Order parameter of elongated liquid crystal droplets: The method of retrieval by the coherent transmittance data

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(Received 9 December 2005; published 12 September 2006)

The inverse light-scattering problem for polymer dispersed liquid crystal film is considered. An optical method to retrieve the tensor order parameter of liquid crystal droplets arranged in a monolayer has been developed. The method is based on the measurement of coherent transmission coefficients of film at normal illumination and comparison with the results of the direct light-scattering problem solution. To find the coherent transmission coefficient, the anomalous diffraction approach, and the approximation of effective refractive indices are used. The dependence of the tensor order parameter on the applied voltage for elongated liquid crystal droplets with the rigidly fixed poles is retrieved by the available experimental data. The obtained results are in correlation with the results of known visual observations of liquid crystal droplet structure and calculations of the director field in droplets with rigidly-fixed poles.

DOI: 10.1103/PhysRevE.74.031704 PACS number(s): 42.70.Df, 61.30.−v

I. INTRODUCTION

There are many types of composite liquid crystal (LC) materials. Among them are polymer-dispersed liquid crystal (PDLC) films. In PDLC films the liquid crystal droplets are embedded into a solid polymer matrix. The molecular organization inside the droplet depends on the boundary conditions imposed by anchoring on the droplet surface [1–5]. Under the applied electric field the orientation of LC molecules changes. The effect of controlled light scattering is implemented. The electro-optical response of PDLC film depends on the configuration of liquid crystal molecules in the droplet, size, and shape of the LC droplets, their concentration in a layer, parameters of polymer matrix, film thickness, and the applied voltage. PDLC films are widely studied for use in various practical applications (light modulators, optical shutters, TV projection systems, displays, color filters, polarizers, etc.) [6,7]. To optimize their characteristics we have to know that parameters and their influence on the electro-optical response. That is why the development of methods of their determination is an important problem of optics of PDLC films.

At present the rigorous solutions for the direct light-scattering problem (calculation of characteristics of scattered light by the known particle and film parameters) for some types of films are developed. The solution of the inverse light-scattering problem (determination of particle and/or film parameters from the characteristics of scattering light) is much less tractable, even for films with homogeneous spherical particles. Liquid crystal droplets are inhomogeneous particles. It dramatically complicates the solution of the direct and inverse light-scattering problems.

The phenomenological theory for investigation of PDLC films [8–15] uses molecular S (to describe the orientation of molecules in an elementary volume of LC), droplet S_d (to describe the orientation structure of LC molecules in the droplet), and film S_f [to describe the orientation of directors (optical axes) of the LC droplets in the film] order parameters. This hierarchy of order parameter was introduced by the authors of Ref. [10]. In the case of the cylindrical symmetry the scalar order parameters are used. In general, to describe the orientation structure of PDLC films and other composite materials (polymeric nets, porous glasses, field nematics, etc.) it is necessary to use tensor order parameter. That parameter affords a basis for investigation of light propagation in PDLC films. The problem is how to extract order parameter. It can be based on the inverse light-scattering problem solution. As for any inverse light-scattering problem, there is no general technique for its solution. The method depends on the type of the film. Here we consider PDLC films containing aligned elongated LC droplets with rigidly fixed poles. The films are manufactured by the unidirectional stretching. The stretching causes the transformation of initially spherical LC droplets into the ellipsoidal ones. This type of films was discovered by the authors of Ref. [16]. The films are used as the scattering polarization optical elements and intensity light modulators [17–19].

In the present paper we propose a method for the retrieval of tensor order parameter of aligned spherical and ellipsoidal nematic LC droplets. We solve the direct problem of determining the coherent transmission coefficient of the PDLC film in which LC droplets are arranged in a monolayer. Components of the tensor order parameter are retrieved by the comparison of theoretical results for the direct problem solution with the experimental dependence of the coherent transmission coefficient on the applied voltage. The applicability of the method is demonstrated with the experimental data for films containing elongated LC droplets with rigidly fixed poles [20–22].

II. COHERENT TRANSMISSION COEFFICIENT OF THE PDLC MONOLAYER

Consider a PDLC monolayer in which the ellipsoidal nematic LC droplets with semiaxes a, b, c are oriented by their long axes mainly along the x axis (Fig. 1). In the laboratory frame (x,y,z) the plane (x,y) coincides with the plane of the monolayer and the z axis is normal to the layer. In the absence of applied voltage to the internal orientation structure of the LC droplets with rigidly fixed poles has axial

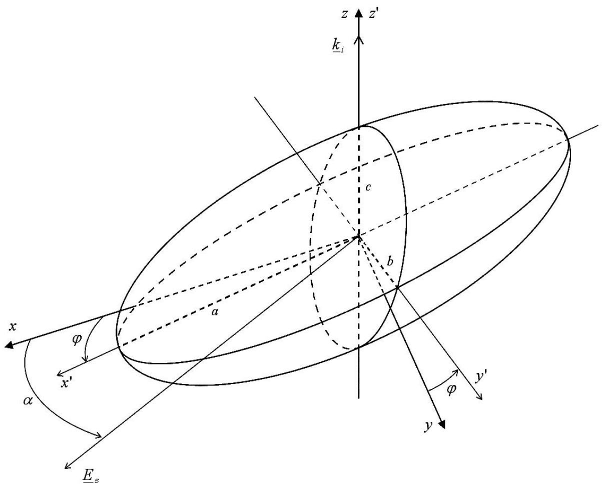

FIG. 1. Scheme of LC droplet in the monolayer. Notations are in the text.

symmetry relative to the long axis a (or axis x' in the local frame (x', y', z') associated with the LC droplet). An individual LC droplet of monolayer is shown in Fig. 1. Angle φ determines the orientation of the long axis a of the LC droplet about the x axis of the laboratory frame. The monolayer is illuminated by a nonpolarized plane wave with the wave vector $\underline{k}_i$. The light scattered by the monolayer has electric field vector $\underline{E}_s$. Two components of coherent transmitted light polarized parallel and perpendicular to the x axis are measured. The angle $\alpha=0$ corresponds to the component parallel to the x axis. The angle $\alpha=\pi/2$ corresponds to the component perpendicular to the x axis.

The coherent transmission coefficient (regular transmittance) is determined by the ratio of the intensity of light transmitted through the monolayer in the direction of the incident wave to the intensity of incident light. We consider very large droplets compared to the wavelength. In such a case the influence of multiple scattering on the film transmittance is negligible. The single scattering approximation can be applied [23–26]. The coherent transmission coefficient T_c under this approximation is determined as follows [14,26]:

$$T_c = 1 - Q\eta + \frac{Q^2 L}{2}\eta^2, \tag{1}$$

where

$$Q = \frac{4\pi}{k^2\langle\sigma\rangle}\,\mathrm{Re}\langle f_{vv}(0)\rangle, \tag{2}$$

$$\frac{Q^2 L}{2} = \frac{4\pi^2}{k^4\langle\sigma\rangle^2}\left(|\langle f_{vv}(0)\rangle|^2 + |\langle f_{vh}(0)\rangle|^2\right), \tag{3}$$

Q is the extinction efficiency factor, $k=2\pi/\lambda_p$, λ_p is the incident wave length in the binding polymer, $\langle\sigma\rangle$ is the mean projection area of the LC droplets on the monolayer plane, $f_{vv}(0)$ and $f_{vh}(0)$ are VV and VH components of the vector amplitude function of scattering at a zero scattering angle [27,28], angle brackets $\langle\,\rangle$ are the statistical averaging over the size of the LC droplets and the orientations of their long axes; η is the filling coefficient of the monolayer (the area fraction of droplets in the monolayer): $\eta=N\langle\sigma\rangle/A$; N is the number of LC droplets in the monolayer, and A is the monolayer area.

To find the components of the vector amplitude function of scattering we make use of the anomalous diffraction approximation [11,12,27–30] and an approximation of the effective refractive indices of LC droplets [8,9]. Using these approximations, we have found:

$$f_{vv}(0) = \frac{k^2\sigma}{\pi}\{K(iv_{da})\cos^2(\alpha-\varphi) + K(iv_{db})\sin^2(\alpha-\varphi)\}, \tag{4}$$

$$f_{vh}(0) = \frac{k^2\sigma}{2\pi}\{K(iv_{db}) - K(iv_{da})\}\sin 2(\alpha-\varphi), \tag{5}$$

where $\sigma=\pi ab$, K is the van de Hulst function [28],

$$v_{da,db} = 2kc(n_{da,db}/n_p - 1), \tag{6}$$

n_{da} and n_{db} are the effective refractive indices of the LC droplet for the waves polarized along a and b axes of ellipsoid, respectively; n_p is the refractive index of the polymer matrix.

In averaging over the size of LC droplets and their orientation, we assume: (i) director configuration in the droplet does not depend on droplet size; (ii) angular distribution of droplets is uniform with the probability density

$$p(\varphi) = \begin{cases} 1/(2\varphi_m), & |\varphi| \leqslant \varphi_m \\ 0, & |\varphi| > \varphi_m \end{cases}, \tag{7}$$

where φ_m is the maximum value of the angle of deviation of the LC droplet long axes from the x axis; (iii) there are the following relationships between the droplet semiaxes:

$$\frac{c}{a} = \varepsilon_1 = \text{const}, \quad \frac{c}{b} = \varepsilon_2 = \text{const}, \tag{8}$$

(iv) gamma distribution in LC droplet sizes is implemented

$$p(c) = \frac{\mu^{\mu+1}}{\Gamma(\mu+1)}\frac{c^{\mu+1}}{c_m^{\mu+1}}\exp(-\mu c/c_m), \tag{9}$$

where Γ stands for the gamma function, μ is the distribution parameter, c_m is the modal size. Note that commonly the logarithm-normal function and gamma function to describe the distribution in droplets sizes [5,31] are used. For stretched PDLC the gamma function is applied [32,33].

Then we have:

$$\mathrm{Re}\langle f_{vv}(0)\rangle = \frac{k^2}{2\varepsilon_1\varepsilon_2}[\langle c^2\,\mathrm{Re}\,K(iv_{da})\rangle(1+\cos 2\alpha\,\mathrm{sinc}(2\varphi_m)) + \langle c^2\,\mathrm{Re}\,K(iv_{db})\rangle(1-\cos 2\alpha\,\mathrm{sinc}(2\varphi_m))], \tag{10}$$

$$\mathrm{Im}\langle f_{vv}(0)\rangle = \frac{k^2}{2\varepsilon_1\varepsilon_2}[\langle c^2 \,\mathrm{Im}\, K(iv_{da})\rangle(1+\cos 2\alpha \,\mathrm{sinc}(2\varphi_m)) + \langle c^2 \,\mathrm{Im}\, K(iv_{db})\rangle(1-\cos 2\alpha\,\mathrm{sinc}(2\varphi_m))], \tag{11}$$

$$\mathrm{Re}\langle f_{vh}(0)\rangle = \frac{k^2}{4\varepsilon_1\varepsilon_2}[\langle c^2 \,\mathrm{Re}\, K(iv_{db})\rangle - \langle c^2 \,\mathrm{Re}\, K(iv_{da})\rangle] \times \sin 2(\alpha-\varphi)\mathrm{sinc}(2\varphi_m), \tag{12}$$

$$\mathrm{Im}\langle f_{vh}(0)\rangle = \frac{k^2}{4\varepsilon_1\varepsilon_2}[\langle c^2 \,\mathrm{Im}\, K(iv_{db})\rangle - \langle c^2 \,\mathrm{Im}\, K(iv_{da})\rangle] \times \sin 2(\alpha-\varphi)\mathrm{sinc}(2\varphi_m). \tag{13}$$

Here $\mathrm{sinc}(x)=\sin(x)/x$,

$$\langle c^2 \,\mathrm{Re}\, K(iv_{da,db})\rangle = c_m^2 \frac{(\mu+2)(\mu+1)}{\mu^2} B_1, \tag{14}$$

$$\langle c^2 \,\mathrm{Im}\, K(iv_{da,db})\rangle = c_m^2 \frac{(\mu+2)(\mu+1)}{\mu^2} B_2, \tag{15}$$

$$B_1 = \frac{1}{2} + \frac{\mu+1}{(\mu+2)(v'_{da,db})^2}\left[1 - \left(\cos\left(\arctan\frac{v'_{da,db}}{\mu+1}\right)\right)^{\mu+2} \times \left(1+(v'_{da,db})^2\frac{(\mu+2)^2}{(\mu+1)^2}\right)^{1/2} \cos\left((\mu+2)\arctan\frac{v'_{da,db}}{\mu+1} - \arctan\left(v'_{da,db}\frac{\mu+2}{\mu+1}\right)\right)\right], \tag{16}$$

$$B_2 = \frac{\mu+1}{(\mu+2)(v'_{da,db})^2}\left(\cos\left(\arctan\frac{v'_{da,db}}{\mu+1}\right)\right)^{\mu+2} \times \left(1+(v'_{da,db})^2\frac{(\mu+2)^2}{(\mu+1)^2}\right)^{1/2} \sin\left((\mu+2)\arctan\frac{v'_{da,db}}{\mu+1} - \arctan\left(v'_{da,db}\frac{\mu+2}{\mu+1}\right)\right), \tag{17}$$

$$\langle\sigma\rangle = \pi\frac{1}{\varepsilon_1\varepsilon_2}c_m^2\frac{(\mu+2)(\mu+1)}{\mu^2}, \tag{18}$$

$$v'_{da,db} = 2k\langle c\rangle(n_{da,db}/n_p - 1), \tag{19}$$

where $\langle c\rangle = c_m(\mu+1)/\mu$ is the mean value of the ellipsoid semiaxes c in the direction of illumination.

Using expressions (1)–(3) and (10)–(19), we find that the coherent transmission coefficient T_c is independent of the ratio of the droplet axes ε_1 and ε_2. It means that coherent transmittance for the monolayer of ellipsoidal droplets and for the monolayer of spherical droplets are the same if the filling coefficient of layer and the sizes of droplets in the z-axis direction are the same.

The orientation structure of liquid crystal molecules in nematic LC droplets with rigidly fixed poles is bipolar and has an axial symmetry along the a axis when the applied electric field is less than the threshold one. At the value of the applied field more than the threshold value, the symmetry of LC droplet sharply decreases [16,21,22]. To characterize the director configuration of the LC droplet with rigidly fixed poles we need to introduce into the consideration the tensor order parameter $\underline{\underline{S}}_d$. In our case this tensor

$$\underline{\underline{S}}_d = \begin{pmatrix} S_{da} & 0 & 0 \\ 0 & S_{db} & 0 \\ 0 & 0 & S_{dc} \end{pmatrix}, \tag{20}$$

where S_{da}, S_{db}, and S_{dc} are the tensor components. They depend on the applied voltage and characterize the statistical orientation ordering of the LC molecules inside the droplets along the ellipsoid axes a,b,c (see Fig. 1). There is the relationship for the tensor components [34]:

$$S_{da} + S_{db} + S_{dc} = 0. \tag{21}$$

To find the values of n_{da} and n_{db} from Eq. (19) we use the effective refractive indices approximation [8,9]. Under this approximation the LC droplet with an actual director configuration is changed by the optically equivalent droplet with the unidirectional LC molecules alignment. The refractive indices of an equivalent droplet are determined by the values of refractive indices of the droplet with the actual configuration of liquid crystal. Based on the results of [8,32,35] we obtained the following expressions for effective refractive indices n_{da} and n_{db}:

$$n_{da} = n_{iso} + \frac{2}{3}\Delta n S_{da}, \tag{22}$$

$$n_{db} = n_{iso} + \frac{2}{3}\Delta n S_{db}. \tag{23}$$

Here $n_{iso}=(2n_o+n_e)/3$, n_o, and n_e are the ordinary and extraordinary refractive indices of LC, $\Delta n = n_e - n_o$ is the optical anisotropy of LC.

In case of the axial symmetry of droplet's molecules configuration along the a axis we have:

$$n_{da} \equiv n_{de} = n_{iso} + \frac{2}{3}\Delta n S_d, \tag{24}$$

$$n_{db} \equiv n_{do} = n_{iso} - \frac{1}{3}\Delta n S_d, \tag{25}$$

where S_d is the scalar order parameter, n_{de} and n_{do} are the effective refractive indices of droplet for extraordinary and ordinary waves, respectively.

III. RETRIEVAL OF THE ORDER PARAMETER AND DISCUSSION

To demonstrate our method the available experimental data of [16,20–22] are used. The measurements were fulfilled on the samples prepared by the mixing of nematic LC 5CB in polyvinylbutyral in weight ratio 1:1 from the solution in ethyl alcohol. This solution was poured on the teflon substrate. After evaporation of ethyl alcohol the PDLC monolayer film of spherical LC droplets with diameter 20–30 μm was formed. Then the film was separated from the substrate and stretched. As a result the LC droplets changed shape into an ellipsoidal one. The film length was increased by about three times during the stretching process. After stretching the droplet had bipolar director configuration with the rigidly fixed poles situated at the ends of the long axis of the droplet. In absence of applied voltage the internal orientation structure of droplets has an axial symmetry relative to the long axis a. At the applied voltage the poles remained rigidly fixed and the director configuration in the droplet had a reflection symmetry in the plane. In Fig. 1 the x axis corresponds to the stretching direction. The droplets are oriented by their long axes mainly along the x axis. There is the following relationship between droplet semiaxes: $a > b > c$.

To retrieve the components S_{da} and S_{db} of the tensor order parameter $\underline{\underline{S}}_d$ the experimental data for the coherent transmission coefficient of the PDLC monolayer obtained by the authors of [20,21] are used: LC refractive indices $n_e = 1.73$, $n_o = 1.53$; $n_p = 1.527$; maximum angle of deviation of the long axes of droplets from the direction of their mean orientation $\varphi_m = 15°$; mean size of droplet semiaxes $\langle c \rangle = 6$ μm; the gamma-distribution parameter $\mu = 16$; the monolayer filling coefficient $\eta = 0.435$. The above indicated refractive indices n_e and n_o are experimental values [20], parameters n_p, η, $\langle c \rangle$, μ, and φ_m are determined by analysis of the experimental and theoretical data.

The monolayer is illuminated by nonpolarized light of the He-Ne laser with a wavelength $\lambda = 0.633$ μm normally to the sample plane. The analyzer selects the coherent components of transmitted light polarized perpendicularly $T_\perp$ and parallel $T_\parallel$ to the x axis (direction of the film stretching).

The experimental data for parallel $T_{ex\parallel}$ and perpendicular $T_{ex\perp}$ components of coherent transmission coefficient T_{ex} of the film on the applied voltage V are shown in Fig. 2 (they are indicated by the open circles). The retrieved dependences of coherent transmittance on the applied voltage are displayed in the figure by the solid lines. To retrieve tensor order parameter of droplets we need to consider theoretical dependences for the parallel $T_{c\parallel}(S_{da}, S_{db} = -1/2)$ and perpendicular $T_{c\perp}(S_{da} = -1/2, S_{db})$ components of coherent transmission coefficient T_c. As it follows from Eqs. (22) and (23)

$$T_{c\parallel}(S_{da}, S_{db} = -1/2) = T_{c\perp}(S_{da} = -1/2, S_{db}) = T_c. \quad (26)$$

The results of calculations at the parameters of the considered film are displayed in Fig. 3.

We retrieve $T_{c\parallel}(V)$, $T_{c\perp}(V)$, $S_{da}(V)$, and $S_{db}(V)$ by solving the system of equations for each experimental pair of values $T^i_{ex\parallel}(V_i)$ and $T^i_{ex\perp}(V_i)$:

$$T^i_{c\parallel}(V = V_i, \alpha = 0, \varepsilon \leqslant \varepsilon_s, S_{da}, S_{db}) = T^i_{ex\parallel}(V_i),$$

$$T^i_{c\perp}(V = V_i, \alpha = \pi/2, \varepsilon \leqslant \varepsilon_s, S_{da}, S_{db}) = T^i_{ex\perp}(V_i). \quad (27)$$

Here index i indicates the ith experimental values of V_i, $T^i_{ex\parallel}(V_i)$, $T^i_{ex\perp}(V_i)$, and the ith retrieved values of $T^i_{c\parallel}(V_i)$ and $T^i_{c\perp}(V_i)$,

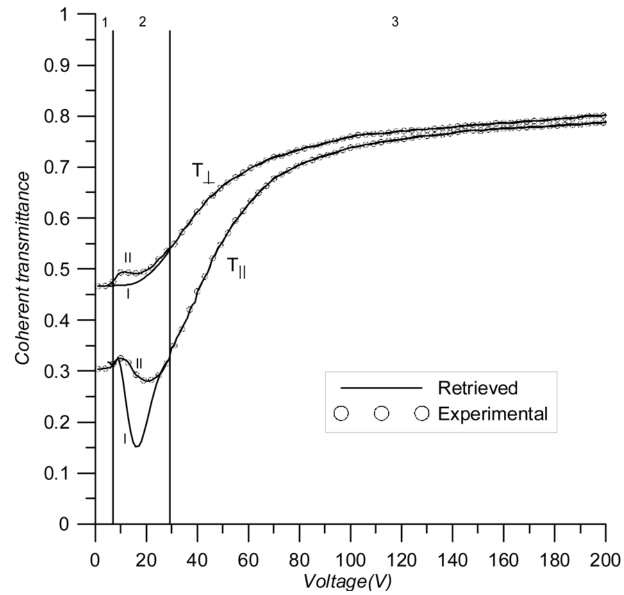

FIG. 2. The dependences of the parallel $T_\parallel$ and perpendicular $T_\perp$ components of coherent transmission coefficient on the applied voltage V. Solid lines are retrieved dependences, open circles are experimental data [20,21]. The film parameters are: $\eta = 0.435$, $\langle c \rangle = 6$ μm, $\mu = 16$, $n_e = 1.73$, $n_o = 1.53$, $n_p = 1.527$, $\varphi_m = 15°$. Target value of relative retrieval error $\varepsilon_s = 0.001$. The vertical lines separate three regions (1, 2, 3) of typical dependences of coherent transmittance on applied voltage. In region 1 the values of applied voltage are less than the threshold value. In region 2 the dependences of coherent transmittance oscillate. In region 3 the dependences of coherent transmittance are monotonic. Curves I indicate the results of calculations by way I. Curves II indicate the results of retrieval by way II.

$$\varepsilon = \frac{|T_{ex} - T_c|}{T_{ex}} \quad (28)$$

stands for the relative error of retrieval for components of coherent transmission coefficients, ε_s is the target relative error of retrieval. The retrieved dependences of $T_{c\parallel}$ and $T_{c\perp}$ on the applied voltage V at $\varepsilon_s = 0.001$ are shown in Fig. 2 by solid lines.

To retrieve the dependences of coherent transmittance and tensor order parameter components on the applied voltage we divide the whole range of applied voltage into three regions. In Fig. 2 and in Fig. 4 they are labeled as 1, 2, and 3. In the region 1 applied voltage is less than the threshold value. Here coherent transmittance weakly depends on the applied voltage. In region 2 the coherent transmittance is an oscillating function of the applied voltage. In region 3 the coherent transmittance is a monotonic function of the applied voltage.

The number of regions is determined by the electro-optical response of a film. It depends on the droplets parameters [21,36]. The experimental dependences we used are typical for the films with large droplets. There are films where monotonic dependence of coherent transmittance in a whole range of applied voltage is implemented. Commonly they have a smaller size.

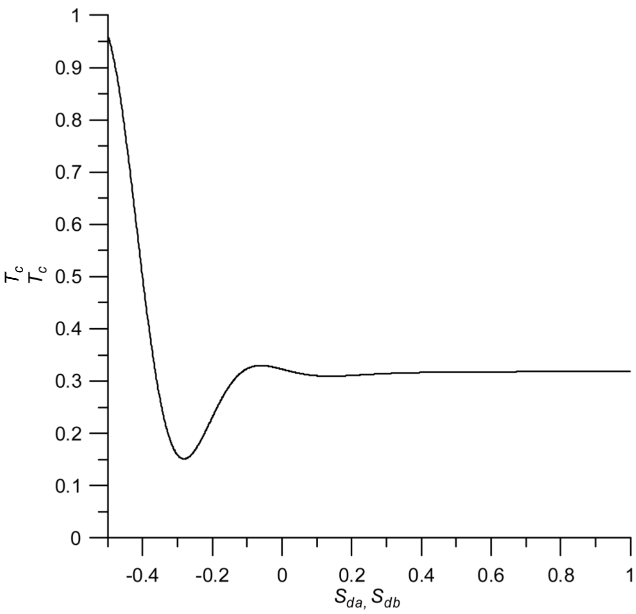

FIG. 3. Theoretical dependences of the coherent transmission coefficient T_c on the order parameter components S_{da} and S_{db}, $[T_c(S_{da})=T_c(S_{db})]$. $\eta=0.435$, $\langle c\rangle=6$ μm, $\mu=16$, $n_e=1.73$, $n_o=1.53$, $n_p=1.527$, $\varphi_m=15°$.

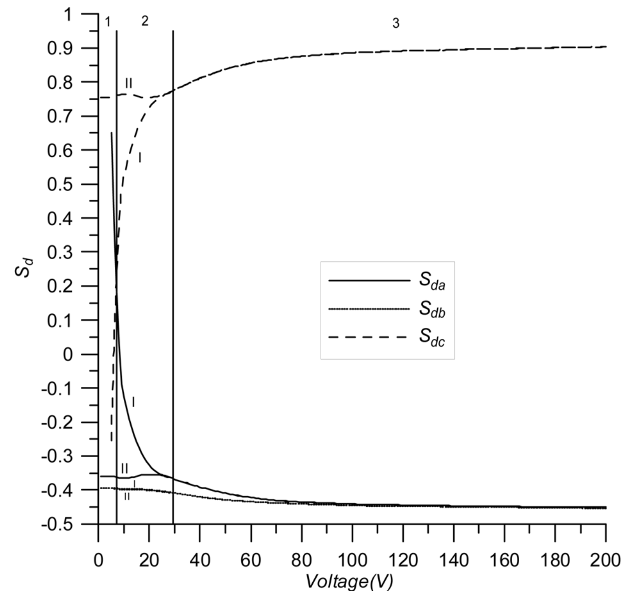

FIG. 4. The retrieved dependences of S_{da}, S_{db}, and S_{dc} on the applied voltage V. The vertical lines separate the same three regions (1,2,3) of typical dependences of coherent transmittance on applied voltage as in Fig. 2. Curves I indicate the results of calculations by way I. Curves II indicate the results of retrieval by way II. $\eta=0.435$, $\langle c\rangle=6$ μm, $\mu=16$, $n_e=1.73$, $n_o=1.53$, $n_p=1.527$, $\varphi_m=15°$; $\varepsilon_s=0.001$.

As it follows from the results of our analysis of the direct and inverse light-scattering problem solutions the order parameter components have to be continuous functions of applied voltage and the two ways of order parameter retrieval have to be considered.

Way I is based on the assumption of monotonic dependence of order parameter components on applied voltage. Here the condition of monotony has to be written in the form:

$$S_{da}(V_{i+1}) \leqslant S_{da}(V_i), \quad V_i < V_{i+1},$$

$$S_{db}(V_{i+1}) \leqslant S_{db}(V_i), \quad V_i < V_{i+1}, \tag{29}$$

where V_i and V_{i+1} are two consecutive values of applied voltage measurements. As follows from the analysis of our problem in the frame of the effective refractive indices approximation we have to find components S_{da} and S_{db} in the range $[1\cdots-0.5]$ and $[0\cdots-0.5]$, respectively. In some cases the retrieved dependences of the order parameter components on applied voltage have discontinuities. To avoid them we used the technique described below.

The possibility of nonmonotonic dependence of order parameter components on applied voltage must not be ruled out. Way II takes into account this feature. In such a case the retrieved range of order parameter components can differ from the first way. It can be found from the theoretical dependence of coherent transmittance on the order parameter components. We have to choose the interval where this dependence is monotonic and the conditions $T_{ex}^{\min} \geqslant T_c^{\min}(S_{da})$, and $T_{ex}^{\max} \leqslant T_c^{\max}(S_{da})$ are fulfilled. Here $T_{ex}^{\min}$ and $T_{ex}^{\max}$ are the minimum and maximum of experimental values of coherent transmittance, $T_c^{\min}(S_{da})$ and $T_c^{\max}(S_{da})$ are the minimum and maximum values of the theoretical coherent transmittance dependence on S_{da}, respectively. It should be careful so at the interval of the oscillating dependence of coherent transmittance on applied voltage the order parameter components can be retrieved incorrectly. The considered experimental data as follows from Fig. 3 the nonmonotonic dependences of the order parameter components $S_{da}(V)$ and $S_{db}(V)$ are implemented if they are sought in the range $[-0.5\cdots-0.28]$. The experimental dependencies of coherent transmittance and order parameter components on applied voltage are retrieved without discontinuities in this range.

The retrieved $S_{da}(V)$, $S_{db}(V)$, and $S_{dc}(V)$ functions by the experimental data presented in Fig. 2 are displayed in Fig. 4. The order parameter component S_{dc} is calculated by Eq. (21).

In region 3 the coherent transmittance is a monotonic function of the applied voltage. The dependences $T_c(V,\underline{\underline{S_d}})$, $S_{da}(V)$, $S_{db}(V)$, and $S_{dc}(V)$ retrieved by both ways are the same.

In region 2 the coherent transmittance is an oscillating function of the applied voltage. The oscillations on the theoretical dependence $T_c(S_{da})$ are more pronounced than the ones in the considered experimental data. The values of $S_{da}(V)$, $S_{db}(V)$, and $S_{dc}(V)$ retrieved by the first and the second way are different. The first way does not allow one to retrieve all of the experimentally observed oscillations in detail. Therefore using the retrieved functions $T_c(V,\underline{\underline{S_d}})$, $S_{da}(V)$, and $S_{db}(V)$ for some intervals of experimental values of coherent transmittance we interpolate the dependences of $S_{da}(V)$ and $S_{db}(V)$ by the numerical method. The obtained results are shown by the solid and dotted lines I in Fig. 4, respectively. Using these evaluated data for $S_{da}(V)$ and $S_{db}(V)$ we calculate the dependences of coherent transmittances on the applied voltage. The proper data for $T_{c\parallel}$ and $T_{c\perp}$ are displayed in Fig. 2 by line I. Clarification of the discrepancies between the theoretical and experimental dependencies of coherent transmittance is the straightforward way of our future activity. The second way allows one to retrieve the values of $T_c(V,\underline{\underline{S}}_d)$, $S_{da}(V)$, and $S_{db}(V)$ for all experimental data. In Fig. 2 and in Fig. 4 these dependences are indicated by curves II.

In region 1 the coherent transmittance weakly depends on the applied voltage. Under the first way, keeping in mind that in our case the component S_{da} tends to unity if applied voltage tends to zero, the component S_{db} has a weak dependence on applied voltage, and extending the determined order parameter dependences from the second region into the first one we predict the behavior of $S_{da}(V)$ and $S_{db}(V)$ in region 1. These dependences and corresponding calculated coherent transmittance dependencies are shown in Fig. 4 (curves I) and in Fig. 2 (curves I), respectively. The second way allows one to find the values of $T_c(V,\underline{\underline{S}}_d)$, $S_{da}(V)$, and $S_{db}(V)$ for all regions.

Retrieval by the first way is more sensitive to the film parameters than retrieval by the second way. Both ways give close results for the $S_{db}(V)$ component in the first and second regions and different results for the $S_{da}(V)$ component. In the third region both ways give the same retrieved dependencies of order parameter components on the applied voltage.

We suppose that the results of retrieval by the first way are more precise so the monotonic dependence of order parameter on the applied voltage is most likely for the considered film. This dependence correlates with the results of visual observations of LC droplet structure and calculation of the director configuration of the LC droplets with rigidly fixed poles by minimizing the free energy [21]. In the general case we cannot exclude the nonmonotonic dependence of the order parameter on the applied voltage. That is why both ways are considered. The described features take place if oscillation electro-optical response is implemented. There is no difference in the results obtained by the two ways if the dependence of the electro-optical response on the applied voltage is monotonic.

IV. CONCLUSIONS

We worked out the method to retrieve the tensor order parameter of aligned LC droplets arranged in the monolayer. The method is based on measurements of the coherent transmission coefficients of polymer-dispersed liquid crystal film and comparison with the results of the solution of the direct problem. The solution for films containing elongated LC droplets with rigidly fixed poles is presented.

The proposed technique can be applied to other types of PDLC films, including bipolar droplets with moving poles in the applied field, if there is a solution to the direct scattering problem.

Here the normal illumination of the film is considered. An oblique elimination provides additional opportunities for the inverse problem solution.

The method can be used to estimate the director configuration in small LC droplets where optical microscopy measurements are not available.

It can be tailored to determine the refractive index of a polymer matrix where liquid crystal domains are located. That refractive index depends on a fraction of liquid crystal dissolved in matrix after the polymerization-induced phase separation process and affects the scattering in PDLC films. The fraction of liquid crystal dissolved in the polymer matrix can be determined by the light-scattering measurements.

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