasmon resonance, due to the increase in graphene electron temperature, causes the observed nonlinearity [4].

References

1. L. Ju, B. Geng, J. Horng, C. Girit, M. Martin, Z. Hao, H. A. Bechtel, X. Liang, A. Zettl. Y. R. Shen, F. Wang, *Nat. Nanotechnol.* **6**.10 (2011).
2. F. H. L. Koppens, D. E. Chang, F. J. García de Abajo, *Nano Lett.* **11**.8 (2011).
3. M. Gullans, D.E. Chang, F.H.L. Koppens, F.J. García de Abajo, M.D. Lukin, *Phys. Rev. Lett.* **111**.24 (2013).
4. M. M. Jadidi, J. C. König-Otto, S. Winnerl, A. B. Sushkov, H. D. Drew, T. E. Murphy and M. Mittendorff, arXiv:1512.07508 (2015).

Figures

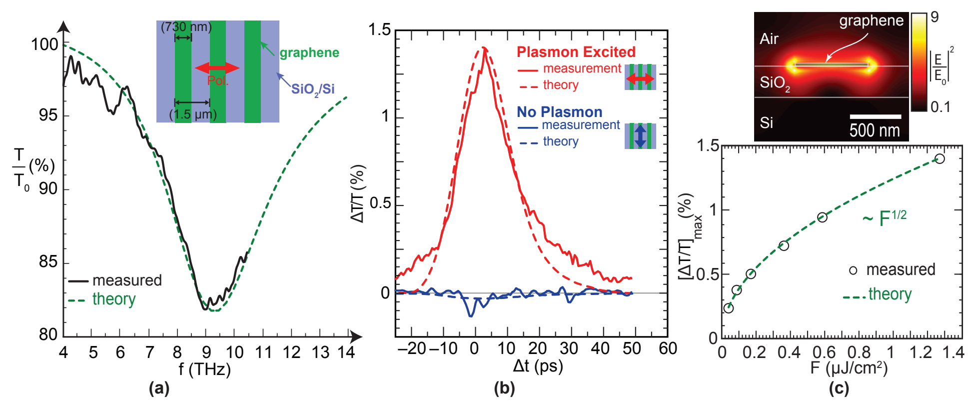

Fig. 1: **(a)** Measured and calculated linear transmission spectrum (T) of the graphene nanoribbons array, showing a decreased transmission at the plasmon frequency of 9.4 THz (T_0: bare substrate transmission). The inset shows the geometrical parameters of graphene ribbons array on SiO_2/silicon substrate. **(b)** The red curves show the pump-probe response ($\Delta T/T$: relative change of probe transmission) at plasmon resonance when pump and probe were polarized perpendicular to the graphene ribbons (plasmon excited). The blue curves show the response for the same incident pump fluence, but opposite polarization (no plasmon), and the nonlinear response is correspondingly much lower. The dashed theory curves are based on a thermal model for nonlinear plasmonic (red) and Drude (blue) absorption in graphene. **(c)** *Top*: Calculated electric field intensity $|E|^2$ at the plasmon resonance of graphene ribbons, relative to the incident plane-wave intensity. It shows a strong field confinement on the graphene that is the origin of the observed plasmon-enhanced nonlinearity. *Bottom*: Peak of relative transmission change vs. pump fluence, that exhibits a square-root dependence.