Optically Driven Terahertz Wave Polarization Control by Single-Wall Carbon Nanotube Thin Film

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***Abstract*—Magneto-optic Faraday effect in unaligned single-wall carbon nanotube thin films with different geometric parameters was experimental studied in a frequency range 0.2–0.8 THz at a controlled room temperature of 291–293 K, and a relative humidity of 40–45%. A change of 15° in an azimuth angle, and of 10° in an ellipticity angle was achieved.**

***Index Terms*—terahertz time-domain spectroscopic polarimetry, unaligned single-wall carbon nanotubes, polarization control, polarization properties, Stokes parameters, Faraday effect.**

I. INTRODUCTION

EFFICIENT and affordable tunable devices for modulating the characteristics of electromagnetic (EM) waves are essential for the development of modern terahertz (THz) technologies. In this regard, one of the most important tasks of photonics is a study of advanced materials, on a basis of which it is possible to create devices with characteristics that exceed all existing analogues. A promising solution to the foregoing problem is a study of carbon nanomaterials-based structures (CNBSs) for use as a functional medium in THz modulators.

From a point of view of physics, one of the methods to control the polarization properties of the CNBSs is to use the magneto-optic Faraday effect (MOFE), and the magneto-optic Kerr effect (MOKE). Therefore, recent research is concentrated in a field of studying an influence of an external optical pumping (OP), and an external static magnetic field (MF) on the properties of carbon nanotubes (CNTs), and development of the tunable THz polarizers based on them [1]. But despite the great progress in research of CNTs, the influence of the geometric parameters of nanotubes on their optical properties in the THz frequency range has not yet been sufficiently studied.

The goal of this work was an experimental study of unaligned single-wall carbon nanotubes (U-SWCNTs) with different geometric parameters using the THz time-domain spectroscopic polarimetry (TDSP) method with an external near infrared (NIR) OP system to obtain their polarization properties.

II. MATERIALS AND METHODS

For the study, two U-SWCNTs samples with different geometric parameters were selected. The U-SWCNTs were synthesized by the chemical vapor deposition (CVD) method on a nitrocellulose micropore filter (NCMF) using ethanol gas without adding the hydrogen [2]. Then the CNTs were transferred from the NCMF onto the transparent float glass (TFG) substrates.

The diameters of CNTs were calculated using the Kataura plot and were 1.1–1.4 nm for the Sample No. 1, and 1.1–1.3 nm for the Sample No. 2. The length of the CNTs was visualized by the transmission electron microscopy and was 10–15 µm for the Sample No. 1, and 0.3–1.0 µm for the Sample No. 2. The CNTs film thickness was calculated from an optical absorbance at 550 nm and was 109.0 nm for the Sample No. 1, and 331.1 nm for the Sample No. 2. To study a surface morphology of the samples, scanning electron microscopy (SEM) images were obtained. Based on the SEM images, it can be seen that the CNTs are distributed over the substrates in a form of a disordered mesh with a various brightness, which also means a various density of CNTs.

To study the polarization properties of the experimental samples using the THz-TDSP method [3], a system based on a THz time-domain spectrometer, three wire grid polarizers, a 980 nm laser for creating the external OP of $0.2\,\mathrm{Wcm^{-2}}$, $0.6\,\mathrm{Wcm^{-2}}$, and $1.0\,\mathrm{Wcm^{-2}}$, and an axially magnetized NdFeB magnet for creating an external static MF of $\sim 0.3\,\mathrm{T}$ were used. Temporal waveforms of the THz signals transmitted through the experimental samples under the various external influences were recorded at the parallel and the crossed by 45° positions to the transmission direction of the polarizers. All measurements were done under a controlled room temperature of 291–293 K, and a relative humidity of 40–45 %. Experimental samples and setup are shown in **Figure 1 (a–c)**.

III. RESULTS AND CONCLUSION

Experimental frequency dependences of an azimuth angle ψ and an ellipticity angle χ of a polarization ellipse (PE) of the EM waves transmitted through the samples in the range 0.2–0.8 THz were calculated from the Stokes parameters:

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} |E_1|^2 + |E_2|^2 \\ |E_1|^2 - |E_2|^2 \\ 2\,|E_1|\,|E_2|\cos\delta \\ 2\,|E_1|\,|E_2|\sin\delta \end{bmatrix}, \tag{1}$$

$$\begin{bmatrix} \psi \\ \chi \end{bmatrix} = \begin{bmatrix} 0.5\arctan\left(S_2 \cdot S_1^{-1}\right) \\ 0.5\arcsin\left(S_3 \cdot S_0^{-1}\right) \end{bmatrix}, \tag{2}$$

where S_0, S_1, S_2, and S_3 are Stokes parameters; E_1, and E_2 are complex amplitudes of parallel and perpendicular components of an electric field vector $\mathbf{E}$, and δ is a phase difference between them. Results are shown in **Figure 1 (d–i)**.

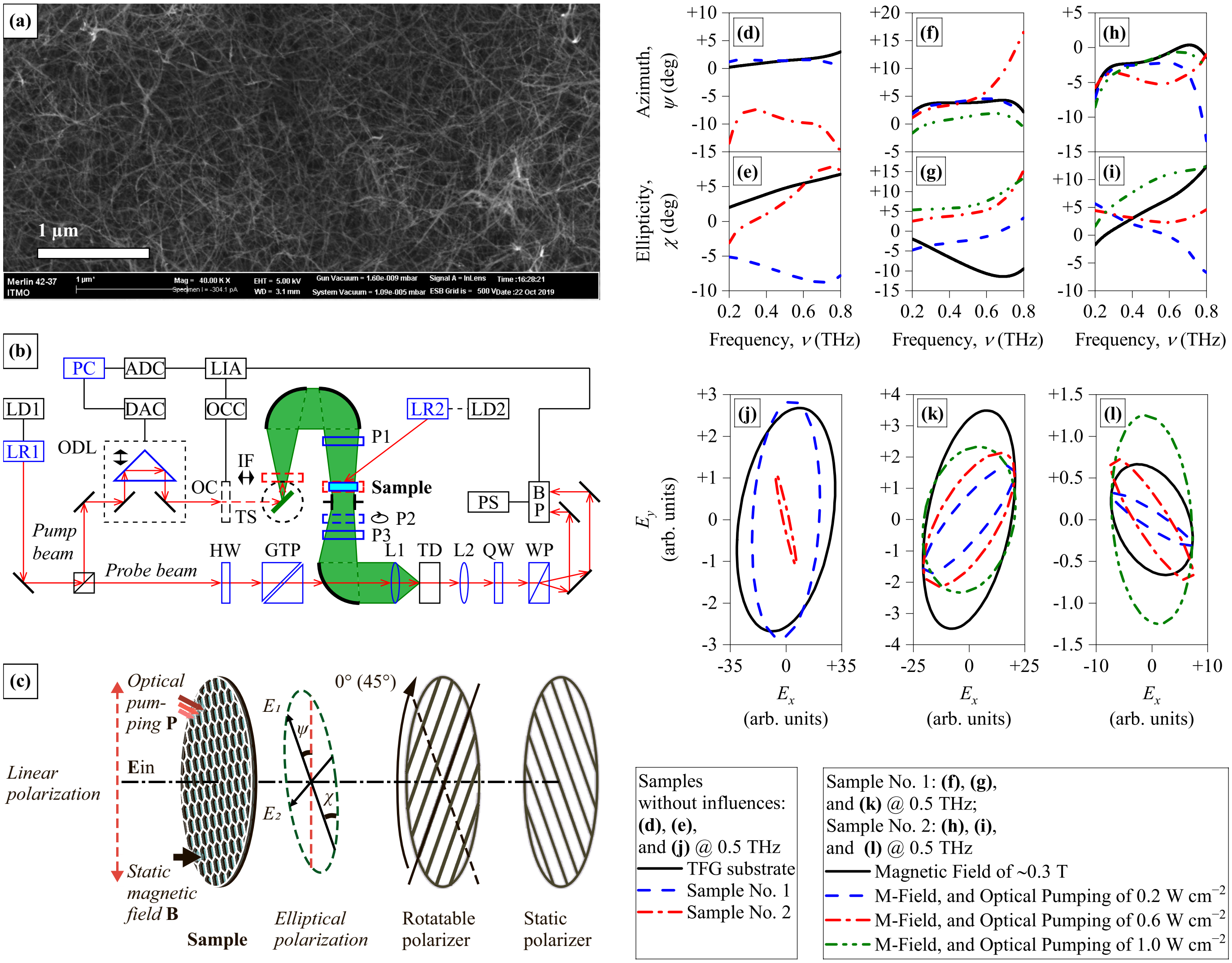

Fig. 1. **(a)** SEM image of the U-SWCNTs with scale bar of 1 µm; **(b)** scheme of the experimental setup (**ADC**—analog-to-digital converter; **BP**—balanced photodetector; **DAC**—digital-to-analog converter; **GTP**—Glan–Taylor prism; **HW**—half-wave plate; **IF**—poly(tetrafluoroethylene) (PTFE) ((C_2F_4)n) infrared cut-off filter; **L1**, **L2**—lenses; **LD1**, **LD2**—laser diodes' drivers; **LIA**—lock-in amplifier; **LR1**—femtosecond Yb:KYW 1040 nm laser; **LR2**—980 nm laser; **OC**—optical chopper; **OCC**—optical chopper controller; **ODL**—optical delay line; **P1**, **P3**—static polarizers; **P2**—rotatable polarizer; **PC**—personal computer; **PS**—balanced detector power supply; **QW**—quarter-wave plate; **TD**—THz radiation detector based on the CdTe crystal; **TS**—THz radiation source based on the InAs crystal; **WP**—Wollaston prism); **(c)** schematic representation of the samples under the external influences; frequency dependences of **(d)**, **(f)**, and **(h)** the azimuth angle ψ, and **(e)**, **(g)**, and **(i)** the ellipticity angle χ of the PE of the EM waves transmitted through the samples; and **(j)**, **(k)**, and **(l)** PEs of the EM waves transmitted through the samples at the frequency of 0.5 THz.

To better understand the dynamics of changes in the polarization properties of the experimental samples under the external influences, PEs of the EM waves transmitted through the samples were calculated. Results are shown in **Figure 1 (j–l)**. From the obtained experimental results, it is seen that, under the NIR OP of $1.0\,\mathrm{W cm^{-2}}$, and the external static MF of $\sim 0.3\,\mathrm{T}$ the azimuth angle changes up to 15°, and the ellipticity angle changes up to 10° relative to the U-SWCNT thin films without influences. The changes in the angles are a result of the MOFE. Also, the complex morphology of the surface of the U-SWCNTs, consisting of the disordered mesh of the CNTs, which was confirmed by the SEM images, has an effect on the modulation of the polarization properties.

It can be seen that the U-SWCNTs is an efficient material for devise optically tunable polarizers, which are necessary in cutting-edge THz security and telecommunication systems.

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