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Depolarization of partially coherent light in liquid crystals

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In the paper we present results of analysis of partially coherent light depolarization in two types of liquid crystals possessing linear birefringence controlled by temperature and external electric field changes. Some experimental results of degree of polarization measurements for different light sources as a superluminescent diode and a laser diode are also presented.

Keywords: depolarization of light, liquid crystals, coherency of light.

1. Introduction

Degree of polarization (DOP) of the partially coherent light diminishes during propagation in birefringent media. The phenomenon is well known in both types of optical fibers: low-birefringence fibers used in long-distance telecommunication systems [1] and highly birefringent fibers used, e.g., in optical fiber rotation sensors based on idea of optical fiber Sagnac interferometer with low coherent light source [2] as well as in polarimetric sensors [3]. Problem of polarization degree fading during propagation of partially temporal coherent light through solid crystals has been recently analyzed in details [4] based on the Mueller matrix formalism with an additional depolarization matrix. Since elements of the depolarization matrix depend on the coherence length, on azimuth of the light as well as on birefringence of the crystal, liquid crystals characterized by high linear birefringence seem to be a very interesting medium for such research.

It should be pointed out that depolarization of light caused by scattering and reflection of light in liquid crystals has been investigated for several years [5]. The depolarization was only a few percent and mechanism of the phenomenon was not explained. In the paper we are dealing with depolarization of light with different temporal coherency passing through liquid crystals and the depolarization may be relatively very high up to 50% and more for low coherence light sources.

2. Depolarization of partially coherent light in birefringent media

In general, partially temporary coherent light becomes depolarized during propagation through birefringent media. This depolarization depends on coherency of light characterized by the coherence length ΔL, birefringence of the medium defined as $\Delta n_{eff} = n_{fast} - n_{slow}$ as well as azimuth of light beam versus fast and slow axes of medium birefringence [4]. Depolarization may be described by the Mueller-Stokes matrix equation [6]

$$[\mathrm{S}^{\mathrm{out}}]=[\mathrm{D_c}][\mathrm{M}][\mathrm{S}^{\mathrm{in}}], \tag{1}$$

where [M] is the Mueller matrix of the medium and $[\mathrm{D_c}]$ is, so-called, depolarization matrix [4], since DOP may be directly calculated from elements of the Stokes vector

$$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}. \tag{2}$$

The depolarization matrix has diagonal shape

$$[\mathrm{D_c}] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & P_c & 0 & 0 \\ 0 & 0 & P_c & 0 \\ 0 & 0 & 0 & P_c \end{bmatrix}, \tag{3}$$

where P_c for light sources with Lorentzian spectrum like laser diodes LDs and for Gaussian spectrum, that is typical for gas lasers as well as for light emitting diodes LEDs and also for superluminescent diodes (SLDs) are equal to [4]

$$\mathrm{P}_{\mathrm{c}Lor} = \sqrt{1 - \frac{4\left[1-\exp\left(-2\dfrac{\Delta n_{eff}\, l}{\Delta L}\right)\right]}{\left(\dfrac{|E_{0x}|}{|E_{0y}|}+\dfrac{|E_{0y}|}{|E_{0x}|}\right)^2}},$$
$$\mathrm{P}_{\mathrm{c}Gauss} = \sqrt{1 - \frac{4\left[1-\exp\left(-2\left\{\dfrac{\Delta n_{eff}\, l}{2\sqrt{\ln 2}\,\Delta L}\right\}^2\right)\right]}{\left(\dfrac{|E_{0x}|}{|E_{0y}|}+\dfrac{|E_{0y}|}{|E_{0x}|}\right)^2}}, \tag{4}$$

where E_{0x} and E_{0y} are the amplitude electric field components of light, Fig. 1.

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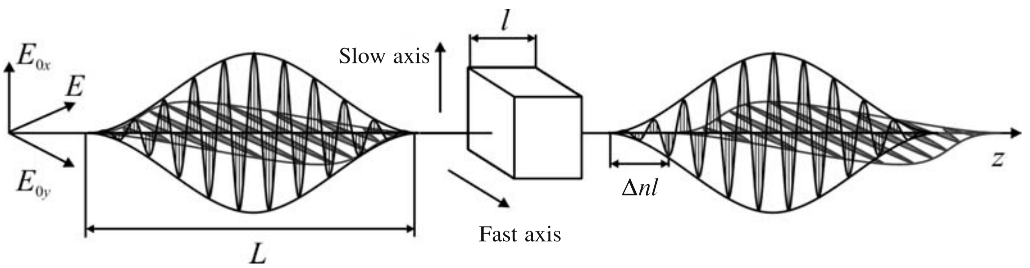

Fig. 1. Length shift Δnl of partially coherent light passing through liquid crystal cell with linear birefringence, L is the length of a wave package of incoming light.

Both components of the linearly polarized light coupled into the liquid crystal may have different phase velocities. This causes a phase shift between both components and simultaneously the linearly polarized light is transformed into circular, elliptical or linear polarization depending on value of the induced phase shift. For the totally coherent light, its state of polarization (SOP) changes but DOP is equal to 1 even for long pass lengths of light in the liquid crystal. For the partially coherent light characterized by the coherence length ΔL, phase shift may be so high that the light outgoing from the liquid crystal cell may be almost totally unpolarized due to the fact, that both components are shifted into different wave packages, in general, with their different frequency and noncoherent to each other. It means that for the same degree of polarization of the input beam we obtain different degree of polarization of the transmitted light depending on temporary coherency of light passing through birefringent medium. Results of example calculations are shown in Table 1.

Table 1. Degree of polarization fading due to transmission partially coherent light (*Gaussian, **Lorentzian spectra) through birefringent medium with azimuth 45° ($E_{0x} = E_{0y}$).

Light source	$\Delta L = \lambda^2/\Delta\lambda$	$L_s = \Delta nl$ (20 µm, Δn = 0.5)	$L_s/\Delta L$	P_c
Natural*	~1 µm	10 µm	10	~0
LED*	~20 µm	10 µm	0.5	0.91
SLD*	5–10 µm	10 µm	1–2	0.24–0.70
LD**	1–100 m	10 µm	10^{-7}–10^{-2}	0.99–1
He-Ne*	0.1–100 m	10 µm	10^{-7}–10^{-4}	~1

3. Liquid crystals as birefringent media

Liquid crystals (LCs) are strongly anisotropic substances, what is manifested in their optical properties by birefringence. Nematics, one of mesomorfic classes of LCs show a specific molecular ordering by preserving some degree of fluidity and rotational freedom. It makes them the optically uniaxial material with $n_e > n_o$ which can be fully characterized by the difference in the indices of refraction $\Delta n_{eff} = n_e - n_o$. In typical nematic liquid crystals, Δn_{eff} may range between 0.05 and 0.5. Nematic liquid crystals (NLCs) are highly sensitive to external influences. Electric field applied to the NLC cell, due to dielectric anisotropy of NLCs may change their molecular orientation and so change the effective cell birefringence. The birefringence of NLC also depends on temperature, because of thermal fluctuations of the direction of molecules in NLC structure.

In our experiments, the 80-µm-thick cell filled with 4-n-pentyl-4-cyanobiphenyl (5CB), 60- and 80-µm-thick cells filled with 4-trans-4'-hexyl-cyclohexyl-isothiocyanatobenzene (6CHBT) were used (Figs. 2 and 3). These are the standard liquid crystal compounds used in many areas of applications. The birefringence Δn of 5CB is around 0.2 and Δn of 6CHBT is 0.15, both at 22°C. The highest birefringence is at the melting temperature T_m, the lowest at the clearing temperature T_{NI}, and it vanishes in the isotropic phase. For 5CB liquid crystal used in this research, the temperatures are T_m = 22.5°C and T_{NI} = 35°C whereas for 6CHBT are T_m = 23°C and T_{NI} = 43°C.

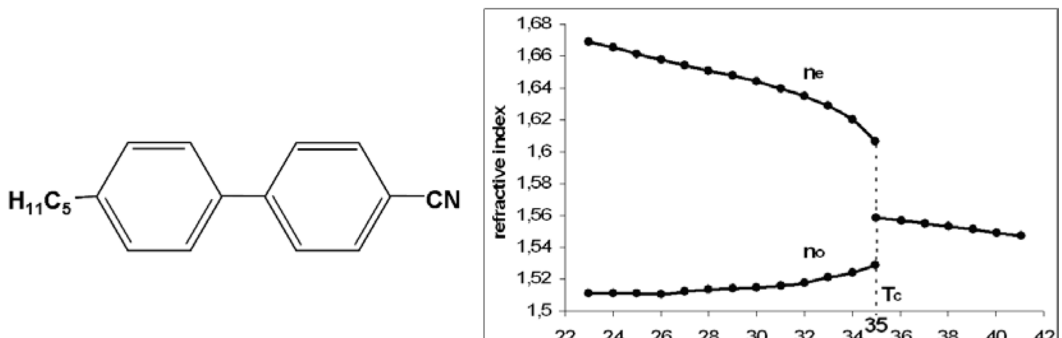

Fig. 2. Formula of 4-n-pentyl-4-cyanobiphenyl (5CB) and its refractive indices.

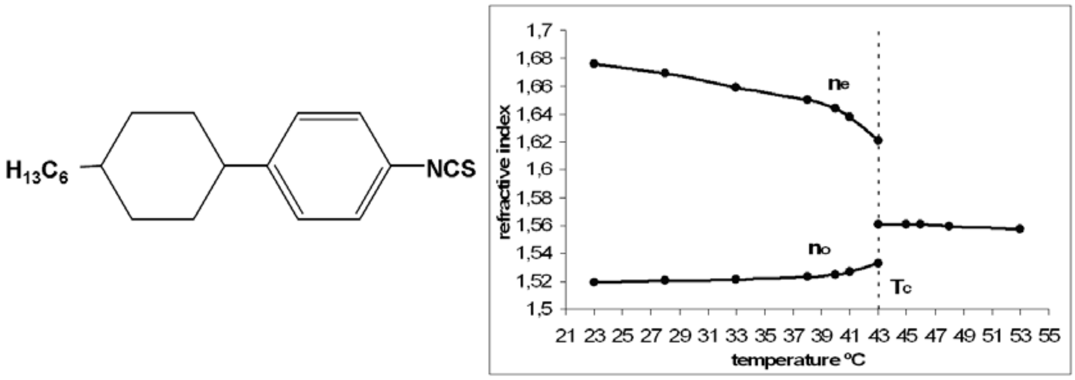

Fig. 3. Formula of 4-trans-4'-hexyl-cyclohexyl-isothiocyanatobenzene (6CHBT) and its refractive indices.

4. Experimental

The experimental set up is shown in Fig. 4. In the experiments, the super luminescent diode (SLD) was used (λ = 830 nm). The spectral width $\Delta\lambda$ of the SLD was 30 nm and hence coherence length of the emitting light was 23 μm according to the formula

$$\Delta L = \frac{\lambda^2}{\Delta\lambda}. \tag{5}$$

Additionally, a light source with high temporal coherence was used in the measurements as well. It was a laser diode lasing at 670 nm with spectral width less than 0.15 nm and its coherence length was greater than 3 mm. The light was polarized by a high-quality Glan-Thompson polarizer. The LC cell was placed horizontally on the rotating table enabling changes in the angle between orientation of molecules and electric vector of light wave (Fig. 5).

Two electrodes were attached to the sample in order to control the alignment of the LC molecules by electric field. The glass walls of the cell were covered with a thin layer of indium tin oxide (ITO) that does not introduce changes in DOP. The molecules were reoriented by the electric field to another position, parallel to the electric field. After exceeding the Freedericksz threshold, the LC molecules are reoriented and hence birefringence has decreased. Orientation of the LC molecules was controlled by AC voltage supplied by the functional generator. Measurements were carried out for 0 V, 9 V, and 13 V. The intensity of light was detected by optical power meter. The LC cells could be heated in order to change anisotropic phase of liquid crystal into isotropic one. We made measurements for 25°C and 48°C.

The elements of the Stokes vector were calculated from intensities of light measured by optical power meter according to the following equations

$$S = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \begin{bmatrix} I_{(0,0)} + I_{(0,90)} \\ I_{(0,0)} - I_{(0,90)} \\ 2I_{(0,45)} - I_{(0,0)} - I_{(0,90)} \\ I_{(0,0)} + I_{(0,90)} - 2I_{(\lambda/4,45)} \end{bmatrix} \tag{6}$$

where the first subscript index means lack or presence of quarter wave plate and the second one gives azimuth of an analyzer, both placed in front of photo-detector.

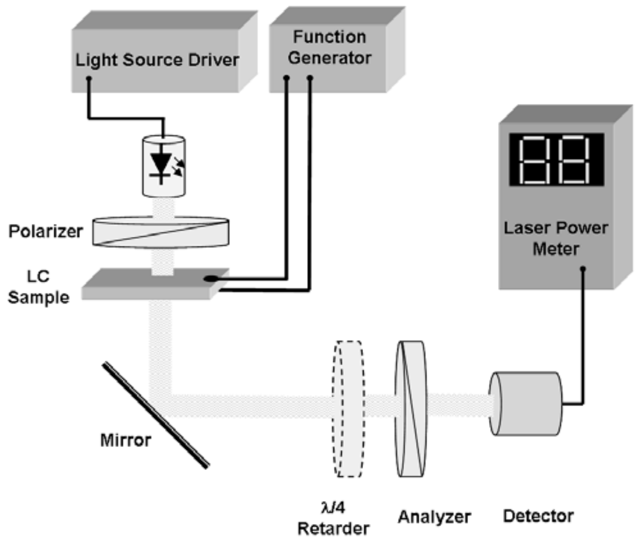

Fig. 4. The experimental setup.

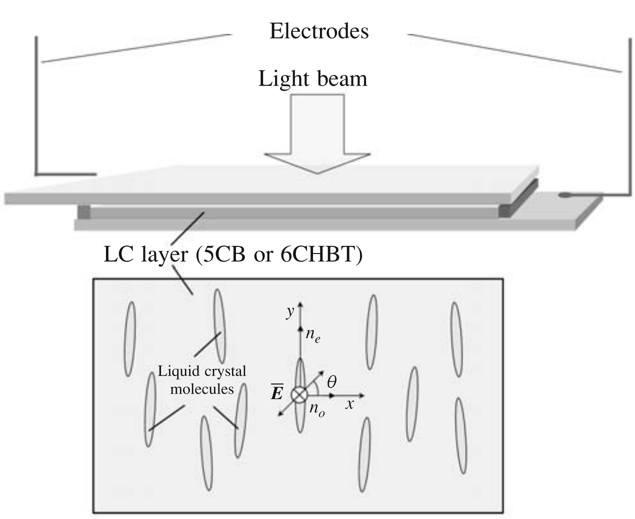

Fig. 5. The scheme of LC cell used in experiments; dimensions of the LC molecules not in scale.

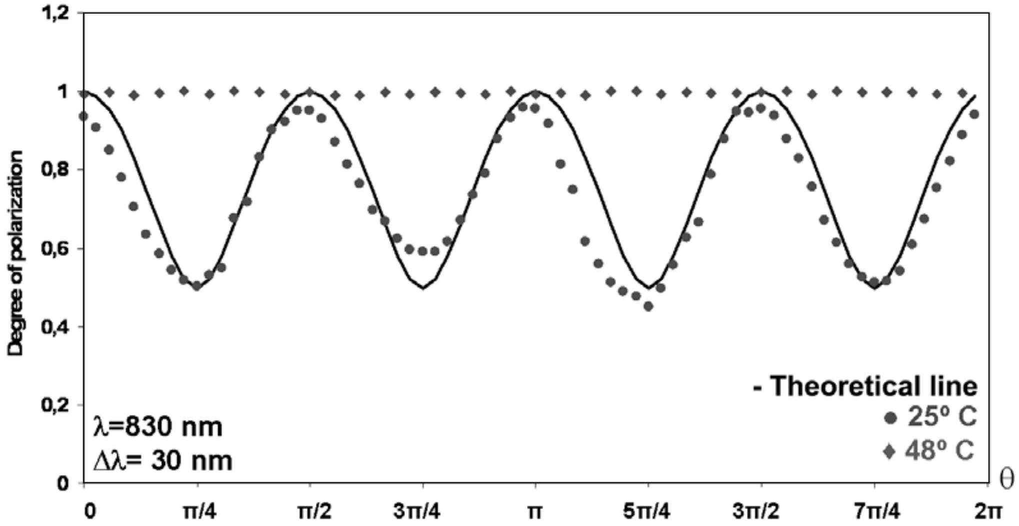

Fig. 6. Angular dependence of DOP for anisotropic (25°C) and isotropic (48°C) phases for 80-μm-thick PCB LC cell, theoretical line is plotted, based on Eq. (4), $\theta = \tan^{-1}(E_{0y}/E_{0x})$.

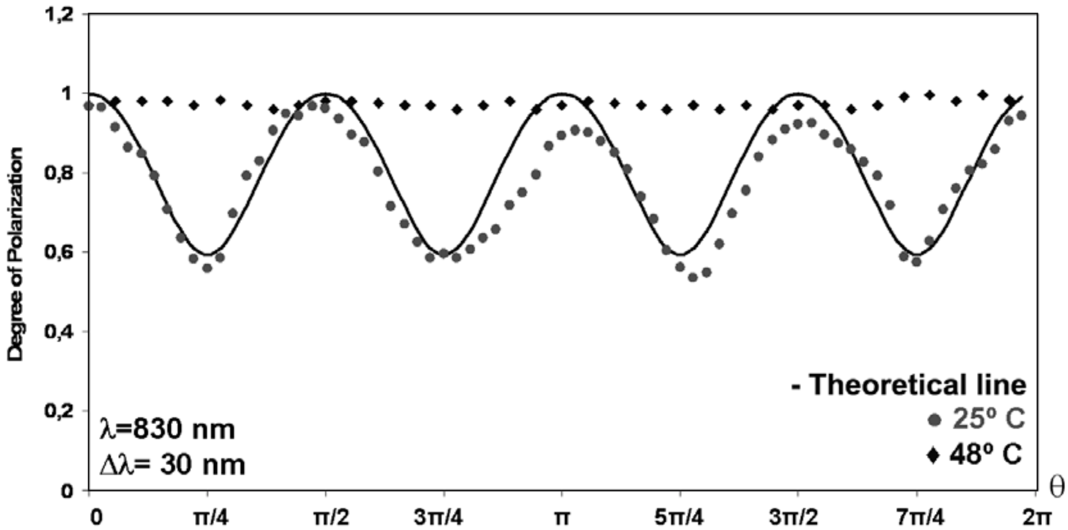

Fig. 7. Angular dependence of DOP for anisotropic (25°C) and isotropic (48°C) phases for 60-μm-thick 6CHBT LC cell.

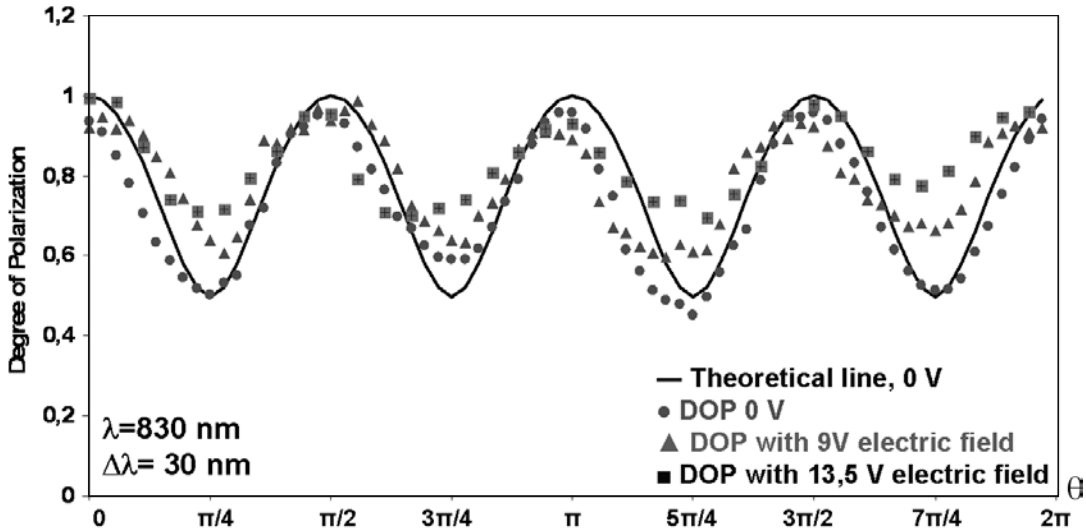

Fig. 8. Angular dependence of DOP for 80-μm-thick PCB LC cell in electric field.

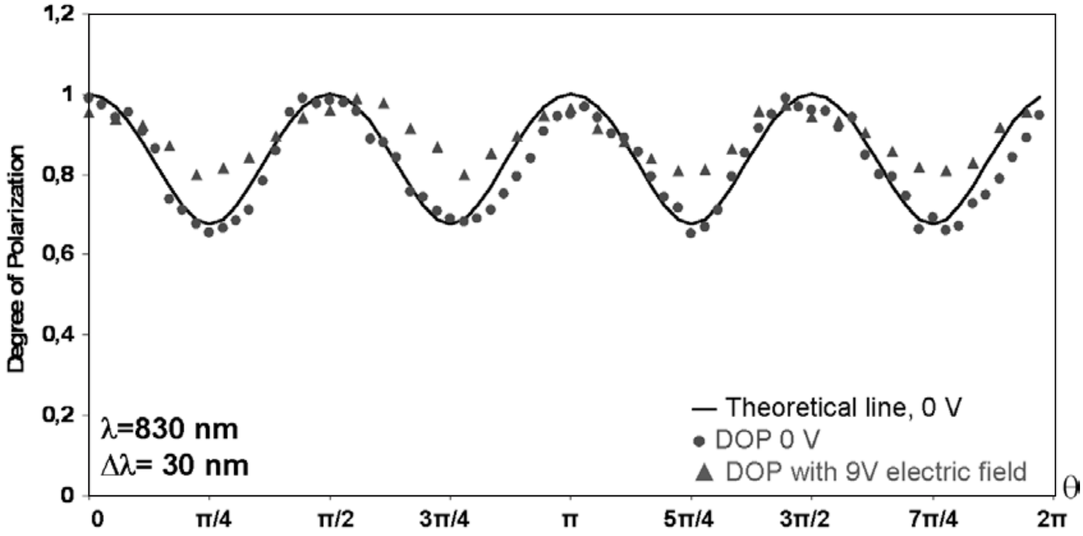

Fig. 9. Angular dependence of DOP for 60-μm-thick 6CHBT LC cell in electric field.

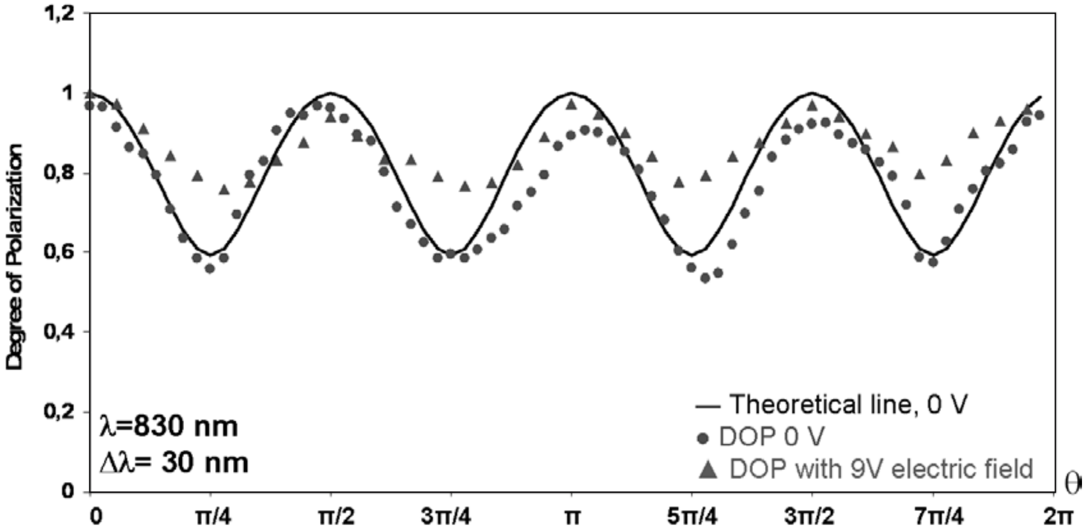

Fig. 10. Angular dependence of DOP for 80-μm-thick 6CHBT LC cell in electric field.

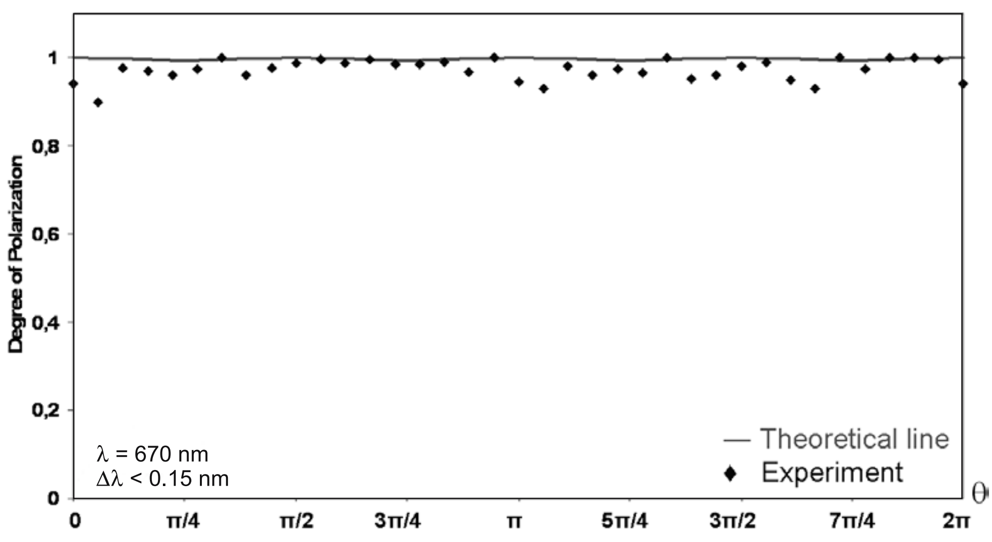

Fig. 11. Angular dependence of DOP for 80-μm-thick PCB LC cell illuminated by laser diode at 25°C.

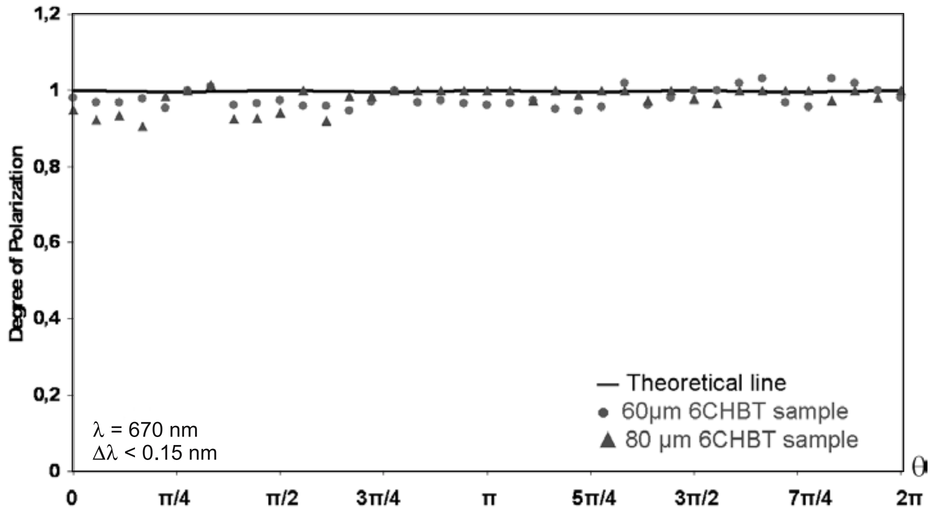

Fig. 12. Angular dependence of DOP for 60- and 80-µm-thick 6CHBT LC cells illuminated by laser diode at 25°C.

The mirror, showed in the experimental set up, does not change the DOP during our measurements.

5. Results and discussion

At the beginning, the degree of polarization for different temperatures was measured. At 25°C, the DOP varies between 0.5 and 1 for 5CB (Fig. 6). After heating the liquid crystal sample up to 48°C, the degree of polarization was 1 for all azimuths. According to the theory, the birefringence at the temperature above the clearing temperature has vanished.

The same measurement was made for 60-µm-thick 6CHBT LC cell. The degree of polarization for 6CHBT at room temperature diminishes to 0.6. After heating, the degree of polarization was 0.98 for all azimuths (Fig. 7).

Next, the birefringence in electric field was measured. The PCB LC cell was connected to the generator, as shown in Fig. 4. Without electric field (0 V), the experimental data follows the theoretical curve. When electric field was switched on, increase in DOP was observed for some azimuths (Fig. 8). The same measurements were made for 60- and 80-µm-thick 6CHBT LC cells (Figs. 9 and 10). The DOP without electric field varies between 0.66 and 0.98. Applying the 9-V electric field, the degree of polarization was between 0.8 and 0.98. We have predicted theoretically that electric field diminished the birefringence of LC cells and no depolarization should be observed. The results showed that we changed the birefringence only partially and DOP diminished slightly. We think that it was caused by too thick cells used in experiments and also too low voltage applied to the electrodes. Besides, frequency of the voltage given by generator was not optimized for electrical parameters of the LC cells.

We have also used laser diode lasing light beam with coherence length two orders of magnitude greater than for the light emitted by SLD. The DOP did not change significantly, as shown in Figs. 11 and 12, what is in a very good agreement with theoretical prediction.

6. Conclusions

Depolarization of light in liquid crystals due to scattering has been investigated for several years [5]. We have observed high depolarization of light caused by birefringence of liquid crystals when partially temporary coherent light is passing through the LC cell. The depolarization strongly depends on isotropic/anisotropic phase of liquid crystals as well as may be controlled by external electric field.

The phenomenon may have an influence on parameters of liquid crystal devices like retarders, displays, etc., particularly when low temporal coherent light sources like halogen lamp, light emitting diodes, and superluminescent diodes are used.

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