

Liquid crystal dispersions of carbon nanotubes: dielectric, electro-optical and structural peculiarities

L. Dolgov^{1*}, O. Koval'chuk², N. Lebovka³, S. Tomylo^{2,4}, and O. Yaroshchuk²

¹*Institute of Physics, University of Tartu, 51014 Tartu, Estonia*

²*Institute of physics, NASU, prospect Nauki 46, 03028 Kyiv, Ukraine*

³*Institute of Biocolloidal Chemistry, NASU, Vernadskii Prosp. 42, 03142 Kyiv, Ukraine*

⁴*Taras Shevchenko National University, Physical Faculty, prospect Glushkova 2, 03022 Kyiv, Ukraine*

1. Introduction

Liquid crystals (LCs) turn out to be excellent hosts for carbon nanotubes (CNTs). Having molecular structure similar to CNTs, LCs perfectly incorporate CNTs into own structure. Particularly, the liquid crystalline orientational order can be imposed on CNTs so that aligned ensembles of these particles can be attained (Dierking et al., 2004). This alignment can be patterned by patterning alignment of LC host. Furthermore, the alignment axis of CNTs can be easily driven by the LC reorientation in the external field (Dierking et al., 2008); CNTs follow reorientation of LC director demonstrating guest-host effect known for molecular solutions and dispersions of anisotropic nanoparticles in LC hosts (Blinov & Chigrinov, 1996). Finally, LC can be removed and thus pure aligned CNTs can be obtained (Lynch & Patrick, 2002). This altogether means that LC gives unique opportunity for controllable alignment of CNTs.

On the other hand, CNTs bring a number of improvements to LC layers used in electro-optic devices (Qi & Hegmann, 2008). The LC doping by CNTs reduces response time (Huang et al., 2005; Chen et al., 2007; Lee et al., 2008) and driving voltage (Lee et al., 2004), suppresses parasitic back flow and image sticking typical for LC cells (Lee et al., 2004; Baik et al., 2005; Chen & Lee, 2006).

The LC-CNTs systems are not limited to nematic matrices. A series of unique LC-CNTs composites based on thermotropic and lyotropic materials with different LC mesophases is developed and characterized (Weiss et al., 2006; Lagerwall et al., 2006, Lagerwall et al., 2007; Cervini et al., 2008; Podgornov et al., 2009).

A symbiosis of LC and CNTs rouses rapidly increasing interest. The number of publications on this subject grows in geometrical progression. The major results of these studies are summarized in several recent reviews (Lagerwall & Scalia, 2008; Rahman & Lee, 2009).

* on leave of absence from *Institute of physics, NASU, prospect Nauki 46, 03028 Kyiv, Ukraine*

A present chapter is focused on remarkable dielectric, electro-optical and micro-structural peculiarities of LC-CNTs dispersions, their correlation and mutual influence. It is mainly based on authors' original results obtained within recent years. The structure of this chapter is the following. The introductory part (section 1) gives short introduction to LC-CNTs composites and elucidates benefit of combination of LC and CNTs. It also outlines a field of questions further considered. A section 2 gives details of our samples and experimental methods. The next three sections correspondingly consider dielectric, electro-optical and structural peculiarities of LC-CNTs composites. Each of these topical sections starts with a short review and lasts with the authors' original results. The final, conclusion part (Section 6), summarizes most interesting properties of LC-CNTs suspensions, their application perspectives and mention some exciting problems for further investigations.

2. Materials and methods

2.1 Liquid crystalline media and chiral dopant

Nematic LCs EBBA (Reakhim, Russia), 5CB, MLC6608, and MLC6609 (Merck, Germany) were used as LC hosts. EBBA was purified by fractional crystallization from the n-hexane solution, 5CB, MLC6608, MLC6609 were used as obtained. Some characteristics of these LCs are presented in Table 1.

LC	Nematic mesophase	dielectric anisotropy $\Delta\varepsilon$, optical anisotropy Δn	Reference
EBBA	308.9 - 350.6 K	$\Delta\varepsilon=-0.13$, $\Delta n=0.25$ at 313 K	Goncharuk et al., 2009
5CB	295.5- 308.3 K	$\Delta\varepsilon=13$, $\Delta n=0.177$ at 298 K	Blinov & Chigrinov, 1996
MLC6608	clearing point at 363 K	$\Delta\varepsilon=-4.2$, $\Delta n=0.0830$ at 293 K	Licristal®, 2002
MLC6609	clearing point at 364.5 K	$\Delta\varepsilon=-3.7$, $\Delta n=0.0777$ at 293 K	Licristal®, 2002

Table 1. Characteristics of LC media.

S811 (Merck, Germany) was used as chiral dopant.

2.2 Multiwalled carbon nanotubes

The multiwalled carbon nanotubes (SpetsMash Ltd., Ukraine) were prepared from ethylene by the chemical vapor deposition method (Melezhyk et. al., 2005). Typically, these CNTs have an outer diameter of about 12–20 nm and the length of about 5–10 μm . The specific electric conductivity σ of the powder of compressed CNTs was about 10^3 S/m along the compression axis.

2.3 Preparation of LC-CNTs composites

The all LC-CNTs composites were prepared by 20 min stirring of LC and CNT mixtures using the ultrasonic mixer equipped with a cup horn, at the frequency of 22 kHz and the output

power of 150 W. The concentration of CNTs, c , was varied in the range 0-2 wt %. Doping of CNTs has not influenced essentially the phase transition temperatures of LC-CNTs composites.

2.4 Cells

The cells for electro-optical and dielectric measurements were made from glass substrates containing patterned ITO electrodes and aligning layers of polyimide. The polyimides AL2021 (JSR, Japan) and SE5300 (Nissan Chemicals, Japan) were used for homeotropic alignment of LC EBBA, MLC6608 and MLC6609, while the polyimide SE150 (Nissan Chemicals, Japan) was utilized for planar alignment of LC 5CB. The polyimide layers were rubbed by a fleecy cloth in order to provide a uniform planar alignment of LC in either field-on state (EBBA, MLC6608 and MLC6609) or a zero field (5CB). The cells were assembled so that the rubbing directions of the opposite aligning layers were antiparallel. A cell gap was maintained by the glass spacers of appropriate size (16 μm , if not otherwise stated). Finally, these cells were filled capillary with neat or CNTs doped liquid crystals heated to isotropic state. In some dielectric measurements the cells without alignment layers were utilized. The structure of LC-CNTs composites was monitored by observation of the filled cells placed between crossed polarizers, both by naked eye and in an optical polarizing microscope.

2.5 Electro-optical measurements

The electro-optical measurements were carried out using the experimental setup described in (Koval'chuk et al., 2001a). The cell was set between two crossed polarizers so that the angle between the polarizer axes and the rubbing direction was 45°.

The sinusoidal voltage 0-60 V (at frequency $f=2$ kHz) was applied to the cell. The voltage was stepwise increased from 0 to 60 V and then decreased back to 0; the total measuring time, i.e., time of voltage application, was about 1 min. The transmittance of the samples was calculated as $\eta=(I_{out}/I_{in})\cdot 100\%$, where I_{in} and I_{out} are intensities of the incident and transmitted light, respectively.

2.6 Dielectric measurements

The dielectric spectra in the frequency region between $5\cdot 10^{-2}$ and 10^6 Hz were recorded by measurement of the frequency f dependences of resistance R and capacitance C using the oscilloscopic method (Twarowski & Albrecht, 1979; Koval'chuk, 1998). The voltage signal applied to the tested cell had a triangle form with amplitude of 0.25 V. The parallel connected R - C circuit was used as an equivalent scheme of the cell and the values of the real (capacitive) ε' and imaginary (ac conductance) ε'' components of the permittivity $\varepsilon=\varepsilon'+i\varepsilon''$ of a composite were then calculated. Based on ε'' data the sample conductivity σ was determined using a formula:

$$\sigma = 2\pi\varepsilon_0\varepsilon''f, \quad (1)$$

where ε_0 is a dielectric constant.

The ac electrical conductivity was also measured by a LCR meter 819 (Instek, 12 Hz-100 kHz) in the non-relaxation frequency range preliminarily determined from the dielectric spectra. All the measurements were repeated at least 5 times in order to calculate the average values and errors.

3. Dielectric studies of LC composites doped with carbon nanotubes

The interest to the electrophysical behavior of LC composites doped with carbon nanotubes is continuously growing (Lebovka et al., 2008; Lu & Chien, 2008; Koval'chuk et al., 2008). Dispersed nanotubes essentially influence the concentration and spatial distribution of charges in LC cells and thus determine the actual electric field applied to the composites and their electro-optic response (Lee et al., 2004, Huang et al., 2005). These composites demonstrate huge changes in electrical conductivity σ with a small change of CNT concentration c ($c < 0.5$ wt %) (Lisetski et al., 2007; Dierking et al., 2008; Lisetski et al., 2009; Zhao et al., 2009). Besides, the σ vs. c curve shows clear percolation behavior (Lebovka et al., 2008; Koval'chuk et al., 2008; Goncharuk et al., 2009). The huge conductivity increase may result in dielectric breakdown and local heating effects (Jayalakshmi & Prasad, 2009). Monitoring of electrical conductivity identified two time scales in reorientation dynamics of liquid crystal-nanotubes dispersions. These scales are associated with the reorientation of the liquid crystal texture (the short time scale) and with the reorientation of the carbon nanotubes (the long time scale) (Dierking et al., 2008). The electrical conductivity and the dielectric constant of LCs doped with carbon nanotubes demonstrate extraordinary large changes in electric and magnetic field driven reorientation experiments (Dierking et al., 2004; Jayalakshmi & Prasad, 2009). In spite of these extensive studies, many aspects of LC-CNTs composites remained unclear. In particular, it was not well clarified the nature of electrical conductivity and charge transfer in different phase states of LC, at different concentrations of CNTs and in relations with the magnitude of applied voltage and frequency. The present paragraph is focused on these problems.

3.1 Dielectric spectra

Figure 1 presents typical dielectric spectra of 5CB-CNTs (a) and EBBA-CNTs (b) composites. The measurements were done at the temperatures falling within nematic phase of LC medium, $T=297$ K (5CB) and $T=313$ K (EBBA). The LC alignment is planar in case of 5CB and homeotropic in case of EBBA. According to Fig. 1, three frequency ranges, namely, $f < 10^2$ Hz (A), 10^2 Hz $< f < 10^5$ Hz (B) and $f > 10^5$ Hz (C) can be distinguished. As is commonly accepted (Craig, 1995), the frequency range (A) reflects the near electrode barrier layers processes, the frequency range (B) corresponds to the bulk polarization and charge transfer and the frequency range (C) reflects the relaxation process caused by transition from the electronic and dipole polarization to only electronic polarization of LC phase.

In (A) and (C) ranges, the noticeable dispersions of the real ε' and imaginary ε'' components were observed. The data analysis has shown that Cole-Cole approximation (Haase & Wrobel, 2003; Chelidze et al., 1977) can be applied for estimation of corresponding low- and high-frequency times of dielectric relaxation, τ_A and τ_C :

$$\varepsilon^* = \varepsilon_\infty + (\varepsilon_0 - \varepsilon_\infty)/(1 + i2\pi f\tau). \quad (2)$$

Here, ε^* is a complex dielectric permittivity, ε_0 and ε_∞ are the limiting values for the frequencies $f = 0$ and $f = \infty$.

Fig. 1 demonstrates that CNT dopant substantially modifies dielectric spectra of LC. These changes in different frequency ranges are further analyzed.

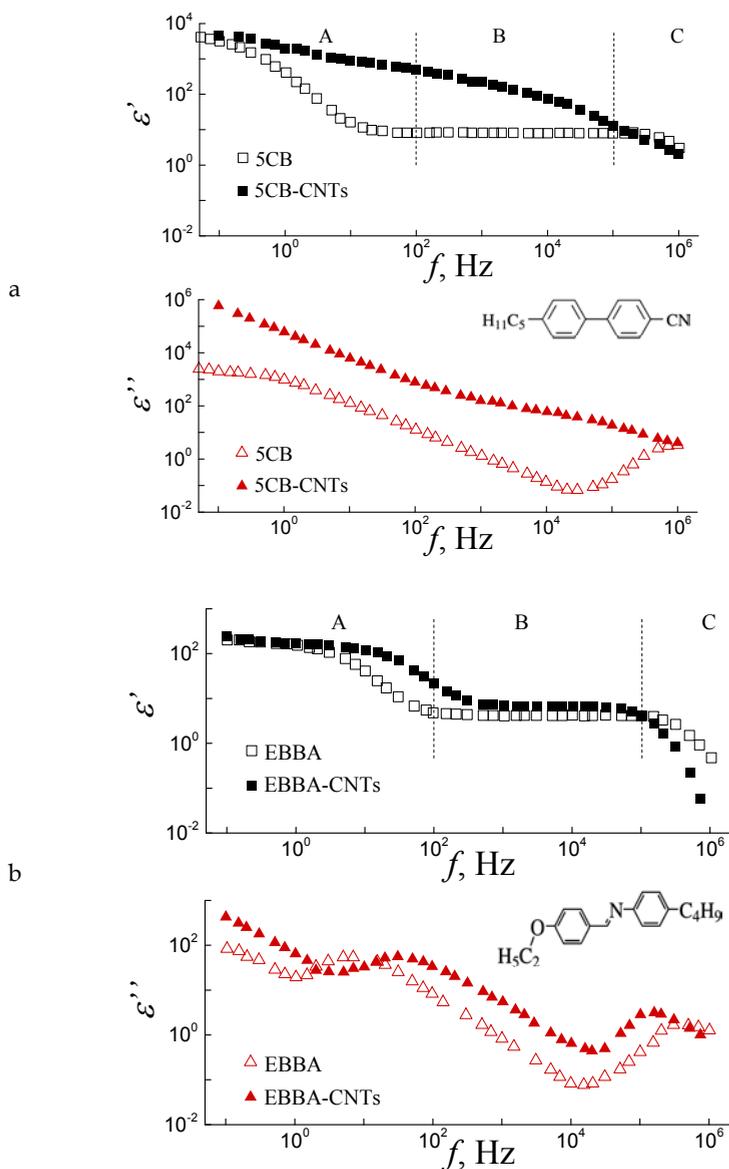


Fig. 1. Complex permittivity components ϵ' and ϵ'' versus frequency f for pure LC and LC-CNTs composites of 5CB (a) and EBBA (b). The concentration of CNTs c is 0.25 wt % (a) and 0.5 wt % (b). Chemical formulas of 5CB and EBBA are given on corresponding $\epsilon''(f)$ graphs.

3.2 Electrical conductivity: Intermediate frequency range

We begin with the intermediate frequency range (B). In this range, large active resistances of the double electric layers (DEL) formed near the cell electrodes are shunted by their capacitance diminishing with a field frequency f (Koval'chuk, 1998; Koval'chuk, 2000; Barbero & Olivero, 2002; Koval'chuk, 2001b). Because of this, the range (B) characterizes volume properties of samples.

Based on formula (1), alternating current conductivity of the composite bulk can be estimated. In a general case, the alternating current conductivity σ of LC-CNTs samples can be represented as a sum of the frequency-independent ionic conductivity σ_i associated with LC, and the frequency-dependent electronic hopping conductivity σ_e , associated with CNTs, $\sigma = \sigma_i + \sigma_e$. These two contributions to the electric conductivity can be easily separated because of considerable frequency dependence of σ_e . The σ_e component becomes essential at CNT concentrations comparable and higher than a threshold concentration c_c corresponding to conductivity percolation discussed in the next subsection. The frequency-independent component σ_i is typical for ionic conductivity of liquids (Frenkel, 1955).

3.2.1 Percolation behavior

Different composites filled with CNTs typically demonstrate percolating behavior of the electrical conductivity σ , when sharp transition from the prevailing ionic to the prevailing charge hopping conductivity occurs at some threshold concentration c_c (Grossiord et al., 2006; Mamunya et al., 2008). At this concentration, the CNTs form a percolation network or cluster that spans the whole system (Stauffer & Aharony, 1992; Torquato, 2002). A theory predicts an inverse proportionality between c_c and the aspect ratio r of the conductive filler particles, $c_c \sim 1/r$ (Balberg et al., 1984; Foygel et al., 2005).

For CNTs with very high aspect ratio, typically, $r \approx 500-1000$, this theoretical estimation results in extremely low values of the percolation threshold, $c_c < 0.1$ wt %, which is in full correspondence with available experimental data (Lisunova et al., 2007; Mamunya et al., 2008; Lebovka et al., 2009).

The percolation behavior of electrical conductivity in different LC-CNTs composites was recently reported (Lisetski et al., 2007; Lebovka et al., 2008; Koval'chuk et al., 2008; Lisetski et al., 2009; Goncharuk et al., 2009). Fig. 2 demonstrates electrical conductivity σ versus filler concentration c curve for 5CB-CNTs samples, which is typical for the LC-CNTs composites. Here, the 5CB is planar oriented in a $16 \mu\text{m}$ cell. The measurements were carried out at 100 Hz, when frequency dependence of σ was practically absent and thus the ionic contribution to σ was dominating. The threshold increase of σ was observed for the values of CNT concentration c between 0.02 and 0.2 wt %. The experimental data were analyzed using the least-square fitting to scaling equation (Stauffer & Aharony, 1992)

$$\sigma \propto (c - c_c)^t. \quad (3)$$

As a result, the percolation threshold concentration c_c and conductivity transport exponent t were determined. The insert in Fig. 2 shows c_c and t versus temperature dependencies. There are evident the considerable temperature dependencies for both c_c and t .

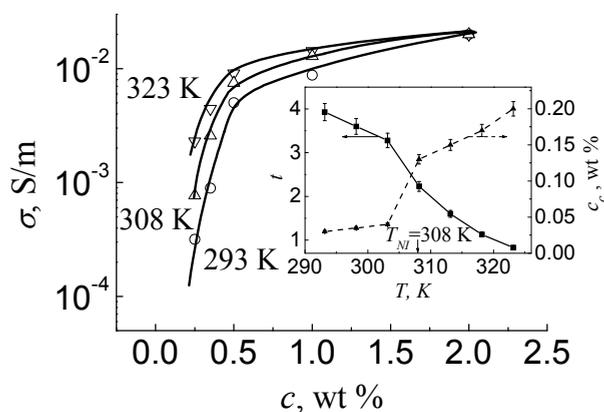


Fig. 2. Electrical conductivity σ versus concentration of nanotubes c in 5CB-CNTs composites for different temperatures T . Insert shows the conductivity exponent t and percolation threshold concentration c_c versus temperature T . The samples were planar oriented in a 16 μm cell, $f=100$ Hz.

Increase of the percolation threshold c_c with a temperature T is inessential within nematic mesophase ($T < T_{NI} \approx 308$ K), however, it becomes noticeable in isotropic phase. At $T=325$ K the threshold concentration reaches $c_c \approx 0.2$ wt %. Such character of $c_c(T)$ curve may be caused by number of effects such as change in the Brownian motion intensity, degree of the orientational order of nanotubes, etc. These factors influence degree of connectedness between the nanotubes and, as result, the percolation threshold (Kyrylyuk & van der Schoot, 2008). The effects of nanotubes' alignment on the percolation behavior were discussed recently, however, they still are not completely clear (Du et al., 2005; Behnam et al., 2007; Kyrylyuk & van der Schoot, 2008). More perfect alignment of CNTs inside the nematic phase is expected. However, it can be assumed that highly aligned nanotubes practically don't intersect each other and fail to create percolation paths. The highest electrical conductivity was experimentally observed for slightly aligned, rather than isotropic, composites (Du et al., 2005). Recent Monte Carlo simulations have also demonstrated that conductivity may be strongly dependent on the measurement direction and the degree of nanotube alignment (Behnam et al., 2007). Along with inducing alignment, nematic LC host stabilizes structure of CNTs damping their Brownian motions. Together with imperfect orientational order of CNTs it may explain the lower concentration threshold of CNTs in the nematic phase comparing with that in the isotropic state (see inset in Fig. 2).

Temperature decrease in the conductivity exponent t (see formula (3)), possibly, reflects changes in the conductivity mechanism and structure of the percolating clusters. The values of conductivity transport exponents $t \approx 4/3$ and $t \approx 2$ are characteristic for the ordinary 2d (two-dimensional) and 3d (three-dimensional) random percolations, respectively. Note that for the studied systems the 2d-3d crossover percolation behavior (Muller et al., 2003;

Lebovka et al., 2002) with $4/3 < t < 2$ was expected, because the restricted width of the cell ($d \approx 16 \mu\text{m}$) was comparable with the length of CNTs ($l \approx 5\text{--}10 \mu\text{m}$). Moreover, it was found that for the 3d composite filled with anisotropic particles t decreases substantially with increase in the aspect ratio (Foygel et al., 2005). The noticeable deviations from predictions of the standard percolation theory were also observed for systems with diverging local conductances, when distances between adjacent particles are broadly distributed (Johner et al., 2007). The reported transport exponent t often exceeds its classical values, reaching even the values as large as $t=5\text{--}10$ (Johner et al., 2008). Generally, the value of t extracted from the percolation data for CNT-filled composites may be dependent on the distribution function of distances between adjacent conducting particles (Mdarhri et al., 2008).

Note that $c_c(T)$ and $t(T)$ behave discontinuously in the vicinity of nematic-isotropic transition, $T_{NI} \approx 308 \text{ K}$. It reflects strong dependence of the percolating characteristics on the phase state of LC host.

3.2.2 Temperature dependence and energy of activation

In the investigated range of temperature the electrical conductivity σ of the LC-CNTs composites increases with a temperature that is characteristic for the nonmetallic behavior. Moreover, temperature dependence of σ can be satisfactorily described by Arrhenius relationship (Lebovka, 2008):

$$\sigma \propto \exp(-W/kT), \quad (4)$$

where W is the activation energy, k is Boltzman's constant.

Figure 3 shows typical Arrhenius plots for 5CB-CNTs (a) and EBBA-CNTs (b) composites corresponding to different concentrations of nanotubes, c .

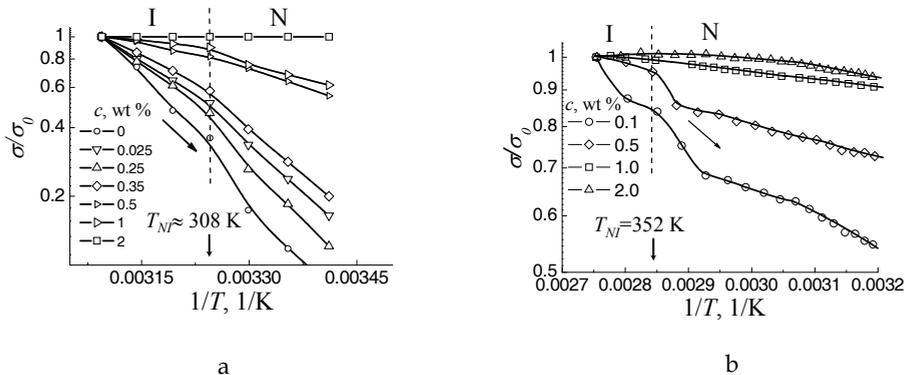


Fig. 3. Relative conductivity σ/σ_0 versus inverse temperature $1/T$ for planar oriented 5CB-CNTs (a) and unoriented EBBA-CNTs (b) composites at different concentrations of nanotubes c . Here, σ_0 corresponds to the electrical conductivity at some reference temperature, which was 323 K in case (a) and 363 K in case (b). The cell gap d was $16 \mu\text{m}$ (a) and $500 \mu\text{m}$ (b), the frequency f was 100 Hz (a) and 1000 Hz (b). Arrows mark direction of temperature change.

In these experiments, the conductivity data were recorded in the cooling regimes accounting for the possible influence of the thermal pre-history. The obtained Arrhenius plots of $\sigma(T)$ curves were rather linear within the temperature ranges corresponding to nematic or isotropic phase; however, some deviations from linear behavior were observed near nematic-to-isotropic transition points. Moreover, the slopes were always larger in nematic phase than in isotropic phase; it corresponds to higher activation energy of the electrical conductivity in nematic phase. This can be explained by the restriction of the charge mobility in the nematic phase that is related to distortion of the LC director field in the vicinity of charge carriers (Belotskii et al., 1980). This distortion sphere surrounding the charged particle arises as a result of LC molecule orientation in the electric field generated by this particle.

Figure 4 presents examples of concentration dependencies of the activation energies determined from the Arrhenius plots in nematic phases of 5CB-CNTs and EBBA-CNTs composites.

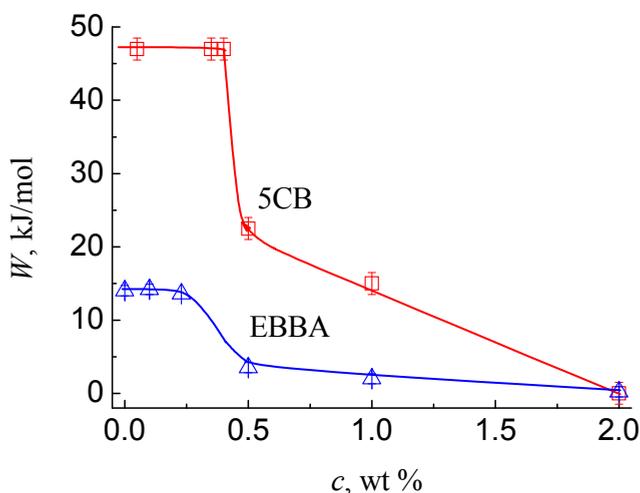


Fig. 4. Activation energy W of electrical conductivity versus concentration of CNTs c for planar oriented 5CB-CNTs and unoriented EBBA-CNTs composites. The values of W were determined from data corresponding to temperature ranges of nematic phases of 5CB and EBBA. The cell gap d was 16 μm (5CB) and 500 μm (EBBA), the frequency f was 100 Hz (5CB) and 1000 Hz (EBBA), the measuring voltage U was 0.25 V (5CB) and 1 V (EBBA).

Though values of W were determined for different LC media, for planar oriented (5CB) and unoriented (EBBA) composites, using different cell gaps and different protocols for σ measurements, similar tendencies were observed in $W(c)$ dependencies: W was constant at small concentrations below the percolation threshold and started to decrease above the percolation threshold approaching $W \approx 0$ kJ/mol at $c \geq 2$ wt %.

This behavior reflects the dominating role of ionic transport mechanism at concentrations below the percolation threshold with activation energy $W_i \approx 47$ kJ/mol (5CB) and $W_i \approx 15$ kJ/mol (EBBA). So, below the percolation threshold, the conducting LC-CNTs composites behave as semiconductors. This behavior is also typical for polymer-CNTs composites, where electrical conductivity is an increasing function of temperature, which was explained by thermally assisted hopping or charge tunneling between the conducting particles (Barrau et al., 2003). The decrease of W above the percolation threshold might be explained by the increasing role of charge transport through the CNT structure. Comparing with ionic conductivity of LC, electronic conductivity of CNTs is characterized by low temperature coefficient (Eletskii, 2009). This might decrease the apparent activation energy W of LC-CNTs composites and this tendency should essentially enhance with concentration of CNTs.

3.2.3 Hysteretic behavior and effect of positive temperature coefficient

It was previously demonstrated that temperature affects the spatial arrangement of CNTs in the LC matrix and changes percolation characteristics. The LC-CNTs composite typically displays also the electrical conductivity heating-cooling hysteresis and the pronounced effect of positive temperature coefficient of resistivity (PTC effect) (Lebovka et al., 2008; Goncharuk et al., 2009). Figure 5 presents examples of the electrical conductivity σ heating-cooling hysteresis for EBBA-CNTs unoriented composites in the thick cell ($d \approx 500$ μm). In these experiments, the composites that were initially solid were heated from room temperature up to 363 K and then cooled. The total time of the heating-cooling cycle was about 1 h. The hysteretic loops were most pronounced for CNT concentrations in the vicinity of the percolation transition ($c \approx 0.1$ wt %) and became inessential at higher values of c (figure 5).

The heating-cooling hysteretic behavior of electrical conductivity reflects strong agglomeration and rearrangement of nanotubes during the thermal curing. The abrupt decrease of the $\sigma(T)$ curve in the vicinity of melting point T_{SN} may be caused by several factors. Firstly, CNTs align within the nematic domains. It lowers degree of connectivity of the nanotubes. Besides, the initial network is also partially damaged by thermal expansion of the host EBBA matrix (Lebovka et al., 2008; Lebovka et al., 2009). At high concentration of CNTs the network formed in LC is rather strong because of high density of connectedness between the nanotubes. This strong network cannot be easily destroyed by the Brownian motion and LC reorientation intensified by heating and phase transitions. This explains weakening of hysteretic and PTC effects at $c > c_c$. Note that these effects are especially strong in thick cells, when the length of individual nanotubes, $l \approx 5$ -10 μm , is small comparing with a cell gap d . In this case, the Brownian motion of individual nanotubes is unrestricted by nanoparticle interaction with the cell walls and so the Brownian motion and the LC orientational rearrangement are dominating factors in the observed reconstruction of CNTs network during thermal processing.

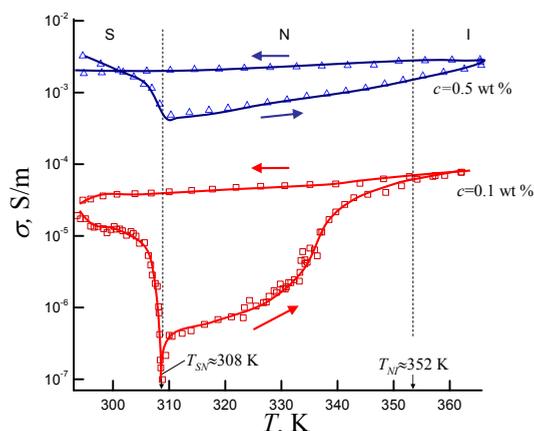


Fig. 5. Heating-cooling hysteresis of electrical conductivity σ for unoriented EBBA-CNTs composites. The measurements were made in a thick 500 μm cell, $f=1$ kHz, $U=1\text{V}$. The arrows show directions of temperature changes.

3.3 Frequency and voltage dependence

The frequency dependent contribution of electrical conductivity is common for disordered and/or highly alloyed solids (Gantmaher, 2005; Shklovskii & Efros, 1984). It was explained by correlated barrier hopping, tunneling or percolation model (Shklovskii & Efros, 1984; Mott & Davis, 1971, Pike, 1972). Typically, the power law dependences

$$\sigma \propto f^m \text{ or } \varepsilon'' \propto f^{m-1} \quad (5)$$

were observed. Here, m is a frequency exponent.

In the hopping transport model, the current carrier is assumed to hop over a potential barrier between neighboring localized sites and this model predicts that m is slightly lower than 1 and it decreases with rise of temperature. It is different from the tunneling model where the charge carrier is assumed to tunnel across the potential barrier. The tunneling model predicts smaller values of the frequency exponent ($0.4 < m < 0.8$) and temperature independent value of m . In the percolation theory, the critical exponent m is considered to be universal and determined only by statistical properties of the percolation clusters. The values of m obtained from numerical studies of random composites were in the range of 0.6–0.8 (Straley, 1977). The experimentally found m values near the percolation threshold were reported to be about 0.8–0.9 for carbon black composites (Jager et al., 2001), and 0.66 (Kim et al., 2003) or 0.85–0.9 (Liu et al., 2007) for carbon nanotube dispersions in polymers.

The studied dispersions of CNTs on the base of LCs demonstrated $\sigma(f)$ curves strongly depending on CNT concentration and temperature (Koval'chuk et al., 2008). The value of σ was practically independent on f at small concentrations of CNTs ($c < 0.1$ wt % for 5CB) and became a power function of the frequency f at larger c . Examples of $\sigma(f)$ dependences for 5CB-CNTs composites are presented in the insert in Fig. 6a. It is evident that increase of CNT concentration c above c_c results in increase of both ionic σ_i and electronic σ_e contributions, while below $c_c \approx 0.1$ wt % the ionic contribution is dominating. The increase of

the ionic contribution σ_i with c can be partially caused by the increased concentration of ions introduced with impurities presented in CNTs. However, this factor is hardly a dominating one because of thorough purification of CNTs used in our studies. The more likely reason is facilitation of ionic transport through the charge exchange mechanism assisted by nanotubes. Such mechanism may be efficient due to the large dielectric constant of the CNTs, which results in strong attraction between impurity ions and nanotube surface (Jagota et al., 2005). This conclusion is supported by presence of double electric layer (DEL) shunting effect assisted by CNTs (see section 3.5). At CNTs concentrations between 0.1 and 0.35 wt %, $\sigma_i = \text{const}$ and $\sigma_e = f^m$, which means that σ_i and σ_e can be easily separated. Above $c = 0.35$ wt %, the component σ_e becomes frequency independent that complicates its separation. The frequency independence of σ_e may be the evidence of the transition from the hopping charge transfer to the quasimetallic electronic transfer typical for CNTs. This implies very tight network with direct connections between the nanotubes so that the conductivity barrier between them is rather low.

Figure 6a also presents frequency exponent m vs. the concentration c at 297K. The $m(c)$ dependence is a non-monotonic function with a maximum $m \approx 0.32$ near the concentration $c \approx 0.25$ wt %. Increase of m with c at $c < 0.25$ wt % reflects initial process of CNT cluster formation. In this interval of concentrations, the mechanism of electrical transport is mixed: electrical transport is governed by electron hopping/tunneling mechanism inside CNT clusters and by ionic mechanism between clusters. Above the percolation threshold, at high concentrations of CNTs ($c > 0.25$ wt %), agglomeration of different clusters occurs and contacts between them are multiple. This results in formation of homogeneous ohmic conducting structure, when electron hopping/tunneling mechanism is inessential and electrical conductivity becomes frequency independent.

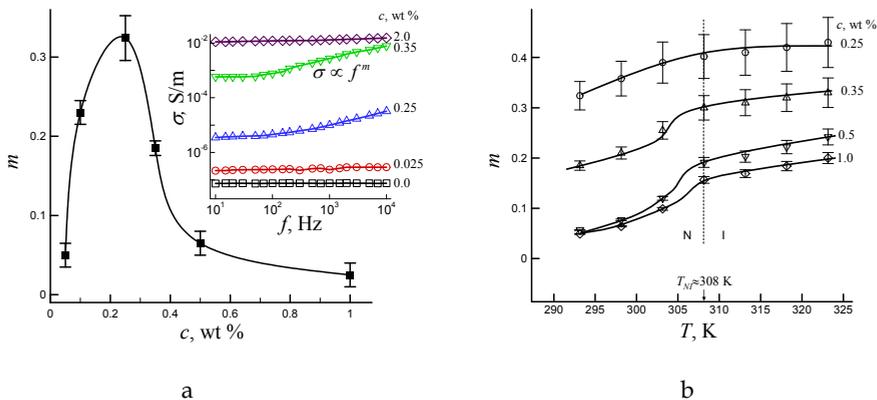


Fig. 6. Frequency exponent m versus (a) CNT concentration ($T = 297$ K) and (b) temperature for planar oriented 5CB-CNTs composites. Insert shows the conductivity σ versus frequency f plots for different concentrations of CNTs c .

The temperature dependencies of frequency exponents m for 5CB-CNTs composites are presented in Fig. 6b. The value of m is an increasing function of temperature. The evident changes in slope of $m(T)$ curves can be observed in the vicinity of nematic-isotropic

transition, $T_{NI} \approx 308$ K. The obtained data evidence a noticeable influence of the phase state of LC matrix on the charge transport mechanism. This effect can be easily explained accounting for the expected alignment of CNTs inside the nematic matrix (Dierking et al., 2004).

Note that observed behavior of the frequency exponent (rather small values of m ($m < 0.3$) and positive thermal coefficient ($dm/dT > 0$)) contradict with the classical hopping and tunnelling transport theories, predicting $dm/dT < 0$ (Mott & Devis, 1971; Pike, 1972). The percolation theory also predicts rather high values of m , in the range of 0.6–0.8 (Straley, 1977). Note that critical exponent m may vary significantly depending on peculiarities of microstructure and morphology of the composite (Liu et al., 2007). However, at the moment, there is no theory available for explanation of the anomalously small values of m observed in 5CB-CNTs composites.

Large positive thermal coefficient $dm/dT > 0$ obtained for nematic mesophase indicates enhancing of the frequency dependent contribution to electrical conductivity σ . This behavior, possibly, reflects the temperature changes in the percolating CNT networks inside the LC-CNTs composites. As was earlier discussed, temperature increase results in damage of the connectivity in percolation structures and, hence, in decrease of the “effective” filling concentration. Naturally, it resulted in increase of m with temperature T for concentrations above 0.25 wt % (Fig. 6b). This conclusion supports also the observed increase of the percolation threshold concentration c_c with temperature T (insert in Fig. 2).

A noticeably nonlinear behavior was also observed for current–voltage characteristics of LC-CNTs composites (Lebovka et al., 2008). Figure 7 presents voltage dependencies of electrical conductivity σ/σ_0 for EBBA-CNTs composites at different values of temperature T and concentration of nanotubes c .

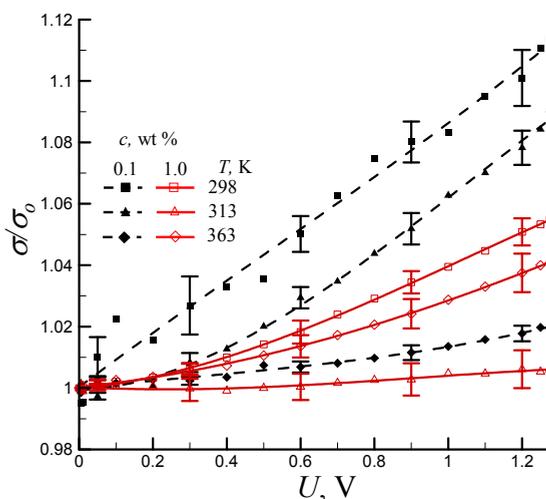


Fig. 7. Relative electrical conductivity σ/σ_0 versus measuring voltage U for composite EBBA-CNTs at different values of temperature T and concentration of nanotubes c . Here, σ_0 is electrical conductivity in the limit of $U=0$ V. The samples were randomly aligned in the 500 μm cells, $f=1$ kHz.

Such nonlinear behavior can be explained on the basis of hopping-tunneling model of transport disruption across the insulating LC regions between the CNTs, which predicts the following field dependence for electrical conductivity (Mott & Davis, 1971)

$$\sigma \propto \sinh(e\lambda_h E / kT), \quad (6)$$

where e is the elementary charge, λ_h is the average hopping distance, E is the applied electric field, and k is the Boltzmann constant.

The theory predicts weakening of the non-linear behavior with temperature T in full correspondence with experimental observations (Fig. 7). The most pronounced non-linear behavior was observed in the vicinity of the percolation threshold ($c_c \approx 0.05-0.1$ wt %). It was becoming less explicit above the percolation threshold, where multiple direct contacts between different CNTs were formed. The observed weakening of the current-voltage nonlinear behavior above the percolation threshold (Fig. 7) correlates with decrease of electrical conductivity activation energy (Fig. 4).

3.4 Dielectric relaxation and near-electrode processes: Low frequency range (A)

The dielectric spectra in the most low frequency range (A) ($f < 10^2$ Hz) are mainly determined by the near-electrode processes and electron exchange between electrodes and ions (Koval'chuk, 1998; Koval'chuk, 2000; Barbero & Olivero, 2002; Koval'chuk, 2001c). In this range, the most important changes, provoked by presence of CNTs, were observed for the imaginary (ac conductance) component ε'' , while changes for real (capacitive) component ε' were smaller. At low frequencies ($f < 0.5$ Hz), increase of the component ε'' was observed by doping LC (both 5CB and EBBA) with CNTs (Fig. 1).

This behavior can be explained by enhancement of the electron component in electrical transport through the near-electrode layers, governed by the presence of CNTs in a composite. In fact, the CNTs serve as shunts of the double electrical layers providing paths for the electron exchange between electrodes and impurity ions inside LC.

The shunting effect observed at low frequencies ($f < 0.5$ Hz) and related with the presence of CNTs was characterized in terms of the dielectric loss tangent, $\tan \delta_s$, which is given by

$$\tan \delta_s = \varepsilon'' / \varepsilon'. \quad (7)$$

Note that $\tan \delta_s$ characterizes dielectric losses in the near electrode layers and thus is a surface parameter.

Figure 8 presents $\tan \delta_s$ as a function of CNT concentration c for 5CB-CNTs composites.

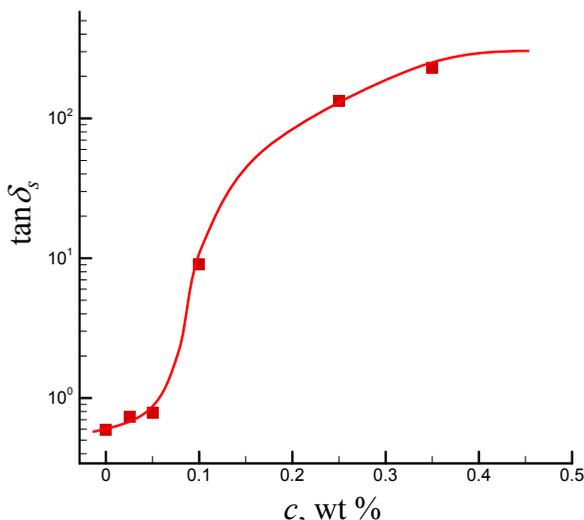


Fig. 8. Dielectric loss tangent $\tan \delta_s$ versus CNTs concentration c for planar oriented 5CB-CNTs composites in a 16 μm cell at $T=293$ K, $f=0.1$ Hz.

At small concentrations of CNTs ($c < 0.05$ wt %), $\tan \delta_s$ is rather small and dielectric parameters of the near-electrode layers are determined by the properties of 5CB itself. However, the abrupt rise of $\tan \delta_s$ in the interval of c values between 0.05 and 0.1 wt % evidences about formation of effective shunting paths as elements of a percolation network of CNTs characterized by the same concentration threshold.

The width of the near-electrode layers λ_s can be estimated (Koval'chuk, 2001a; Koval'chuk, 2001c):

$$\lambda_s \approx d \varepsilon_o^C / 2 \varepsilon_o^A, \quad (8)$$

where ε_o^A and ε_o^C are the limiting values of ε for the frequency ranges (A) and (C). For example, for pure EBBA, the estimated width of near-electrode layer λ_s is about 0.3 μm and it is practically independent from the cell thickness d (Fig. 9). The doping of EBBA by CNTs (0.5 wt %) results in a noticeable increase of λ_s . This might be caused by increased concentration of ionic impurities or structural modification of DELs in presence of CNTs.

The low-frequency relaxation process characterized by the time τ_A we assign to dipolar polarization relaxation of LC molecules. These molecules can be anchored to the surfaces of the cell and to a skeleton of CNTs acting as a spatially distributed surface in LC host. For pure EBBA, τ_A is an increasing linear function of a cell gap d . The linear increase of the dipole relaxation time with d in the near-electrode zone τ_A was also observed for the planar oriented LC media (Yaroshchuk et al., 2005). It was established that value of τ_A decreases with the increase of electric conductivity. The similar tendency observed for EBBA doped with CNTs (Fig. 9) may be explained by high shunting efficiency of CNTs in the near-electrode zones and the ionic impurities introduced in LC together with CNTs.

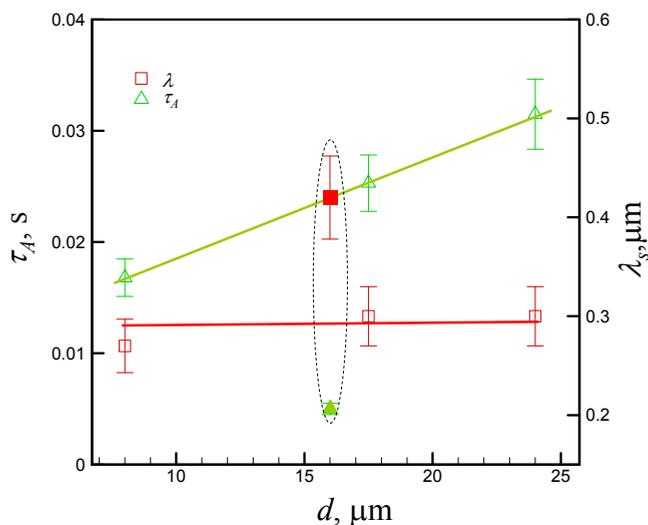


Fig. 9. Near-electrode layer width λ_s and low-frequency relaxation time τ_A vs. a cell gap d for pure EBBA (open symbols) and EBBA-CNTs composite ($c=0.5$ wt %) (filled symbols). The EBBA media was homeotropically oriented.

3.5 High frequency dielectric relaxation: High frequency range C

The high frequency dielectric relaxation time τ_C was practically independent of d for pure EBBA ($\tau_C \approx 0.67$ μs), and doping by CNTs (0.5 wt %) resulted in increase of τ_C ($\tau_C \approx 2.5$ μs). The similar tendency of τ_C to increase was observed also for 5CB-based composites, where $\tau_C \approx 0.56$ μs for pure 5CB and $\tau_C \approx 0.94$ μs for 5CB-CNTs (0.5 wt %) composite.

4. Electro-optic studies of LC-CNTs composites

Electrically controlled birefringence is a major property of LCs utilized in liquid crystal displays (LCDs), optical shutters, LC lenses and other LC devices. The present section considers influence of CNTs on the electro-optic properties of LC layers. It consists of three subsections. Subsection 4.1 refers to recent improvements of reversible LC response achieved owing to CNT addition. Subsection 4.2 is based on our original results concerning the irreversible electro-optical response of the LC-CNTs systems named as electro-optic memory (Dolgov et al., 2008; Dolgov et al., 2008a). At last, subsection 4.3 describes enhancement of the memory effect in the systems with induced chirality (Yaroshchuk et al., 2010).

4.1 Reversible electro-optic response

Generally, nematic LC devices utilize reversible response of LC layers on the applied voltage (Blinov & Chigrinov, 1996). The characteristics of this response, such as controlling voltage, switching on and off times, contrast ratio, etc., are quite important operational parameters of the LC devices. The major trend in improvement of these parameters is associated with synthesis of new mesogenic compounds and development of new eutectic

LC mixtures on their base. The other direction recently arose due to intensive development of nanotechnologies. Some types of nanoparticles turned out to be very useful fillers fundamentally expanding the range of mechanical, dielectric, magnetic, and optical characteristics of LCs (Qi & Hegmann, 2008).

Among nanoparticles as fillers for LCs, carbon nanotubes take special place. Due to strong shape anisotropy they possess strong anisotropy of polarizability. Therefore embedding even small amount of CNTs ($c < 0.05$ wt %) into liquid crystal host may essentially increase (case of LC with $\Delta\epsilon > 0$) (Lee et al., 2004) or decrease (case of LC with $\Delta\epsilon < 0$) (Huang et al., 2005) dielectric anisotropy. Driving voltage is inversely proportional to the module of $(\Delta\epsilon)^{1/2}$ and so it may be essentially influenced by carbon nanotubes.

As it was mentioned in section 3.2.1, carbon nanotubes (at $c \geq 0.01$ wt %) generally enhance conductivity of LCs. However, at minute amount of nanotubes (~ 0.001 wt %), this effect is inessential. At the same time, the nanotubes may affect significantly the number of free-moving ions and their distribution within the cell by means of ion adsorption and shunting of double electric layers (see section 3). As a result, a minute doping by carbon nanotubes allows to suppress a number of parasitic ionic effects peculiar to LC electro-optic devices, such as a field screening (Lee et al., 2004), image sticking (Baik et al., 2005), transient current (Chen & Lee, 2006), back flow (Huang et al., 2005; Chen et al., 2007) and hysteresises of capacitance and transmittance (Lee et al., 2004; Baik et al., 2005). This results in lowering of driving voltage (Lee et al., 2004) and shortening of response times (Chen et al., 2007). Along with nematic LCs, CNT dopant may improve properties of LCDs based on ferroelectric LCs. Specifically, it fastens response of the deformed helix ferroelectric liquid crystal displays (Prakash et al., 2009). The changes in structure and resistivity of double electric layers and the composite's rotational viscosity due to carbon nanotubes are discussed as the possible reasons of such speeding-up of the electro-optic response.

4.2 Irreversible electro-optic response: effect of electro-optical memory

The irreversible response is not typical for nematic LCs commonly used in LC devices. However, the embedded nanoparticles grant this property to LCs (Kreuzer et al., 1992; Glushchenko et al., 1997). Regarding LCs filled with CNTs, interesting memory effect has been recently observed in isotropic phase of LC material (Basu & Iannacchione, 2008). It consists in irreversible change of dielectric constant of LC-CNTs composite under the applied voltage and is explained by formation of pseudonematic domains near the CNTs reorienting in the electric field. Since there is no restoring force in the isotropic phase, after the field is off, these domains keep the orientation induced in the electric field.

In what follows, a different memory effect is considered. It is peculiar only to the nematic mesophase of LCs with $\Delta\epsilon < 0$ homeotropically aligned before the action of the electric field. Besides, to realize this effect, the concentration of CNTs in the LCs should be considerably higher ($c > 0.01$ wt %) than in the case of composites with the reversible electro-optic response ($c \sim 0.005$ wt %).

To elucidate this memory effect, let us consider transmittance η of the samples placed between pair of crossed polarizers as a function of the applied voltage U . The $\eta(U)$ curves for the EBBA-CNTs samples are presented in Fig. 10.

In these experiments the voltage was smoothly increased to 60 V and then decreased to 0 V. One can notice that the $\eta(U)$ curves have oscillating character. The $\eta(U)$ oscillations mean that optical phase incursion during the switching of LC is much more higher than $\pi/2$. The

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