Graphene plasmons embedded in a gain medium

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Graphene plasmonics has attracted much attention because of its remarkable properties such as tunable conductivity and extreme confinement. However, one of the major drawbacks to develop more efficient devices based on graphene plasmons remains losses. Here we study how the introduction of a gain medium surrounding graphene can affect plasmonic modes, both in 1D and 2D settings. We show the presence of a critical gain in 1D structures when the losses are entirely compensated. Furthermore, using numerical simulations and analytical models, we demonstrate a resonant gain leading to enhanced absorption in 2D graphene ribbons.

Introduction

Graphene is a 2-dimensional hexagonal lattice of carbon atoms. At mid-infrared frequencies, graphene behaves as a metallic layer. Plasmonic modes guided by graphene sheets have been demonstrated, leading to remarkable sub-wavelength confinement [1]. However, due to the well-known trade-off between confinement and losses in plasmonic devices, one can not achieve propagation lengths suitable for technologic development if nothing is done to overcome the losses of these plasmonic modes. In this paper, we show how the introduction of a gain medium surrounding graphene sheets can lead to improved propagation lengths using analytical models and simulations with COMSOL Multiphysics, a commercial finite element based software package. We then show how the extinction cross-section of graphene ribbons can be dramatically improved by tuning the gain medium surrounding those ribbons.

Surface plasmons in graphene

To derive the graphene plasmon (GP) dispersion relation, one can model the graphene sheet by a plane that possesses a conductivity $\sigma(\omega)$ [2]. To describe harmonic propagation we use the convention $e^{-i\beta z}$. With this convention, one can see that if $\Im(\beta) > 0$, the mode amplitude is amplified along the propagation direction. Solving Maxwell's equations leads to the dispersion relation for the GP propagation constant β :

$$\beta = \pm\sqrt{\varepsilon_r k_0^2 - \frac{4\omega^2\varepsilon_0^2\varepsilon_r^2}{\sigma(\omega)^2}} \tag{1}$$

Where ε_0 is the vacuum permittivity, ε_r is the relative permittivity of the medium surrounding the graphene sheet, and $k_0 = \frac{\omega}{c}$.
In order to obtain a clearer expression for β, we assume that the $\varepsilon_r k_0^2$ term in Eq. 1 is negligible (GPs are extremely confined modes with $\beta \gg \varepsilon_r k_0^2$), which is the case for the

frequency range we consider here. The dispersion relation is

$$\beta = \frac{2i\omega\varepsilon_0}{\sigma(\omega)}\varepsilon_r \tag{2}$$

This relation can be used to derive various characteristics of GPs, such as their confinement in the direction perpendicular to the graphene sheet or their propagation length $L = \frac{1}{2|\Im(\beta)|}$. One can see that the propagation length becomes infinite if the imaginary part of the propagation constant $\Im(\beta)$ vanishes. In the next section we explain how this can be achieved using a gain medium surrounding the graphene sheet.

Critical gain in 1D structures

We now show how losses due to graphene can be entirely compensated using a gain medium surrounding the graphene sheet. We assume that the gain medium is described by its relative permittivity $\varepsilon_r = \varepsilon_R - i\varepsilon_I$. With this convention, a medium with $\Im(\varepsilon_r) > 0$ is a gain medium.
Using Eq. 2, one finds that $\Im(\beta) = 0$ (and thus an infinite propagation length) for $\varepsilon_{I\text{crit}}$ satisfying :

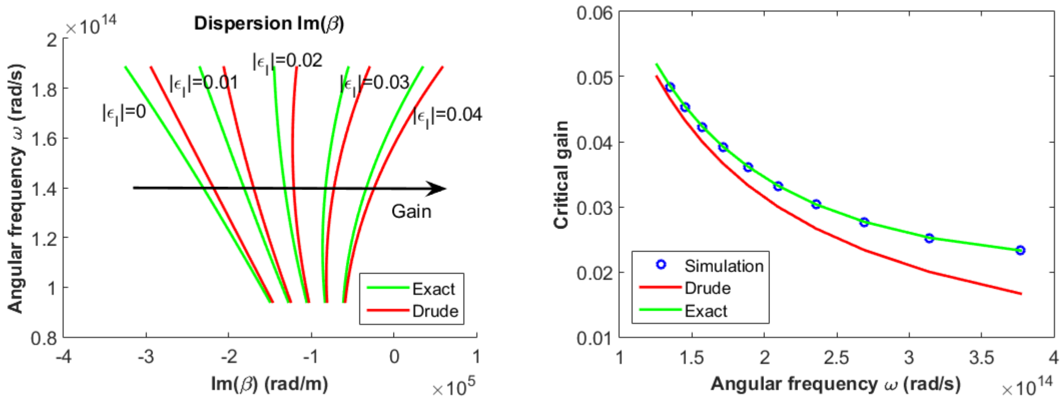
$$\varepsilon_{I\text{crit}} = \varepsilon_R \frac{\Re\left[\sigma(\omega)\right]}{\Im\left[\sigma(\omega)\right]} \tag{3}$$

To get further insight into the parameter dependencies hidden by $\sigma(\omega)$ in Eq 1, we use the Drude approximation for graphene [2] :

$$\sigma_{\text{Drude}}(\omega) = \frac{e^2 E_F}{\pi\hbar^2}\frac{-i}{\omega - i\tau^{-1}} \tag{4}$$

Here E_F is the Fermi energy and τ^{-1} is the relaxation time of electrons in graphene. Injecting Eq. 4 into Eq. 1, one finds :

$$\Im(\beta) = \frac{2\varepsilon_0\pi\hbar^2}{e^2 E_F}\left(-\varepsilon_I\omega^2 - \varepsilon_R\tau^{-1}\omega\right) \tag{5}$$



(a) (b)

Figure 1: (a) Comparison between Eq. 1 (green) and Eq. 5 (red). The dispersion curve goes towards positive values when gain is added. (b) Comparison between Eq. 3 (green) and Eq. 6 (red) and finite-element simulations (blue dots).

The dispersion relation of $\Im(\beta)$ is represented for several values of gain $|\varepsilon_I|$ in Figure 1a where one can see that for a sufficient value of gain, $\Im(\beta)$ becomes positive and GPs propagate without losses. The condition $\Im(\beta) = 0$ is achieved for a particular value of gain :

$$\varepsilon_{I\text{crit}} = \frac{-\varepsilon_R}{\omega\tau} \tag{6}$$

Figure 1b shows the comparison between Eq. 3 and Eq.6. While the exact model describes precisely the simulation results, the Drude approximation is not perfect, but is useful to show parameter dependencies more clearly.

Resonant gain in 2D graphene ribbons

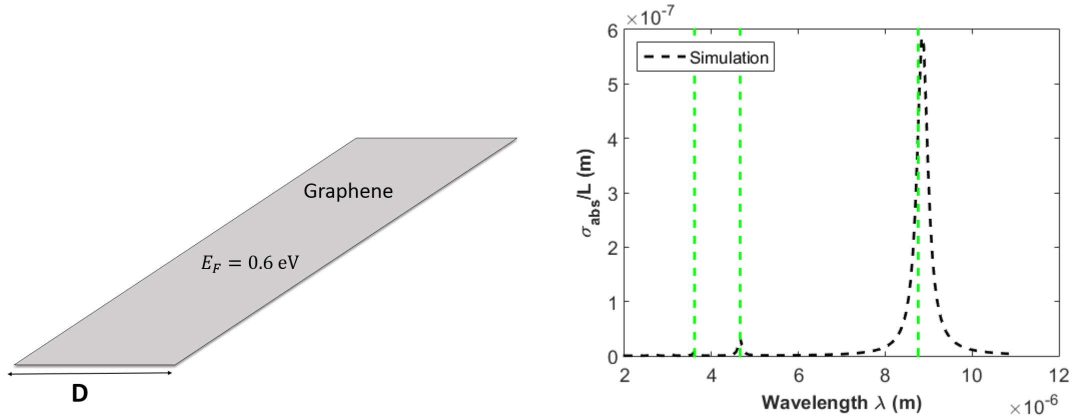
Now we consider 2D graphene ribbons of width D (Figure 2a). A stationary mode in the transverse direction can only exist if the following condition is fulfilled:

$$2\beta D + 2\Phi_R = 2\pi m \tag{7}$$

Where β is the propagation constant from Eq. 1, $\Phi_R = -0.75\pi$ is the non-trivial phase reflection at the edge of the ribbon [3] and m is the mode order. Using this simple model we can predict the resonance frequencies of the ribbon given by:

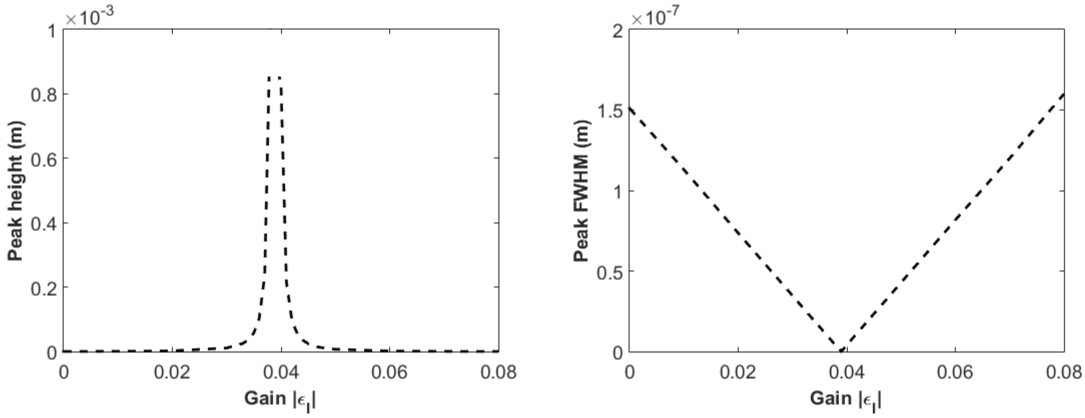
$$\omega = \frac{\pi(m+0.75)\Im\left[\sigma(\omega)\right]}{2\varepsilon_0\varepsilon_r D} \tag{8}$$

We carried out finite-element simulations and simulated the extinction cross section of the graphene ribbon. Results are shown in Figure 2b and peak positions are in good agreement with the results predicted by Eq. 8.



(a) (b)

Figure 2: (a) Graphene ribbon and notation used. (b) Extinction spectrum of graphene ribbons without gain medium for $D = 200$ nm and $E_F = 0.6$ eV. Vertical green dashed lines represent the peak positions predicted by Eq. 8



(a) (b)

Figure 3: (a) Extinction peak height. (b) Extinction peak width.

We then introduce gain surrounding the graphene ribbons. We compute the characteristics of the extinction peaks as a function of $|\varepsilon_I|$ (Figure 2b shows these peaks with no gain medium). We find that for a specific value of gain, the extinction cross section is considerably enhanced as shown in Figures 3a and 3b. The value of this resonant gain can be estimated by considering the polarizability of graphene ribbons [4] and imposing that both real and imaginary parts vanish.

Conclusion

We studied how the introduction of a gain medium surrounding graphene can lead to complete compensation of graphene-induced losses for surface plasmon modes in graphene sheets. We then showed how the extinction cross-section of graphene ribbons can be enhanced considerably by tuning the gain around these ribbons.

Acknowledgement

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