Optica Applicata, Vol. XLIV, No. 4, 2014
DOI: 10.5277/oa140405

Coloring of radiation scattered by polymer-dispersed liquid crystals

PETER MAKSIMYAK, ANDREY MAKSIMYAK, ANDREY NEHRYCH*

Correlation Optics Department, Chernivtsi University,
2 Kotsyubinsky St., Chernivtsi, 58012 Ukraine

*Corresponding author: nehrych@ukr.net

We analyze the effects of coloring of a beam traversing a light-scattering medium. Spectral investigation of the effects of coloring has been carried out using a solution of liquid crystal in a polymer matrix (polymer-dispersed liquid crystals – PDLC). It is shown that the result of coloring of the beam at the output of the medium depends on the magnitudes of the phase delays of the singly forward scattered partial signals. We consider the influence of interference coloring effect on the transmission scattering and spatial-frequency filtering of the radiation which has passed through the PDLC.

Keywords: polymer-dispersed liquid crystals, coloring effect, scattering, spatial-frequency filtering.

1. Introduction

Investigations, where the interference principle of spectrum forming was used, have been performed in optical schemes based on Michelson [1] and Fabry–Pérot interferometers [2] as well as near singular points [3–9]. Investigations of spectral transmittance were mainly performed for liquid crystal monolayers. Depending on the applied voltage, in the optical scheme with crossed polarizers, the color of polychromatic radiation that has passed through liquid crystals is formed. Polymer-dispersed liquid crystals (PDLC) can also be used as an object performing the spectral selection of polychromatic radiation depending on the applied voltage. But the nature of this phenomenon is different.

In this paper we have investigated the interference mechanism of forming of the spectrum which passes through the PDLC. For this, we have considered an experimental model of polychromatic light passing through PDLC, spatial-frequency filtering radiation by PDLC and the transmission of radiation by PDLC depending on the applied voltage.

The mechanism of coloring of a beam passing a light-scattering medium, irrespectively of the nature of this medium, can be divided into several steps:

1. Division of the illuminating beam into two components, *i.e.*, a non-scattered field and a singly forward scattered field with some phase delay (see Fig. 1);

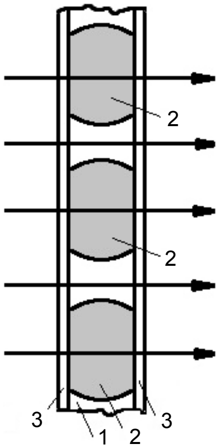

Fig. 1. Transition of radiation through PDLC: 1 – polymer, 2 – LC drops, 3 – quartz glass.

2. Interference of non-scattered with the forward scattered part of the radiation, when the zero interference fringe is observed in the resulting field;

3. Coloring of the resulting radiation due to subtracting from the spectrum of the illuminating beam the spectral component for which the average phase difference of the interfering beams is close to $\pi + 2n\pi$.

2. Experimental research

2.1. The effects of coloring of the PDLC

We have studied the effects of coloring of the composite "liquid crystal–polymer matrix". The sample of such composite permits us to study the effects of interference coloring as a function of path difference between the beams passing through polymer and liquid crystal as well as a function of the intensity ratio of such beams. Changing the path difference of the interfering beams was achieved by changing the voltage applied to the cell. Such composites are drops of a liquid crystal (LC) with sizes 10 μm dispersed in a polymer matrix (PM). We used a nematic liquid crystalline mixture E7 (Merk). As a polymer matrix, we used photopolymer composite NOA65 (Norland Company, USA) that is sensitive to ultraviolet radiation. The weight parts of the polymer and the liquid crystal are 1:2. The components are carefully mixed at a temperature of 20°C. A drop of the mixture is placed between two glass plates covered with conducting ITO films. The thickness of the composite layer is 10 μm being controlled by spacers. The cell is assembled with UV-curing glue. Figure 2 shows the area of the studied sample of the size (100×75) μm in crossed polarizers and Fig. 3 shows the histogram of the drop size distribution.

Phase separation results in formation of an optically inhomogeneous medium which strongly scatters the light. The intensity of the scattered light depends on the differences in the refractive indices between LC drops and polymer. The index of refraction of the photopolymer NOA65 (n = 1.524) is close to the ordinary refractive index of

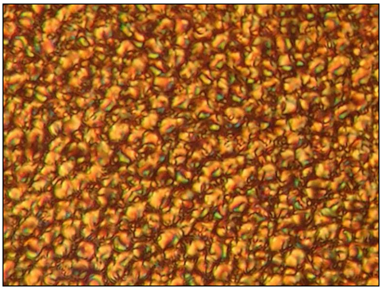

Fig. 2. Microphotograph of the PDLC in the crossed polarizers.

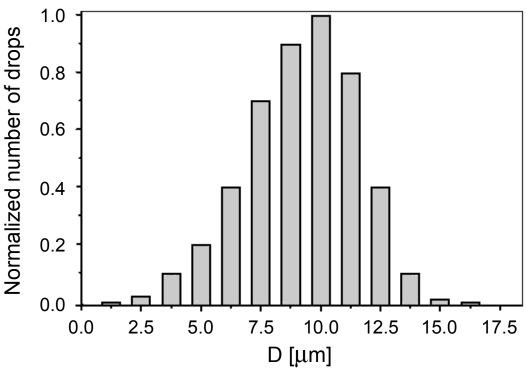

Fig. 3. Histogram of the drop size distribution.

a liquid crystal E7 (n = 1.521). Birefringence of LC E7 is Δn = 0.225. Generally, optical axes of LC drops without applied voltage are oriented chaotically. Applying an electrical current results in orientation of the optical axes of LC drops along the direction of the illuminating beam incidence (we consider the case of normal incidence, *cf*. Fig. 1). Increasing the applied voltage results in equalizing the magnitudes of the refraction indices of LC and PM and, hence, in increasing the transmittance of the system. Decreasing the voltage will increase the path difference between the components passing the LC and PM in the forward direction, and thus increases light scattering.

The experimental arrangement is shown in Figure 4.

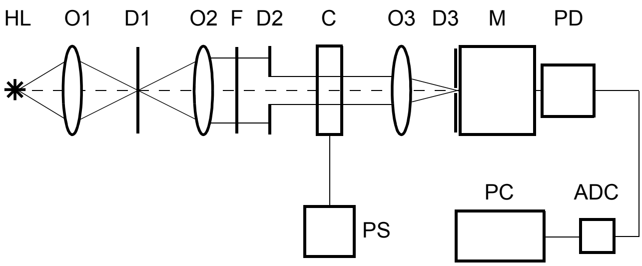

Fig. 4. Experimental arrangement: HL – radiation source, D1, D2, D3 – diaphragms, O1, O2, O3 – objectives, F – spectral filter, C – studied cell, M – monochromator, PD – photodetector, ADC – analogue-to-digital converter, PC – computer, PS – power supply.

Such optical system facilitates the selection of the regular component of radiation scattered by PDLC. The spectrum of the regular component of radiation is measured using a monochromator. The electrical signal of the photodetector is transferred to the computer. One applies an alternating voltage to the studied PDLC from the generator.

The partial beams passing the drops of LC and polymer travel along different paths, and can be considered at far field as plane waves with some phase difference. The change in the effective refractive index of the LC drops in the direction of radiation, and thus the change in the path difference between the beams is the reason that changing the applied voltage leads to redistribution between transmittance and light scattering of PDLC.

The results of such processing of the data of experimental measurements are represented in Fig. 6. For a voltage of 3.2 V one observes a dip in the blue domain of the spectrum. It means that the path difference between two interfering components provides the opposite phases of the "blue" components. Investigations of PDLC by

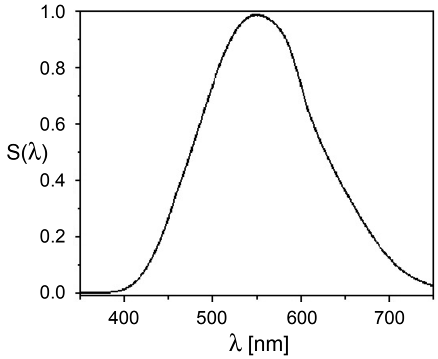

Fig. 5. Spectrum of the illuminating beam.

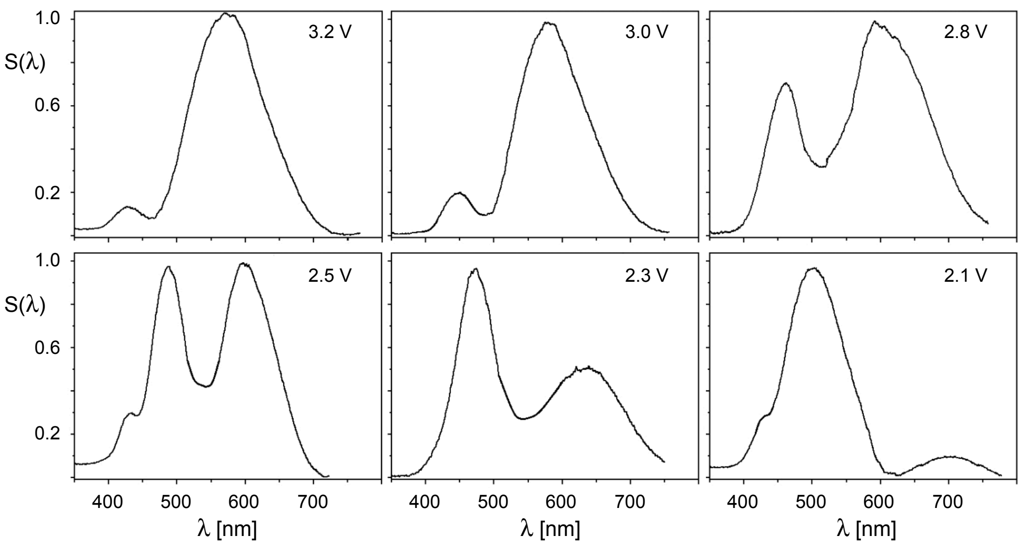

Fig. 6. The transmission spectra for different applied voltages.

a microinterferometer with a calibrated path difference showed that at the voltage of 3.2 V the opposite phase is achieved when the path difference is equal to 690 nm. From the condition of the opposite phases for the spectral component $3\lambda_b/2 = 690$ nm, one finds $\lambda_b = 460$ nm. For a decrease in the applied voltage, the path difference between the interfering beams increases and one observes a shift in the spectral gap from the blue domain to the red one.

2.2. The model experiment with Michelson interferometer

To confirm the experimental results obtained for PDLC, we perform the model experiment in which studied polychromatic radiation is passing through a Michelson interferometer (Fig. 7).

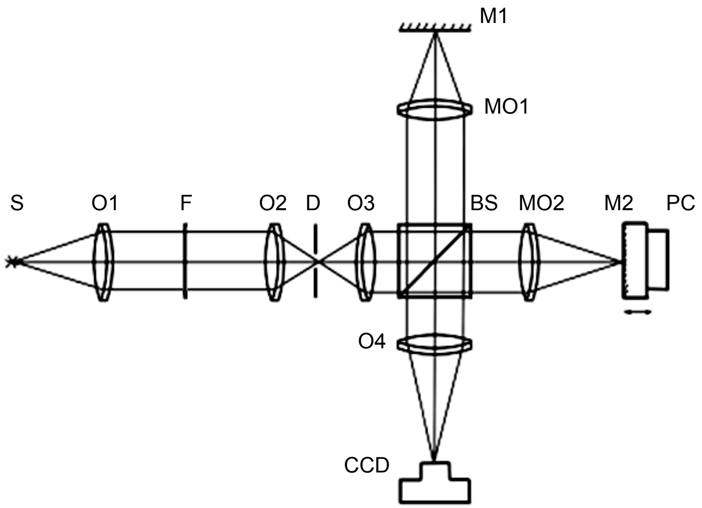

Fig. 7. Experimental arrangement: S – source; O1, O2, O3 and O4 – objectives; M1, M2 – mirrors; D – diaphragm; BS – beam-splitter; MO1 and MO2 – microobjectives; PC – piezo-ceramics.

The mirror M2 is shifted along the direction of propagation of the beam, facilitating a controlled change in the optical path delay in the interferometer. One can detect the resulting field and record the interferogram at a zero interference fringe using a CCD-camera.

The experimental results are obtained with a coaxial interference of the two fields of equal amplitudes. In Fig. 8 we present an interferogram where the coloring effect is observed within each interference fringe.

The output spectrum can be calculated by the interference law for the spectral region:

$$S(\lambda) = \frac{1}{2} S_0(\lambda)\left[1 + \cos(\Delta\varphi)\right]$$

where $S_0(\lambda)$ is the radiation source spectrum, the phase difference $\Delta\varphi$ is given by $\Delta\varphi = 2\pi\Delta l/\lambda$ where Δl is the path difference between the interfering beams.

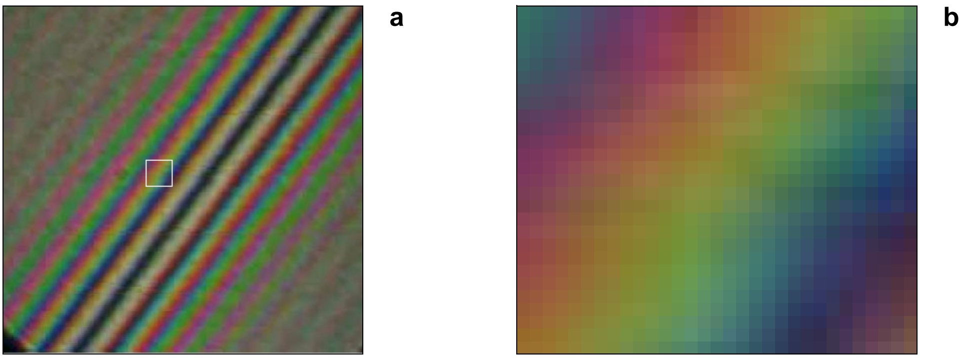

Fig. 8. Interferogram (**a**); investigated area of interferogram (**b**).

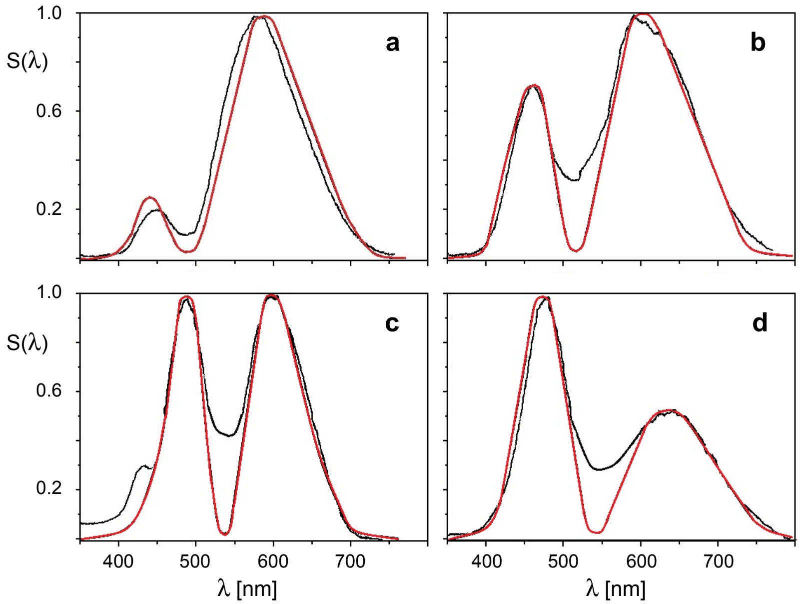

Fig. 9. Changing spectrum of radiation that has passed through a Michelson interferometer (red line) and PDLC (black line).

Smoothly changing the path difference in the interferometer arms, the spectral dependences represented in Fig. 9 (red line) have been obtained. We compare the results. In both cases there is a decrease in certain spectral component, because the path difference between the interfering components leads to antiphase. But spectral minima were deeper than in the experiment with a Michelson interferometer because the radiation intensities in the reference and object interferometer arms are strictly equal.

Selecting PDLC sample thickness and components concentration, one can increase the modulation depth and use PDLC such as operating spectral filters.

Further we consider some possible practical applications of the spectral filtering effect by PDLC.

3. Spatial-frequency filtering by PDLC

For experimentally obtained PDLC scattering indicatrix at small angles a significant redistribution of radiation intensity subject to applied voltage was observed, which provided the possibility of spatial-frequency filtering (see Fig. 10).

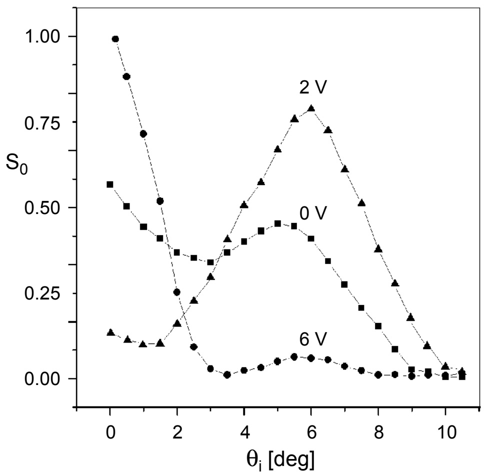

Fig. 10. Scattering indicatrix S_0 at small angles region for voltages 0, 2, and 6 V.

When voltage applied to PDLC is equal to zero, the scattering indicatrix S_0 has two maxima for scattering angles 0 and 5°. In this case, the incident radiation is partially transmitted and partially scattered by a PDLC sample. When voltage equals 2 V, the maximum of the regular component is not observed – transition is actually absent; whereas the regular component for $\lambda = 633$ nm is decreased by interference, the sample scatters radiation strongly. The maximum of the scattering indicatrix S_0 corresponds to the scattering angle 6°. When the applied voltage is equal to 6 V, PDLC transmits the regular component of radiation. This component is increased by interference, and the scattered component of radiation is actually absent.

For experimental investigation of spatial-frequency filtering of test images, the optical scheme shown in Fig. 11 has been used. As a test image, we used a fragment of the fifth-order Sierpinski fractal of the minimum element size 25 μm.

At zero voltage (Fig. 12) the filtering is absent and the PDLC transmits high as well as low spatial frequencies. All elements of the fractal are observed. At voltage 2 V a PDLC layer is a spatial filter of high frequencies. High spatial frequencies are scattered, whereas low spatial frequencies are quenched by interference. The minimal elements of the fractal are seen in the image, in the absence of other elements. At 6 V

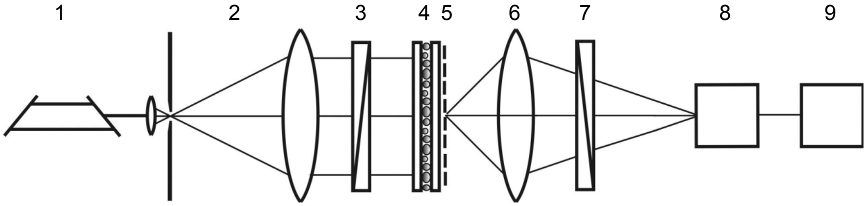

Fig. 11. Optical scheme: 1 – He-Ne laser (λ = 632.8 nm), 2 – collimator, 3, 7 – polarizer, 4 – PDLC cell, 4 – objective, 5 – photomask, 6 – objective (d = 2 cm, f = 8 cm), 8 – CCD-camera, 9 – computer.

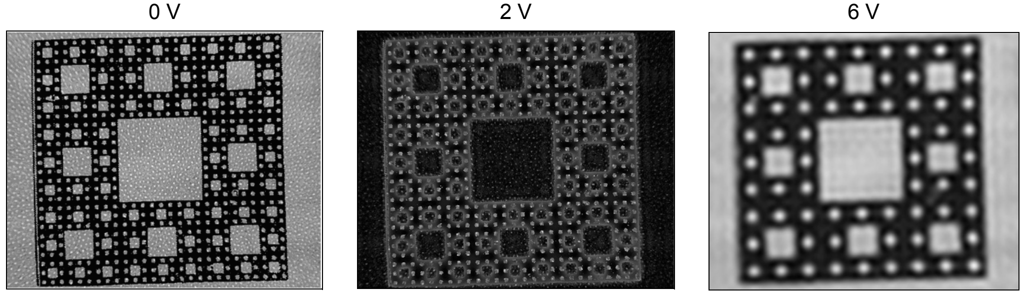

Fig. 12. Experimentally obtained images of a photomask fragment.

we can observe all elements of the fractal, except for minimal. In this case a PDLC layer is a spatial filter of low frequencies. The regular component of radiation and the scattered component in the regular aperture are transmitted.

4. Optical correlation investigations of PDLC

In the framework of the random phase screen (RPS) model, we used an optical correlation technique for measuring statistical characteristics of a field, which allowed to determine the statistical characteristics of PDLC.

The optical scheme of the experiment is based on the Mach–Zehnder interferometer (Fig. 13). Transverse displacement between the beams in the interferometer is set by moving one of the mirrors. The transverse coherence function is determined by measuring the resulting field visibility in a zero interference fringe.

It is difficult to divide the regular and scattered components of radiation by limiting an aperture. One can do this interferentially, within the framework of the RPS model, by investigating the dependences of the phase variance σ^2, which characterizes the scattered component and transmittance T, on the voltage for different polymer concentrations (Fig. 14). For PDLC with polymer concentration 15% and 20%, one observes the minimum of transmittance at a voltage of 2 V. This is due to the interference of the partial beams that have passed through the LC and the polymer, which leads to the suppression of a red spectral component. Moreover, PDLC with 15% of polymer may be used as effective optical shutters because of a small change in the applied voltage aimed at a great change in transmitted radiation.

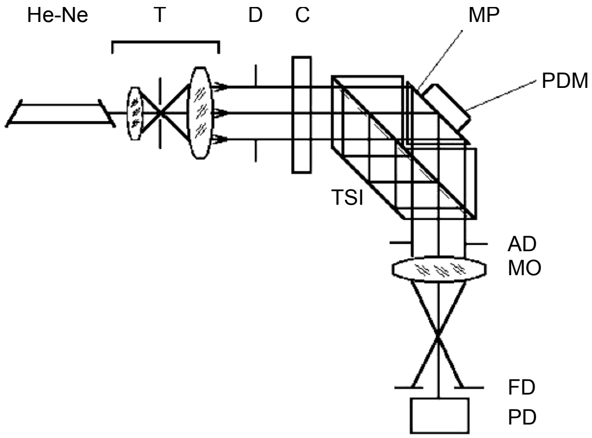

Fig. 13. Experimental arrangement: He-Ne – laser ($\lambda = 632.8$ nm), T – inverse telescopic system, D – diaphragms, C – PDLC cell, TSI – transverse-scanning interferometer, MP – movable prism, PDM – prism displacement mechanism, FD – field-of-view diaphragm, MO – microobjective, AD – aperture diaphragm, PD – photodetector.

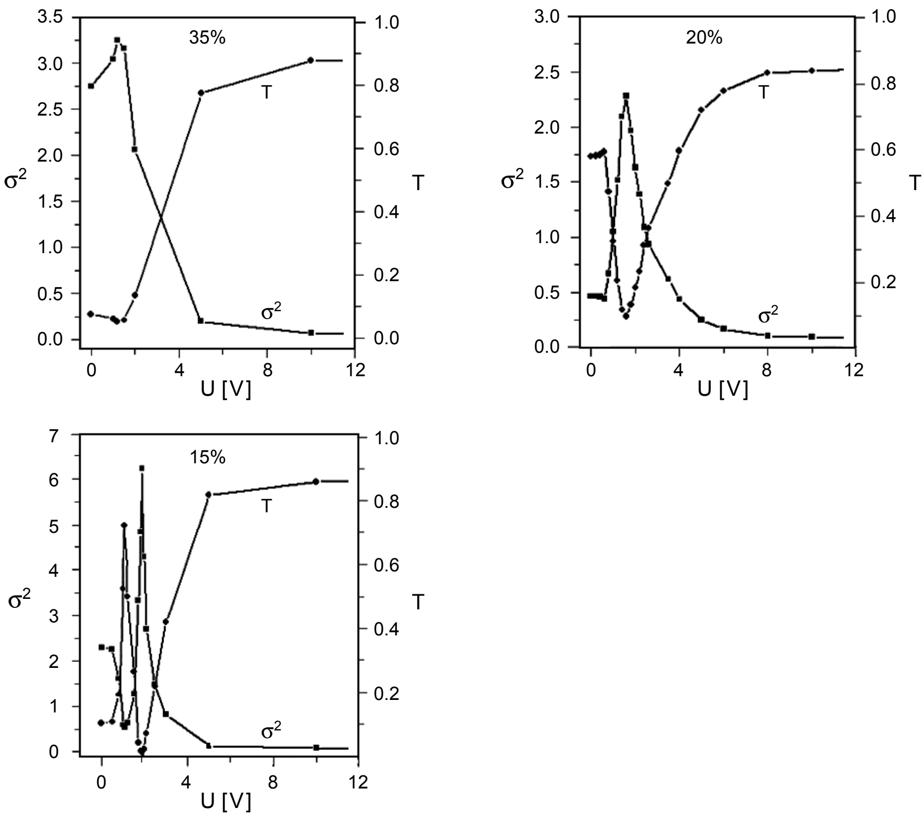

Fig. 14. Phase variance σ^2 and transmittance T of PDLC with different polymer concentrations.

5. Conclusions

We have illustrated the interference origin of the mechanisms of coloring the radiation passing through PDLC in the forward direction. It has been shown that coloring of the output beam from PDLC depends on the magnitudes of the phase delays for singly scattered forward partial signals.

Interference origin of the coloring effect has been confirmed by the model experiment based on the Michelson interferometer.

Experimentally investigated effects of spatial-frequency filtering of radiation by PDLC and anomalous behavior in interference transition of radiation by PDLC are based on the phenomena of an interference decrease in a red (λ = 632.8 nm) spectral component in PDLC with polymer concentration φ_p = 15% at a voltage of about 2 V.

References

[1] BRUNDAVANAM M.M., VISWANATHAN N.K., DESAI N.R., *Spectral anomalies due to temporal correlation in a white-light interferometer*, Optics Letters **32**(16), 2007, pp. 2279–2281.

[2] AHARON O., ABDULHALIM I., *Liquid crystal Lyot tunable filter with extended free spectral range*, Optics Express **17**(14), 2009, pp. 11426–11433.

[3] ANGELSKY O.V., HANSON S.G., MAKSIMYAK P.P., MAKSIMYAK A.P., NEGRYCH A.L., *Experimental demonstration of singular-optical colouring of regularly scattered white light*, Journal of the European Optical Society – Rapid Publications **3**, 2008, article 08029.

[4] ANGELSKY O., MOKHUN A., MOKHUN I., SOSKIN M., *The relationship between topological characteristics of component vortices and polarization singularities*, Optics Communications **207**(1–6), 2002, pp. 57–65.

[5] ANGELSKY O.V., BESAHA R.N., MOKHUN I.I., *Appearance of wave front dislocations under interference among beams with simple wave fronts*, Optica Applicata **27**(4), 1997, pp. 273–278.

[6] ANGELSKY O.V., POLYANSKII P.V., HANSON S.G., *Singular-optical coloring of regularly scattered white light*, Optics Express **14**(17), 2006, pp. 7579–7586.

[7] ANGELSKY O.V., POLYANSKII P.V., FELDE C.V., *The emerging field of correlation optics*, Optics and Photonics News **23**(4), 2012, pp. 25–29.

[8] ANGELSKY O.V., USHENKO A.G., BURKOVETS D.N., USHENKO YU.A., *Polarization visualization and selection of biotissue image two-layer scattering medium*, Journal of Biomedical Optics **10**(1), 2005, article 014010.

[9] ANGEL'SKII O.V., USHENKO A.G., ERMOLENKO S.B., BURKOVETS D.N., PISHAK V.P., USHENKO YU.A., PISHAK O.V., *Polarization-based visualization of multifractal structures for the diagnostics of pathological changes in biological tissues*, Optics and Spectroscopy (English translation of Optika i Spektroskopiya) **89**(5), 2000, pp. 799–804.

Received June 5, 2014