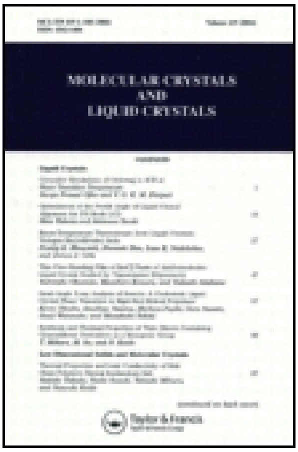

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# Experimental Investigation of the Polarization Plane Rotation of Light in Cholesteric Liquid-Crystalline Film with an Anisotropic Defect Layer

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# Experimental Investigation of the Polarization Plane Rotation of Light in Cholesteric Liquid-Crystalline Film with an Anisotropic Defect Layer

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*This paper experimentally demonstrated that in the cholesteric liquid-crystalline films it is possible to induce defect, which can be controlled by external electric field. Three cases of induced defects were examined and the main result of the experiment is that the rotation of polarization plane has maximum value when light first propagates through chiral liquid-crystalline photonic structure and then falls to the anisotropic layer. We have also supporting calculations, showing an agreement between experimental results and theoretical calculations. We present a new liquid crystal device configuration that performs as a tunable linear polarizer for both polarized and unpolarized lights.*

**Keywords** Chiral photonic crystals; cholesteric liquid crystals; defect structures; selective reflection

## Introduction

Cholesteric liquid crystals (CLCs) are interesting one-dimensional materials because of their spontaneous self-assembly into periodic structures and the photonic band gap can be tuned over a wide range of frequencies. In terms of their optical properties, a prominent feature of cholesterics is the helical structure of their director axes. Such helicity gives rise to selective reflection and transmission of circularly polarized light [1,2]. CLCs are also optically active structures. Liquid crystals, containing chiral molecules have a self-organizing helicoidal structure; these mediums belong to 1D chiral photonic crystals (CPC). The main difference between photonic crystals and CPCs is that the photonic band gap in CPCs exists only for one circular polarization (for case of normal light incidence), coinciding with the chiral medium helix sign. CPCs, such as cholesteric liquid crystals and artificial chiral-made crystals, can function as tunable filters, switches, and lasing devices. As a result, CLCs are now well established in basic research as well as in development for applications and commercial use. Several studies on chiral photonic crystals have shown that it is possible to create localized additional modes within the photonic band gap by inducing a defect into the periodic structure [3,4]. Chiral photonic crystals have attracted scientists and engineers for the past decade also because their properties offer ways to control light polarization. The investigation of polarization characteristics [5], namely polarization plane

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rotation and light polarization controlling, is important from the point of view of application in modern photonics and optoelectronics. The aim of this work is to experimentally and theoretically investigate the characteristics of the behavior of light polarization in the cholesteric liquid-crystalline mediums in the presence of induced defects. By applying a voltage to different pairs of electrodes, we have changed the defect location inside the system and have also observed the influence of the defect layer's location in the chiral photonic structure [6]. This paper discussed normal light incidence. We experimentally discovered and theoretically confirmed some new features of CPCs taking into account the polarization characteristics of light. Let us note, that the chiral photonic crystal with an anisotropic defect layer used in our experiment was a planar cholesteric liquid crystal in which the defect was induced by an external electric field. So, the most important peculiarity of chiral photonic crystals is related to control of their optical characteristics. From this point of view it is extremely interesting to examine the use of liquid-crystalline mediums, if we take into account the wide possibility to control them by an external field (including optical [7]). We present a new liquid crystal device configuration that performs as a tunable linear polarizer for both polarized and unpolarized light.

## Sample Preparation

In order to investigate polarization plane rotation of light, cholesteric liquid-crystalline cells were prepared. A mixture of right-handed pelargonium (X – 17), left-handed oleate (X – 26) and E-7 nematic liquid crystals in the ratio of 30:60:10 was prepared. The mixture was green in color and it was illuminated by laser radiation with the wavelength $\lambda_R = 530$ nm. The thickness of our sample was 40 $\mu$m. The inner surfaces of glass substrates were first coated with thin polymide layer and were then rubbed with a special material. As a result, the orientation of CLCs director was parallel to the surfaces, which means that the helix axis was perpendicular to the surfaces of the cell. The mixture was filled into the empty cell by capillary action. Since we considered three cases of induced defects, we prepared two CLC cells. The electrodes' thickness was 1$\mu$m and the distance between them was 1mm. The sandwiched cholesteric liquid-crystalline cell used in our experiment is presented in Fig. 1.

## Experiment

By applying an electric field to the planar oriented cholesteric liquid-crystalline layer, the rotation of polarization plane of light was observed. The voltage applied to the CLC cell changes the direction of molecular orientation (direction of director). Our estimations show that non-locality of the field results in induction of the defect with a thickness of 2 $\mu$m. As presented in Fig. 2 we focused on three interesting cases: defect was induced near the input substrate, in the center and near the exit substrate of the film. By applying a voltage to different pairs of electrodes, we have changed the defect location inside the system. At certain values of applied voltage the induced anisotropic layer acts as a half-wavelength plate, which changes handedness of polarization [8].

$$d \sim \frac{\lambda}{2(n_e - n_o)}, \tag{1}$$

where $d$ is the thickness of defect layer, $\lambda$ is the wavelength, $n_e$ and $n_0$ are the extraordinary and ordinary refractive indices, respectively. As we know, circularly polarized light reflected


**Figure 1.** Sandwiched CLC cell (the light of laser radiation propagates perpendicular to the surface of CLC film).

from the CLC cell does not change its polarization direction. If the defect is located in the center of the film, the band gap for both polarizations becomes prohibited, meaning that right-handed and left-handed polarizations reflect. If defect is located near the one of substrates, then one of the polarizations transmits and the other polarization reflects.

We want to emphasize some peculiarities of the polarization plane rotation of light, which arises under the influence of electric field. In order to investigate polarization plane rotation, first we found the selective reflection gap and, for this range, we have investigated rotation of polarization plane. For our sample the selective reflection gap lies in the range of 15–25°C. Figure 3 illustrates the scheme of our experimental set-up. After passing through the prism and polarizer laser radiation (diode pumping semiconductor laser with

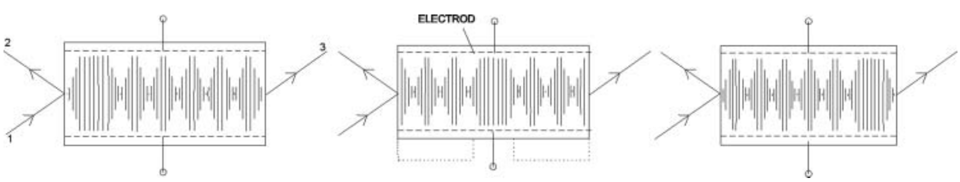


**Figure 2.** Schematic diagram of CLC cell model with an anisotropic defect: defect was induced a) near the input substrate of the film, b) in the centre of CLC film and c) near the exit substrate of the film (1-incident light, 2-reflected light and 3-transmitted light).

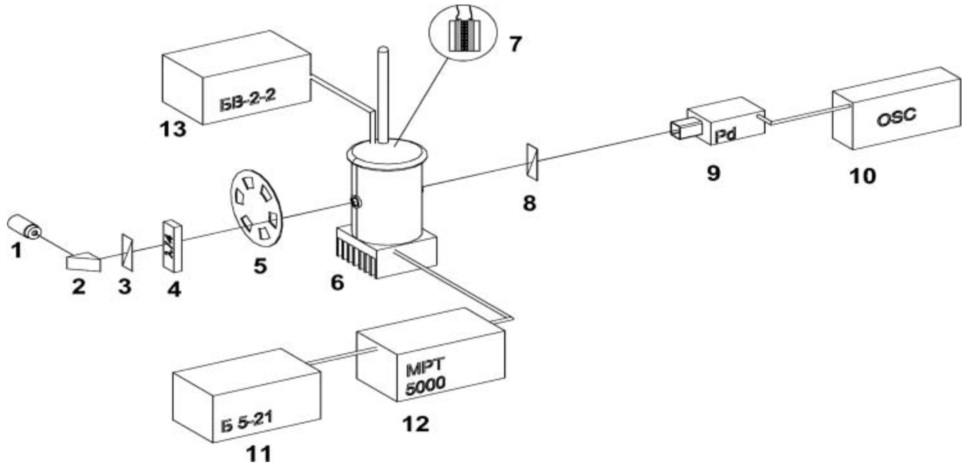


**Figure 3.** Scheme of experimental set-up: 1. Source of laser radiation, 2. Prism, 3. Polarizer, 4. λ/4 wavelength-plate, 5. Modulator, 6. Microrefrigerator, 7. CLC cell, 8. Polarizer, 9. Photodiode, 10. Oscillograph, 11. DC source, 12. Controller of temperature, 13. Source of constant voltage.



$0.53\mu$m wavelength and 30mW power in CW regime) becomes plane-polarized light, then passes through quarter-wave plate and becomes circularly polarized. We used a modulator in order to obtain discontinuous regime of laser radiation. Subsequently, light falls on the microrefrigerator (the temperature of microrefrigerator was smoothly changed by temperature controller) and propagates into CLC cell after which it passes through second polarizer (our polarizers were crossed) and falls on photodiode. Eventually, we have observed the pulse on the screen of the oscillograph. So, we will discuss the phenomenon of polarization plane rotation for three cases mentioned above.

## Method of Analysis

The problem was solved by Ambartsumian's layer addition modified method [9] adjusted to solution of such problems. A ***CLC layer*** with a defect can be treated as a multi-layer system: ***CLC(1)-Defect Layer (DL)-CLC(2)*** (Fig. 2b).

Let us present the solution of the boundary problem of light transmission through the multi-layer system in the form:

$$\vec{E}_r = \hat{R}\vec{E}_i, \vec{E}_t = \hat{T}\vec{E}_i, \tag{2}$$

where the indices $i$, $r$ and $t$ denote the incident, reflected and transmitted waves' fields, $\hat{R}$ and $\hat{T}$ are the reflection and transmission matrices, where $\vec{n}_p$ and $\vec{n}_s$ are the unit vectors of orthogonal linear polarizations, $E^p_{i,r,t}$ and $E^s_{i,r,t}$ are corresponding amplitudes of the incident, reflected and transmitted waves.

$$\vec{E}_{i,r,t} = E^p_{i,r,t}\vec{n}_p + E^s_{i,r,t}\vec{n}_s = \begin{bmatrix} E^p_{i,r,t} \\ E^s_{i,r,t} \end{bmatrix},$$

According to Ambartsumian's layer addition modified method, if there is a system consisting of two adjacent (from left to right) layers, $A$ and $B$, then the reflection transmission matrices of the system, $A$+$B$, viz. $\widehat{R}_{A+B}$ and $\widehat{T}_{A+B}$, are determined in terms of similar matrices of its component layers by the matrix equations:

$$\widehat{R}_{A+B} = \widehat{R}_A + \tilde{\widehat{T}}_A \widehat{R}_B[\widehat{I} - \tilde{\widehat{R}}_A \widehat{R}_B]^{-1} \widehat{T}_A, \tag{3}$$
$$\widehat{T}_{A+B} = \widehat{T}_B[\widehat{I} - \tilde{\widehat{R}}_A \widehat{R}_B]^{-1} \widehat{T}_A,$$

where the tilde denotes the corresponding reflection and transmission matrices for the reverse direction of light propagation, and $\hat{I}$ is the unit matrix. The exact reflection and transmission matrices for a finite ***CLC layer*** (at normal incidence) and a defect (isotropic or anisotropic) layer are well known [10,11]. First, we attach the ***DL*** with the ***CLC Layer (2)*** from the left side, using the matrix Eqs (3). In the second stage, we attach the ***CLC Layer (1)*** with the obtained ***DL-CLC Layer (2)*** system.

The ellipticity $e$ and the azimuth $\psi$ of the transmitted light are expressed by $\chi = E_t^s / E_t^p$ through the following formulas:

$$\psi = \frac{1}{2}\text{arctg}\left(\frac{2\text{Re}\,(\chi)}{1 - |\chi|^2}\right), \quad e = tg\left(\frac{1}{2}\,\text{arcsin}\left(\frac{2\text{Im}\,(\chi)}{1 + |\chi|^2}\right)\right). \tag{4}$$

## Results and Discussion

We have changed the outer electric field between 500–950V and measured rotation angles of polarized ellipses with respect to the primary direction. In order to define the primary direction, we rotated the exit polarizer by *π/4* from the crossed position of polarizers. The ellipticity $\sqrt{I_{\min}/I_{\max}}$ of transmitted light and the rotation of ellipse were determined for each measurement. The cholesteric liquid-crystalline layer parameters are: $\varepsilon_1 = 2{,}85$, $\varepsilon_2 = 0{,}00000001$, $\varepsilon_3 = 2{,}47$, $\varepsilon_4 = 0{,}00000001$, $\sigma = 0{,}324$, $\mathrm{L} = 7\sigma$. The parameters of defect layer are: the defect layer thickness is $d = 2$ $\mu$m, $\varepsilon_1^d = 2{,}85$, $\varepsilon_2^d = 0{,}00000001$, $\varepsilon_3^d = 2{,}47$, $\varepsilon_4^d = 0{,}00000001$. Figure 4 corresponds to the case when defect was induced near the input substrate of the film. In this case light falls directly to the anisotropic defect layer and the polarization plane rotates only by a few degrees. Low and high temperatures correspond to the short and long wavelength boundaries, respectively. T = 17°C is the peak temperature for the gap of selective reflection. In Fig. 4, the first graphic represents experimental result and the second graphic shows the dependence of polarization azimuth on the defect layer thickness for λ = 0,50 $\mu$m wavelength, which is one of the boundaries

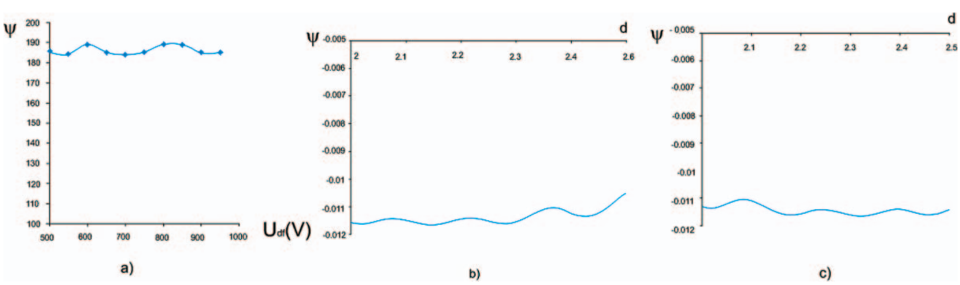


**Figure 4.** Experimental and theoretical results for polarization azimuth when defect was induced near the input substrate of the film: a) dependence of rotation of polarization plane on applied voltage, b) dependence of polarization azimuth on defect layer thickness for λ = 0,50 $\mu$m wavelength, c) dependence of polarization azimuth on defect layer thickness for λ = 0,54 $\mu$m wavelength.

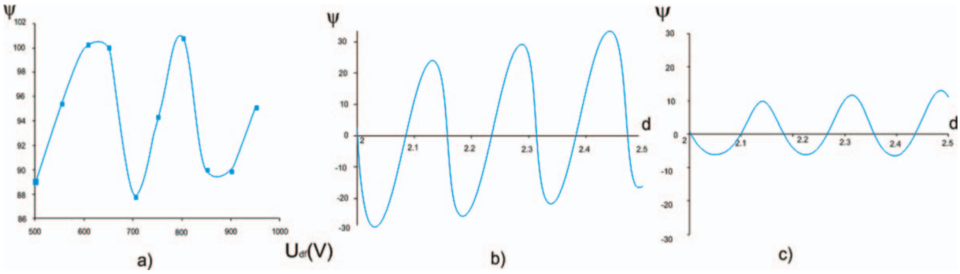

**Figure 5.** Experimental and theoretical results for polarization azimuth when defect was induced in the centre of the cholesteric liquid-crystalline film: a) dependence of rotation of polarization plane on applied voltage, b) dependence of polarization azimuth on defect layer thickness for $\lambda = 0{,}50\ \mu$m wavelength, c) dependence of polarization azimuth on defect layer thickness for $\lambda = 0{,}54\ \mu$m wavelength.

of selective reflection gap. The last graphic is the same dependence but for $\lambda = 0, 54\ \mu$m wavelength, which is the other boundary of Bragg's range.

As it is seen from Fig. 5, we obtained the dependence of polarization plane rotation on the applied voltage and dependences of polarization azimuth on defect layer thickness, when defect was induced in the centre of CLC film. In this case polarization plane rotates obviously.

In Fig. 6, similar dependences are presented. The measurements were performed for different temperatures. Our calculations show that the polarization plane rotation has maximum value, when defect is induced near the exit substrate of the film.

We have also investigated (both theoretically and experimentally) polarization ellipticity for the normal light incidence. Polarization ellipticity depends on the applied voltage and defect layer thickness for the boundaries of Bragg reflection are presented in Fig. 7. The first corresponds to the case when defect was induced near the input substrate of the film.

In Fig. 8 the dependences of polarization ellipticity are presented for the case when defect was induced in the center of CLC film.

In Fig. 9 similar dependences are presented for the case when defect was induced near the exit substrate of the film.

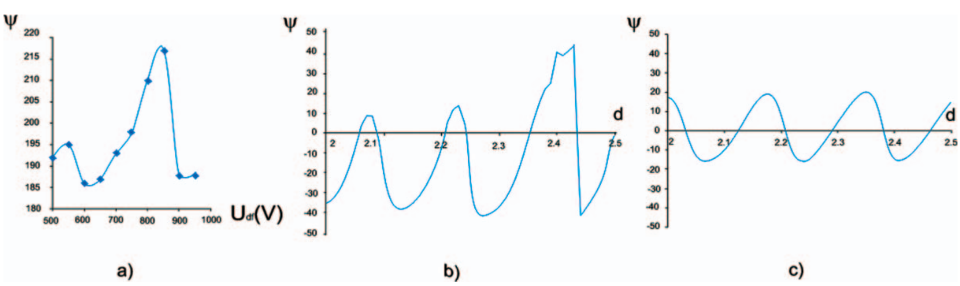

**Figure 6.** Experimental and theoretical results for polarization azimuth, when defect was induced near the exit substrate of the film: a) dependence of rotation of polarization plane on applied voltage, b) dependence of polarization azimuth on defect layer thickness for $\lambda = 0{,}50\ \mu$m wavelength, c) dependence of polarization azimuth on defect layer thickness for $\lambda = 0{,}54\ \mu$m wavelength.

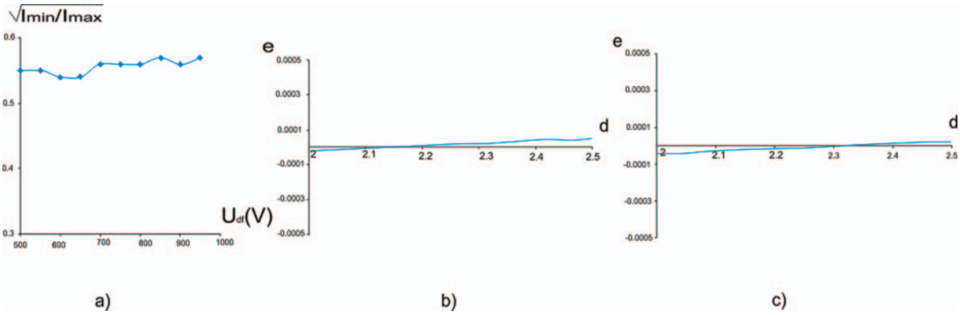


**Figure 7.** Experimental and theoretical results of ellipticity for the case when defect was induced near the input substrate of the film: a) dependence of polarization ellipticity on applied voltage, b) dependence of polarization ellipticity on defect layer thickness for λ = 0,50 $\mu$m wavelength, c) dependence of polarization ellipticity on defect layer thickness for λ = 0,54 $\mu$m wavelength.

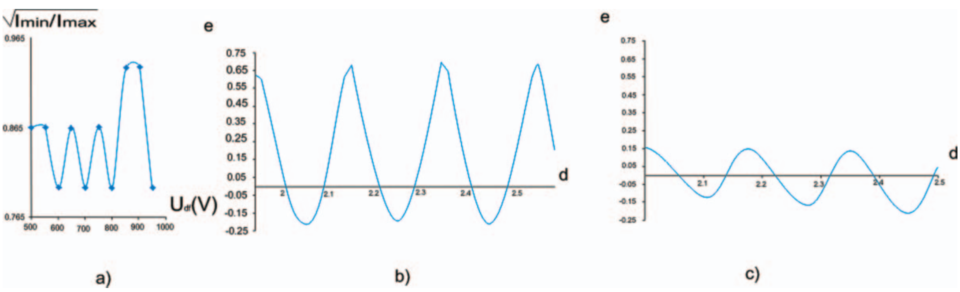


**Figure 8.** Experimental and theoretical results of ellipticity for the case when defect was induced in the centre of the film: a) dependence of polarization ellipticity on applied voltage, b) dependence of polarization ellipticity on defect layer thickness for λ = 0,50 $\mu$m wavelength, c) dependence of polarization ellipticity on defect layer thickness for λ = 0,54 $\mu$m wavelength.

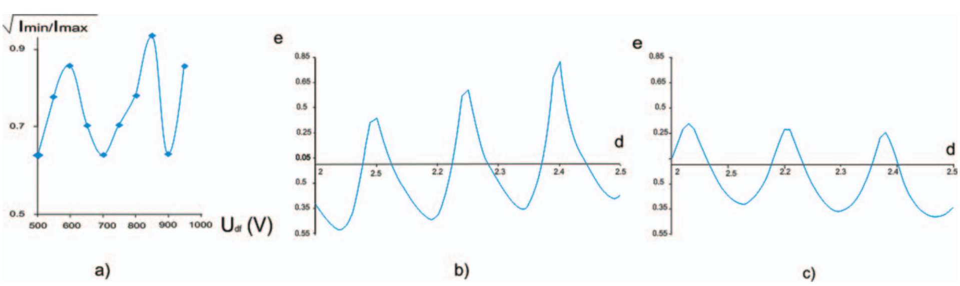


**Figure 9.** Experimental and theoretical results of ellipticity for the case when defect was induced near the exit substrate of the film: a) dependence of polarization ellipticity on applied voltage, b) dependence of polarization ellipticity on defect layer thickness for λ = 0,50 $\mu$m wavelength, c) dependence of polarization ellipticity on defect layer thickness for λ = 0,54 $\mu$m wavelength.

## Conclusion

Concluding, let us note that the ellipticity of polarization will be changed when the defect is moved from one border to the other. The main propose was to obtain large rotation with small loss leading to the main result of the experiment being that the polarization plane rotation has maximum value, when light at first propagates through chiral liquid-crystalline photonic structure and then falls to the anisotropic layer. So, in this paper we have experimentally investigated the possibility of anisotropic defect creation inside cholesteric liquid-crystalline (CLC) films. We have also considered characteristics of the behavior of light polarization in the presence of induced defect in the cholesteric liquid-crystalline mediums. We have investigated the influence of defect layer's location in the CLC cells. We have also shown that it is possible to control the rotation of polarization plane of light due to induced defect. As a result of our calculations, we came to the conclusion that the theory is in good agreement with the experimental results. Our results can be used in the system as a band optical diode for circularly polarized incident light, as well as in the sources of elliptically polarized light with tunable ellipticity.

## Acknowledgments

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