TERAHERTZ SHIELDING EFFECTIVENESS AND OPTICAL TRANSMITTANCE OF GRAPHENE MULTILAYER THIN SHEETS

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Advanced short range wireless communication systems will be based on the use of a larger bandwidth than the ones of current systems, thus exploiting the frequency range from 300 GHz up to 3 THz [1], [2]. Standardization and regulation activities of the IEEE 802.15 IG THz deal with wireless systems operating at 300 GHz and beyond. Terahertz communication technologies require innovations in materials and processes for EMI optimal control in the THz regime. Single-wall carbon nanotube films have been investigated in the far infrared region as substitutes for metallic films in various applications. A more attractive choice for EMI shielding applications is offered by graphene, which is characterized by planar structure, excellent electrical and optical properties, thermal conductivity, high current density, mechanical flexibility, and immunity to electromigration [3]-[6].

A new research project was carried out to propose new models for the analysis of the shielding effectiveness of graphene multilayer thin films in the lower THz range taking into account the frequency dependence of the electrical conductivity. Graphene-coated transparent substrates are also considered. Moreover, already known models have been applied to estimate the optical transmittance. The modeling approach was used to the performance analysis of graphene-based thin sheets in the frequency range up to 1 THz.

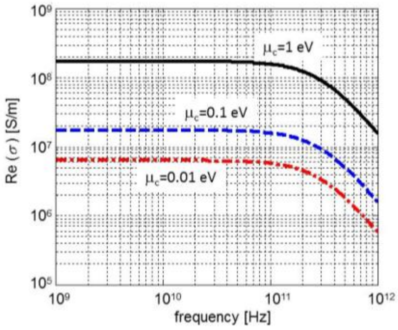
The dynamical 2D conductivity of graphene can be expressed from the Kubo's formula in the THz frequency range and below, where the interbands contributions are negligible. The following form, which coincides with the Boltzmann-Drude's expression, describes the conductivity due to intraband transition of a moderate doped graphene:

$$\sigma_{\text{intra}}^{2\text{D}}(\omega) = \frac{\sigma_0^{2\text{D}}}{1 + j\omega\tau} \tag{1}$$

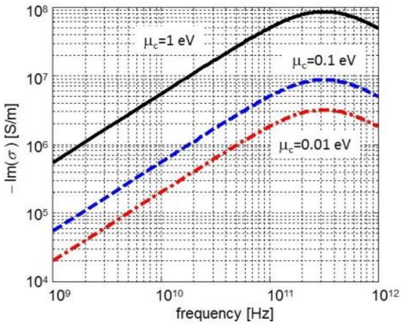
in which ω is the radial frequency, τ is the scattering time, and $\sigma_0^{2\text{D}}$ is the 2D-dc conductivity of the monolayer. In general, $\sigma_0^{2\text{D}}$ is a function of the chemical potential μ_c, of the room temperature T and of τ. The 3D frequency dependent conductivity is given by the Drude's model:

$$\sigma(\omega) = \frac{\sigma_0}{1 + j\omega\tau} \tag{2}$$

in which the 3D-dc conductivity σ_0 is estimated as $\sigma_0^{2\text{D}}(\mu_c, T, \tau)/\delta$, δ being the inter-graphene distance. Fig.1 shows the frequency spectra of the real and imaginary parts of $\sigma(\omega)$ for different values of μ_c at T=300 K. The negative value of the imaginary part enables TM surface wave propagation in the multilayer graphene sheet.



(a)



(b)

Fig.1.Frequency spectra of the real- (a) and negative imaginary-(b) part of the 3D conductivity for different values of the chemical potential μ_c, being scattering time τ equal to 0.5 ps.

In the near-infrared and visible wavelength ranges (400 nm – 2500 nm), the photon energy is large enough to induce interband transitions. Above approximately 10 THz the quantum-dynamical interband term, which appears in the Kubo's formula, makes a not negligible contribution to the conductivity and must be included in the calculation. The real part of the dynamical conductivity due to such interband transitions can be expressed in the following form:

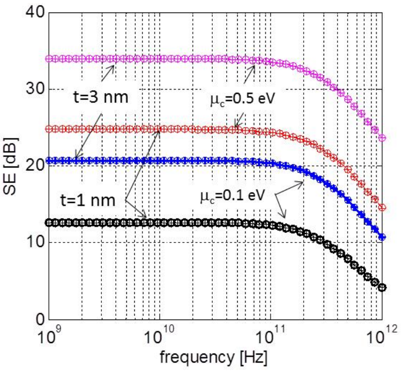


Fig.2. Frequency spectra of the shielding effectiveness for different values of thickness t and chemical potential μ_c, being τ = 0.5 ps

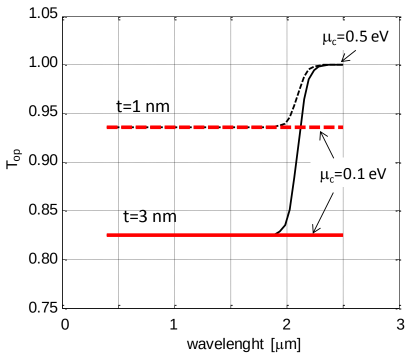


Fig.3. Optical transmittance as function of the wavelength for different values of thickness t and chemical potential μ_c.

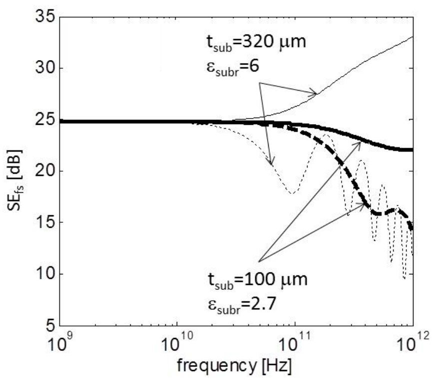


Fig.4. Frequency spectra of the SE_{fs} of polycarbonate (t_s =100 μm)- or glass (t_s =320 μm)-substrate coated by graphene multilayer sheet with t=1 nm.

$$\sigma_{\mathrm{inter}}^{2\mathrm{D}}(\omega)=\frac{\pi e^2}{4h}\left[\tanh\left(\frac{\hbar\omega+2\mu_{\mathrm{c}}}{4TK_{\mathrm{B}}}\right)+\tanh\left(\frac{\hbar\omega-2\mu_{\mathrm{c}}}{4TK_{\mathrm{B}}}\right)\right] \tag{3}$$

The imaginary part of the conductivity in the optical wavelength can be ignored due to the small overall absorption. The 3D-optical conductivity $\sigma_{\mathrm{op}}(\omega)$ can be obtained from the 2D-one divided by δ, like for $\sigma(\omega)$.

Graphene can be randomly stacked to realize N-layer graphene thin sheet, with N<10. In the following, the multilayer graphene thin sheet is regarded as a homogeneous and isotropic material with thickness $t=N\delta$. The shielding effectiveness SE is defined as:

$$SE = 20\log\left|\frac{E^{\mathrm{i}}}{E_{\mathrm{t}}}\right| = 20\log\left|T^{-1}\right| \tag{4}$$

in which T is the sheet transmission coefficient, given by the ratio of the transmitted- to the incident-electric fields, E_{t} and E^{i}, respectively. Transmission coefficient is obtained by using the transmission line approach for thin sheet [8], [9]. According to the Beer-Lambert law, the optical transmittance $T_{\mathrm{op}}(\omega)$ of a homogeneous film with thickness much smaller than the light wavelength (400 nm – 2500 nm) is given by:

$$T_{\mathrm{op}}(\omega)=\left(1+\frac{\eta_0\sigma_{\mathrm{op}}(\omega)\,t}{2}\right)^{-2} \tag{5}$$

Let's consider a graphene multilayer thin sheet with thickness t equal to 1 nm or 3 nm, chemical potential μ_{c} equal to 0.1 eV or 0.5 eV, and relaxation time τ=0.5 ps. Fig.2 shows the obtained frequency spectra of the shielding effectiveness. The optical transmittance is estimated as function of the wavelength for sheet thickness equal to 1 nm or 3 nm and μ_{c} equal to 0.1 eV or 0.5 eV. The computed frequency spectra are represented in Fig.3.

Next, let's consider a transparent substrate coated by the graphene multilayer sheet with thickness t =1 nm, relaxation time τ=0.5 ps and chemical potential μ_{c}=0.5 eV. Fig.4 shows the computed frequency spectra for polycarbonate substrate with t_{s} = 100 μm, $\varepsilon_{\mathrm{sr}}$=2.7 and glass substrate with t_{s} = 320 μm, $\varepsilon_{\mathrm{sr}}$=6 and n_{s}=1.517, by using rigorous formulation (dotted line) and short-line hypothesis (continuous line). The proposed modeling approach highlights the strong dependence of the shielding effectiveness on the chemical potential μ_{c} and relaxation time τ of the graphene multilayer sheet. The third important parameter in the shielding design is the graphene film thickness t, which produces opposite effects on the shielding effectiveness and the optical transmittance.

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