UDC 681.7:520
DOI: 10.20535/2077-7264.2(76).2022.265684

© O. H. Ushenko, Doctor of physics and mathematics of science, Professor, I. V. Soltys, PhD in physics and mathematics science, Associate professor, O. V. Dubolazov, Doctor of physics and mathematics of science, Associate professor, M. M. Matymish, student, Chernivtsi National University, Chernivtsi, O. H. Liniuchev, PhD in technical science, Assistant, Igor Sikorskyi KPI, Kyiv, Ukraine

POLYGRAPHIC LASER TOMOGRAPHY SYSTEM AND ALGORITHMS FOR COMPUTER DIGITAL RECONSTRUCTION OF THE BULK STRUCTURE OF POLYMERIC MATERIALS

A method of 3D Mueller-matrix reproduction of the distributions of the parameters of linear and circular birefringence and dichroism of partially depolarizing methyl acrylate layers is proposed and substantiated. The dynamics of the change in the value of the statistical moments of the 1st–4th orders characterizing the distributions of the optical anisotropy parameters of the polycrystalline structure of the partially depolarizing methyl acrylate layer in various 'phase' sections of its volume is investigated and analyzed.

Keywords: laser reconstruction; optical anisotropy; polymers; acrylate; diagnostics.

Introduction

Traditionally, the methods and tools of Mueller-matrix polarimetry (MMP) have been developed within the framework of two limiting approximations. The first is the search for relationships between angular (1D Indicatrix) and coordinate (2D Mueller-matrix images — MMI) distributions of the Mueller matrix elements and the structure of polymer layers [1–7]. The second is the MMP of optically thin, non-depolarizing polymer films [6–10] with subsequent reproduction of the distributions of the parameters of phase and amplitude anisotropy.

The further development and generalization of the MMP techniques of the 3D polycrystalline structure of methyl acrylate layers with different light scattering multiplicity or different depolarizing ability is urgent.

Our article is aimed at the development and experimental testing of the 3D Mueller-matrix method for reproducing the distributions of the phase and amplitude aniso-

ISSN 2077-7264. Технологія і техніка друкарства. 2022. № 2(76)

tropy parameters of partially depolarizing methyl acrylate layers of various optical thicknesses.

Method

Dependence of matrix polarimetry is analytically illustrated by the equation [1–6]

$$d\|B\|/dz = \|B(z)\|\|D(z)\|, \qquad (1)$$

where $\|B(z)\|$ — Mueller matrix of the object in the plane z, $\|D(z)\|$ — differential matrix operator.

For optically thin layers, which do not depolarize, but transform the polarization of the probing beam, the matrix operator $\|D(z)\|$ consists of six parameters, that completely describe phase and amplitude anisotropy of the biological layer

$$\|D\| = \begin{Vmatrix} 0 & \Delta_{0,90} & \Delta_{45,135} & \Delta_{\otimes,\oplus} \\ \Delta_{0,90} & 0 & \Phi_{\otimes,\oplus} & -\Phi_{45,135} \\ \Delta_{45,135} & -\Phi_{\otimes,\oplus} & 0 & \Phi_{0,90} \\ \Delta_{\otimes,\oplus} & \Phi_{45,135} & -\Phi_{0,90} & 0 \end{Vmatrix}. \qquad (2)$$

Here

— $\Delta_{0,90}$, $\Delta_{45,135}$ — linear dichroism;

— $\Phi_{0,90}$, $\Phi_{45,135}$ — linear birefringence for orthogonal components 0°–90° and 45°–135°;

— $\Delta_{\otimes,\oplus}$ and $\Phi_{\otimes,\oplus}$ — circular dichroism and birefringence for right- (⊗) and left- (⊕) circularly polarized components.

Parameters of phase and amplitude anisotropy determined by the following relations:

$$\Phi_{0,90} \equiv \delta_{0,90} = \frac{2\pi}{\lambda}\Delta n_{0,90} l; \quad \Delta n_{0,90} = n_0 - n_{90}; \qquad (3)$$

$$\Phi_{45;135} \equiv \delta_{45;135} = \frac{2\pi}{\lambda}\Delta n_{45;135} l; \quad \Delta n_{45;135} = n_{45} - n_{135}; \qquad (4)$$

$$\Phi_{\otimes,\oplus} \equiv \phi = \frac{2\pi}{\lambda}\Delta n_{\otimes,\oplus} l; \quad \Delta n_{\otimes,\oplus} = n_{\otimes} - n_{\oplus}; \qquad (5)$$

$$\Delta_{0,90} \equiv \tau_{0;90} = \frac{2\pi}{\lambda}\Delta\tau_{0;90} l; \quad \Delta\tau_{0,90} = \tau_0 - \tau_{90}; \qquad (6)$$

$$\Delta_{45;135} \equiv \tau_{45;135} = \frac{2\pi}{\lambda}\Delta\tau_{45;135} l; \quad \Delta\tau_{45;135} = \tau_{45} - \tau_{135}; \qquad (7)$$

$$\Delta_{\otimes;\oplus} \equiv \chi_{\otimes;\oplus} = \frac{2\pi}{\lambda}\Delta\tau_{\otimes;\oplus} l; \quad \Delta\tau_{\otimes;\oplus} = \tau_{\otimes} - \tau_{\oplus}. \qquad (8)$$

Here n_j and τ_j — refractive indices and absorption for orthogonal polarized components (0°–90°, 45°–135° and ⊗–⊕) amplitudes of laser irradiation.

In the future (without reducing the completeness of the analysis) according to [7] we consider the generalized parameters of linear birefringence (Φ) and dichroism (Δ)

$$\Phi = \sqrt{\Phi^2_{0;90} + \Phi^2_{45;135}}; \qquad (9)$$

$$\Delta = \sqrt{\Delta^2_{0;90} + \Delta^2_{45;135}}. \qquad (10)$$

On a series of fragments in fig. 1 shows a schematic arrangement of the main optical units of a polarization interferometer, which implements layer-by-layer three-dimensional reconstruction of the parameters of the polycrystalline architectonics of polymer layers.

The illuminating beam of the gas He-Ne laser *1* with the help of a system

ISSN 2077-7264. Технологія і техніка друкарства. 2022. № 2(76)

ISSN 2077-7264. Технологія і техніка друкарства. 2022. № 2(76)

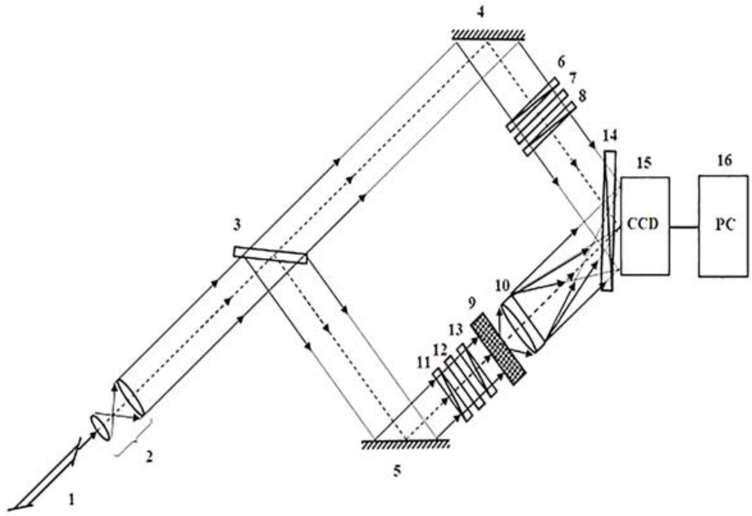

Fig. 1. Optical layout of a polarization Muller-matrix interferometer

of microobjectives *2* is converted into a parallel optical probe, which is divided by an optical cube *4* into illuminating and reference.

'The irradiating one' with the help of a rotating mirror *4* is directed through the polarizing filter *6–8* in the direction of the sample of the biological layer *9*. The polarization-inhomogeneous image of the object *9* is projected by the lens *10* into the plane of the digital camera *14*. 'The reference' beam is directed by the mirror *5* through the polarization filter *11–13* into the plane of the polarization-inhomogeneous image of the object *9*. As a result, an interference pattern is formed, which is recorded by a digital camera *14*. The formation of polarization states of the 'irradiating' and 'reference' beams is carried out using polarizing filters *6–8* and *11–13*, each of which contains two linear polarizers and a quarter-wave plate.

Results

Layered maps of phase and amplitude anisotropy parameters of methyl acrylate layers.

A series of fragments in fig. 2–5 shows the polarization-reproduced

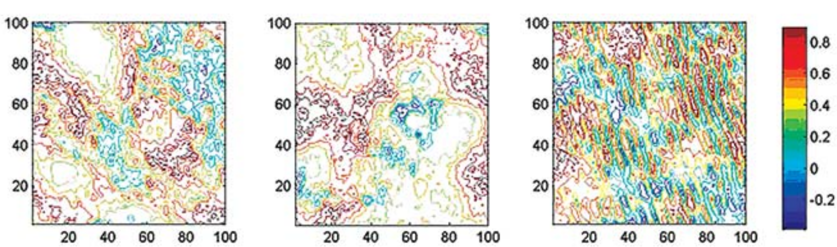

Fig. 2. Layer-by-layer 2D distributions of the linear birefringence (LB) of the partially depolarizing (τ = 1,02) methyl acrylate layer

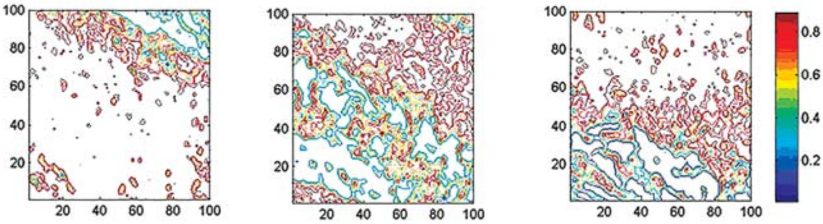

Fig. 3. Layer-by-layer 2D distributions of the linear dichroism (LD) of the partially depolarizing (τ = 1,02) methyl acrylate layer

2D distributions of the linear and circular birefringence and dichroism of an optically anisotropic fibrillar network of an optically thick layer (attenuation coefficient $\tau = 1{,}02$, degree of depolarization Λ = 57 %) of methyl acrylate in three 'phase' sections — $\phi_1 = 0{,}6$; $\phi_2 = 0{,}9$; $\phi_3 = 1{,}2$.

Discusion

From the analysis of the data shown in fig. 2–5 series of experimentally reproduced layer-by-layer distributions of the linear and circular birefringence (LB, CB) and dichroism (LD, CD) of the polycrystalline structure of methyl acrylate layers follows the presence individual structure of its parameters for each type of optical 3D anisotropy.

Comparison of the coordinate distributions of linear birefringence LB and dichroism LD revealed their dependences both on the 'phase' cross section h and on the type of optical anisotropy.

From a physical point of view, this fact can be associated with the peculiarities of the polycrystalline structure of the methyl acrylate layers. For small values of ($\phi \prec 0{,}6$), single scattering prevails in the volume of methyl acrylate. Therefore, within the framework of the corresponding partial phase cross sections of 3D distributions LB(ϕ, x, y) and LD(ϕ, x, y), there is a direct relationship between the polycrystalline structure of methyl acrylate layers and the value of linear birefringence. An increase in the level ϕ corresponds to a large multiplicity of light scattering, which leads to averaging of the parameters of linear birefringence and dichroism.

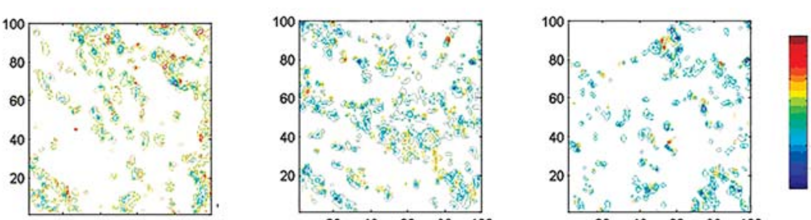

Fig. 4. Layer-by-layer 2D distributions of the circular birefringence (CB) of the partially depolarizing (τ = 1,02) methyl acrylate layer

ISSN 2077-7264. Технологія і техніка друкарства. 2022. № 2(76)

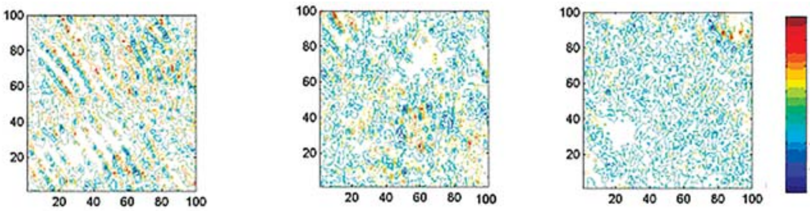

Fig. 5. Layer-by-layer 2D distributions of the circular dichroism (CD) of the partially depolarizing (τ = 1,02) methyl acrylate layer

A different picture takes place in the case of 3D polarization reproduction of volumetric distributions of the magnitude of circular birefringence CB(ϕ, x, y) and dichroism CD(ϕ, x, y). Layer-by-layer maps of these parameters of phase and amplitude anisotropy.

Conclusions

A method of 3D Muller-matrix reproduction of the distributions of the parameters of linear and circular birefringence and dichroism of partially depolarizing methyl acrylate layers is proposed and substantiated.

The dynamics of the change in the value of the statistical moments of the 1st–4th orders, characterizing the distributions of the optical anisotropy parameters of the polycrystalline structure of the partially depolarizing layer (τ = 1,02; Λ = 57 %) methyl acrylate in various 'phase' sections of its volume, has been investigated and analyzed.

References

1. Tuchin, V. V. (2015). Tissue optics and photonics: biological tissue structures [review]. *J. Biomed. Photonics Eng.*, 1(1), 3–21.

2. Tuchin, V. V. (2015). Tissue optics and photonics: light-tissue interaction [review]. *J. Biomed. Photonics Eng.*, 1(2), 98–134.

3. Manhas, S., & et al. (2006). Mueller matrix approach for determination of optical rotation in chiral turbid media in backscattering geometry. *Opt. Express*, 14(1), 190–202.

4. Deng, Y., & et al. (2007). Characterization of backscattering Mueller matrix patterns of highly scattering media with triple scattering assumption. *Opt. Express*, 15(15), 9672–9680.

5. Ushenko, A. G., & Pishak, V. P. (2004). *Laser Polarimetry of Biological Tissue: Principles and Applications*. in Handbook of Coherent-Domain Optical Methods: Biomedical Diagnostics, Environmental and Material Science, vol. I. Ed. by Tuchin, V. V. Boston: Kluwer Academic Publishers, pp. 93–138.

6. Angelsky, O. V., Ushenko, A. G., Ushenko, Yu. A., Pishak, V. P., & Peresunko, A. P. (2010). *Statistical, Correlation and Topological Approaches in Diagnostics of the Structure and Physiological State of Birefringent Biological Tissues*. in Handbook of Photonics for Biomedical Science, pp. 283–322. Ed. by V. Tuchin, V. CRC PressTaylor&Francis group: Boca Raton, London, New York.

ISSN 2077-7264. Технологія і техніка друкарства. 2022. № 2(76)

7. Ushenko, Y. A., Boychuk, T. M., Bachynsky, V. T., & Mincer, O. P. (2013). *Diagnostics of Structure and Physiological State of Birefringent Biological Tissues: Statistical, Correlation and Topological Approaches.* in Handbook of Coherent-Domain Optical Methods, Springer Science+Business Media, p. 107, New York.

8. Lu, S. Y., & Chipman, R. A. (1996). Interpretation of Mueller matrices based on polar decomposition. *J. Opt. Soc. Am.*, A 13(5), 1106–1113.

9. Ushenko, V. A., Dubolazov, O. V., & Karachevtsev, A. O. (2014). Two wavelength Mueller matrix reconstruction of blood plasma films polycrystalline structure in diagnostics of breast cancer. *Applied Optics*, 53(10), B128–B139.

10. Prysyazhnyuk, V. P., Ushenko, Yu. A., Dubolazov, A. V., Ushenko, A. G., & Ushenko, V. A. (2016). Polarization-dependent laser autofluorescence of the polycrystalline networks of blood plasma films in the task of liver pathology differentiation. *Appl. Opt.*, 55, B126–B132.

В науковій статті представлено матеріали, які висвітлюють новий експериментальний метод поляризаційної томографії полікристалічної структури полімерних фазово-неоднорідних шарів. Метод заснований на формалізмі векторно-параметричного опису лазерних полів за допомогою параметрів вектора Стокса.

Ключові слова: лазерна реконструкція; оптична анізотропія; полімери; акрилат; діагностика.

Надійшла до редакції 27.09.22