Graphene plasmonics: Tunable coupling with nano-cavities

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Since graphene supports low loss surface plasmon polaritons (SPPs) in the infrared range, we theoretically investigate the coupling of the SPPs in patterned sheets with nano-cavities. By using the finite-element method, we illustrate SPP propagation in filter-type circuits. Resonant frequencies are observed as a dip in the reflection spectrum, and fully described by the coupled mode theory. The shift of frequency is easily obtained by tuning the doping of graphene (e.g. via voltage tuning). We can reach quality factors up to 42 for cavities of 20nm length around 5µm wavelength. This may pave the way towards ultra-compact optoelectronic devices.

Introduction

Graphene has a lot of interesting properties in various domains, but we will focus here on its optical properties in the near-infrared range of frequencies. The plasmonic modes of graphene has already been theoretically and experimentally studied, and some applications were pointed out [1]. For example, propagating plasmons in nano-ribbons were investigated in [2] and directional couplers were designed in [3].

Here we present a filter-type circuit based on graphene nano-cavities. By means of the finite-element method (COMSOL), we compute the reflection of a surface plasmon polariton (SPP) along a 2D ribbon. We observe deep dips in the reflection spectrum and an easy tuning of the resonant frequency. This remarkable circuit application comes from the specific properties of graphene.

Materials and method

The two dimensional system is composed of a semi-infinite nano-ribbon of graphene (waveguide) and a small ribbon (cavity) of length W_c at distance d from the first one (Figure 1). The background medium is air with $n_{air} = 1$. Graphene is modelled as a thin layer of $t = 0.5$nm thickness with the edges rounded by semicircular profiles to avoid large field in the corners. The material is characterized by a dielectric function $\varepsilon(\omega) = 1 + 4\pi i\sigma/\omega t$. We use the surface conductivity $\sigma(\omega, E_F)$ obtained via the Kubo-Greenwood formulation [4] where ω is the light angular frequency and E_F is the Fermi energy relative to the Dirac points, which can be chemically or electrostatically tuned. The relaxation time of scatterers in graphene is fixed to 10^{-12}s.

The plasmonic mode is excited along the first ribbon and the reflection is measured. On the right part of Figure 1, the normalized H_z field is plotted at a resonant frequency and we observe high concentration of the field in the cavity.

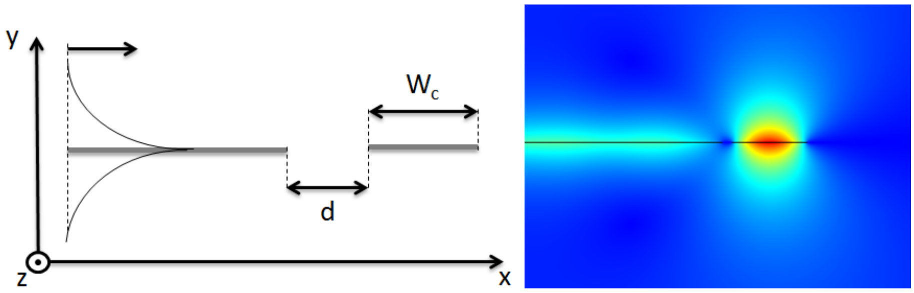

Figure 1: 2D structure studied, the plasmonic mode is excited on the graphene ribbon along the x-direction (left). $|H_z|$ field of a resonance for $E_F = 0.3eV$ and $\lambda = 7.95\mu$m (right).

Coupled Mode Theory (CMT)

The resonances in the reflection spectrum can easily be described by the Coupled Mode Theory (CMT) [5]. This is based on a development of the solution in eigenmodes. The cavity mode is characterized by a waveguide coupling lifetime τ_c, an absorption lifetime τ_a and a radiation lifetime τ_r. We find for the reflection

$$R(\omega) = R_{wg} \frac{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_a} - \frac{1}{\tau_c} + \frac{1}{\tau_r}\right)^2}{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_a} + \frac{1}{\tau_c} + \frac{1}{\tau_r}\right)^2} \tag{1}$$

where ω_0 is the resonant frequency and R_{wg} is the reflection without the cavity. Since lifetimes are supposedly independent, one writes $1/\tau = 1/\tau_a + 1/\tau_c + 1/\tau_r$. It turns out we can neglect τ_r in regard to $\tau_c \approx \tau_a \approx 10^{-13}$s. Indeed, integrating the energy escaping the system, we find that radiation losses are less than 0.01%. In this report, the reflections are normalized and we plot R/R_{wg}.

We can analytically model the absorption lifetime via $\tau_a = 1/v_g\Im(\beta)$ where v_g is the group velocity and β is the propagation constant of the plasmonic mode. $\Im(\beta)$ indicates the imaginary part.

Tuning graphene for tunable resonances

The results are plotted in Figure 2. The cavity has a size of $W_c = 75$nm and it is separated of $d = 10$nm from the waveguide. The doping of graphene is shifted from $E_F = 0.2$eV to $E_F = 0.5$eV and we show a shift of the resonant wavelength from $\lambda = 10$ to 6μm. This can be realized by introducing a gate voltage on the graphene ribbon. Table 1 shows different fitted parameters from these spectra using Equation 1.

First of all, we observe that the theoretical absorption lifetime matches the fitted value, increasing with the doping of graphene. It can be understood considering the interband transitions in graphene. They occur above a threshold related to the Fermi energy ($2E_F$) which can be shifted to higher frequencies by larger doping [6]. That has an impact on the imaginary part of the propagation constant : doping graphene decreases its value, leading to less losses.

On the contrary, τ_c decreases when increasing doping level. Note that the coupling lifetime is tunable: it increases with the distance d (not shown) since it depends on an overlap integral of the fields.
For this configuration, a point $R = 0$ is reached only for $E_F = 0.3eV$ where $\tau_a = \tau_c$, leading to a critical coupling (see Equation 1).

The resonances can be described more analytically by the phase condition $2\Re[\beta(\omega)]W_c + 2\varphi_r = 2m\pi$ with φ_r the phase induced by the reflection at the edge of the ribbon, and m an integer. Since φ_r is relatively constant in our range of frequencies, the (first order) resonance always occurs at the same value of the propagation constant $\beta = 30.2\mu\text{m}^{-1}$. This is a consequence of the special properties of graphene : just applying a gate voltage shifts the optical properties to another range of frequencies, so this value of β is reached for a wavelength depending on doping.

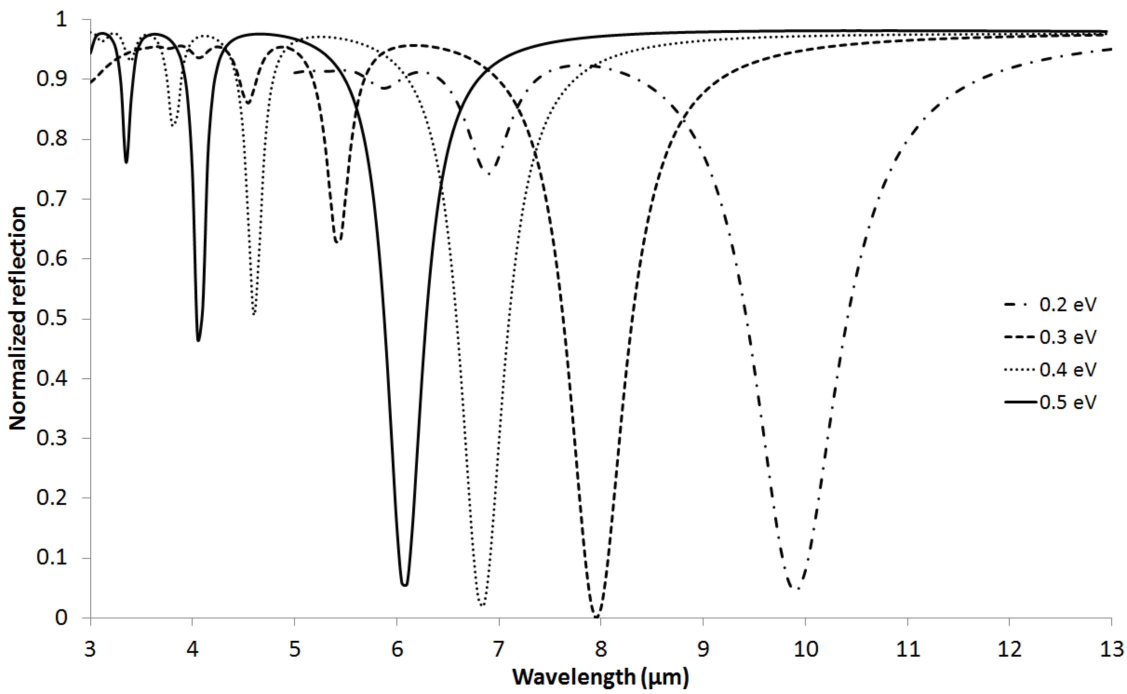

Figure 2: Normalized reflection spectrum R/R_{wg} for different doping of graphene (E_F). Three orders orders of resonances are shown for each E_F and a shift in the resonant wavelength is observed.

The second order dip is less deep than the first order one. Indeed, the coupling is less efficient, so τ_c is bigger. If we examine equation 1, in order to deepen the dip, we would have to increase τ_a, and thus decrease the losses in graphene. In the case of 0.4eV doping, the second order dip has a quality factor $Q = 15$. The value is higher than the one obtained for the first order dip (where $Q = 13$), but it is mainly due to the resonant frequency ω_0.

In order to improve the quality factor, one needs smaller cavities i.e. bigger resonant frequencies. However, going in this direction increases losses, interband transitions occurring when $\omega > 2E_F$. Thus, in order to avoid huge losses, we need to increase this threshold, doping graphene. When $E_F = 1$eV, one reaches a quality factor of $Q = 42$

Doping (eV)	Fitted				Theoretical
	τ_c (10^{-13}s)	τ_a (10^{-13}s)	ω_0 (10^{14}rad/s)	Q	τ_a (10^{-13}s)
0.2	2.6	1.7	1.9	9.2	1.7
0.3	2.0	2.0	2.4	12	2.0
0.4	1.7	2.2	2.8	13	2.3
0.5	1.5	2.3	3.1	13	2.4

Table 1: Result table of the fitted lifetimes and resonant frequency ω_0 for the first order mode. Theoretical absorption lifetime is also shown. The quality factors are also computed from the fitted parameters as $Q = \omega_0/\Delta\omega_{FWHM}$.

with a cavity of $W_c = 10$nm. This occurs for $\lambda = 2.8\mu$m. It has the same order of magnitude than the quality factor of localized surface plasmon resonance of metals like silver ($Q \approx 30$) or gold ($Q \approx 10$) [7].

Conclusion

From our simulations based on the optical conductivity of graphene, we demonstrated a filter-type circuit, exited with SPPs. The resonances are fully described with CMT and tuning the resonance frequency can easily be performed by tuning the applied gate voltage on the graphene nano-ribbon. We computed a cavity of 10nm width with a quality factor of $Q = 42$ at a wavelength 2.8μm.

Acknowledgement

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