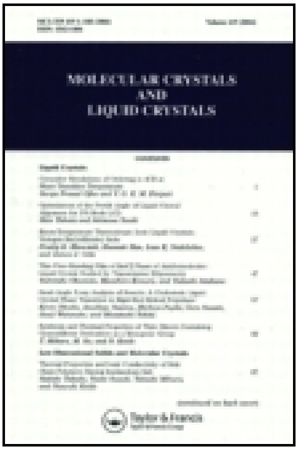

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Polariscope: Theory and Experiment

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Polariscope: Theory and Experiment

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The process of propagation of a polarized light beam through the optical system consisting of nematic liquid crystal layer with irregular thickness and circularly oriented director and a linear polarizer has been considered. It has been shown that every state of light polarization of the incident beam has its own, unique intensity distribution after this optical system. The form of the intensity distribution does not depend on the wavelength of the incident radiation.

Keywords: liquid crystal; light polarization; polariscope

INTRODUCTION

Polarized light has a variety of practical applications. For instance, using polarized light one can derive information about some constants of investigated materials, mechanical stresses in them and so on. Therefore, measuring the parameters of optical polarization is a very important problem. Usually, for this purpose, different combinations of birefringent plates and linear polarizers are used[1]. However, these devices have some weak points, for example, they are inertial and expensive. Besides, they are sensitive to the wavelength of the analyzed light. Therefore, using them it is very difficult to measure the parameters of optical polarization in the real-time regime. That is why their field of applications is limited. In work[2], it has been proposed that the layer of nematic liquid crystal with irregular thickness and circularly oriented director and a linear polarizer can be used as noninertial analyzer of the state of the optical polarization. As far as we know, this idea has received neither further theoretical investigations nor experimental realization. The present work is devoted to theoretical investigation and experimental observation of the process of propagation of polarized light through the liquid crystalline layer prepared by above mentioned way.

THEORY

Let us investigate the process of propagation of polarized light beam in the proposed optical system (see fig.1) in the most general case.

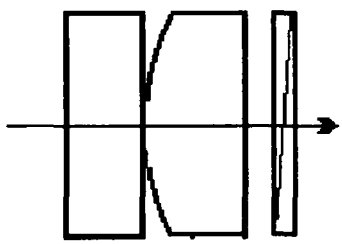

FIGURE 1 Scheme of polariscope

A Nematic liquid crystal is placed between a circle glass plane-parallel plate (1) and a convex-plane lens (2) with radius of curvature R_{cur}. The thickness of liquid crystalline layer depends on the distance from the optical axis **Z** of the proposed device. The director of the molecules of liquid crystal is oriented along concentric circles with center in point **O** (see fig. 2). A linear polarizer (3) is placed after lens (2).

In further, we will consider that the transmission axis of the linear polarizer is vertically oriented and polarized light propagates along **Z**. In polar coordinate system, in point (r, φ) of the liquid crystalline layer, the angle between the direction of optical axis of molecules (e.g. director) and **Y** axis is equal to φ and the thickness is given as:

$$l(r) = \frac{r^2}{2R_{cur}} \tag{1}$$

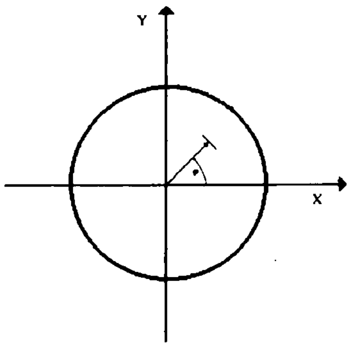

FIGURE 2 Alignment of the director

The further theoretical investigation of the process of propagation of polarized light beam through the proposed optical system will be based on the Jones matrix formalism[3].

Let us consider that a plane polarized monochromatic light wave $\overline{E} = E_0 \cdot e^{kr - \Omega t}$ is normally incident on the polariscope. In that case, its Jones vector can be written as:

$$E = \begin{pmatrix} a \\ b \end{pmatrix} \tag{2}$$

where $a = E_X / \sqrt{I}$, $b = E_X / \sqrt{I}$, I - intensity of the analyzed light, E_X and E_Y are the components of the electric field along **X** and **Y** axis, respectively. In every point (r,φ) of the layer, Jones vector transforms as:

$$E' = P \cdot R(-\varphi) \cdot T(r) \cdot R(\varphi) \cdot E \tag{3}$$

Here are

$$R(\varphi) = \begin{pmatrix} \cos(\varphi) & \sin(\varphi) \\ -\sin(\varphi) & \cos(\varphi) \end{pmatrix} \tag{4}$$

- the matrix of the rotation of the coordinate system at angle φ,

$$R(-\varphi) = \begin{pmatrix} \cos(\varphi) & -\sin(\varphi) \\ \sin(\varphi) & \cos(\varphi) \end{pmatrix} \tag{5}$$

- the matrix of the inverse rotation,

$$T(r) = \begin{pmatrix} e^{-1/2\Delta nl(r)ki} & 0 \\ 0 & e^{1/2\Delta nl(r)ki} \end{pmatrix} \tag{6}$$

- the Jones matrix of the liquid crystalline layer, and

$$R(\varphi) = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \tag{7}$$

- the Jones matrix of the polarizer with vertical orientation of the transmission axis. The ultimate formulas for the components of the Jones vector of transmitted light with arbitrary optical polarization are written in the following form

$$a' = 0 \tag{8}$$

$$b' = \sin(\varphi)e^{-i\Gamma}(a\cos(\varphi) + b\sin(\varphi)) + \cos(\varphi)e^{i\Gamma}(b\cos(\varphi) - a\sin(\varphi)) \tag{9}$$

where $\Gamma = \Delta nl(r)k$. In that case, the intensity distribution of the transmitted light is given by

$$\begin{aligned} I = |b|^2 \cos^2(\Gamma/2) - \sin(\Gamma)\sin(2\varphi)\,\mathrm{Im}(ba^*) + \sin^2(\Gamma/2)[|a|^2 \sin^2(2\varphi) + \\ + |b|^2 \cos^2(2\varphi) - 2\cos(2\varphi)\sin(2\varphi)\,\mathrm{Re}(ba^*)] \end{aligned} \tag{10}$$

It is apparent from this formula that each state of the optical polarization of the transmitted light beam has its own, unique intensity distribution on the output of the optical system. Moreover, the form of distribution does not depend on the wavelength of the incident light beam.

Let us obtain the formulas of intensity distribution for the following states of optical polarization: linear vertical polarization, linear horizontal polarization, linear polarization with azimuth 45^0, linear polarization with azimuth 135^0, left-hand circular polarization, right-hand circular polarization. The results of calculations are summarized in Table 1.

TABLE 1 Analytical formulas of intensity distributions for some states of light polarization.

Jones vector	Formula of intensity distribution
$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$	$1-\sin^2(\Gamma/2)\sin^2(2\varphi)$
$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$	$\sin^2(\Gamma/2)\sin^2(2\varphi)$
$\begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}$	$1/2 - 1/2\sin^2(\Gamma/2)\sin(4\varphi)$
$\begin{pmatrix} -1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}$	$1/2 + 1/2\sin^2(\Gamma/2)\sin(4\varphi)$
$\begin{pmatrix} 1/\sqrt{2} \\ i/\sqrt{2} \end{pmatrix}$	$1/2 - \sin(\Gamma)\sin(\varphi)\cos(\varphi)$
$\begin{pmatrix} 1/\sqrt{2} \\ -i/\sqrt{2} \end{pmatrix}$	$1/2 + \sin(\Gamma)\sin(\varphi)\cos(\varphi)$

It is clear from formula 10 and Table 1, that the form of intensity distribution does not depend on the wavelength of the incident light, which is not the case of its size that depends on the wavelength. Typical patterns of the intensity distribution are shown in fig 3. For their calculations, we took the following parameters: Δ=0.2, R=32 meters, λ=0.476 μm. The size of each pattern is equal to 30 mm × 30 mm.

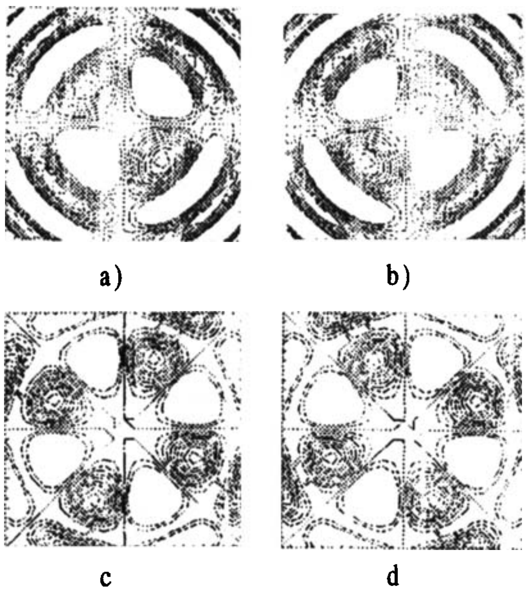

FIGURE 3 Graphics of intensity distributions for some states of light polarization (computer simulation): a) right-hand circular polarized light, b) left-hand circular polarized light, c) linear polarized light (azimuthal is equal 45^0), d) linear polarized light (azimuthal is equal -45^0).

EXPERIMENT

The proposed optical system is made from two glass plates, one of them is circular plane - parallel glass plate with diameter 50 mm and thickness 20 mm, the other is convex - plane lens with the same diameter and thickness but with radius of curvature 32 meters. The inner side of each plate, with respect to the proposed optical system, is covered with a polymer coating in order to rub circularly oriented grooves on it. The space between the two plates is filled with nematic liquid crystal 5CB. Necessity of using a lens with large radius is explained by the following reason: for distinctive observation of intensity distribution, the phase shift between orthogonal components of light wave field should take values from 0 to 2π (not $2\pi n$) along the illuminated area with radius r_{il}. This requirement is given as

$$\frac{\Delta n k r_{il}^2}{2R_{cur}} = 2\pi \tag{11}$$

From which it follows that

$$r_{il} = \sqrt{\frac{\lambda R_{cur}}{\Delta n}} \tag{12}$$

It is apparent from this formula that if R_{cur} is small, then the size of illuminated should be small too. However, in this case, it would be very difficult to observe the intensity distribution without special devices. In the case of our experiment, Δn=0.2, R=32 meters, and λ=0.476 μm and λ=0.514 μm, hence, according to (11) the radius of illuminated area must be about r_{il} = 10 mm.

The experimental setup is shown in fig. 4 . The source of radiation was an Argon laser, operating at λ=0.476 μm and λ=0.514 μm. The polarization switch device was constructed on base of a tunable quarter - wave plate described in[4]. It provided quality of polarization of 0.99 ± 0.01. In order to form a light beam with required transverse radius we used a beam expander consisting of short-focal-length lens (3) (F=3 mm) and long-focal-length lens (4) (F=280 mm). The angle of beam divergence behind

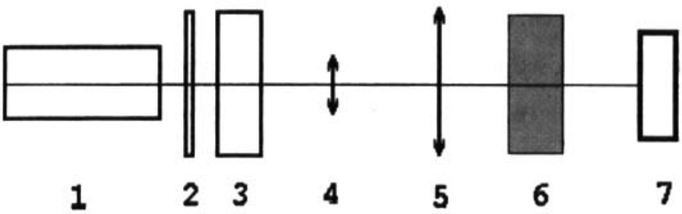

FIGURE 4 Experimental setup

The telescopic system was measured by the criterion e^{-1} of the intensity at maximum and its value was equal to 3^0. The proposed optical system was placed behind the beam expander. Registration of the intensity distribution was carried out either by visual observation or by a CCD camera. In the latter case, attenuation filters were placed before the CCD camera. In our experiment, we used the light beam with the following states of optical polarization (see Fig. 5, 6): linear horizontal polarization (1), linear polarization with azimuth 45^0 (2), linear polarization with azimuth 135^0 (3), linear vertical polarization (4), left-handed circular polarization (5), right-handed circular polarization (6). It is easy to see from fig. 4 that every state of optical polarization of incident light beam has its own, unique intensity distribution after the proposed device.

Utilizing these patterns of intensity distributions, information about the parameters of the state of optical polarization of the incident light beam can be derived. In order to do it, it is necessary to fix the points, where the values of intensity is equal to 0, that are dark spots on the patterns. In these points, the light polarization is linear and perpendicular to the transmission axis of the output polarizer. So, this state of polarization can be describe by the following Jones vector:

$$E' = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

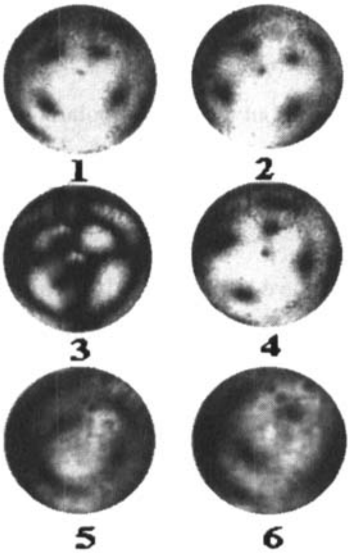

FIGURE 5 Distributions of intensity after polariscope λ=0.476 μm.

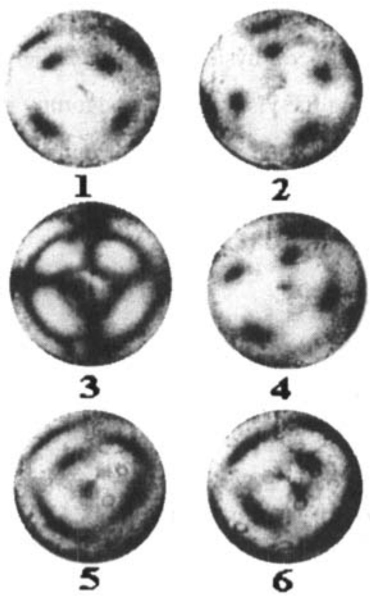

FIGURE 6 Distributions of intensity after polariscope λ=0.514 μm.

Substituting this vector and the polar coordinates of the dark spots into:

$$E = R(-\varphi)\cdot T^{-1}(r)\cdot R(\varphi)P^{-1}\cdot E'$$

we can derive information about the state of polarization of incident light.

CONCLUSION

In the present work, we have demonstrated the possibility of creation of a universal device which allows us to measure the state of the optical polarization in real-time regime. This device doesn't contain any mechanical details, therefore it is easy to use. Proposed device can be used as universal, noninertial analyzer of the state of light polarization.

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