Time reflection and time refraction of graphene plasmons

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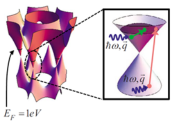
Plasmons in 1D graphene sheets

Graphene plasmon advantages:

- Extreme confinement
- Low losses
- High tunability
- No radiative losses

Tunability via the graphene Fermi level E_F [1]

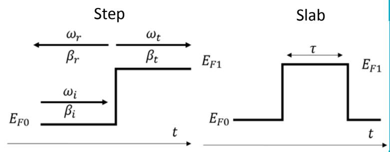


Graphene can be modeled with a Drude-like conductivity, leading to a simple dispersion for graphene plasmons:

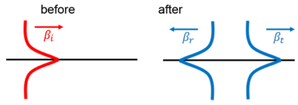
$$\sigma(\omega) = \frac{e^2 E_F}{\pi\hbar^2}\frac{i}{\omega + i\tau_{gra}^{-1}} \qquad Re(\beta) = \frac{2\varepsilon_0\varepsilon_r\pi\hbar^2\omega^2}{e^2 E_F}$$

Time interfaces

We consider a graphene plasmon propagating along a graphene sheet and we abruptly change the Fermi level E_F. This is what we call a time interface. We use two types of profiles: a step and a slab.



The time interface creates a transmitted and a reflected plasmon. In the step case, the frequency of the incident plasmon is different from the frequency of the reflected and transmitted plasmons.



Analytical Model

To ensure that Maxwell's equations remain valid at all times, the electric displacement and magnetic induction must remain continuous at all times [2]. Assuming that the step interface occurs at $t = 0$, we have the conditions:

$$\vec{D}(t=0^-) = \vec{D}(t=0^+) \qquad \vec{B}(t=0^-) = \vec{B}(t=0^+)$$

These conditions imply the conservation of the plasmon propagation constant: $\beta_i = \beta_t = -\beta_r$

Since we change E_F, the plasmon frequency has to change to keep β unchanged:

$$\frac{\omega_i}{\sqrt{E_{F0}}} = \frac{\omega_t}{\sqrt{E_{F1}}} = \frac{\omega_r}{\sqrt{E_{F1}}}$$

This allows to find the Fresnel coefficients for graphene plasmons at a time interface:

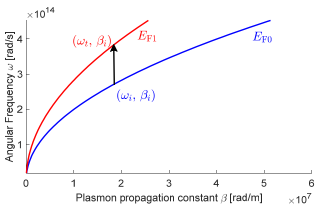
$$R_{step} = \left(\frac{\gamma - 1}{2\gamma}\right)^2 \qquad R_{slab} = \frac{1}{4}(\gamma - \gamma^{-1})^2 \sin(\gamma\omega\tau)^2$$

$$T_{step} = \left(\frac{\gamma + 1}{2\gamma}\right)^2 \qquad T_{slab} = 1 + R_{slab}$$

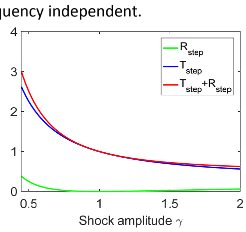
With τ the time slab length and $\gamma = \sqrt{\frac{E_{F1}}{E_{F0}}}$

STEP

In the step case, this process corresponds to a direct transition between two plasmonic modes.

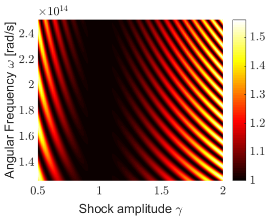


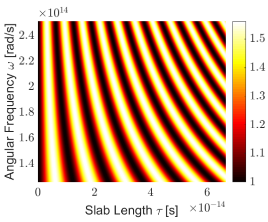
In the step case, the only relevant parameter is the shock amplitude γ. The transmission is frequency independent.



SLAB

In the slab case, this process is highly tunable with parameters γ, τ and ω.

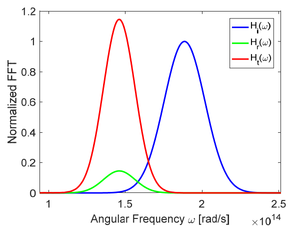




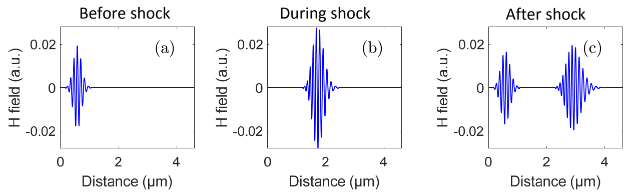
Simulation results

In order to validate our results, we ran finite element method (FEM) simulations.

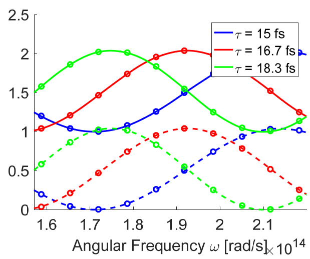
For a step interface with a negative γ, the transmitted and reflected plasmons have a lower frequency than the incident plasmon.



We also clearly see how the reflected and transmitted pulses appear along the propagation direction:



FEM simulations are in perfect agreement with our analytical model for the two types of interfaces.



We can also give an interpretation of the transmittance in terms of energy:

For the step case, since the transmisson and reflection coefficients are frequency independent we have:

$$R_{step} = \frac{U_r}{U_i} \qquad T_{step} = \frac{U_t}{U_i}$$

For the slab case however, the transmission coefficients are frequency dependent:

$$\int T_{slab}(\omega)P_i(\omega)d\omega = U_t\,, \quad \int R_{slab}(\omega)P_i(\omega)d\omega = U_r$$

This means that energy can be injected into the forward propagating plasmons since unlike in 'conventional' refraction, the tramsmittance can be greater than one.

Conclusion

We describe the behaviour of graphene plasmons incident on a time boundary with an analytical model backed up by FEM simulations. We show that it is possible to reflect plasmons and to inject energy in the forward propagating plasmons. This can be useful for frequency selective filters, amplifiers and modulators.

References

[1] M. Jablan, H. Buljan, and M. Soljačić, Plasmonics in graphene at infrared frequencies, *Phys. Rev. B*, **80**, 245435, (2009)

[2] Y. Xiao, D. N. Maywar, and G. P. Agrawal, Reflection and transmission of electromagnetic waves at a temporal boundary, *Opt. Lett.* , **39 (3)**, 574-577, (2014)