Investigation of Terahertz Radiation Generation on Optically Pumped Monolayer Graphene

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***Abstract*—in this paper the experimental investigation of conductivity variation of monolayer graphene on polyethylene terephthalate and quartz substrates using optical pumping by continuous radiation wavelength of 980 nm and pumping power up to 350 mW is demonstrated. The experiments were carried out on terahertz time-domain spectrometer. Conductivity changing is caused by variation of Fermi level and heating by continuous pumping radiation. Negative monolayer graphene conductivity was obtained on quartz substrate.**

***Index Terms*—terahertz radiation, graphene, terahertz time-domain spectroscopy**

I. INTRODUCTION

Terahertz (THz) radiation is electromagnetic radiation in the frequency range from $0.1\cdot10^{12}$ to $10\cdot10^{12}$ Hz. This frequency range lies between infrared (IR) and microwave electromagnetic spectrum, so sometimes THz frequency range is called far-infrared or submillimeter wavelength region. Also, the THz range covers in the energy range for molecular rotation of polar molecules and librations of macromolecules. This means that using THz radiation we can identify different chemical (explosive) and biological materials. Moreover, terahertz radiation is transparent for various plastic, clothes and paper, that is allowed to detect hidden objects. So, terahertz radiation is actively used in security systems, spectroscopy, biomedical imaging, and industrial production processes.

For a long time terahertz radiation was inaccessible for scientists and engineers, because terahertz emitters and detectors were absent. But for the last decades researchers constructed this type generators and detectors and led off terahertz devices, what is significant step for terahertz optics development. Nowadays, one of the topic ideas of terahertz generator development is terahertz emitters based on graphene.

In this paper a possibility of terahertz radiation generation by monolayer graphene on polyethylene terephthalate (PET) and quartz substrates using optical pumping was experimentally considered by obtaining of negative graphene conductivity. The experiments were carried out on terahertz time-domain spectrometer.

II. EXPERIMENTAL SETUP AND SAMPLES

In this research we used dielectric substrates (polyethylene terephthalate (PET), quartz) that are transparent for terahertz radiation and have low absorption coefficient in terahertz frequency range. Also we used the bare substrates that have the same thickness with samples with graphene.

The experimental THz TDs is shown in Figure 1.

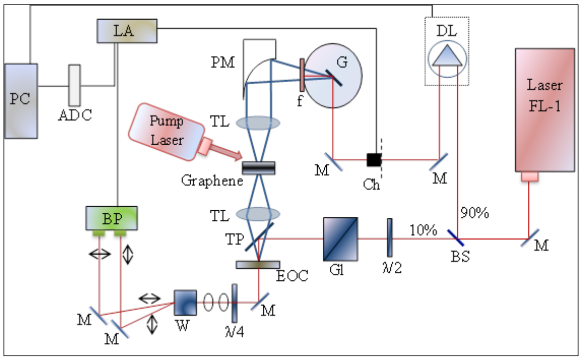

Fig.1. Scheme of the time-domain THz spectrometer. Detailed setup description is provided in [1].

For pumping continuous wave laser ATC-S8-F200 was used. Pump radiation incidents on graphene by 45° angle. The pump wavelength is 980 nm and pumping power was up to 350 mW. The experiments were carried out at room temperature.

III. DATA-PROCESSING OPERATION

After Fourier transform of experimentally recorded THz waveforms we obtained the complex amplitude spectrum of THz wave transmitted through the sample [2]:

$$\dot{E}(\omega) = E(\omega)e^{-i\varphi(\omega)}, \tag{1}$$

where $E(\omega)$ - amplitude spectrum, $\varphi(\omega)$ - phase spectrum.

Using data from equation (1) the dispersions of real and imaginary parts of refractive indices can be calculated by following formulas:

$$n'(\omega) = 1 + \frac{[\varphi_s(\omega) - \varphi_R(\omega)]c}{d\cdot\omega}, \tag{2}$$

$$n''(\omega) = \frac{\lambda}{4\pi}\left(\frac{1}{d}\ln\frac{E_R(\omega)}{E_S(\omega)}\right), \tag{3}$$

where d is a sample thickness, φ_R and φ_s are phases of the complex amplitudes of reference and sample signals respectively, c is light speed, $E_R(\omega)$ and $E_S(\omega)$ are

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amplitude spectra of reference and sample signals respectively, λ is a wavelength.

Then, monolayer graphene complex conductivity can be calculated by the next equation [3]:

$$\dot{\sigma}_f(\omega) = \frac{[\frac{[\dot{n}_{\text{sub}}(\omega)+1]\dot{\mathrm{E}}_{\text{sub}}(\omega)}{\dot{\mathrm{E}}(\omega)} - \dot{n}_{\text{sub}}(\omega)-1]}{Z_0}, \qquad (4)$$

where $\dot{n}_{\text{sub}} = n'_{sub} + in''_{sub}$ - complex refractive index of bare substrate, $\dot{E}_{\text{sub}}(\omega)$ and $\dot{E}(\omega)$ are complex amplitude spectra for bare substrate and sample with graphene respectively, Z_0=377 Om is the impedance of free space.

It is worth noting, the complex permittivity can be obtained from the following equation:

$$\dot{\varepsilon}_f(\omega) = 1 + i\frac{\dot{\sigma}_f(\omega)}{\omega\varepsilon_0 t_f}, \qquad (5)$$

where ε_0 is the dielectric constant, t_f is a thin (graphene) thickness. So, as seen from the equation (5) if the real part of graphene conductivity is becoming negative, the imaginary part of permittivity is becoming negative too, that means generation process instead absorption.

IV. RESULTS

In the Figure 2 the real part of conductivity of monolayer graphene on PET substrate under the influence of optical radiation by various pumping power is shown.

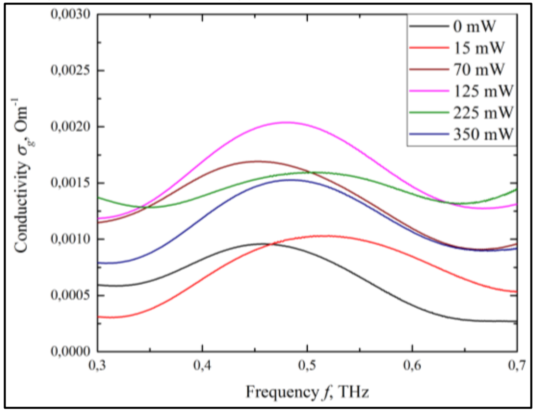

Fig. 2. Experimental spectra of monolayer graphene conductivity on PET substrate.

From Figure 2 it is seen that graphene conductivity is increasing with increasing of optical pumping power. But after 125 mW it directs toward negative values.

In Figure 3 the spectra of conductivity of graphene on quartz substrate were shown. According the paper [4] the substrate permittivity influences on graphene conductivity, so spectra of graphene conductivity on PET differentiate with spectra of graphene conductivity on quartz.

In the high frequency range graphene has negative conductivity without optical pumping. This result repeats four times in different experimental series. The explanation of the effect of negative graphene conductivity without pumping can be found in paper [4].

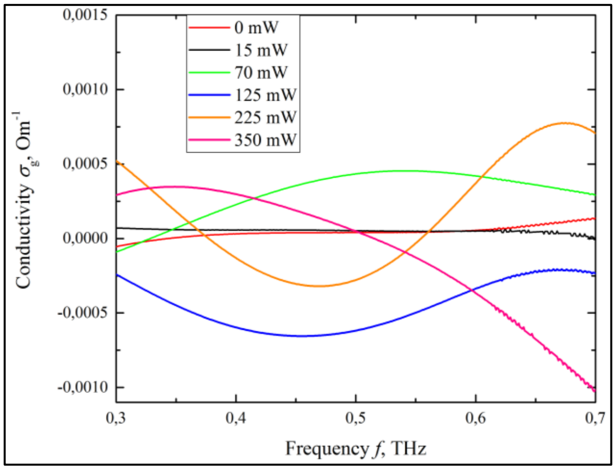

Fig. 3. Experimental spectra of monolayer graphene conductivity on quartz substrate.

As well as in PET case the conductivity of graphene on quartz substrate increases with pumping power increasing, but for 125 mW the conductivity is become negative. By growing the pumping power the conductivity is partially becoming positive, but somewhere is still negative.

V. CONCLUSION

It is shown that monolayer graphene on different substrates has diverse dynamics of conductivity value changing. Experimentally negative conductivity of monolayer graphene on quartz substrate was obtained, that means the generation of radiation in these frequency ranges. The negative conductivity on PET substrate was not obtained, but at pumping power more than 350 mW it may be possible.

VI. FUTURE PLANS AND ACKNOWLEDGMENT

In near future I plan to carry out experiments with temperature and magnetic field influence on graphene conductivity (currently, it is only at theoretical simulation stage). And due to IEEE MTT-S Undergraduate/Pregraduate Scholarship I can to complete my project. I would like to thank IEEE MTT for the opportunities that are given to students all over the world in their research projects development.

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