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Novel and Classical Materials Used in the Plane of Polarization of Light Rotation: Liquid Crystal with WS_2 Nanotubes

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Abstract: It is well known that among the materials used in the daily lives of individuals and also in industrial applications, the specific structures applied in biomedicine occupy a special place. It is connected with the possibility to expand our basic physical-chemical knowledge and regarded to the real application of novel structures in the interdisciplinary arena. In this paper, a comparative study is conducted on the influence of different materials: sugar, DNA, WS_2 nanoparticles, dyes—on the rotation of the plane of polarization of light. Firstly, this effect is shown namely for a liquid crystal mixture doped with WS_2 nanotubes. On the one hand, it is shown that the new materials are quite suitable for use in sugar-meters and polarimeter devices instead of sugar solutions. On the other hand, the rotation of the plane of polarization of light in solutions with DNA and WS_2 nanoparticles in water or in the liquid crystal mixture can predict a larger angle of the rotation of the polarization plane of the light and can find a better design than in volumetric classical sugar solutions. This makes it possible to expand the application of these materials to the technical devices.

Keywords: rotation of the polarization plane of the light; sugar; dyes; DNA; WS_2; visible-range laser irradiation

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1. Introduction

Over the last decade, the field of material science has produced numerous novel findings. Bulk inorganic crystals have been replaced by organic systems with good success in terms of their basic parameters and design.

In this regard, due to the relevance of the physical-chemical effects in studying new organic materials with electro-optical properties that can compete with inorganic structures, and considering the possibility of implementing the organic systems in the optimization of technological processes—as well as their possible application in telecommunications, displays, lasers, biomedical technology, industrial production, etc.—the study of the characteristics of innovative structured organic materials is timely and quite in demand. Fullerene nanoparticles (NPs), quantum dots (QDs), shungite, dyes, carbon nanotubes, DNA, WS_2 NPs, reduced graphene oxides, La NPs, etc., can be used to produce structured organic compounds and to predict and improve their features [1–10]. It was found, for example, that the introduction of fullerene in the film of an organic compound increased the photoconductivity by two orders of magnitude compared with the photoconductivity of pure C_{60} films [1]; it was shown that fullerene- and shungite-doping increased the laser-induced change of the refractive index in the thin films of the polyimide structure [2,3]; the C_{60}-grafted graphene nanosheet formation was reported in work by [4], which testified the significantly improved electron transport in the poly-(3-hexylthiophene)-based bulk heterojunction solar cells. This also changes the overall device performance, yielding a power conversion efficiency of about 1.22%. The unique properties of the aforementioned QDs were shown in paper [5], in which the authors provided information about inter-dot hopping amplitudes, quantum dots' energy levels and their occupancies prior to an abrupt change in bias voltage. The authors of paper [6] clearly showed that the optimization of the interactions between an LC host and QD nanoparticles via distortion minimization of the local LC ordering, demonstrates a practical method for the preparation of thermodynamically stable colloids of nanoparticles in nematic LC matrixes. The authors of work [7] showed the synthesis of lanthanide nanoparticles included in DNA functionalized by hexadecyltrimethylammonium chloride, which led to the creation of a new composite for use in photonics; the same induced refractive parameters were discussed in paper [8] via use of fullerenes, DNA and QD nanoparticles. The authors of paper [9] demonstrated thermal-optical switching with low-power consumption and fast response based on the graphene-doped polymer compound; an interesting molecular dynamic study of the Janus-like structure was shown in paper [10], where significant DC conductivity contributions were observed for all considered materials at high temperatures and low frequencies. It was established that the absolute value of DC conductivity increased by six orders of magnitude with increases in the alkyl chain length. This observed conductivity behavior was discussed with respect to a percolation-like transition taking place at an alkyl chain length of about six carbon atoms.

At the same time, it should be mentioned that this study, namely regarding the optical and photoconductive effects in organic materials occupies a special place. This is due to a significant expansion in the fields of application of the latter, since the photon energy lies in the range of the electronic and the vibrational transitions in matter [11–13]. Therefore, this circumstance allows the use of light to obtain unique information about the structural, polarization, and dynamic properties of the materials. Rotation of the polarization plane of light in classical materials and in structured ones were investigated by different scientific and technical groups in the papers [14–20]. Some theoretical vision [14] and the observation of the rotation of plane polarized light in a microcavity parametric oscillator were presented [15]. The rotation of the polarization plane of light waves traveling in an optical fiber lying on a space curve based on parallel transport or due to geometrical defects is described in paper [16–18]. Due to the induced defect, it is possible to control the rotation of the plane polarized light propagating through the liquid-crystalline structure as shown and verified in the literature [19,20].

The purpose of the current paper is to identify and demonstrate the advantage of the novel materials, which can be used in the realization of the effect connected with the rotation of the polarization plane of light. It can potentially be used in civil engineering applications to develop sugar-meter and polarimeter devices with the extended types of the new materials. Thus, in the current paper, the optical effect of the rotation of the polarization plane of light *firstly* is considered in liquid crystal (LC) systems doped with WS_2 nanotubes. A comparison is made regarding the change in angle of rotation of plane polarized light when one uses classical sugar solutions, certain dyes, DNA, etc.

2. Materials and Methods

In the present study, we focused on the problem of the rotation of the plane of optical radiation polarization in the off state of the LC thin film doped with WS_2 nanoparticles. After this, we compared the results obtained in the current experiment with that shown by us for previously investigated materials (non-water soluble and water-soluble dyes, sugar water solution, DNA) for the same aim. LC cells were made based on the mixture of 4′-pentyl-4-biphenylcarbonitrile (Aldrich Co., Wyoming, IL, USA) with a thickness of 10 microns. The doped LC mixture was placed between two crown K8 glass substrates. These substrates were produced by the Vavilov State Optical Institute (Saint-Petersburg, Russia). All LC cells were assembled in a twisted nematic (TN) configuration. Liquid crystals were sensitized by the WS_2 nanotubes at a concentration of 0.05–0.5 wt%; these unique WS_2 nanotubes, whose properties were established previously in detail [21–23], were provided to us by the group led by Professor R.Tenne (Department of Molecular Chemistry and Materials Science, Weizmann Institute of Science, Israel) and tested by us for the switching improvement and for the study of the orientation relief changing, as reported in papers [24,25]. It should be mentioned that a scanning electron microscope (SEM) image of the WS_2 nanotube powder was previously shown in paper [25].

Let us briefly show the current scheme regarding the effect of the rotation of the polarization plane of light. Figure 1 demonstrates the classical evidence to obtain the rotation angle after light is transferred through a medium containing sugar-water solution as the classical material to demonstrate the effect. The formula for estimating the angle of the rotation [12] is shown in Equation (1):

$$\alpha = \alpha_{sp}\, c \times l \tag{1}$$

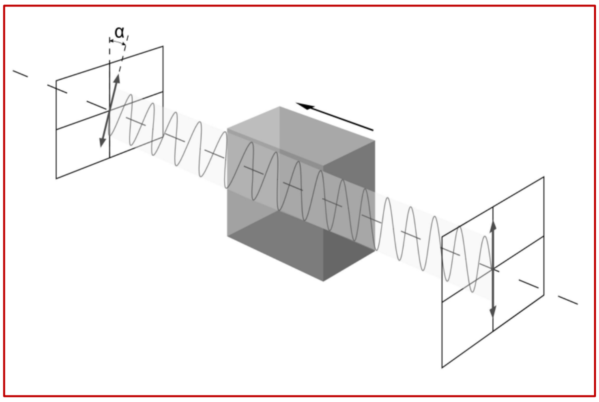

Figure 1. Classical presentation setup to show the effect of the light plane polarization rotation.

Here, α_{sp}—specific value of the rotation for the sugar; *c*—the concentration of the sugar in the water; *l*—is the dimension of the cuvette.

To determine the rotation of the polarization plane of light in the current work, a Nd:YAG laser (second harmonic, at a wavelength of λ = 532 nm) was used, operating in continuous mode with a power of 5 mW. The beam was subsequently passed through a set of required light filters. The optical signal was recorded on a photodiode, which was connected to an oscilloscope. Then, the structures studied were placed in series between the polarizer and the analyzer (Figure 2).

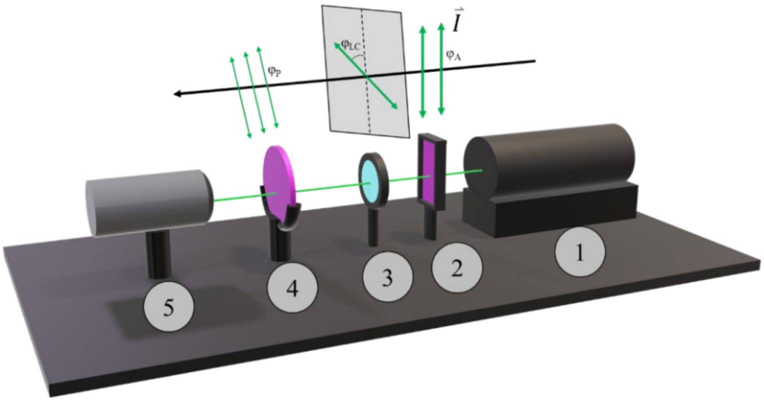

Figure 2. Experimental scheme for the measurement of the light plane polarization rotation: 1—Nd:YAG laser (532 nm); 2—polarizer; 3—tested LC cell; 4—analyzer; 5—photodiode with the oscilloscope.

In the set-up shown in Figure 2 the values of the φ_P, φ_{LC}, and φ_A are corresponded to the change of the laser beam orientation through the passage of the first polarized, LC cell and analyzer, respectively.

We have modified the scheme in order to evaluate the effect for doped LC cells. In this case, the initial position of the polarizer and analyzer was chosen in such a way that when two glass K8 crown substrates with an air gap of 10 µm were placed, the transmission maximum could be observed. Of course, the plates comprised of K8 crown glass were investigated for any potential effects on the change in plane of the polarization of light under the experimental conditions. No additional influence associated with the change in rotation angle due to application of the two glass substrates was detected.

3. Results and Discussion

The configurations of the studied doped LC cells differed only in the concentration of the sensitizer, which makes it possible to ignore the rotation of the polarization plane in glass substrates when comparing them. By changing the position of the analyzer, we were able to successfully measure the transmission of the samples in this study (Figure 3).

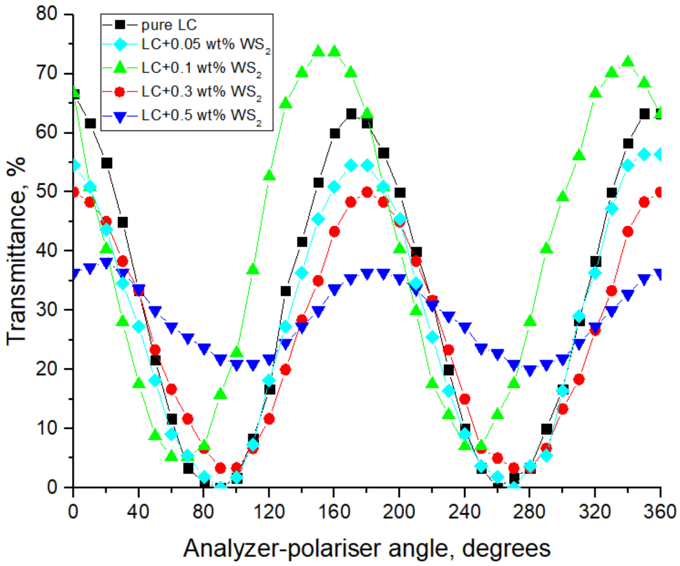

Figure 3. The dependency of the transmittance versus the angle between the analyzer and the polarizer.

As the concentration of the sensitizer increases, the deviation from the extreme corresponding to the pure LC also increases (Table 1). It should be noted that the negative value of the average deviation at a concentration of 0.05 wt.% lies within the measurement error.

Table 1. The rotation of the plane of the polarization in the considered LC cells.

Extremum	Pure LC	LC with WS$_2$ Sensitizer Using 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
The average deviation from pure LC, °		−0.5	−19.2	7.3	15.5

At the same time, due to the optical absorption of WS$_2$ nanotubes and their orientation in the LC medium, the optical transmission partially decreases. The exception is observed for the LC cell with a content of WS$_2$ nanotubes close to 0.1 wt.%. Based on the study of the photorefractive and dynamic properties, this concentration corresponds to the concentration optimum, at which a transition from the nematic LC phase to the quasi-smectic state is observed [24,26,27]. Thus, due to the observation of the transition from the nematic phase to the quasi-smectic phase for LC compounds with the concentration of WS_2 nanotubes of 0.1 wt.%, it should be noted that the physical effect in the smectic LC is different from the LC in the nematic phase; this was established by scientific teams who tested the smectic LC cells as the pure, and as the doped ones [28–30]. This can explain partially the differences in the effect shown in Figure 3 for the rotation of the polarization plane of light for cells with a different content of the dopants. It should be tested in future more carefully, namely for LC cells with the quasi-smectic transition. Perhaps, the initial polarizability observed in the smectic phase of the LC compound can also influence the properties of the quasi-smectic LC mixture in the current effect. It should be mentioned that the increase in transmittance of the LC with 0.1 wt.% of the WS_2 nanotubes can be explained by the formation of regular layers in the quasi-smectic compounds, that can reveal the more orderly system for transmitting radiation.

Let us continue to explain the results. It should be noted that in the general case [28–30], the magnitude of the phase shift depends on the LC layer thickness d and on the optical anisotropy Δn:

$$\Delta\varphi = \frac{2\pi d}{\lambda}\Delta n = \frac{2\pi d}{\lambda}(n_e - n_0) \tag{2}$$

In the off state, the molecules are located along the x-axis, then $\theta = 0$, and $n_e = n_{\|}$. When the threshold value of the electric field is exceeded, the LC molecules begin to orient, θ increases to $\pi/2$, therefore, $n_e = n_{\perp} = n_0$.

$$n_e(\theta) = \frac{n_{\perp} n_{\|}}{\sqrt{n_{\perp}^2(\cos\theta(z))^2 + n_{\|}^2(\sin\theta(z))^2}} \tag{3}$$

The problem is that in the absence of a control electric field, a phase incursion is formed in the LC layer, which depends on the layer thickness and optical properties of the material, namely on their refractive coefficients $n_{\perp}$ and $n_{\|}$. To obtain the required value of $\Delta\varphi$ (see Figure 2) in the off state of the LC cell, it is necessary to change the thickness of the LC layer, the consequences of which cause even more technical difficulties. Therefore, the obtained correlation between the sensitizer concentration and the phase shift value (see Table 1) makes it possible to adapt the developed LC cell to the optical scheme, since in this case, in addition to the thickness, it is possible to vary the sensitizer concentration.

Thus, one can testify the following: (1) At concentrations of 0.05, 0.3, and 0.5 wt% of the WS_2 sensitizer, it is possible to vary the rotation of the polarization plane of the light relative to the pure LC by 15 degrees at an LC layer thickness of 10 μm. At a concentration of 0.1 wt% WS_2, a smaller phase shift is observed relative to the pure LC. (2) Varying the concentration of WS_2 nanotubes renders it unnecessary to adjust the thickness of the LC layers over a wide range and to use the additional polarization plane rotators to match the LC elements with an external optical scheme. (3) The considered LC composites can be used as passive rotators (without applied voltage) of the polarization plane, the rotation of which is tuned by changing the concentration of the WS_2 nanotubes and the LC layer thickness.

To compare these results with the those obtained before, we can consider the data in Table 2. For comparison, regarding the sugar-water solution with a concentration of 0.05 g/cm^3, the angle was 0.5°, but the thickness of the cuvette was 10 mm, not microns.

Table 2. Polarization plane rotation angle for some dyes and DNA.

Sample	Dyes or DNA Content in Water, wt.%	Polarization Plane Rotation Angle, °
DNA * water-based solution	0.3	3–3.8
ENS-291 ** dye in water	0.1	0.12°
ENS-295 *** dye in water	0.1	0.2°
ENS-102 **** dye in water	0.1	0.25

* The data are shown in Ref. [31]. **, ***, **** These dyes' features were shown in Refs. [32,33].

4. Conclusions

The following conclusion provides a summary of the results obtained. Firstly, the evidence of doped LC structures was shown in the prediction and in the visualizations of the optical effect to rotate the polarization plane of the light when the LC mixture was doped with WS_2 nanoparticles. Secondly, the influence of WS_2 nanotube content on the possibility to rotate this angle was presented. Thirdly, a passive mode of the doped LC cells operation was used to show the effect of rotation of the polarization plane of light, facilitating a future study where control of the LC structure using the bias voltage can be employed. Fourthly, the WS_2 nanotubes and DNA bio-particles can be actively applied in optoelectronic devices to utilize the effect of polarization rotation of the light plane.

It should be mentioned that the direction shown can support the previously revealed results, where the LC matrix was instead employed in a biomedical context [34,35]. Moreover, this can pave the way for new applications of the doped LC with WS_2 nanotubes in biomedicine as well, i.e., sugar-meter and polarimeter devices. Owing to its good visualization, this effect can also be utilized in education applications.

Why was the LC matrix used in this study? The fact is that the display industry (computers, watches, gadgets, etc.) uses the LC mesophase very often. Therefore, it is useful to account for the presence of different effects when doping LC compositions to pollute undistorted signals in the optical systems that record and read the information.

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