Graphene-based optically tunable structure for terahertz polarization control

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Abstract. We present a theoretical model of optically tunable graphene-based structure for polarization characteristics control of transmitted terahertz (THz) wave. The experimental verification was performed using a THz time-domain polarimetry setup. The tunability is achieved by applying an external optical pumping and magnetic field. The structure shows the possibility for dynamical control of ellipticity and azimuth angles of polarization state of THz radiation in a transmission mode. This study indicates a strong potential for using graphene-based structures for polarization sensitive applications such as THz wireless communications and biomedical research.

1. Introduction
In recent years, the electromagnetic properties of various two-dimensional (2D) materials, such as graphene, have been actively studied [1]. Useful feature of graphene is the possibility to dynamical control of response on to electromagnetic radiation using various external forces, especially in THz frequency range [2]. Thus, graphene offers a suitable platform for developing tunable THz devices. One of the most important directions in THz science and technology is polarimetry. It is useful tool for polarization dependent applications, such as THz wireless communications, sensing and biomedical diagnostics [3].

In this work, we theoretically demonstrate a graphene-based structure in a static magnetic field that exhibits dynamical polarization control of transmitted THz wave under external optical pumping [4]. Moreover we performed experimental verification of the theoretical findings using time-domain spectroscopic system coupling with infrared pumping laser and static magnet system.

2. Theoretical model
Graphene conductivity in a static magnetic field is described by a tensor with the following diagonal components [5]:

\[
\sigma_{xx}(\omega) = \frac{1 - i\omega\tau}{(1 - i\omega\tau)^2 + (\Omega_c\tau)^2} \sigma_0, \quad \sigma_{yy}(\omega) = \sigma_{xx}(\omega),
\]

\[(1)\]
\[
\sigma_{xy}(\omega) = -\sigma_{yx}(\omega) = \frac{\Omega_c \tau}{1 - i\omega \tau} \left(1 + \frac{(\Omega_c \tau)^2}{2}\right)^2 \sigma_0, \tag{2}
\]

Here \(\Omega_c = eBv_F/\hbar k_F\) is the orbital cyclotron frequency, \(\sigma_0 = 4e^2/(2\pi\hbar)\) is the d.c. conductivity and \(k_F = \sqrt{4\pi\Sigma}\) is the Fermi wave-number. The Fermi wave-number depends on the carrier density \(\Sigma = \Sigma_0 + \Delta\Sigma\). It can be controlled by applying external optical pumping. The azimuth \(\theta\) and ellipticity \(\eta\) angles of polarization state are determined using the ratio between the amplitudes of transmitted s- and p-polarized waves.

The resulting dependencies of azimuth and ellipticity angles of polarization state of the transmitted THz wave on magnetic field for different pumping intensities are shown in Figs. 1 and 2.

**Figure 1.** Azimuth angle of polarization state of transmitted THz wave vs. magnetic field for different continuous-wave (980 nm) optical pumping power.

**Figure 2.** Ellipticity angle of polarization state of transmitted THz wave vs. magnetic field for different continuous-wave (980 nm) optical pumping power.

### 3. Sample and experimental setup

Multilayer graphene was synthesized on the nickel substrate with a thickness of 25 \(\mu\)m by chemical vapor deposition method in quartz furnace. The substrate was etched, and graphene was transported to silicon substrate with a thickness of 1.04 \(\mu\)m (see Fig. 3 (c)).

The sample parameters were measured using THz time-domain spectrometer (in polarimetry mode) under optical pumping of infrared laser with wavelength of 980 nm \((P \approx 1 \text{ W/cm}^2)\) and in NdFeB axial magnetic field of 1.3 T. The scheme of the setup is shown in Fig. 3 (a) [6]. The photo and principal scheme of THz polarizers system (after the sample) are shown in Fig. 3 (b) and (d) correspondingly. Linearly polarized THz wave passes through the graphene sample. After that, polarization acquires the rotation and some ellipticity and transmits through the polarizer which can be rotated and static polarizer which is matched with detector crystal. By recording THz radiation spectra for two different rotation angles of the polarizer, it is possible to calculate the azimuth and ellipticity angles of polarization state of THz wave passed through the sample for various frequencies of interest.

### 4. Experimental results

To retrieve two orthogonal components of the radiation, a method based on usage of two wire-grid polarizers was applied. The processing of measurements was done using coiflet-based denoising...
Figure 3. Scheme of the experimental THz time-domain spectrometer-polarimeter (a). Photo of the polarimeter part containing the sample in magnetic field under optical pumping and using system of polarizers (b). Photo of the multilayer graphene sample on silicon substrate (c). Working principle of the polarizers system which are placed after the sample (d).

Technique and rectangular signal windowing [7], which allowed obtaining noise-free spectra in the frequency range of interest. After that, a standard technique for finding Stokes parameters was implemented [8] using the next formulas:

\[ S_0 = I = E_1^2 + E_2^2, \]  
\[ S_1 = Q = E_1^2 - E_2^2, \]  
\[ S_2 = U = 2E_1E_2 \cos \delta, \]  
\[ S_3 = V = 2E_1E_2 \sin \delta, \]

where \( E_1 \) and \( E_2 \) are amplitudes of parallel and perpendicular components of electric field, and \( \delta \) is the phase difference between them. Here we use azimuth angle \( \theta \) and ellipticity angle \( \eta \) to characterize the polarization state of transmitted wave which can be calculated using the formulas above as:

\[ \eta = \frac{1}{2} \sin^{-1} \left( \frac{S_3}{S_0} \right), \]  
\[ \theta = \frac{1}{2} \tan^{-1} \left( \frac{S_2}{S_1} \right). \]

The results of the experiment are shown in Figs. 4 and 5.
As it can be seen from the Figures, ellipticity angle changes under optical pumping, and influence of magnetic field is almost negligible. Azimuth angle noticeably changes in magnetic field, and this effect increases under optical pumping. So, these results decently fit theory at selected conditions.

5. Conclusions
In conclusion, we have theoretically demonstrated the possibility to control by optical pumping the polarization characteristics of terahertz radiation transmitted through graphene-based structure in a static magnetic field. Obtained theoretical data were decently confirmed by experimental THz time-domain polarimetry. These results may be used in THz polarization sensitive applications.

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