Polarization properties of single-walled carbon nanotube thin film on silicon substrate in terahertz frequency range

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Abstract. Terahertz time-domain spectroscopic polarimetry (THz-TDSP) method was used to study polarization properties of a randomly oriented single-walled carbon nanotube (SWCNT) thin film on a silicon (Si) substrate in terahertz (THz) frequency range under an external optical pumping (OP) and an external static magnetic field (MF). Frequency dependencies of azimuth and ellipticity angles of a polarization ellipse and the polarization ellipse at various frequencies of the Si substrate and the SWCNT thin film on the Si substrate were obtained experimentally. The results confirm the fact that, based on carbon nanotubes, it is possible to devise efficient tunable THz polarization modulators for use in the latest security and telecommunication systems.

1. Introduction
Terahertz (THz) radiation \([1]\) is widely used in physics and astronomy \([2–4]\), chemistry and medicine \([5–7]\), security and telecommunication systems \([8–10]\), and other fields of science and technology \([11–13]\).

Currently, an important area of THz photonics is study of carbon nanotubes under an external optical pumping (OP) \([14,15]\) and an external static magnetic field (MF) \([16,17]\) to devise efficient tunable THz polarization modulators based on them \([18–23]\).

THz frequencies have been proposed for security and telecommunication systems, for example, for communication between geostationary satellites. And amplitude, frequency, and polarization modulators are the basic components in this systems. Also, in THz spectroscopy, fast polarization modulators have a fundamental importance for the investigation of properties of novel materials.

One of the main methods for studying polarization and magneto-optical properties of carbon nanotubes is the THz time-domain spectroscopic polarimetry (THz-TDSP) \([24–28]\).
2. Material and Methods

The randomly oriented single-walled carbon nanotube (SWCNT) thin film on a silicon (Si) substrate and a sample of the Si substrate were studied. SWCNT thin film was synthesized on a nitrocellulose micropore filter by the catalytic ethanol-chemical vapor deposition [29] and then transferred to a Si substrate. SWCNTs diameters were calculated using the Kataura plot [30] and were 1.3–2.0 nm. SWCNTs length was visualized by the transmission electron microscopy [31] and was ∼15 µm. SWCNT film thickness was calculated from the optical absorbance at 550 nm [32] and was ∼110 nm. Si substrate thickness was ∼1 mm.

The samples were studied using the THz-TDSP system based on the THz time-domain spectrometer [33], two polarizers, 980 nm laser for creating an external OP of ∼1.0 W · cm⁻² and NdFeB axially magnetized magnet for an external static MF of ∼1.3 T. Scheme of the experimental THz-TDSP setup and pictures of the experimental samples are shown in Figure 1.

Infrared femtosecond laser beam of Yb:KYW 1040 nm laser is divided into a pump beam and a probe beam. The pump beam passes through the delay line, optomechanical modulator and falls onto the semiconductor indium arsenide crystal surface. Due to mobility of electrons in semiconductor is more than mobility of holes, thereby forming electric dipoles, which oscillate in terahertz frequency range. Constant magnetic field used for rotate dipoles and amplify terahertz radiation. Next, the THz beam is focused into a sample and two polarizers. First polarizer passes vertical component or superposition of vertical and horizontal components, depending on azimuth rotation. Second polarizer is fixed and passes vertical component only. Beams are detected by a balanced detector, which gives an analog signal of the difference in beam intensities. The received signal passes through the lock-in-amplifier and analog-to-digital converter and finally goes to the control device.

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 ellipse of the samples for various frequencies of interest.

3. Results

For each sample, temporal waveforms of the transmitted THz signals under various external influences were recorded using LabVIEW software at parallel and crossed by 45° positions to the transmission direction of the polarizers. Experimental data processing was done using MATLAB software, 4th order coiflet-based denoising technique and rectangular signal windowing [34], which allowed to obtain noise-free spectra. The windowing was done to exclude the influence of the water vapor absorption.

Frequency dependencies of the azimuth $\psi$ and the ellipticity $\chi$ angles of the polarization ellipse of the samples were calculated from the Stokes parameters [35]:

\[
S_0 = E_1^2 + E_2^2, \\
S_1 = E_1^2 - E_2^2, \\
S_2 = 2E_1E_2 \cos \delta, \\
S_3 = 2E_1E_2 \sin \delta, \\
\psi = \frac{1}{2} \sin^{-1} \left( \frac{S_3}{S_0} \right), \\
\chi = \frac{1}{2} \tan^{-1} \left( \frac{S_2}{S_1} \right),
\]

where $E_1$ and $E_2$ are amplitudes of parallel and perpendicular components of electric field vector $E$, and $\delta$ is the phase difference between them.

The results are shown in Figures 2, 3 and 4.
Figure 1. (a) Scheme of the experimental THz-TDSP setup, (b) picture of a cuvette for the experimental samples, (c) picture of the assembled experimental THz-TDSP setup, (d) picture of the Si substrate (highlighted in red), and (e) picture of the SWCNT thin film on the Si substrate (highlighted in red).

Figure 2. Frequency dependences of (a) azimuth angle $\psi$ of polarization ellipse of the Si substrate, (b) azimuth angle $\psi$ of polarization ellipse of the SWCNT thin film on the Si substrate, (c) ellipticity angle $\chi$ of polarization ellipse the Si substrate, and (d) ellipticity angle $\chi$ of polarization ellipse the SWCNT thin film on the Si substrate under external influences.
Figure 3. Polarization ellipse of the Si substrate at frequencies of (a) 0.2 THz, (b) 0.4 THz, (c) 0.6 THz, (d) 0.8 THz, and (e) 1.0 THz under external influences.
Figure 4. Polarization ellipse of the SWCNT thin film on the Si substrate at frequencies of (a) 0.2 THz, (b) 0.4 THz, (c) 0.6 THz, (d) 0.8 THz, and (e) 1.0 THz under external influences.
4. Discussion and Conclusion

The changes in the angles are the result of the magneto-optical Faraday effect. Applying MF to isotropic material cause anisotropy, and as a result a circular birefringence. Taking this into account, the vector of the transmitted linearly polarized wave is not the same as it was before the sample. The azimuth polarization angle rotation caused by Faraday effect depends on free carrier concentration, which can be increased by OP, and the value of the applied MF.

The results confirm the fact that, based on SWCNTs, it is possible to devise efficient tunable THz polarization modulators for use in the latest security and telecommunication systems.

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