Strong optical dichroism in graphene nano-ribbons[1]

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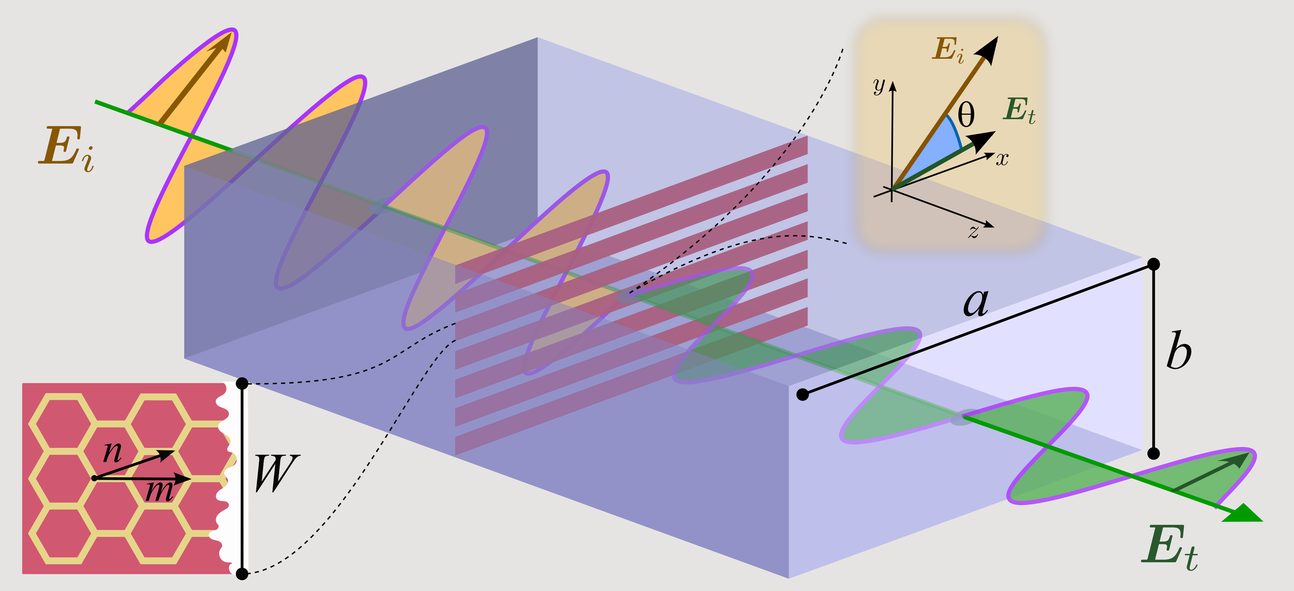
Abstract

The optical conductivity of graphene nanoribbons is analytical and exactly derived. It is shown that the absence of translational invariance along the transverse direction allows considerable intra-band absorption in a narrow frequency window that varies with the ribbon width, and lies in the THz band for ribbons 10–100 nm wide. In this region the anisotropy in the optical conductivity can be as high as two orders of magnitude, which renders the medium dichroic, and allows 100% polarizability with just a single layer of graphene. The effect can be further magnified, and the dichroic frequency band precisely tuned, by enclosing an array of nanoribbons inside a metallic waveguide.[1]

Envisage setup

In this illustration we present the geometry under consideration, consisting of a grid of parallel GNRs perpendicular to the incoming wave. The grid can be inside a metallic cavity with sectional area $a \times b$, and can also be at the interface between two different dielectric media.



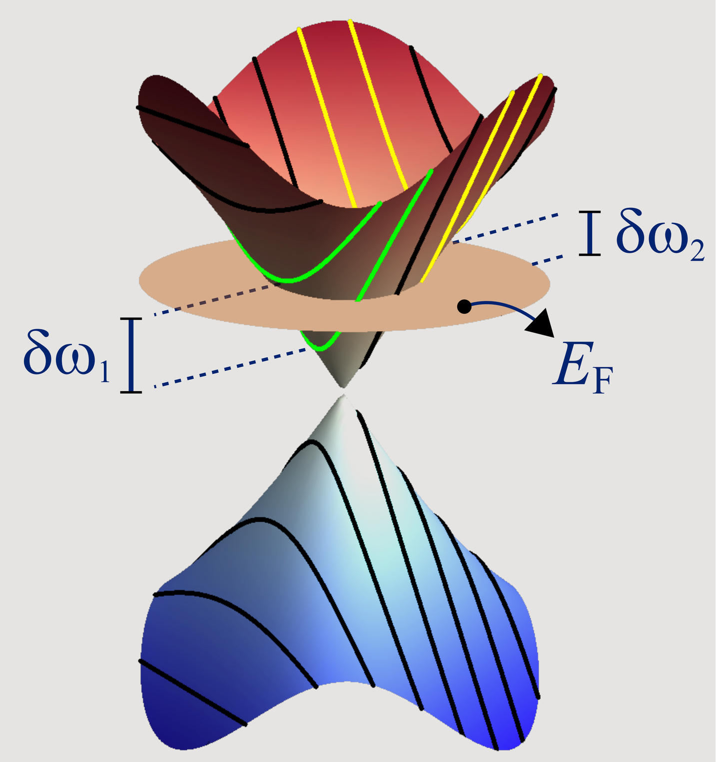
Optical Conductivity

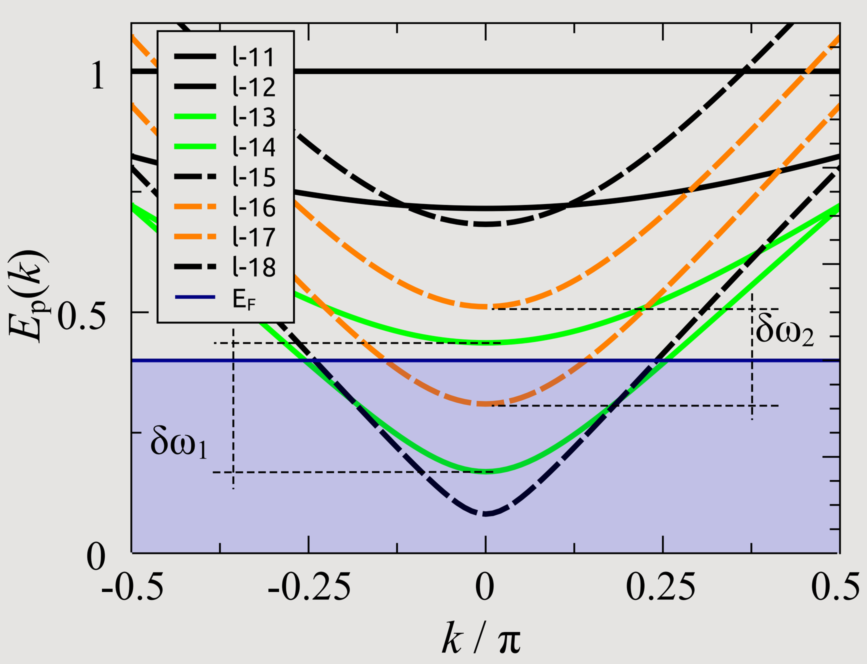
- The energy dispersion for graphene ribbons

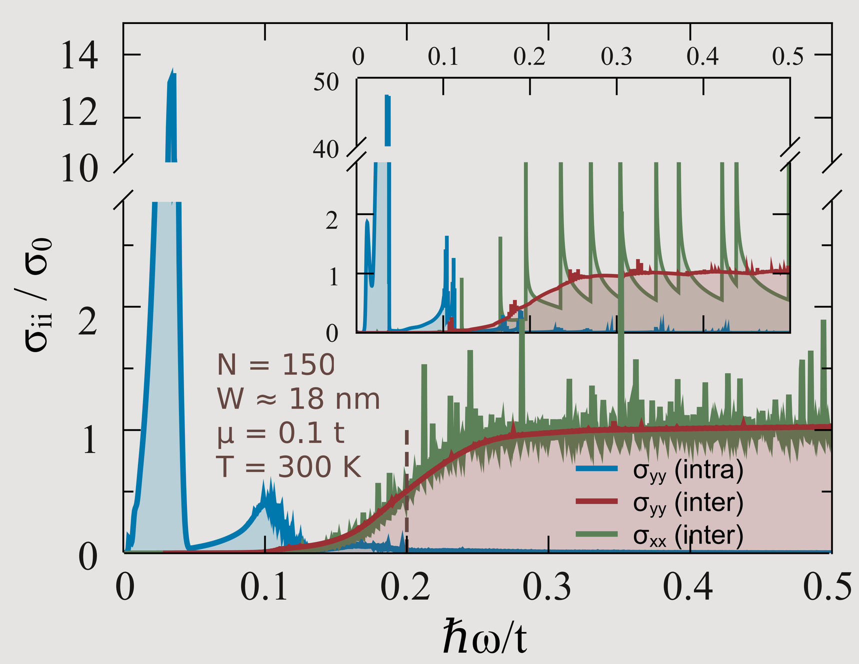
$$\epsilon_{\ell,q} = \sqrt{1 + 4\cos k_\ell \cos(q/2) + 4\cos^2 k_\ell}$$

- and the quantified wavenumber

$$k_\ell = \frac{\pi \ell}{N+1}.$$







Polarizability and polarization angle rotation

- Transmission amplitude

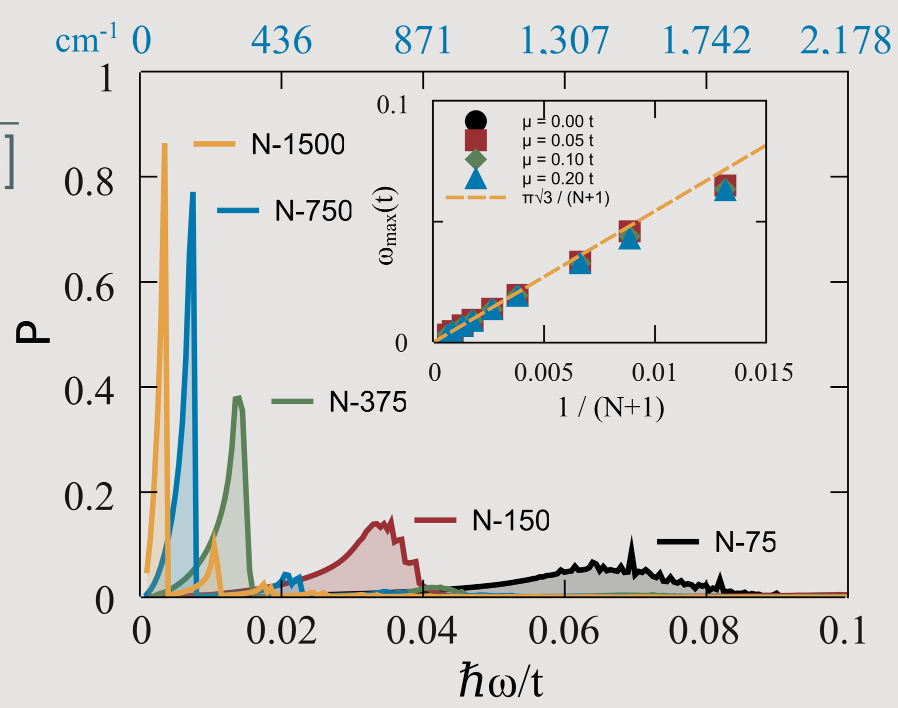
$$t_\alpha(\omega) = \frac{2\,Z^{(2)}}{Z^{(1)} + Z^{(2)}[1 + Z^{(1)}\sigma_{\alpha\alpha}(\omega)]}$$

- Degree of polarization or polarizability

$$\mathcal{P}(\omega) = \frac{|t_x|^2 - |t_y|^2}{|t_x|^2 + |t_y|^2}$$

- Angle of polarization

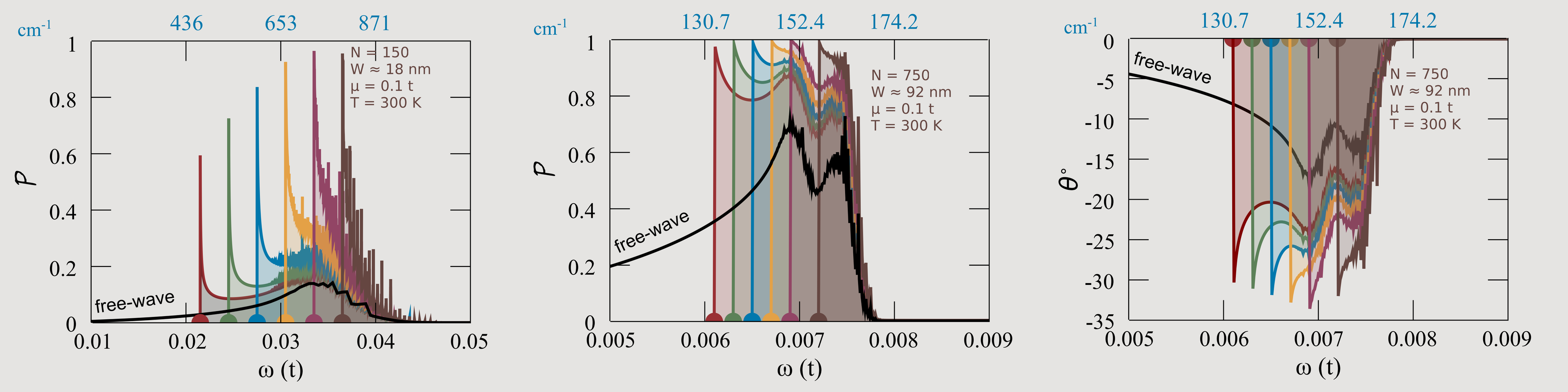
$$\tan\theta^f = \frac{t_y}{t_x}\tan\theta_i$$



Polarizability and polarization angle rotation (cont.)

- Waveguide impedance enhancement for TE modes

$$Z_{mn}(\omega) = Z\frac{\omega}{\sqrt{\omega^2 - \omega_{mn}^2}}, \quad \omega_{mn}^2 = \left(\frac{c^2\pi^2}{\epsilon\mu}\right)\left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right)$$



Derivation of the Optical Conductivity

- Using the analytic ribbon eigenstates

$$|\Psi_{\ell,q,\lambda}\rangle = \mathcal{N}\sum_{n,m} e^{-iq(m+n/2)}\sin(k_\ell n) \times \left(|A,n,m\rangle + \lambda e^{-i\theta_{\ell,q}}|B,n,m\rangle\right),$$

the phase difference between sub-lattices

$$\theta_{\ell,q} = \arctan\frac{2\cos k_\ell \sin(q/2)}{1 + 2\cos k_\ell\cos(q/2)}$$

and the Kubo Formula

$$\sigma_{\mu\nu} = \frac{2ie^2}{\omega S}\sum_{\ell_1,\ell_2,q}\sum_{\lambda_1,\lambda_2}\frac{f(E_{\ell_1,q,\lambda_1}) - f(E_{\ell_2,q,\lambda_2})}{\hbar\omega - (E_{k_2,q,\lambda_2} + E_{k_1,q,\lambda_1}) + i0^+} \times \langle\Psi_{\ell_1,q,\lambda_1}|\, v_\mu\, |\Psi_{\ell_2,q,\lambda_2}\rangle\langle\Psi_{\ell_2,q,\lambda_2}|\, v_\nu\, |\Psi_{\ell_1,q,\lambda_1}\rangle.$$

- Due to the translation invariance along the longitudinal direction, the conductivity reads as

$$\Re\frac{\sigma_{xx}}{\sigma_0} = \mathcal{N}_x\sum_{\ell_0} f(E_{\ell_0,q_0,-}) - f(E_{\ell_0,q,+})\frac{[\cos\theta_{\ell_0,q_0} - \cos(\theta_{\ell_0,q_0} - q_0/2)\cos k_{\ell_0}]^2}{\sin(q_0/2)\cos k_{\ell_0}},$$

where $\mathcal{N}_x = 4/3\sqrt{3}(N-1)$, and q_0 is given by

$$q_0 = 2\arccos\frac{(\Omega/2)^2 - 1 - 4\cos^2 k_{\ell_0}}{4\cos k_{\ell_0}}.$$

- Along the finite direction the translation symmetry is broken and the conductivity reads as

$$\Re\frac{\sigma_{yy}}{\sigma_0} = \frac{\mathcal{N}_y}{\hbar\omega}\sum_{\ell_1,\ell_2}\sum_{\lambda,\lambda'}\mathcal{P}_{\ell_1,\ell_2}\,\delta f^{\lambda,\lambda'}_{q_0,\ell_1,\ell_2}\, M_y^2(q_0,\ell_1,\ell_2),$$

where $\mathcal{N}_y = 4/\sqrt{3}(N+1)(N^2-1)$, $\delta f^{\lambda,\lambda'}_{q_0,\ell_1,\ell_2} = n_F(E_{\ell_1,q_0,\lambda}) - n_F(E_{\ell_2,q,\lambda'})$, and $\mathcal{P}_{\ell_1,\ell_2} = 1 - (-1)^{\ell_1+\ell_2}$. The last factor is

$$M_y^2(q_0,\ell_1,\ell_2) = \frac{\sin^2 k_{\ell_1}\sin^2 k_{\ell_2}}{\sin^2[(k_{\ell_1}+k_{\ell_2})/2]\sin^2[(k_{\ell_1}-k_{\ell_2})/2]} \times \frac{\epsilon_{\ell_1,q_0}\epsilon_{\ell_2,q_0}|\sin(q_0/2)|^{-1}}{|\cos k_{\ell_1}\epsilon_{\ell_2,q_0} + \lambda\lambda'\cos k_{\ell_2}\epsilon_{\ell_1,q_0}|} \times \mathcal{C}_{q_0,\ell_1,\ell_2},$$

where $\mathcal{C}_{q_0,\ell_1,\ell_2} = 1 + \lambda\lambda'\cos(\theta_{\ell_1,q_0} + \theta_{\ell_2,q_0} - q_0)$, and

$$q_0 = 2\arccos\frac{(a_2 - a_1)Q_b + \Omega^2(b_1 + b_2) \pm Q_c}{(b_1 - b_2)^2},$$

with $Q_c = 2\sqrt{\Omega^4 b_1 b_2 + \Omega^2 Q_b Q_a}$, $Q_b = b_1 - b_2$, $Q_a = b_1 a_2 - b_2 a_1$, $a_i = 1 + 4\cos^2 k_{\ell_i}$ and $b_i = 4\cos k_{\ell_i}$.

Summary

- Conclusions
  - ▷ Analytic calculation of the DOS
  - ▷ Analytic solution for conductivity tensor $\sigma_{ij}(\omega)$ at finite temperature
  - ▷ Analytic solution transmission amplitudes, polarizability and polarization angle rotation
- Future work
  - ▷ Strain effects on transport
  - ▷ Sources disorder (other than level broadening)
  - ▷ Interplay between intrinsic dichroism of ribbons and grating dichroism

Reference

[1] F. Hipolito et al. "Enhanced optical dichroism of graphene nanoribbons". In: *Phys. Rev. B* 86 (11 2012), p. 115430. DOI: 10.1103/PhysRevB.86.115430.