Effect of Electron Momentum Relaxation Time on the Terahertz Properties of Graphene Structures

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***Abstract*—In this work we describe the effect of the electron momentum relaxation time on the terahertz properties of periodically-patterned graphene plasmonic structures; more specifically, its effect on the quality of the characteristic plasmonic resonances. From analytical theory as well as numerical simulations, it is observed that the electron momentum relaxation time heavily affects the quality factor of these resonances. In general, for a given electron concentration level, the larger the electron momentum relaxation time the larger the quality factor at resonance.**

I. Introduction

THE terahertz spectrum has been widely explored for a broad range of applications ranging from communications to biomedicine, defense, and so on [1]. In this context, graphene based plasmonics have obtained much attention for terahertz modulation, filtering, and even detection and generation [2-9]. In this work we study the effect of electron momentum relaxation time on the response of graphene plasmonic structures.

The device structure under study corresponds to a single layer of graphene and a metallic grating, which are separated by a thin insulator layer. The grating is employed to couple terahertz radiation into the graphene [10]. The pattern dimensions, i.e. width and spacing of the metallic stripes, are much smaller than the THz wavelength. A schematic of a unit cell of the structure is depicted in Fig. 1a.

II. Discussion

First, from an analytical point of view, the effect of the electron momentum relaxation time on the quality factor of the plasma resonances is analyzed. In order to theoretically analyze the properties of this periodic structure, the transmission line formalism, described in e.g. [11-14], is employed. In this case, the plasmon dispersion can be written as [14]:

$$q = -i\sqrt{i\omega C(i\omega L + R)} \equiv \beta + j\alpha, \qquad (1)$$

where the distributed kinetic inductance $L = \tau/\sigma_{dc}$ and the resistance $R = 1/\sigma_{dc}$ arise from the Drude-like dispersion form of the graphene conductivity [15-16], and the distributed capacitance is given by $C = \varepsilon q(1 + \coth(qd))W$. In the previous expressions: σ_{dc} is the DC conductivity of graphene ($\sigma_{dc} = \tau e^2 v_F \sqrt{n_{2D}}/\sqrt{\pi}\hbar$ where v_F is Fermi velocity, in graphene $v_F \approx 10^6 m/s$, n_{2D} is the graphene electron density, $\hbar$ is the reduced Planck constant, and e is the electron charge), d is the barrier thickness, and τ is the electron momentum relaxation time. The real part of the plasma wave vector is related to the frequency of resonance; and, the quality factor (Q) for plasmons at the frequency of resonance can be evaluated from: $\mathrm{Q} = \beta/2\alpha$, where β and α are defined by Eqn. (1).

Numerical simulations were obtained employing a 3D electromagnetic solver: High Frequency Structure Simulator (HFSS) by ANSYS for the structure depicted in Fig. 1 employing different values for the electron momentum relaxation time in accordance with the discussion in e.g. [5-6]. In our simulations, the graphene layer, was modeled employing a finite thickness (one nanometer) following the procedure employed in [17-20]. Its conductivity and permittivity were set following a Drude-like behavior. Periodic boundary conditions were set in the lateral directions of the unit cell.

Both, evaluation of Eqn. (1) as well as numerical simulations of the plasmonic structures shows that: *the plasmonic resonance and its quality factor Q is commonly limited by the electron momentum relaxation time thus scattering by impurities and phonons during the propagation of plasma waves in the graphene layer.*

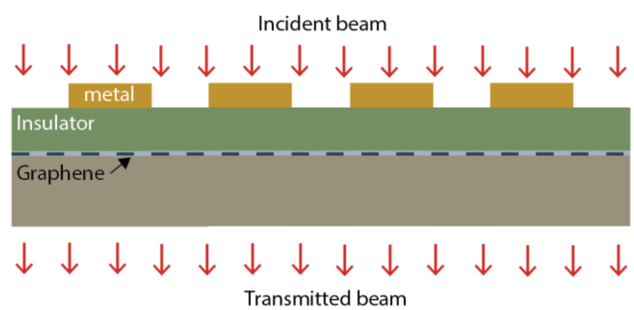

Fig. 1. Sketch of the analyzed graphene plasmonic structure.

III. Results

Figure 2(a) and (b) shows the calculated plasmonic resonance frequency as well as the quality factor as a function of the electron momentum relaxation time in accordance to Eqn. (1), respectively. In the calculations, the electron concentration is set to 0.5×10^{12} cm^{-2}. The insulator layer is modeled with a 30 nm thickness and a relative permittivity of $\varepsilon = 4$, and the unit cell length and metal grating width were set to 0.5 µm and 0.25 µm, respectively. Under this particular case, the calculated frequency of resonance is approximately 1.8 THz and is almost independent of the electron momentum relaxation time in the range 0.1 to 10ps, which correspond to the extremes of the typically achievable range for τ in graphene, as shown in Fig. 2(a).

At resonance, the quality factor is evaluated for different values of momentum relaxation time and its effect is depicted in Fig. 2(b). The quality factor is proportional to the momentum relaxation time. As the quality factor increases, the transmission minima observed at resonance becomes sharper, which is pictured in the numerical simulation results depicted in Fig. 3. It is observed that the quality factor of the resonance for cases where the momentum relaxation time is on the order of femtoseconds become highly degraded. This can be explained due to the high attenuation, α, of the excited plasma wave as it propagates in the graphene sheet.

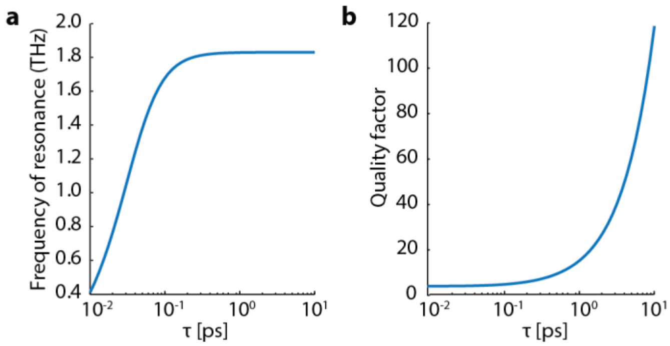

Fig. 2. (a) Plasmonic resonance frequency, and (b) quality factor, as a function of electron momentum relaxation time for a fixed electron concentration. Parameters: unit cell size = 0.5 µm, metal width = 0.25µm, d = 30 nm, $\varepsilon = 4\varepsilon_0$.

In order to obtain the transmission spectra and evaluate the behavior of these structures as the momentum relaxation time is varied, we performed full-wave electromagnetic simulations for the device geometry described in Fig. 1. Figure 3 shows the simulated transmission spectra obtained employing HFSS for different values of electron momentum relaxation time (75fs to 10ps). The observed trend follows the analytical trend discussed in Fig. 2; as electron momentum relaxation time is increased the resonance becomes sharper, which is a signature of a superior Q as analyzed in Fig. 2(b). Moreover, the resonance slightly red-shifts as τ is increased in accordance with what is observed in Fig. 2(a). The fact that the resonances occur at lower frequency than what is depicted in Fig. 2(a) is a result of a different dielectric surrounding environment. In this regard, is worth mentioning that for the simulations depicted in Fig. 3, a 2µm thick polyimide substrate was assumed.

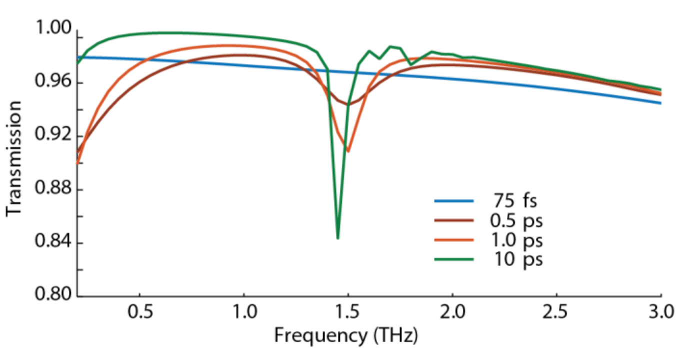

Fig. 3. Simulated transmittance versus frequency for different electron momentum relaxation times for the structure depicted in Fig.1. A 2 µm polyimide substrate was employed in this simulation.

IV. Summary

In conclusion, we have studied the effect of the electron momentum relaxation time on the terahertz properties of periodically-patterned graphene plasmonic structures. Analytical theory as well as computational simulations were performed showing that for a fixed electron concentration the electron momentum relaxation time heavily affects the quality factor of these resonances. In general, for a given electron concentration level, the larger the electron momentum relaxation time the larger the quality factor. In order to experimentally achieve such performance high quality graphene samples, e.g. graphene in BN, should be employed.

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