Basic Notions in Graphene Plasmonics

Nuno Miguel Reis Peres

Santiago de Compostela, 17th of Octobler 2016

Outline

Outline

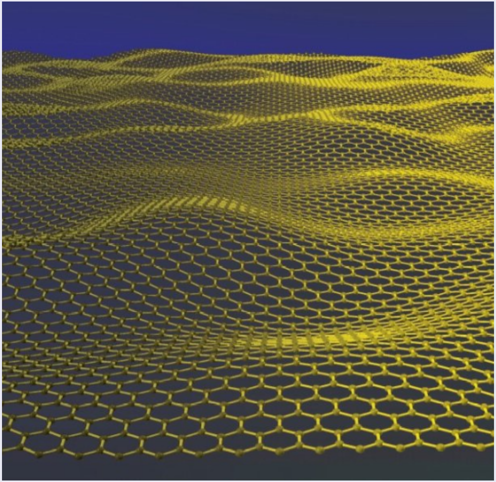
Outline

Lucas Cranach (1472-1553)

Venus and Cupid (1537)

Artistic view of a graphene sheet

Graphene honeycomb lattice



Plasmonics

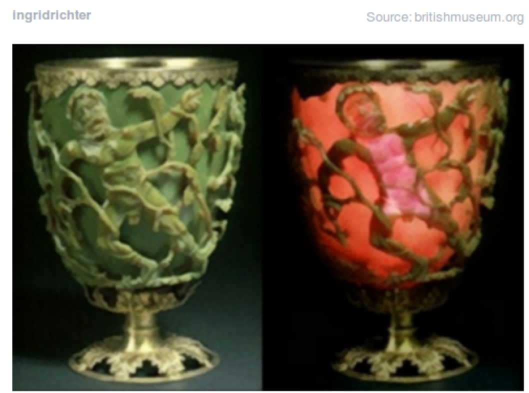
ACS Nano **8**, 1086 (2014)

- Plasmonics deals with the excitation, manipulation, and utilization of surface plasmon-polaritons

- surface plasmon-polaritons are hybridized excitations of radiation with the collective charge oscillations of an electron gas.

Lycurgos cup (4th century AD)

Gold and Silver nanoparticles around 50 nanometres in diameter



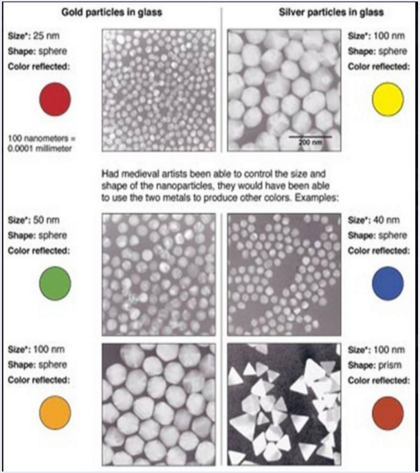
Lycurgus Cup at the British Museum, 4th century AD.

Stained glass (sowing plowed fields)

"September"

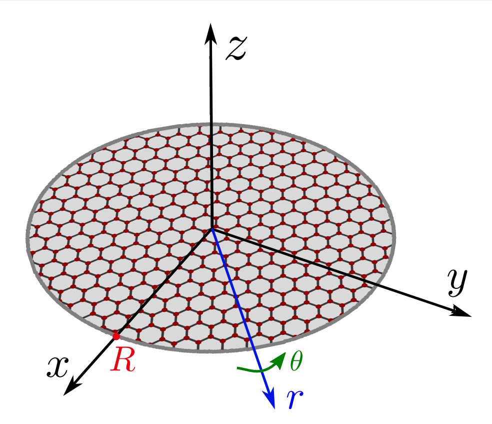
nanoparticles

Dependence on size and shape



Artistic view of a graphene nanostructure

Nanodisk



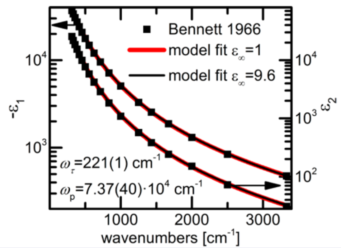
Metal plasmonics

- In general, metal plasmonics is explored in the visible and near-IR
- What about its use in the mid- and far-IR?

Plasmonics in the mid- and far-IR?

Limitations

- Poorly confined in the mid-IR and in the far-IR (THz)
- Reduced field enhancement
- Relatively large losses (when compared to other candidates)



2000 nm = 2 μm = 150 THz ($\sim$Mid-IR)

$$\zeta_M \propto \frac{c}{\omega}\sqrt{\frac{1}{|\epsilon_1|}} = 2\pi\frac{3\times 10^8}{1.5\times 10^{14}}\sqrt{\frac{1}{100}} \sim 1\mu\text{m}$$

Graphene

- What about graphene?

Confinement in graphene ($\lambda = 2000$nm)

Penetration depth in the surrounding dielectric

$$\zeta_G \propto \alpha \hbar c \frac{E_F}{(\hbar\omega)^2} = \frac{1}{137} \times 0.2 \times \frac{0.5}{0.6^2} \sim 0.002\mu\text{m}$$

Comparing metal with graphene

$$\frac{\zeta_G}{\zeta_M} \sim 2 \times 10^{-3}$$

Attenuation in graphene ($\lambda = 2000$nm)

Attenuation length

$$d_G \propto \alpha\hbar c \frac{E_F}{\Gamma\hbar\omega} = \frac{1}{137} \times 0.2 \times \frac{0.5}{0.6 \times 16 \times 10^{-3}} \sim 0.075\mu\text{m}$$

Comparing the two lengths

$$\frac{d_G}{\zeta_G} \sim \frac{0.075}{0.002} \sim 40$$

Some properties

Graphene plasmonics:

- Strong confinement in the mid- and far-infrared (THz)
- Small attenuation
- Tunable due to the real-time control of E_F
- Large field enhancement
- Exist at room temperature (contrary to the 2DEG)

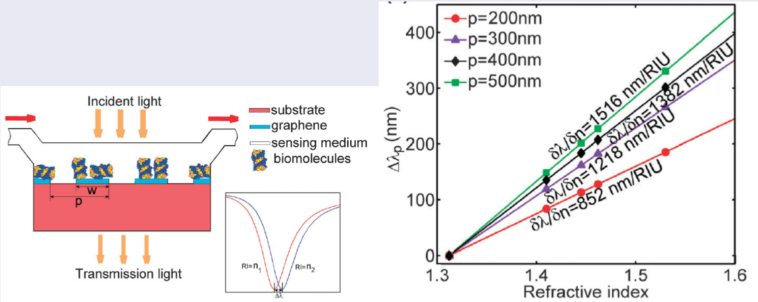
Applications

Graphene plasmonics:

Applications in bio-sensing

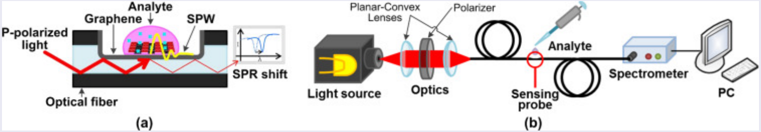
An example: A graphene-based biosensor

Infrared biosensors based on graphene plasmonics —modeling:
Phys. Chem. Chem. Phys., **15**, 17118 (2013)



A fiber-optic graphene-based biosensor

Sensors and Actuators B **187**, 426 (2013)



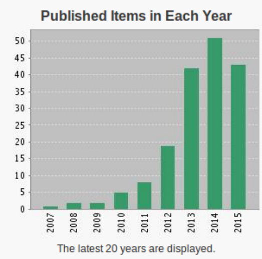
Far-IR plasmonics

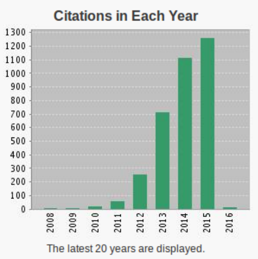
Graphene plasmonics:

- But what is the motivation to study far-IR (THz) plasmonics?

Scientometric indicators for graphene plasmonics in the THz

Web of Science —search key: Graphene+plasmons+THz:





Outline

Terahertz radiation

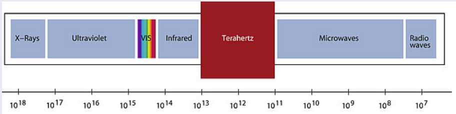
1 THz corresponds to a wavelength of 300 μm, to a wave number of 33 cm^{-1}, and to an energy of 4.1 meV

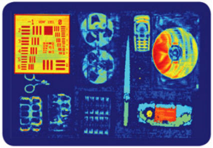
- visible light: creates a photograph
- radio waves: transmit sound
- X-rays: see within the human body
- terahertz waves: create pictures

Fig. 1.5 Photo of racquetball bat (a), the bat in a plastic bag (b), and THz wave (0.6 THz) image of the bat in a plastic bag (c)

A suitcase

Image and photography ...: (TOPTICA)



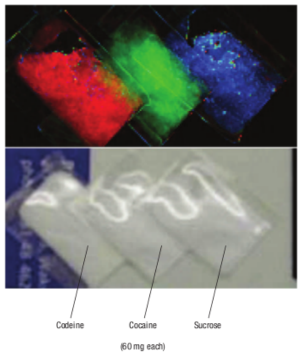


Major advantages:

1. penetration to opaque materials
2. high chemical selectivity

Chemical identification with THz

Cocaine



Terahertz Frequency Detection and Identification of Materials and Objects, edited by Robert E. Miles (Springer, 2007)

What is the relevance of THz?

[X.-C. Zhang and Jingzhou Xu (2009)]

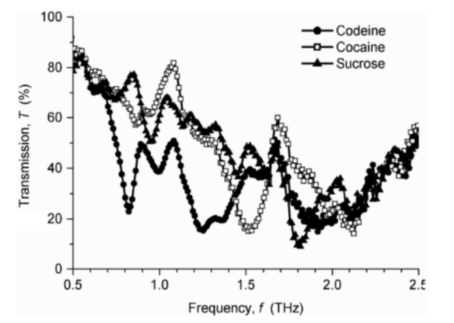
"Many biological and chemical compounds have distinct signature responses to THz waves due to their unique molecular vibrations and rotational energy levels":

Possible applications:

- diagnosis of a disease
- detection of pollutants
- sensing of biological and chemical agents
- quality control of food products
- plastic explosives could be distinguished from suitcases, clothing, common household materials, and equipment

An example: Cocaine, Codeine, and Sucrose

Transmission spectrum:

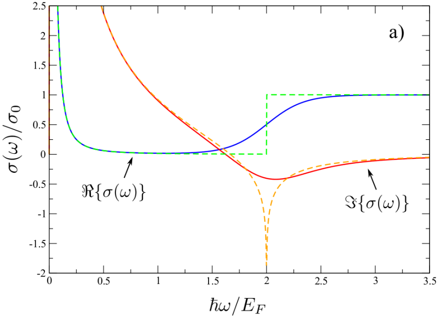


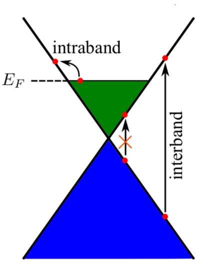
Terahertz Frequency Detection and Identification of Materials and Objects, edited by Robert E. Miles, (Springer, 2007)

Outline

Graphene: optical conductivity

$$\sigma_g = \sigma^{intra}(\omega) + \sigma^{inter}(\omega)$$



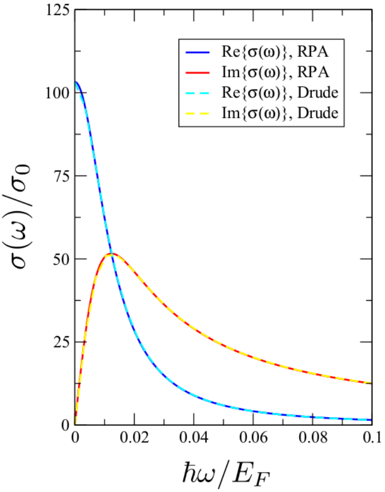


Graphene: optical conductivity

$$\sigma_g \approx \sigma_g^{\mathrm{Drude}} = \frac{e^2}{\pi\hbar}\frac{E_F}{\hbar\gamma - i\hbar\omega}$$

for

$E_F \gg k_B T$ and $2E_F > \hbar\omega$

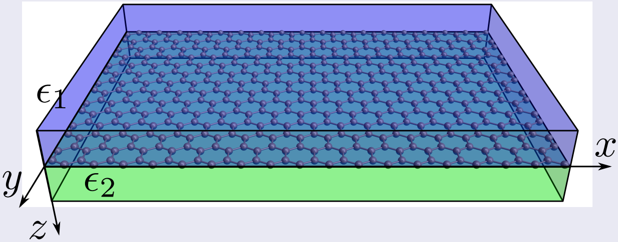


Outline

Outline

Graphene monolayer

Dispersion relation – TM-SPP



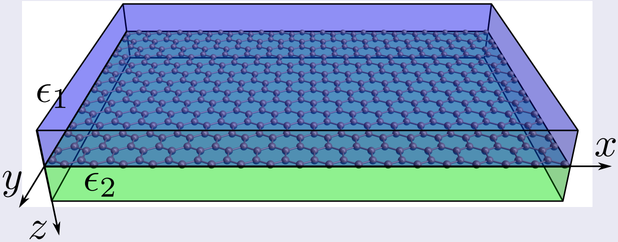
TM solutions:

$$\mathbf{E}_j = (E_{j,x}\hat{\mathbf{x}} + E_{j,z}\hat{\mathbf{z}})\, e^{iqx} e^{-\kappa_j |z|}$$

$$\mathbf{B}_j = B_{j,y} e^{iqx} e^{-\kappa_j |z|} \hat{\mathbf{y}}$$

Graphene monolayer

Dispersion relation – TM-SPP

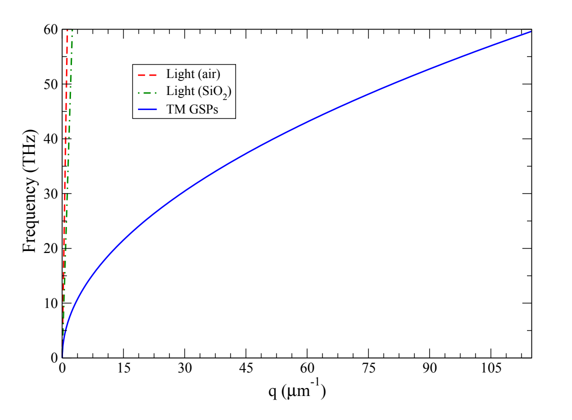


Plasmonic spectrum:

$$\frac{\epsilon_1}{\kappa_1(q,\omega)} + \frac{\epsilon_2}{\kappa_2(q,\omega)} + i\frac{\sigma(\omega)}{\omega\epsilon_0} = 0$$

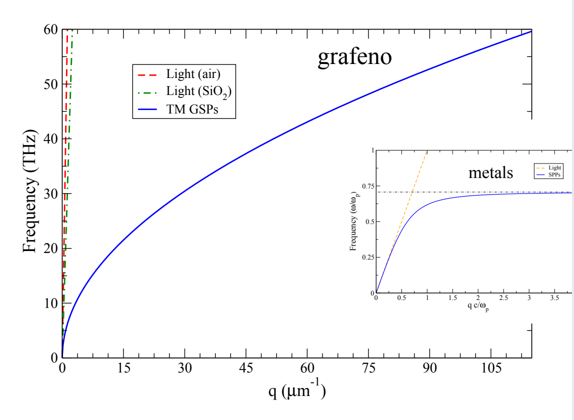
Graphne monolayer

TM-SPP's: numerical solution



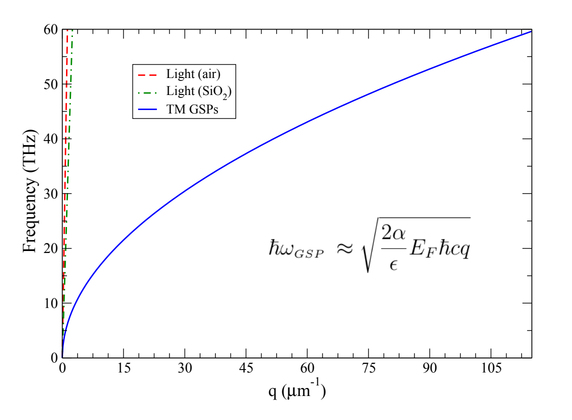
Graphne monolayer

TM-SPP's: numerical solution



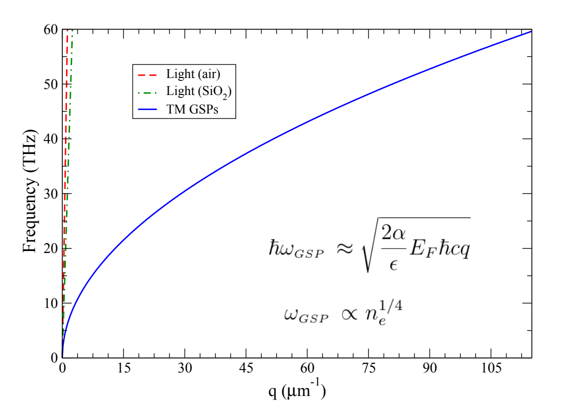
Graphne monolayer

TM-SPP's: numerical solution

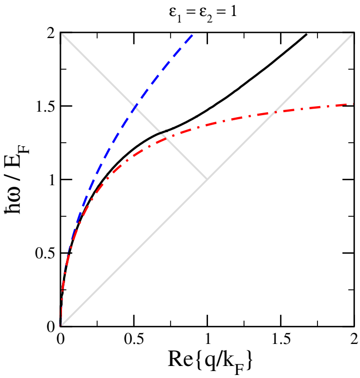


Graphne monolayer

TM-SPP's: numerical solution

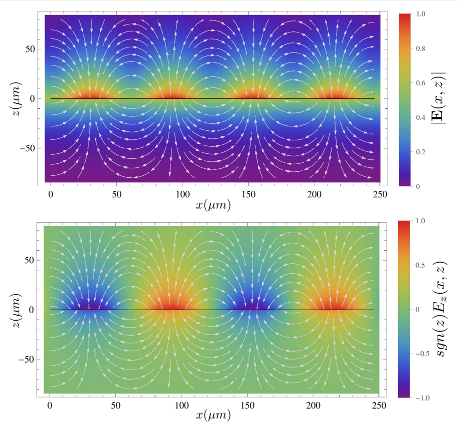


SPP's in graphene: non-local corrections



Surface plamon-polaritons in graphene

SPP's EM field



TM SPP's

- THz range (up to "mid-IR")
- $\lambda_{GSP} \ll \lambda_0$ (até $\lambda_{GSP}/\lambda_0 \sim \alpha$)
- High spatial confinement
- real-time controlled plasmonics

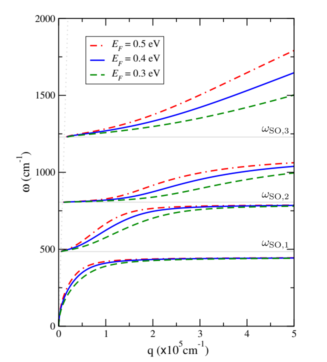
Outline

Engineering surface plasmon-polaritons dispersion

- Coupling to optical surface-phonons of the substrate

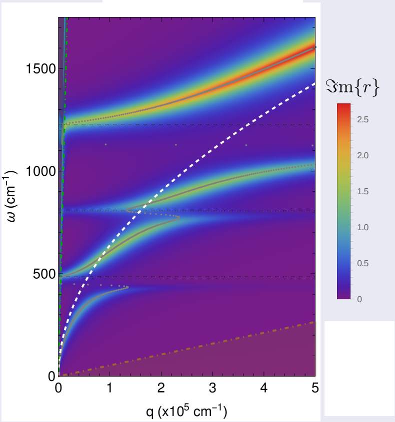
Graphene plasmonic spectrum (graphene on SiO_2): Spectrum

Surface phonon-plasmon-polariton



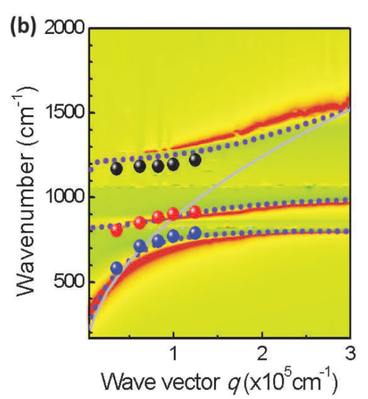
Graphene plasmonic spectrum (graphene on SiO_2): Loss function

Surface phonon-plasmon-polariton: energy-loss function



Graphene plasmonic spectrum (graphene on SiO_2): experimental results

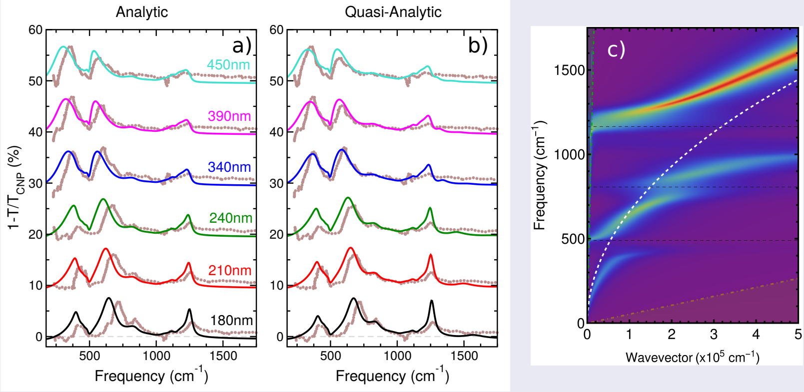
Nano Letters **14**, 2907 (2014)



See also: Nat. Photonics **7**, 394 (2013)

Experimental results

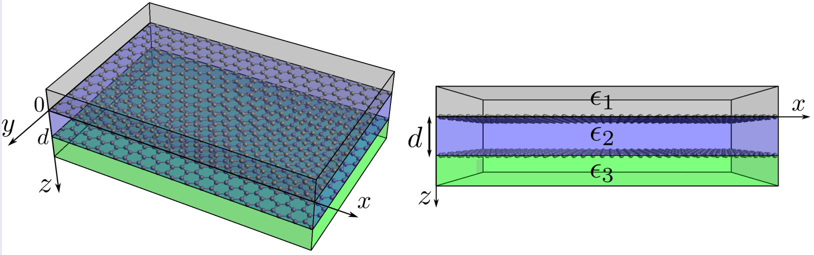
Experiment and theory



Outline

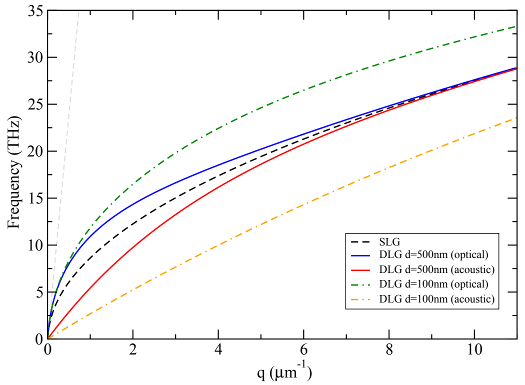
Graphene double-layer

Dispersion relation – TM SPP's



Graphene double-layer

Plasmonic spectrum (GDB) – 2 modes



d small

⇓

evanesc. waves hibridize

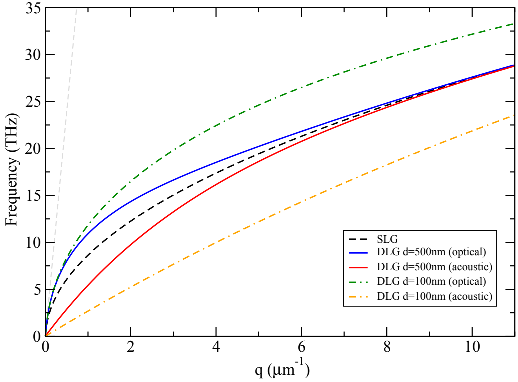
⇓

2 modes:

- symmetric
- anti-symmetric

Graphene double-layer

Plasmonic spectrum (GDB) – 2 modes

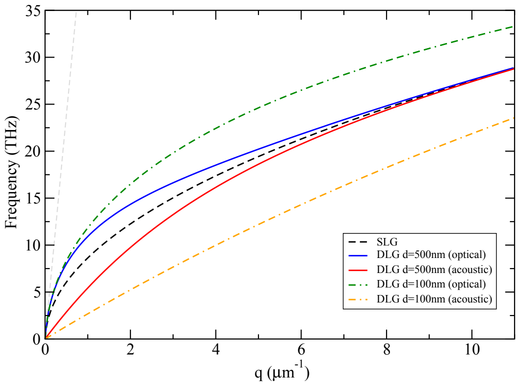


d small
$\Downarrow$
evanesc. waves hibridize
$\Downarrow$
2 modes:

- symmetric
- anti-symmetric

Graphene double-layer

Plasmonic spectrum (GDB) – 2 modes



d small

$\Downarrow$

evanesc. waves hibridize

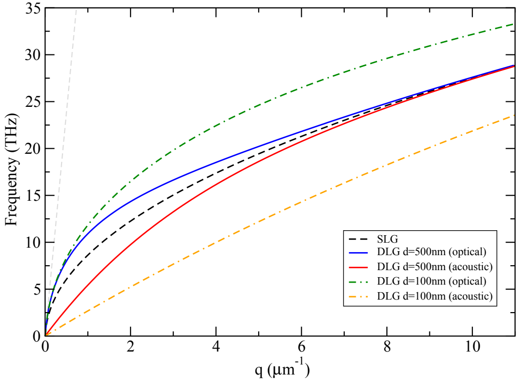
$\Downarrow$

2 modes:

- symmetric
- anti-symmetric

Graphene double-layer

Plasmonic spectrum (GDB) – 2 modes



d small

$\Downarrow$

evanesc. waves hibridize

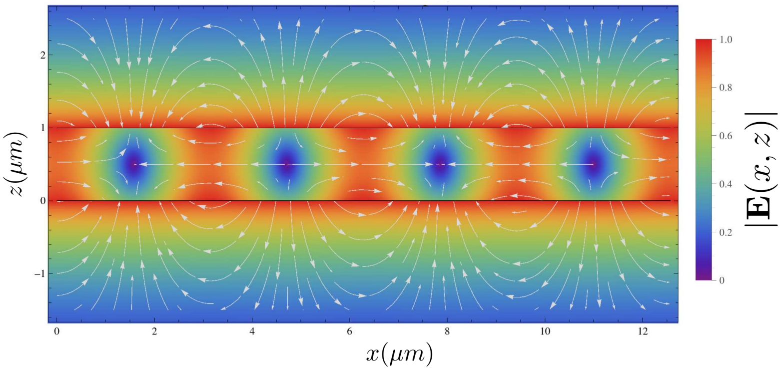
$\Downarrow$

2 modes:

- symmetric
- anti-symmetric

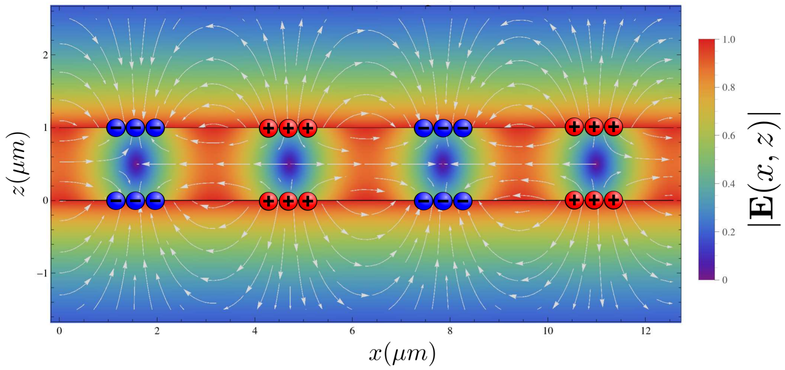
Graphene double-layer

Optical mode



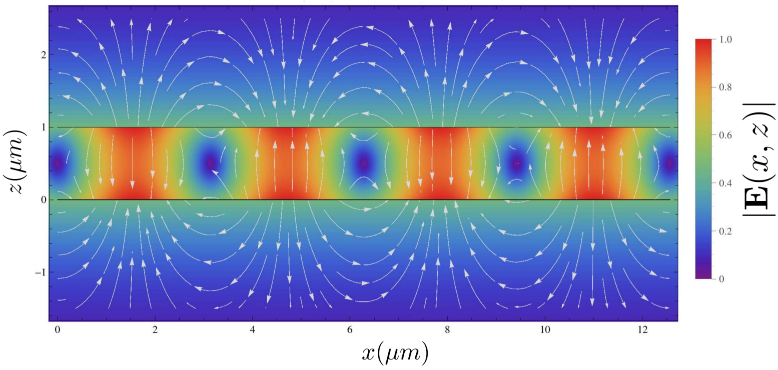
Graphene double-layer

Optical mode



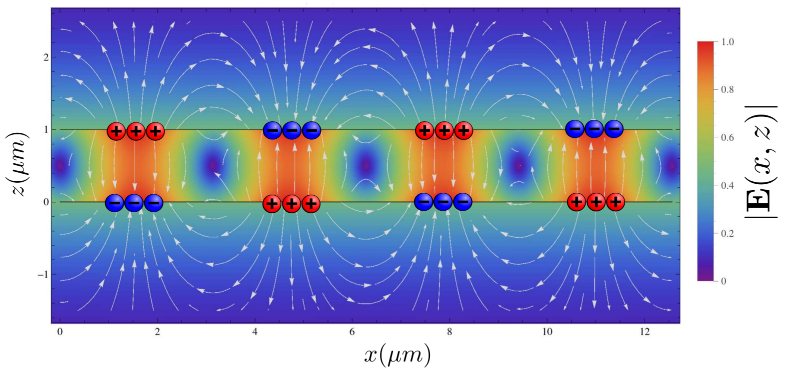
Graphene double-layer

Acoustic mode: highly confined and recently observed



Graphene double-layer

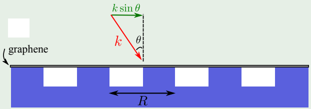
Acoustic mode: highly confined and recently observed



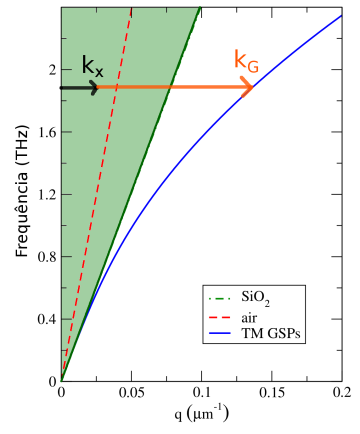
Outline

Conventional methods

Grating coupling

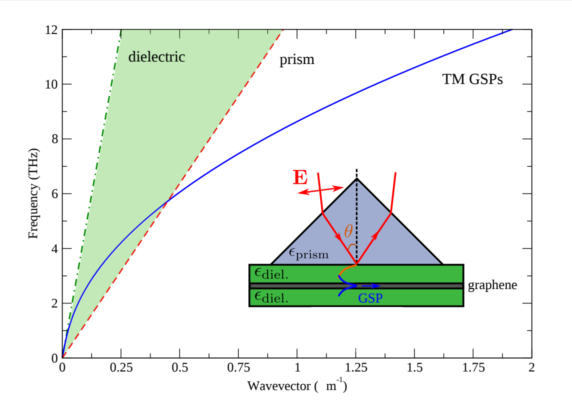


$q \to q + nG$, com $G = 2\pi/R$



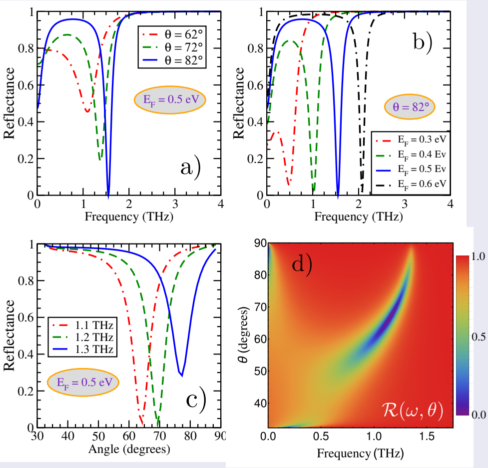
Conventional methods

Prism coupling



Few results for prisma-coupling

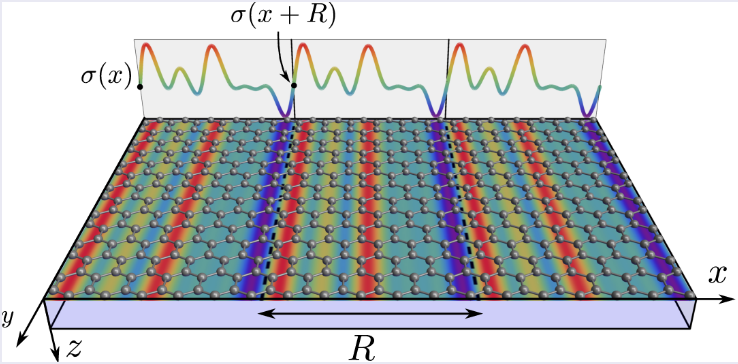
Reflectance curves



Outline

Plasmonics in graphene periodic structures

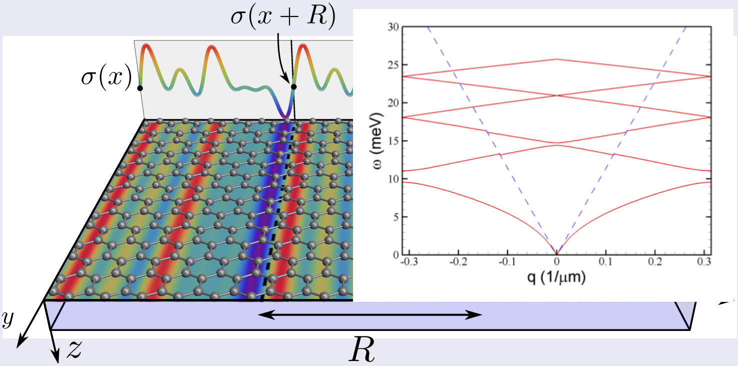
Theoretical model



$q \rightarrow q + nG$, com $G = 2\pi/R$ $\Longrightarrow$ excitation of SPP's becomes possible

Plasmonics in graphene periodic structures

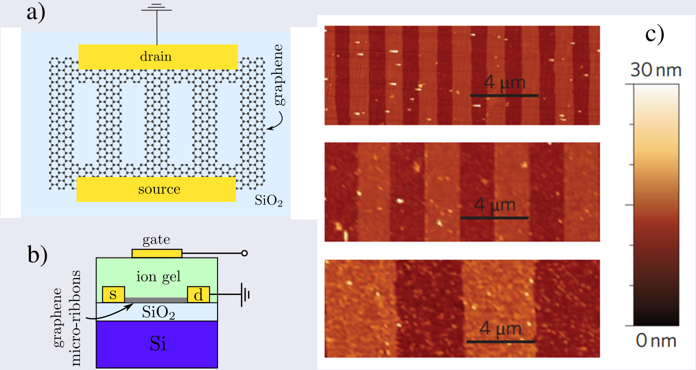
Theoretical model



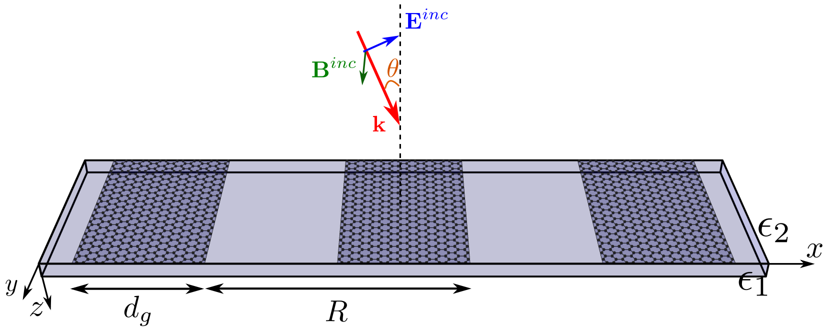
$q \to q + nG$, com $G = 2\pi/R$ $\Longrightarrow$ excitation of SPP's becomes possible

Experimental setup

Graphene plasmonics for tunable terahertz metamaterials, Nature Nanotechnology **6**, 630–634 (2011)

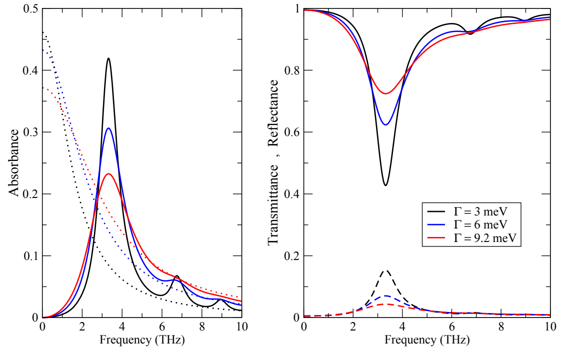


Applications: periodic graphene-stripes



Results: periodic graphene-stripes

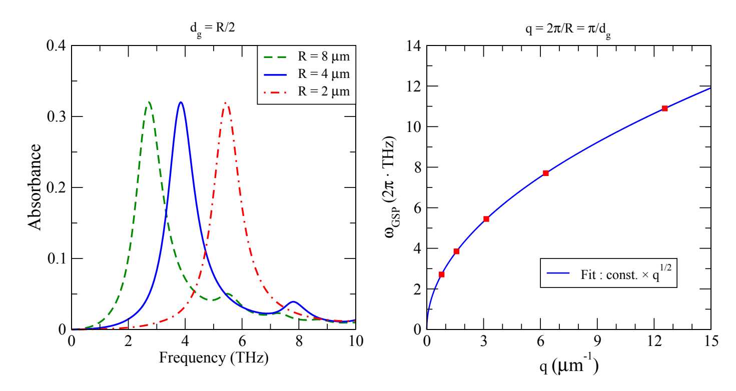
$\mathcal{T}(\omega)$, $\mathcal{R}(\omega)$ e $\mathcal{A}(\omega)$



$E_F = 0.45$ eV, $d_g = 4\ \mu$m, $R = 8\ \mu$m, $\epsilon_1 = 4$, $\epsilon_2 = 3$, $\theta = 0$.

Results: periodic graphene-stripes

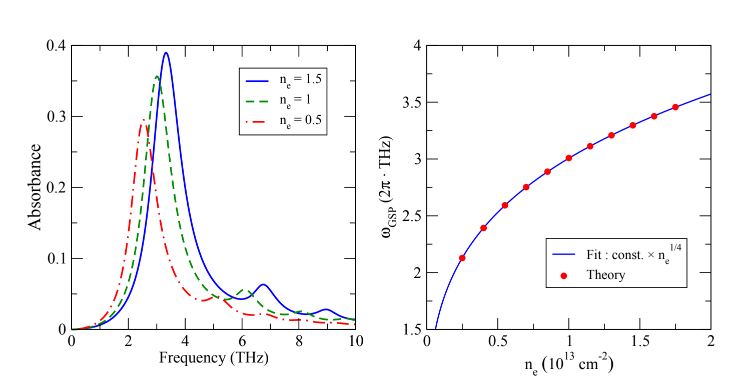
Dependence on d_g ($q = \pi/d_g$):



$\omega_{GSP} \propto q^b$ with $b = 0.5001 \simeq 1/2$ ($d_g = R/2$, $E_F = 0.3$ eV, $\Gamma = 3.7$ meV)

Results: periodic graphene-stripes

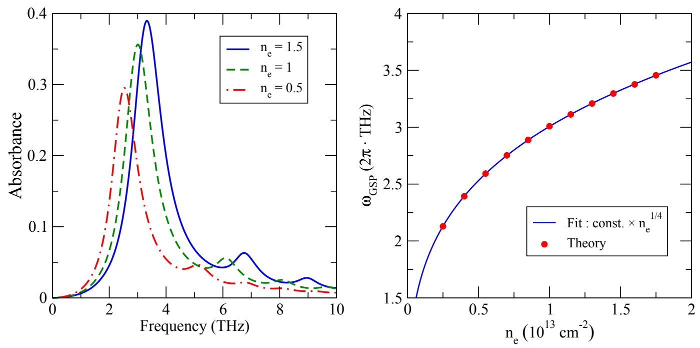
Dependence on n_e:



$\omega_{GSP} \propto n_e^b$ with $b = 0.249 \simeq 1/4$ $(d_g = R/2 = 4\mu$m, $\epsilon_1 = 4$, $\epsilon_2 = 3$, $\Gamma = 3.7$ meV)

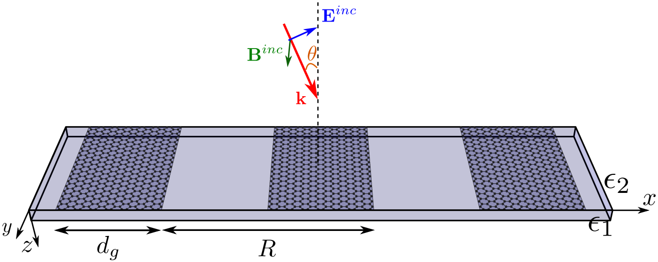
Results: periodic graphene-stripes

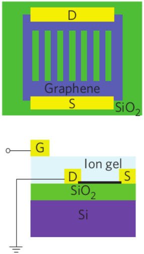
Dependence on n_e:

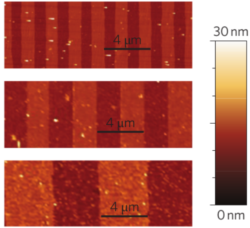


$\omega_{GSP} \propto n_e^{1/4} \rightarrow$ specific of graphene

Theory *vs* Experiment

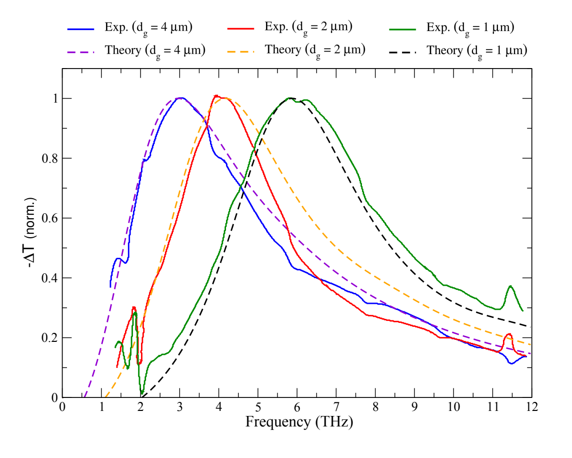






Theory *vs* Experiment

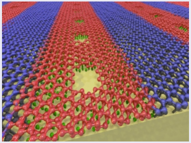
Graphene stripes with different widths:

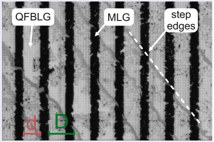


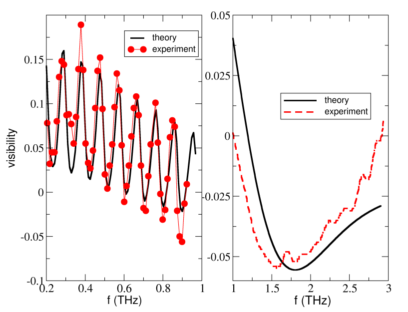
A polarizer made of graphene ribbons

New J. Phys. **15**, 053045 (2015)

$$\text{Visibility} = \frac{T_p - T_s}{T_p + T_s}$$



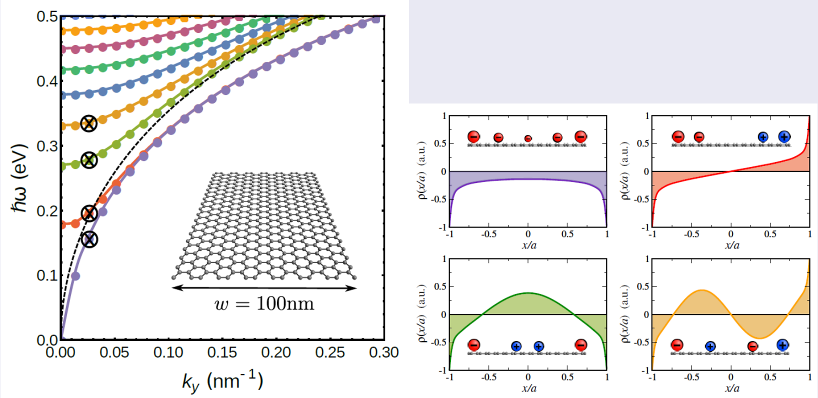




Outline

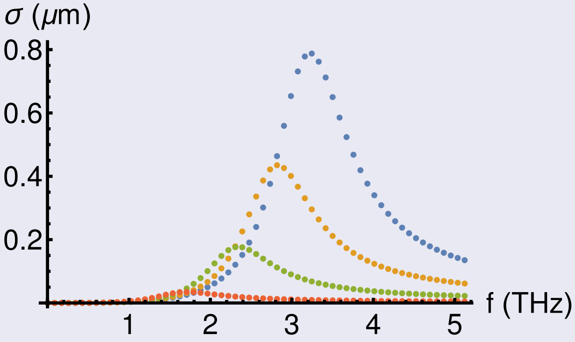
An example of a graphene nanostructure

A single graphene ribbon with $W = 100$ nm



Scattering of a TM-polarized wave by a graphene strip

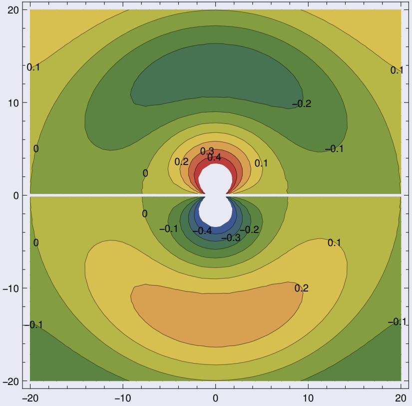
A graphene micro-ribbon with $W = 4\mu$m; $E_F = 0.1, 0.2, 0.3, 0.4$ eV



Scattering echo: $\sigma = \lim_{\rho\to\infty} 2\pi\rho \left|\frac{B_s(\rho)}{B_i}\right|^2$

Scattered magnetic field at resonance: $f = 3.25$ THz for $E_F = 0.4$ eV

Scattered magnetic field due to a graphene micro-ribbon with $W = 4\mu$m —$\Re B_s(x,y)/B_i$



Summary

- Graphene presents itself as a promising material for plasmonics
- Properties of GSPs:
  - THz to mid-IR
  - $\lambda_{GSP} \ll \lambda_0$ (high confinement / high field intensity)
  - weak attenuation
  - Exist at room temperature
  - “active plasmonics”

Bludov *et al.*, Int. J. Mod. Phys. B **27**, 1341001 (2013)

Summary

- Graphene presents itself as a promising material for plasmonics
- Properties of GSPs:
  - THz to mid-IR
  - $\lambda_{GSP} \ll \lambda_0$ (high confinement / high field intensity)
  - weak attenuation
  - Exist at room temperature
  - "active plasmonics"

Bludov *et al.*, Int. J. Mod. Phys. B **27**, 1341001 (2013)

Advertisement