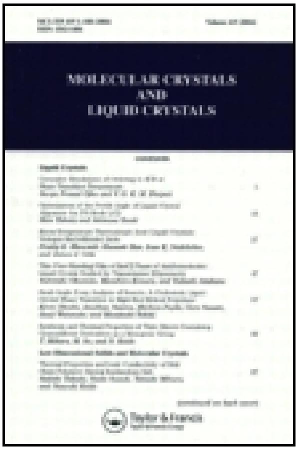

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Optical Properties of Hybrid Aligned Short Pitch Cholesterics

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Diffractive optical properties of selective reflection in short pitch cholesterics are considered in the confined geometry with different boundary conditions at upper and lower substrates. The main difference in the intensities of back selective reflection at the opposite interfaces has been detected. Additionally new stable cholesteric textures were found and explored. The asymmetric structure obtained may be used as non-reciprocal dichroic element. A new method for calculation of light propagation in stratified inhomogeneous anisotropic media, where optical properties may vary along three major axis is proposed and applied for continuous distribution function calculation of helical axes within hybrid aligned cholesteric layer.

Keywords: cholesteric liquid crystals; boundary conditions; dichroic element

INTRODUCTION

The optical properties of cholesteric liquid crystals (LC) has been exciting interest for a long time. Notwithstanding, the investigation field for today mostly covers symmetrical cholesteric structures, where the variation of dielectric constants does not occur in the arbitrary direction. Contemporary methods for calculation of light propagation in an anisotropic media with periodically varying parameters are mostly based on assumption that the variation must occur along the only axis. As a consequence they could hardly be used for more complicated geometry.

In present paper we consider diffractive optical properties of selective reflection in short pitch cholesterics in a confined geometry with different boundary conditions at the upper and lower substrates. In such systems the

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dielectric constants of liquid crystal layer change along with three major axes x, y and z. As a consequence the flat Grandjean texture that is usually observed in monodomain homogeneously aligned cholesteric layers transforms into more complicated planar texture with three-dimensional non flat surface.
The special interest is a geometry when one substrate provides homogeneous planar alignment of molecules at the interface (the helical axis is considered to be normal to the surface plane) and another one provides inhomogeneous polydomain planar texture (the distribution of helical axes in local domains is described, for instance, by Gaussian law and differs from normal to the surface plane). In this case at the homogeneous interface a monodomain flat Grandjean texture with well-known optical properties starts formation. The flat Grandjean texture deforms initially while gradually permeate into the bulk and further breaks up into the small parts i.e. weakly ordered domains upon approach to the opposite surface interface. So the optical properties of planar texture at these two interfaces differ greatly one from each other. Schematic representations of possible optical axis and director configurations have given in Fig.1(a,b).

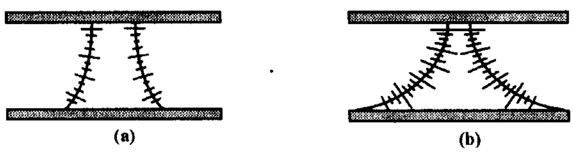

FIGURE 1. Schematic representation of possible director and optical axis configurations in hybrid aligned short pitch cholesteric system (a), (b).

It should be noted that Grandjean texture under the normal incidence of light has a strong back selective reflection while polydomain inhomogeneous planar texture provides strong angular selective scattering. So, the intensity of back scattering could be negligible in compare to the intensity of incident light. This make possible to consider such hybrid aligned short pitch cholesteric system as non-reciprocal dichroic element. Fig.1 represent two types of director configurations and interfacial textures. In Fig.1a it is schematically presented polydomain planar texture at the lower substrate, while in Fig.1b it is schematically presented focal conic texture. The main difference is in the intensities of back selective reflection and angular scattering cones, which has an implicit relationship to the helical axes distribution function not only at the interface, but also in the bulk. In order to simulate the optical properties of such nonlinear structure one must calculate initially the function of spatial distribution of helical axes, which is the probability density to find cholesteric domain in the given spatial direction with given orientation of local optical axis in the direction described by Eiler's angles.

THEORY

The procedure of finding of the domain distribution in ChLCDs as well as experimental setup has been described earlier [1-4]. But in previous papers the calculation procedure described for the samples in which domains have linear helical axes (no bend), and one of the well-known matrix methods [5-7] of the study of electromagnetic wave propagation in stratified anisotropic media might successful be used for their modeling. In contrast to these cases, the domains of the considering here sample possess the bend in helical axis, as a result, calculation of light reflection from and transmission through such media becomes much more complicated and all proposed before methods of computation are incapable.

In this paper we present for the first time more general new matrix formalism for the modeling electromagnetic wave propagation in an inhomogeneous anisotropic media, optical properties of which, in opposite to layered structure, may vary in all three directions. From optical point of view such cholesteric structure may be suitably considered as a sequence of wedges with a small incline angle. Each wedge is considered as a uniaxial optical medium. Direction of the optical axis defined by the director, and it slightly varies from one wedge to another remaining the same inside wedge (see Fig.1). In the similar way to method that was developed by Ko and Sambles [7], we introduce the scattering matrix couples the incoming waves of the system to the outgoing waves of that system.

The optical field in the cholesteric structure can be represented by normal modes. They, in turn, in each wedge may be divided into two sets, with the first set containing the forward modes $\vec{a}$ and the second set containing the backward modes $\vec{b}$. Propagated in the wedged structure radiated light may be represented by a series of the eigenmodes ("o" and "e" waves) guiding with different wave vectors $\vec{k}$. Their polyarization is defined by orientation of the optical axis and a direction of propagation. Let n be a number of the considered electromagnetic waves in the series. In this case the coordinates of vectors $\vec{a}$ and $\vec{b}$ are these waves:

$$\vec{a} = (\vec{E}_{o1}{}^{a} e^{i(wt+\vec{k}_1\vec{r})}, \vec{E}_{o2}{}^{a} e^{i(wt+\vec{k}_2\vec{r})}, \dots, \vec{E}_{on}{}^{a} e^{i(wt+\vec{k}_n\vec{r})}, \vec{E}_{e1}{}^{a} e^{i(wt+\vec{k}_1\vec{r})},$$
$$\vec{E}_{e2}{}^{a} e^{i(wt+\vec{k}_2\vec{r})}, \dots, \vec{E}_{en}{}^{a} e^{i(wt+\vec{k}_n\vec{r})})$$
$$\vec{b} = (\vec{E}_{e1}{}^{b} e^{i(wt-\vec{k}_1\vec{r})}, \vec{E}_{e2}{}^{b} e^{i(wt-\vec{k}_2\vec{r})}, \dots, \vec{E}_{en}{}^{b} e^{i(wt-\vec{k}_n\vec{r})}, \vec{E}_{e1}{}^{b} e^{i(wt-\vec{k}_1\vec{r})},$$
$$\vec{E}_{e2}{}^{b} e^{i(wt-\vec{k}_2\vec{r})}, \dots, \vec{E}_{en}{}^{b} e^{i(wt-\vec{k}_n\vec{r})})$$

Where $\vec{E}_{oi}^{\,a}, \vec{E}_{ei}^{\,a}, \vec{E}_{oi}^{\,b}, \vec{E}_{ei}^{\,b}$ (i=1..n) are amplitudes of eigenmodes with wave vectors $\vec{k}_i$.

Let us consider the interface between the m-th and the (m+1)th wedges. Introduced above vectors are not independent of each other. They are related through the continuity conditions at the interfaces. The relationships are represented by Fresnel's coefficients. So we may express the waves $(\vec{a}_{m+1}, \vec{b}_m)$ through the pair $(\vec{a}_m, \vec{b}_{m+1})$ and write in the matrix form:

$$\begin{pmatrix} \vec{a}_{m+1} \\ \vec{b}_m \end{pmatrix} = \begin{pmatrix} \hat{S}^m{}_{11} & \hat{S}^m{}_{12} \\ \hat{S}^m{}_{21} & \hat{S}^m{}_{22} \end{pmatrix} \begin{pmatrix} \vec{a}_m \\ \vec{b}_{m+1} \end{pmatrix} \tag{1}$$

Where $\hat{S}^m{}_{i,j}$ are relating matrixes. All elements of rows of these matrixes except two for $\hat{S}^m{}_{1,1}$, $\hat{S}^m{}_{2,2}$ and one for $\hat{S}^m{}_{1,2}, \hat{S}^m{}_{2,1}$ are equal to zero. Nonzero elements are products of Fresnel's coefficients by the phase delays $e^{\pm i\vec{k}_i \Delta\vec{r}_i}$, where $\Delta\vec{r}_i$ is a distance that the wave travels inside the wedge [8].

Likewise the waves $(\vec{a}_{m+1}, \vec{b}_{m+2})$ and $(\vec{a}_{m+2}, \vec{b}_{m+1})$ are related at the interface between the (m+1)th and the (m+2)th wedges by the matrix with elements $S^{m+1}{}_{i,j}$. Making use these two matrix expressions and after a few steps of the simple mathematical transformation we obtain the relationship between matrix-columns $(\vec{a}_{m+2}, \vec{b}_m)$ and $(\vec{a}_m, \vec{b}_{m+2})$. There are elements of the relating matrix:

$$\begin{aligned} \hat{S}^{m,m+1}{}_{11} &= \hat{S}^{m+1}{}_{11}(\hat{E} - \hat{S}^m{}_{12}\hat{S}^{m+1}{}_{21})^{-1}\hat{S}^m{}_{11}, \\ \hat{S}^{m,m+1}{}_{12} &= \hat{S}^{m+1}{}_{11}(\hat{E} - \hat{S}^m{}_{12}\hat{S}^{m+1}{}_{21})^{-1}\hat{S}^m{}_{12}\hat{S}^{m+1}{}_{22} + \hat{S}^{m+1}{}_{12}, \\ \hat{S}^{m,m+1}{}_{21} &= \hat{S}^m{}_{22}\hat{S}^{m+1}{}_{21}(\hat{E} - \hat{S}^m{}_{12}\hat{S}^{m+1}{}_{21})^{-1}\hat{S}^m{}_{11} + \hat{S}^m{}_{21}, \\ \hat{S}^{m,m+1}{}_{22} &= \hat{S}^m{}_{22}\hat{S}^{m+1}{}_{21}(\hat{E} - \hat{S}^m{}_{12}\hat{S}^{m+1}{}_{21})^{-1}\hat{S}^m{}_{12}\hat{S}^{m+1}{}_{22}. \end{aligned} \tag{2}$$

This result may easily be extended to the product of more than two matrices, and finally we obtain the scattering matrix of the all system. Thus we find the relationship between incident $(\vec{a}_0)$ and scattered $(\vec{b}_0)$ light:

$$\begin{pmatrix} \vec{a}_N \\ \vec{b}_0 \end{pmatrix} = \begin{pmatrix} \hat{S}^{0,N}{}_{11} & \hat{S}^{0,N}{}_{12} \\ \hat{S}^{0,N}{}_{21} & \hat{S}^{0,N}{}_{22} \end{pmatrix} \begin{pmatrix} \vec{a}_0 \\ \vec{b}_N \end{pmatrix} \tag{3}$$

where N is a number of wedges.

Fresnel's coefficients are calculated by using free coordinate method of Fedorov [9]. A more detail description of the proposed here method with calculation technique will be presented elsewhere [8].

RESULTS AND DISCUSSION

The experimental setup as a whole has designed to measure both the normal reflection and the angular reflection under the normal incidence of light and described in details in [2-4]. Collimated incident light passing through a cholesteric system in the direction normally to the surface plane is partially scattered in all directions. Rest of light is absorbed by the dark opaque layer deposited onto the bottom side of the cell. The light scattered from cholesteric texture is detected by *in-situ* spectrometer PC1000 (Ocean Optics Inc.), which is ruggedized on mobile platform.

The experiment has performed with a strong in-plane anchoring planar alignment of molecules at the interface, which provided by rubbing from one side of polyimide layers coated on the inner side of sandwich type cells with patterned conductive ITO electrodes. The other (opposite) substrate remains unrubbed. Polyimide used in our experiment was PIB94-04 ("Belpolyimide", Belarus). The cell thickness was controlled by silica glass fiber spacers and chosen to be $d \approx 25 \mu m$. Cholesteric liquid crystals were introduced into the cell in its isotropic phase by the vacuum filling.

Liquid crystal material used in our experiments was a mixture of cholesterol derivatives composition CH-12M and commercially available nematic E7 (BDH Ltd.) mixed in proportion 6:4 to achieve the helical pitch $P \approx 0{,}34 \mu m$. The unique feature of this material is that the pitch of cholesteric LC is a temperature independent value in wide temperature range.

Some of the experimental results are represented in Fig.2. It is easy to see that that reflection intensity differs greatly at two interfaces depending on light irradiation direction as we intuitively expected. In order to find the domain distribution function we performed a series of investigations on angular scattering characteristics from both interfaces under the normal incidence of light, which are presented selectively at the various detection angle θ in Fig.3.

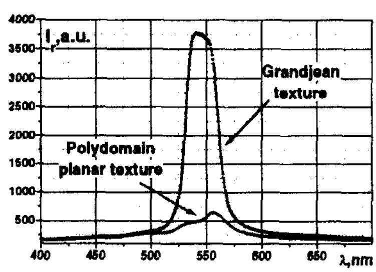

FIGURE 2. Experimental spectra of selective reflection at the opposite interfaces under the normal incidence and normal reflection of light.

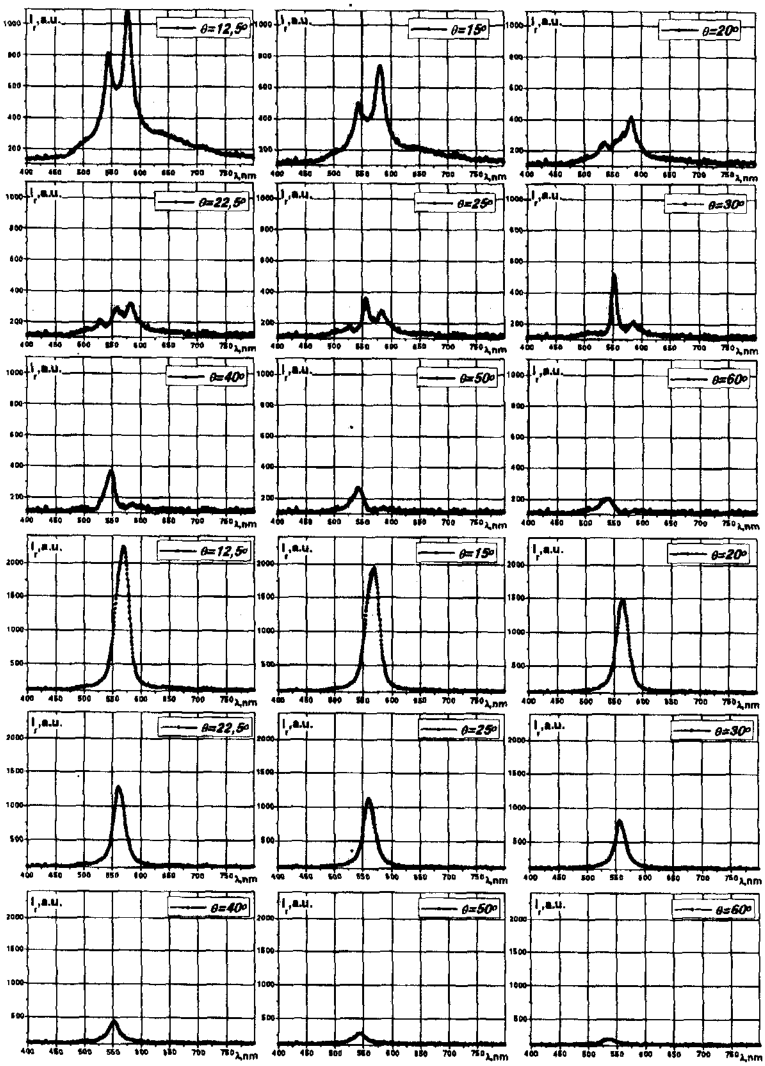

FIGURE 3. Experimental spectra of selective reflection at the opposite interfaces under the normal incidence and angular detection of light. (The upper series represents reflection from the side of rubbed polyimide substrate while lower series represents from non-rubbed one.)

By fitting results of numerical modeling to the experimental data (Fig.3) and varying the bend of the cholesteric helical axis we have found the optimal domain distribution. It is presented in Fig.4 as a function versus the distance inside the cell *d* and the angle of local optical axis inclination from its normal.

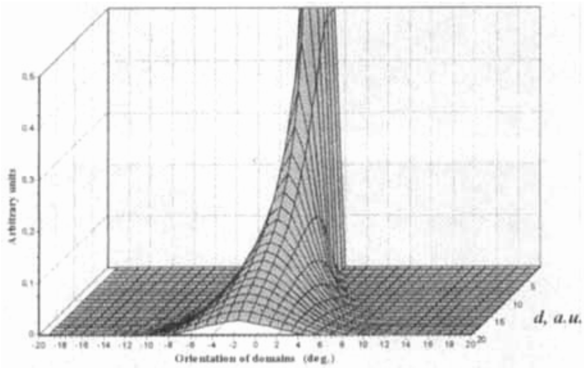

FIGURE 4. Calculated optimal domain distribution function versus the distance inside the cell *d* and the angle of local optical axis inclination from its normal.

The special attention should be paid in Fig.4 to a distance axis *d* because it starts from non zero value. It is well known that rubbed polyimide gives homogeneous planar alignment at the interface so it should be a flat Grandjean texture established at the interface, which is known to give δ function for the helical axes distribution.

The microscopic textures taken from the opposite interfaces, which could be referred to those, presented in Fig.1 are shown in Fig.5. We found new stable uninvestigated textures, which could be ascribed to the geometry of Fig.1b. The efforts now underway to investigate these textures.

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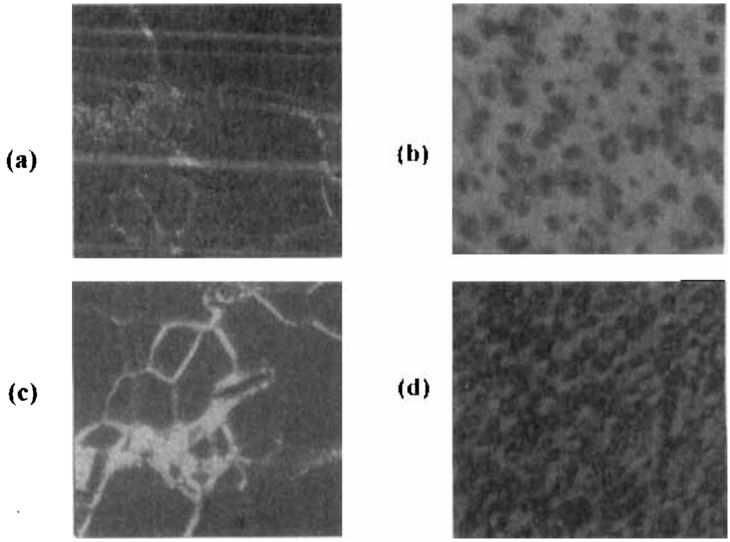

FIGURE 5. Microscopic pictures of hybrid aligned cholesteric textures taken from the opposite surfaces via polarizing microscope. Photos (a) and (b) correspond to a geometry of Fig. 1a. Photos (c) and (d) (new textures) correspond to a geometry of Fig. 1a.
See Color Plate I at the back of this issue.

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