Optical Properties of Graphene on Quartz and Polyethylene Substrates in Terahertz Frequency Range

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Abstract— We report measurements of the real and imaginary part of the optical properties of graphene (refractive index, permittivity, conductivity, penetration depth) in the far-infrared region from 0.1 to 1.2 THz at the temperature of 300 K.

1. INTRODUCTION

Last years graphene increasingly attracts attention of scientists by unusual properties such as high electric and thermal conductivity etc. [1]. Also terahertz (THz) radiation has tremendous potential for applications in imaging, medical diagnosis, health monitoring, environmental control, chemical & biological identification, security infrastructure, military industry. So to use graphene in terahertz optics it would be useful to know dispersion of graphene optical properties, such as refractive index $n(\omega)$, optical conductivity $\sigma(\omega)$ etc.. The purpose of this paper is to experimentally obtain optical properties of graphene in the frequency range of 0.1–1.2 THz.

2. SUBJECT OF RESEARCH

In this research we used dielectric substrates (polyethylene terephthalate (PET), quartz) that are transparent for terahertz radiation, have low absorption coefficient in terahertz frequency range [2, 3]. Also it is possible to transfer the graphene layer on these substrates surface. PET substrate thickness is $d_p = 175\,\mu\text{m}$; the quartz substrate thickness is $d_q = 500\,\mu\text{m}$. The theoretical thickness of graphene is $d_g = 0.345\,\text{nm}$, the grain size is up to $10\,\mu\text{m}$ (Graphenea company). The bare substrates and graphene layer on these substrates are used in the experiment. The sample holder is demonstrated in Figure 1.

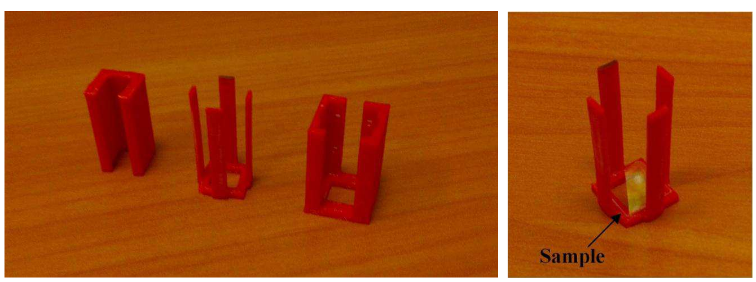


Figure 1: Sample holder.

3. EXPERIMENTAL SETUP

FL-1 — laser of femtosecond pulses, M — mirrors, BS — beam splitter, DL – optical delay line, G — generator of THz radiation based on the crystal InAs, PM — parabolic mirrors, TL — lenses for THz radiation, f — filter of infrared (IR) radiation, TP — translucent silicon plate, Ch — chopper, EOC — electro optical crystal of CdTe, W — Wollaston prism, BP — balanced photodiodes, LA — lock-in amplifier, ADC — analog-to-digital converter, PC — personal computer.

The scheme of THz spectrometer is shown in Figure 2. The laser beam is splitted by two ones in the ratio of 10% to 90%. 10% energy is probe beam, 90% one is pump beam. The pump beam optical path is controlled by optical delay line. The pump beam is modulated by chopper at the frequency of 667 Hz. The generator of THz radiation is based on the crystal InAs in the magnetic system. After passing through IR radiation filter THz beam incidents on the sample. Then, THz radiation induces birefringence in electro-optical crystal. Wollaston prism splits the probe IR beam on two ones with orthogonal polarization, which are detected by balanced photodiodes. Parameters of THz spectrometer: the pump pulse power of 1 W, the pump pulse duration of 200 fs,

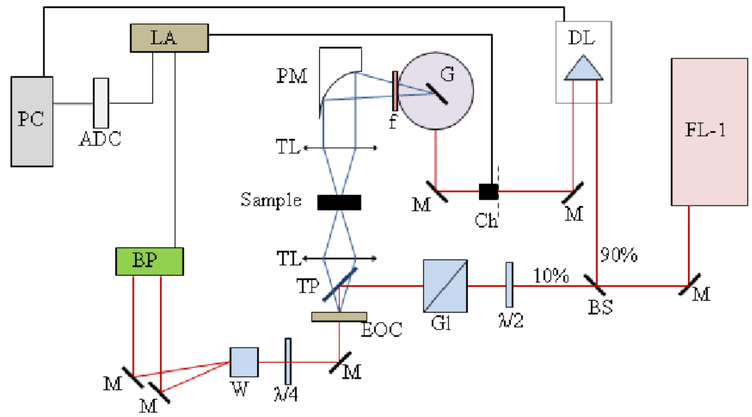
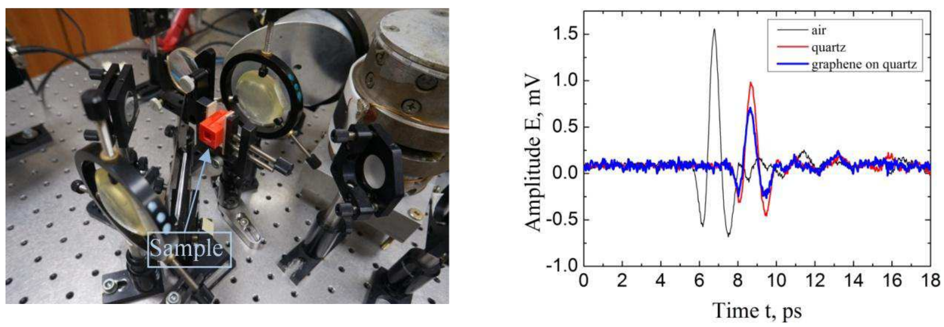


Figure 2: Scheme of the time-domain THz spectrometer in transmission mode.

the frequency range of 0.1–1.2 THz, the average THz radiation power of 30 µW. Photo of the setup and the typical time-domain waveforms are shown in Figure 3.



(a) (b)

Figure 3: (a) Photo of time-domain THz spectrometer in transmission mode and (b) typical waveforms of THz pulses.

4. EXPERIMENT RESULTS

The dispersion of substrates complex refractive indices were extracted by comparing the signal spectrum with the reference spectrum using the transmission method described in [4]. The complex refractive indices of PET and quartz for the frequency range of 0.1–1.2 THz were shown in Figure 4.

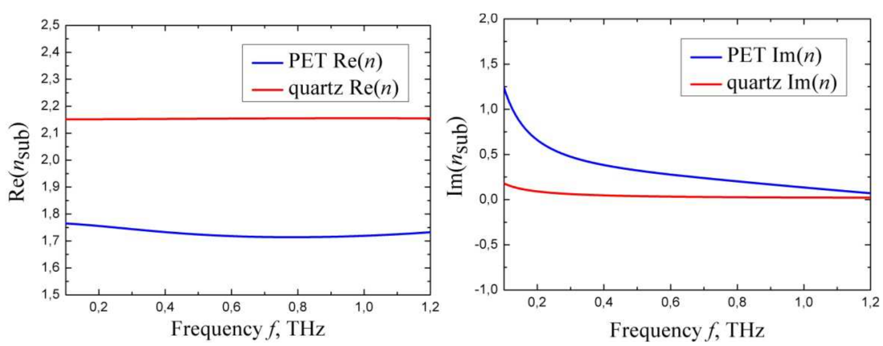


Figure 4: Complex refractive index $\hat{n}_{sub}(\omega)$ of substrates.

The graphene monolayer complex conductivity $\hat{\sigma}(\omega)$ was calculated from the equation [5]:

$$\hat{\sigma}(\omega) = \frac{\left[\frac{(\hat{n}_{sub}(\omega)+1)\hat{E}_0(\omega)}{\hat{E}(\omega)} - \hat{n}_{sub}(\omega) - 1\right]}{Z_0}, \quad (1)$$

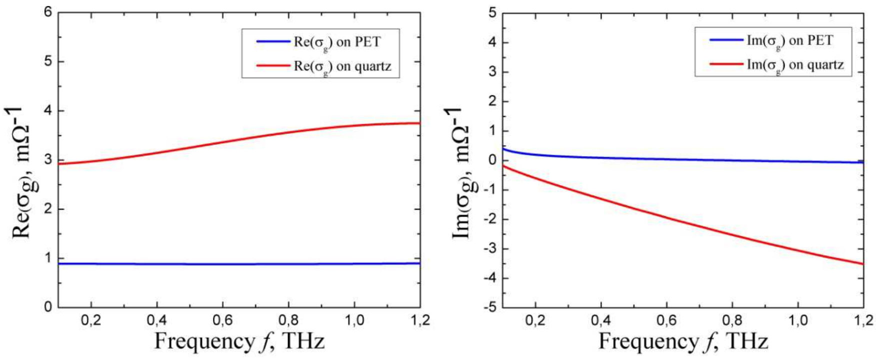


Figure 5: Graphene monolayer complex conductivity $\hat{\sigma}_g(\omega)$.

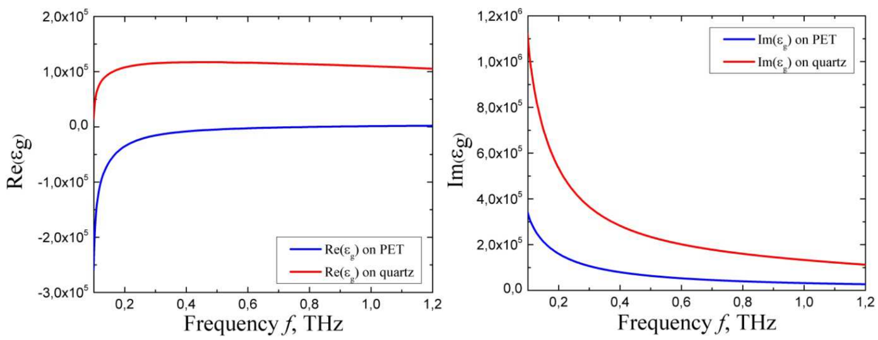


Figure 6: Graphene complex permittivity $\hat{\varepsilon}_g(\omega)$.

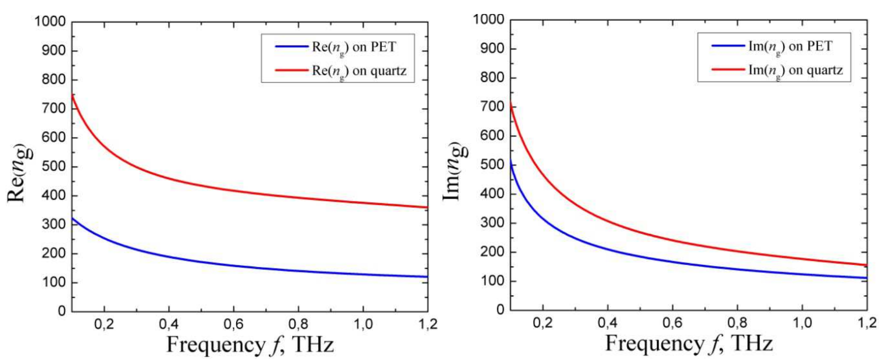
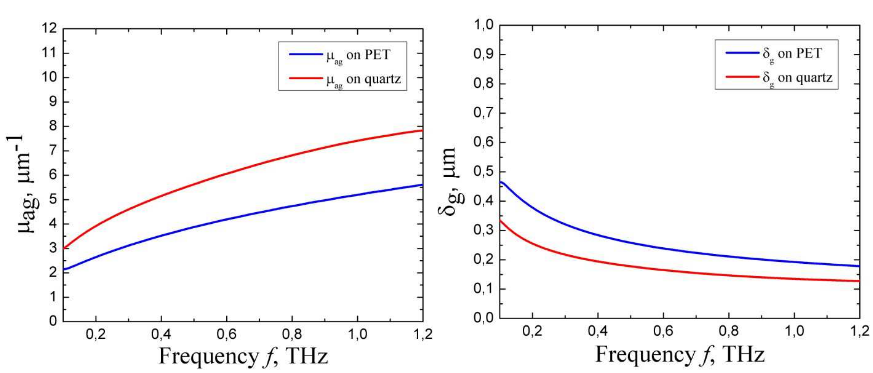


Figure 7: Graphene complex refractive index $\hat{n}_g(\omega)$.



(a) (b)

Figure 8: Graphene (a) absorption coefficient $\mu_{ag}(\omega)$ and (b) penetration depth $\delta_g(\omega)$.

where $\hat{E}_0(\omega) = E_0(\omega) * e^{i\varphi(\omega)}$ is the complex electric field amplitude of THz wave transmitted through the bare substrate; $E(\omega)$ is the complex electric field amplitude of THz wave transmitted through the substrate with the graphene monolayer; $\hat{n}_{sub}$ is the complex substrate refractive index; $Z_0 = 377\,\Omega$ is the impedance of free space. $E_0(\omega)$ and $E(\omega)$ were obtained by Fourier transformation of the time-domain waveforms of THz pulses.

Using the Equation (1) and the substrates complex refractive indices data we can obtain the complex conductivity $\hat{\sigma}_g(\omega)$ of the graphene monolayer for the frequency range of 0.1–1.2 THz (Figure 5).

Then, the graphene complex permittivity $\hat{\varepsilon}_g(\omega)$ can be obtained from the following equation [6]:

$$\hat{\varepsilon}_g(\omega) = 1 - i\frac{\hat{\sigma}_g(\omega)}{\omega\varepsilon_0 t_g}, \tag{2}$$

where ε_0 is dielectric constant; $t_g \approx 0.345$ nm is the graphene monolayer thickness. The calculation results are shown in Figure 6.

The Equation (2) and the measured complex conductivity $\hat{\sigma}_g(\omega)$ allows to obtain several optical graphene properties, such as the complex refractive index $\hat{n}_g(\omega)$, the absorption coefficient $\mu_{ag}(\omega)$ and the penetration depth $\delta_g(\omega)$. The complex refractive index $\hat{n}_g(\omega)$ is shown in Figure 7 for various substrates.

The imaginary part of $\hat{n}_g(\omega)$ allows to calculate the graphene monolayer absorption coefficient $\mu_{ag}(\omega)$ by the next formula:

$$\mu_{ag}(\omega) = \frac{4\pi n''_g(\omega)}{\lambda}, \tag{3}$$

where $n''_g(\omega)$ is the imaginary part of $\hat{n}_g(\omega)$, λ is the wavelength of THz radiation.

The penetration depth $\delta_g(\omega)$ was calculated as $1/\mu_{ag}(\omega)$.

5. CONCLUSION

In this paper, experimentally graphene monolayer general optical parameters for the frequency range 0.1–1.2 THz (the complex conductivity $\sigma_g(\omega)$, the complex permittivity $\varepsilon_g(\omega)$, the complex refractive index $n_g(\omega)$, the absorption coefficient $\mu_{ag}(\omega)$ and the penetration depth $\delta_g(\omega)$) were obtained. This experimental data may be used in practical purposes, that are respective to graphene application.

ACKNOWLEDGMENT

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