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Rotation of the light polarization plane in Liquid Crystals with sensitizers based on WS_2 nanotubes

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The effect of WS_2 nanotubes on the rotation of the polarization plane of *p*-type laser radiation in the nematic liquid-crystal composites based on 4'-pentyl-4-biphenylcarbonitrile (5CB) has been considered. The correlation between the concentration of the injected sensitizer and the phase shift of the optical beam has been demonstrated. The prospects of these materials in display technologies, laser technology and quantum cryptography has been shown.

Keywords: liquid crystals, sensitizing, WS_2 nanotubes, rotation of the light plane of polarization.

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The presented study is an interdisciplinary one at the confluence of materials science, optical electronics, and information technology. In addition to their display applications, nematic liquid crystal (LCs) are used as an electrically and optically reconfigurable medium for adaptive optics [1], holography [2], and IT security [3] purposes. The birefringence effect, which may be controlled by an external field (electric, magnetic, light, or acoustic), is observed in nematic LC structures. This provides an opportunity to modulate optical radiation in phase, amplitude, and polarization. Viscosity and flowability are the advantages of LC materials; therefore, optical elements based on them may be flexible and of a complex shape, and devices may be scaled in size. The refraction index anisotropy of LC elements without an applied electric field allows one to alter the orientation of the polarization plane of radiation passing through the medium. Thus, these elements may be used as a material for passive optical phase shifters and serve as an alternative to aqueous solutions of glucose, dyes, and DNA and semiconductor materials [4–7].

In practical terms, it is more expedient to design LC elements that may be used both with (active mode) and without (passive mode) an electric field. Aligning surfaces with the needed morphology [8,9] and the process of nanoparticle doping of the bulk of LCs [10–12] are used to enhance the brightness, contrast, and response speed. Refraction index anisotropy Δn in an LC medium may change after the introduction of nanoparticles. This also affects the difference in orientation of the polarization plane between incident and transmitted rays

$$\Delta\varphi = \frac{2\pi d}{\lambda}\Delta n = \frac{2\pi d}{\lambda}(n_e - n_o). \qquad (1)$$

Here, d is the LC layer thickness; n_o is the refraction index for an ordinary ray, which is a constant characterizing a specific LC material; and n_e is the refraction index for an extraordinary ray, which depends on the LC director orientation. Near-boundary layers (e.g., aligning coatings) also affect the $\Delta\varphi$ value by altering the director distribution of LC dipoles, which is incorporated into parameter n_e. Note that changes in $\Delta\varphi$ may affect adversely the operation of LC devices in both modes. Therefore, in order to reduce unwanted losses in intensity of the modulated beam, LC elements often need to be aligned in terms of the polarization plane orientation with the optical circuit of a device. This problem is solved partially by adjustment, although it may be infeasible in the case of a close arrangement of functional layers.

It was found in [13–15] that the introduction of tungsten disulfide nanotubes enhances the response speed of LC cells based on 4'-pentyl-4-biphenylcarbonitrile (Aldrich Co.). In the present study, we examine the influence of concentration of WS_2 nanoparticles on the magnitude of variation of the light polarization plane orientation in passing through an LC medium. The obtained results should allow one to use both the LC layer thickness and the WS_2 concentration as adjustable factors in matching an LC cell to a polarizer in terms of the polarization plane orientation. Cells were constructed in the twisted nematic configuration. Two substrates made of K8 glass with a thickness of 3 mm were used for one cell. Conductive coatings based on indium tin oxides were deposited by laser directed deposition onto these substrates [16]. Liquid crystals were doped with WS_2 nanotubes with a concentration of 0.05–0.5 wt.%. A magnetic mixer was used to prepare (within five days) the LC mixture. The nanotube diameter was on the order of 30 nm and varied within a certain interval; the length of particles was 5 or more times greater than their diameter. The properties of WS_2 were examined in more detail

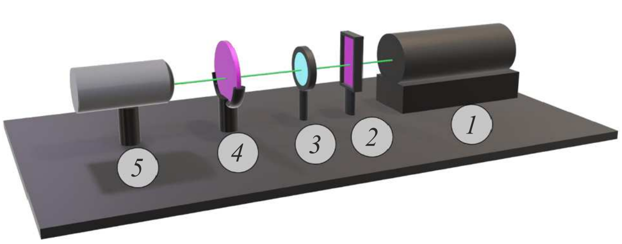

Figure 1. Circuit for determination of the polarization plane rotation of LCs with WS_2. *1* — Nd:YAG laser (532 nm), *2* — polarizer, *3* — studied LC cell, *4* — analyzer, *5* — photodiode with an oscilloscope.

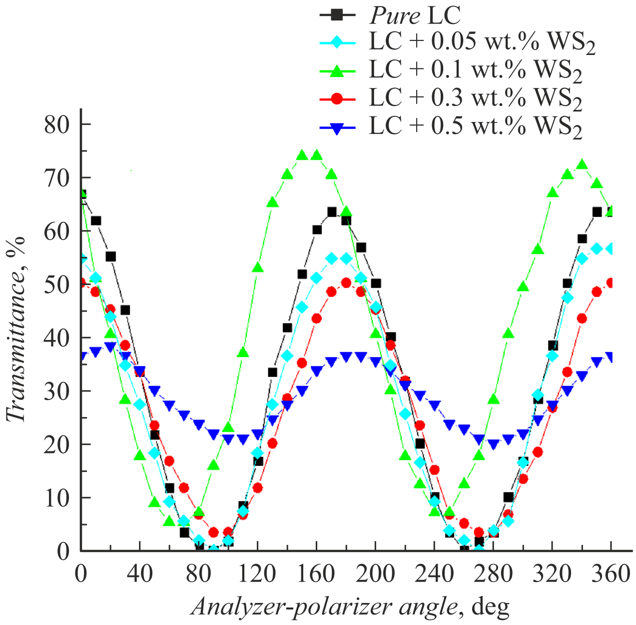

Figure 2. Dependence of the transmittance of LC cells with different sensitizer concentrations on the mutual positioning of the analyzer and the polarizer.

in [17,18]. The absorbance of nanoparticles at a wavelength of 532 nm was on the level of 0.30 [17]. These particles were provided by the research group lead by Professor R. Tenne (Israel). The LC layer thickness (10 μm) was set by teflon gaskets. An Nd:YAG laser ($\lambda = 532$ nm) operated in the CW mode with a power of 5 mW after transmission through SZS-15 and ZS-11 light filters was used to determine the polarization plane rotation. The initial positions of the polarizer and the analyzer were chosen so that the transmittance was maximized when two substrates made of crown glass K8 were mounted with an air gap of 10 μm. The optical signal was detected by a photodiode connected to an oscilloscope. The studied LC cells were positioned between the polarizer and the analyzer (Fig. 1).

Since the LC cells differed only in the sensitizer concentration, variations of the polarization plane orientation in glass substrates could be ignored in comparing these cells. Adjusting the analyzer position, we measured the transmittance of the studied samples at seven different points distributed over the aperture within the bounds of each sample. Figure 2 presents the dependences for the transmittance of samples with different WS_2 concentrations.

The positions of extrema of transmittance were determined for the indicated dependences by approximating them with the Malus's law. The values are listed in Table 1. The deviation from extrema corresponding to pure LCs increases with sensitizer concentration. At the same time, the optical transmittance decreases due to absorption by WS_2 nanotubes and their orientation in the LC medium. The cell with 0.1 wt.% WS_2 is an exception to this rule. It has been demonstrated earlier in the study of photorefractive and dynamic properties that this value corresponds to the concentration optimum at which a nematic–quasi-smectic state transition occurs [13–15]. Thus, this transition also manifests itself as a change in polarization properties. The laser and polarizers were positioned so that the transmittance maxima were at 0 and 180°, while the minima were observed at 90 and 270°. Let us analyze these values in comparison with the data from Table 1 for each extremum, derive differences, and calculate average values for each sample. The obtained values characterize parameter $\Delta\varphi$ of the studied LC cells. Figure 2 also allows one to determine ratio I_{0x}/I_{0y}, where I_{0x} and I_{0y} are the intensity amplitudes of emission from LC cells with axes x and y positioned so that I_{0x} and I_{0y} correspond to the maximum and the minimum transmittance, respectively. Using $\Delta\varphi$ and I_{0x}/I_{0y}, one may determine azimuthal angle α and elliptic angle ε that characterize radiation with elliptic polarization [19,20]:

$$\mathrm{tg}(2\alpha) = \frac{2\sqrt{\frac{I_{0x}}{I_{0y}}}}{1 - \left(\frac{I_{0x}}{I_{0y}}\right)} \cos(\Delta\varphi), \tag{2}$$

$$\sin(2\varepsilon) = \frac{2\sqrt{\frac{I_{0x}}{I_{0y}}}}{1 + \left(\frac{I_{0x}}{I_{0y}}\right)} \sin(\Delta\varphi). \tag{3}$$

The obtained data are presented in Table 2. In the case of pure LCs and LCs with 0.05 wt.% WS_2, emission from the cell may be considered polarized ($I_{0x}/I_{0y} > 100$); composites with 0.1 and 0.3 wt.% WS_2 produce linearly polarized emission (with a certain tolerance, since $10 < I_{0x}/I_{0y} < 100$); at 0.5 wt.% WS_2, elliptic polarization was observed.

The obtained results may be attributed to the influence of WS_2 nanoparticles on the LC director. Let us direct axis z perpendicular to the substrate plane. The dependence of n_e may then be characterized with a sufficient accuracy by the following expression:

$$n_e(\theta) = \frac{n_\perp n_\parallel}{\sqrt{n_\perp^2\left(\cos\theta(z)\right)^2 + n_\parallel^2\left(\sin\theta(z)\right)^2}}. \tag{4}$$

In the ideal case, $n_e = n_\parallel$ ($\Delta n = n_\parallel - n_o$) for the passive LC cell mode and $n_e = n_\perp$ ($\Delta n = n_\perp - n_o$) for the active

Table 1. Variation of the polarization plane orientation in the studied LC cells (in degrees)

Extremum	Pure LCs	LCs sensitized with WS_2 nanotubes of various concentration			
		0.05 wt.%	0.1 wt.%	0.3 wt.%	0.5 wt.%
Minimum I	86.1	85.7	66.4	94.8	101.5
Maximum I	173.8	174.3	155.0	181.9	186.6
Minimum II	266.1	266.0	245.4	272.1	279.8
Maximum II	355.5	353.4	338.1	361.8	375.5
Mean deviation of the extrema position (relative to pure LCs)		−0.5°	−19.2°	7.3°	15.5°

Table 2. Parameters of elliptic polarization in the studied LC cells

Parameter	Pure LCs	LCs sensitized with WS_2 nanotubes of various concentration			
		0.05 wt.%	0.1 wt.%	0.3 wt.%	0.5 wt.%
$\Delta\varphi$,°	4.6	5.1	23.8	−2.7	−10.9
I_{0x}/I_{0y}	334.0	549.0	15.3	17.2	1.8
α,°	−3.1	−2.4	−13.3	−13.5	−14.1
ε, °	0.3	0.2	5.6	−0.6	−5.2

mode. In practice, fluctuations of the LC director and local reorientations of dipoles in the bulk of LCs relative to introduced nanoparticles are observed. The results obtained in the present study may be associated with changes in the refraction index anisotropy $(n_{\parallel} - n_o)$. This is substantiated by data from earlier studies [13,14] into the switching performance of LC cells. It was demonstrated there that the switching time, which is inversely proportional to the anisotropy of permittivity $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp}$, decreases following the introduction of WS_2 nanotubes.

An often-encountered practical scenario is the one where a fixed value of $\Delta\varphi$ needs to be set. This may be done by varying LC layer thickness (1), setting director distribution $\theta(z)$, and adjusting optical LC properties $n_{\parallel}$ and $n_{\perp}$ (4). The threshold switching voltage and the electric field distribution change if the LC layer thickness is altered. One then needs to adjust the operation conditions for control electric pulses and take the variation of absorbance of the medium and the possibility of photorefractive effect into account. The director distribution adjustment (e.g., with the use of aligning coatings) is merely an auxiliary technique, since LC dipoles rearrange primarily in near-surface layers, and the effect grows weaker with distance. The readjustment of optical LC properties by varying the WS_2 concentration within the range of 0.05−0.5 wt.% provides an opportunity for wide-ranging alteration of the polarization plane; therefore, this approach may be used to match LC elements in polarization.

Thus, the observed correlation between the sensitizer concentration and the phase shift (Table 1) makes it possible to adapt an LC cell being designed to the optical circuit, since it allows one to adjust both the thickness and the sensitizer concentration; however, the variation of parameters of elliptic polarization should also be taken into account (Table 2).

Having analyzed the data on reorientation of the polarization plane in LC cells in the off state and compared them with the results reported in [13–15], we arrive at the following conclusions.

1. At an LC layer thickness of $10\,\mu$m and a WS_2 sensitizer concentration of 0.3 and 0.5 wt.%, the polarization plane position may be altered by an average of 7.3 and 15.5°, respectively, relative to the position for pure LCs. If the WS_2 concentration drops to 0.1 wt.%, the alteration magnitude increases to 19.2°. When the concentration decreases further to 0.05 wt.%, only an insignificant position change (0.5°), which may be attributed to measurement errors, photorefractive effect, or a slight deviation of optical properties from those of pure LCs, is observed.

2. The adjustment of concentration of WS_2 nanotubes provides an opportunity to match LC elements to an external optical circuit without any substantial variation of the LC layer thickness and without the use of additional polarization rotators. This is of practical importance for display technology, since an LC–WS_2 nanotube composite material with enhanced spectral and dynamic properties is more likely to be a fine fit for integration into a device body of a fixed thickness. In laser technology and optical cryptography, this correlation is of use in those cases when one cannot alter the LC layer thickness to a significant extent and cannot reposition the polarizer.

3. The discussed LC composites may be used as passive polarization rotators with the rotation magnitude being controlled by the concentration of WS_2 nanotubes and the LC layer thickness. The same goal may be achieved in configurations allowing for operation in the active mode.

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Conflict of interest

The authors declare that they have no conflict of interest.

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