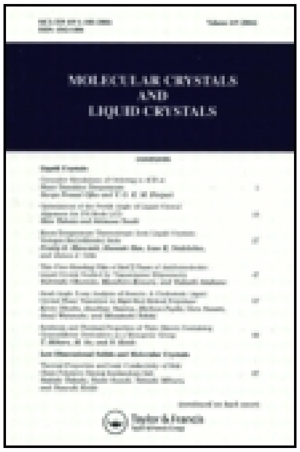

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OPTICAL PROPERTIES OF HOMEOTROPICAL-ALIGNED LIQUID CRYSTAL MICROLENS

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Abstract Effects of orientation in nematic liquid crystal (LC) at non-uniform electric field can be used to create new optical devices. A non-uniform field at LC-cell with asymmetrical electrodes causes a deformation of nematic director and a radial symmetrical distribution of a refractive index is obtained. This LC-cell possesses the lens properties. The optical properties of LC-microlens with homeotropical alignment of nematic have been researched. The diverging property has been obtained in this structure. The LC-microlens focal length - voltage dependence has been investigated.

INTRODUCTION

To develop the devices with variable modulation of phase profile it is necessary to regulate a spatial distribution of either the refractive index or the transmittance in a transparent. In the second case the very small elements must be controlled to create kinoform elements with variable characteristics. This causes great technological difficulties. Hence the development of devices with the variable distribution of the refractive index is more perspective. The modulation of the refractive index by means of alignment of LC at the non-uniform electric field is one of the best possible methods to create the variable non-uniform distribution of the refractive index. The voltage and power used in this method are smaller in comparison with those used by other methods. This allows to avoid greater energy losses. Recently it has been shown that there are possibility to create liquid crystal deflectors[1], lenses[2] and microlenses[3,4]. This paper is a continuation of papers [3,4].

EXPERIMENT

Liquid crystal microlens-cell has been manufactured by using a hole - patterned electrode and an In_2O_3 - coated counter electrode (fig.1). The hole-patterned electrode was made of thin chrome films deposited on a glass substrate and the hole-patterns were produced by means of photolithography. The diameters of holes were 176, 378, 600 and 780 μm.

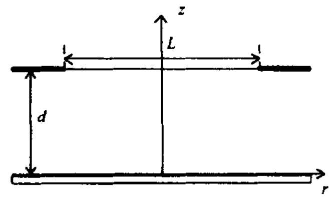


FIGURE 1. The LC-microlens

A nematic liquid crystal with negative dielectric anisotropy was placed in the cell (the mixture of MBBA and EBBA). The homeotropical alignment was attained by means of addition a small amount of lecithin. The thickness of LC-layer at LC-cell was 50 μm. The ac voltage (2 kHz) was applied to electrodes. The investigations carried out by means of an polarization microscope (crossed nicoles). The focal length was measured by using displacement of the microscope objective to obtain a clear image of a focal point (or a ring).

RESULTS AND DISCUSSION

When the voltage is applied across the cell the non-uniform electric field appears in the region of the hole. The molecules are reoriented by the field and the non-uniform distribution of director is obtained. The model of molecular orientation is shown at fig. 2. As a result there appeared the non-uniform distribution of a refractive index. The dependence of the refractive index for the extraordinary ray (e-ray) propagating at an angle θ with the nematic director is given by

$$n(\theta) = \frac{n_o n_e}{\sqrt{n_o^2 \cos^2\theta + n_e^2 \sin^2\theta}} \tag{1}$$

where n_o is an ordinary refractive index, n_e is an extraordinary refractive index.

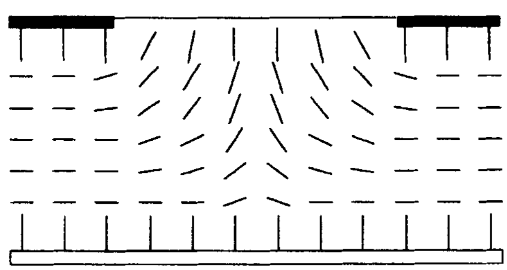


FIGURE 2. A molecular orientation model of homeotropical - aligned microlens with negative dielectric anisotropy.

If the propagation of light is assumed to be parallel to axes z then a phase profile for e-rays $\varphi_e(r)$ is given by

$$\varphi_e = \frac{2\pi}{\lambda}\int_0^d n_e(\theta(z,r))dz \tag{2}$$

where d is the cell thickness, λ is the light wavelength, $n_e(\theta(z,r))$ is the refractive index for the extraordinary ray. The axes z is perpendicular to the surface of the cell. A phase retardation is

$$\delta = \varphi_e - \varphi_o = \frac{2\pi}{\lambda}\int_0^d \left[n_e(\theta(z,r)) - n_o\right]dz \tag{3}$$

where φ_o is the phase of ordinary ray.

The refractive index for extraordinary rays decreases approaching to the center. Its profile is shown at fig. 3. Consequently a diverging lens property can be obtained in this structure. If the phase profile is defined by formula

$$\varphi_e(r) = \begin{cases} \frac{2\pi}{\lambda}\left[n_o + \frac{(r-r_0)^2}{2f}\right] & r \geq r_0 \\ \frac{2\pi}{\lambda}n_o & r < r_0 \end{cases} \tag{4}$$

then LC-microlens is analogous to cylindrical lens with focal length f turned into a ring with its radius equal to r_0. When $r_0 = 0$ the microlens possesses the properties of spherical lens.

Note that the polarization of the diverged light possesses a radial symmetry. The polarization symmetry of ordinary plane wave is axial.

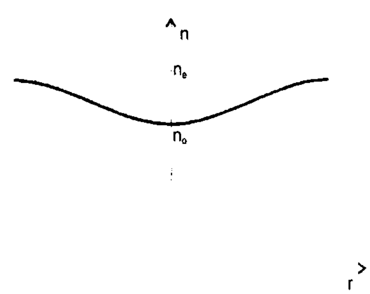


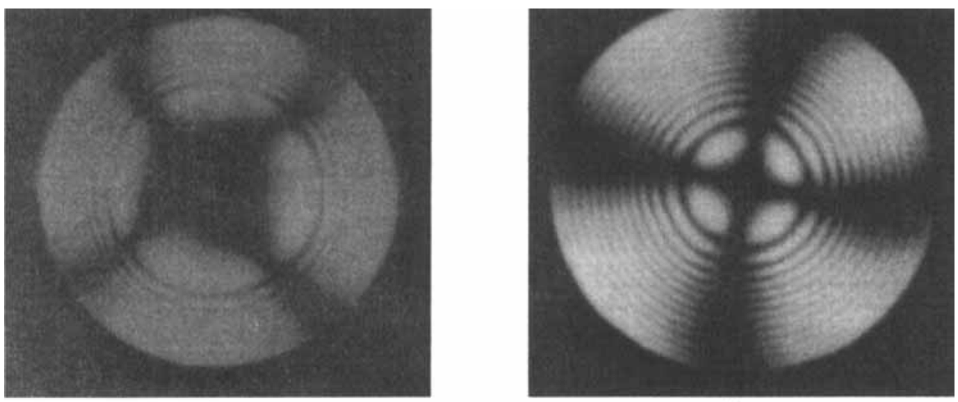
FIGURE 3. The refractive index profile at the homeotrpical - aligned microlens

The experiments show that the light aureole appears at the region of the hole edge at the small value of applied voltage. This is connected with the strongest nonuniformity of the field at this area. It is known that the director reorientation at the non-uniform field is a non-threshold process.

At values of voltage close to a Fredericks threshold voltage the alignment in the center of the hole is homeotropical and a light propagates parallel to the director orientation. Therefore a birefringence is not observed and the area around the center of the hole is dark through polarization microscope with crossed polarizers. As the molecules are reoriented by the radial symmetrical field around the hole edge an appeared phase retardation causes the circular fringe pattern of interference between ordinary and extraordinary rays and a conoscopical cross is observed. The intensity of light at the conoscopical fringe pattern is given by

$$I = I_0 \sin^2 2\alpha \sin^2\left(\frac{\delta}{2}\right) \tag{5}$$

where α is an angle between a polarization vector of the incoming light and the director and δ is the phase retardation. The fringe diameter becomes smaller with increasing the voltage, then the next fringe appears. The interference fringe patterns observed through the microscope are shown at fig. 4.



a b

FIGURE 4. The interference fringe pattern for various voltages (a - U = 10V, b - U = 14V) observed through polarization microscope. The diameter of the hole-pattern is 600μm.

The phase retardation profiles have been drawn according to photographs of fringe patterns at different voltages. Diagrams of a phase retardation are shown at fig. 5. At low values of voltage there is a plateau in the phase retardation profile. When voltage increases a region of reorientation becomes wider and the plateau diameter decreases. There is a value of voltage when it becomes equal to zero. The phase profile is close to lens-like quadratically depended on a distance to the center profile at this value (U≈10V for L = 378μm, U≈14V for L = 600μm). If the voltage increases the phase retardation profile becomes close to linear and then it arches. The fringes assemble to the center of the hole and a defect with Frank index m=2 appears. At the higher voltage the conoscopical cross transform to a swastika. Evidently the radial symmetry of the director distribution is disturbed.

All microlenses have an accompanying defect near the hole. It moves towards the hole with the increasing of voltage. This defect can disturb the symmetry of the lens and cause aberrations. For example the defects cause astigmatism of microlenses with small diameter.

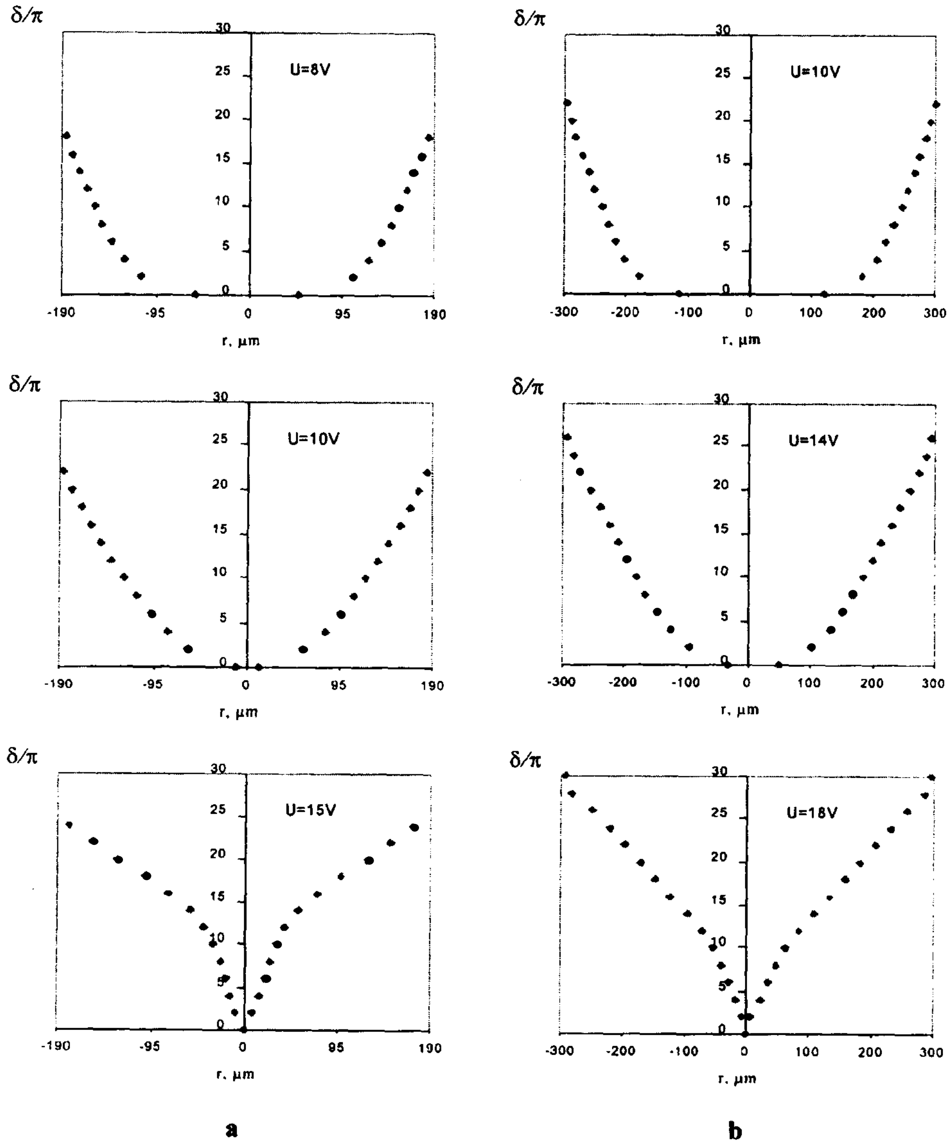


FIGURE 5. The phase retardation profiles at the various voltages (a - L/d=7.3, b - L/d=11.5)

The phase retardation is observed only around the hole edge at low values of voltage. This region is analogous to a cylindrical lens turned to a ring (the ring lens). Its focal line is a ring. The radius of this focal ring decreased with voltage increasing. There is the voltage when the focal ring transforms to a point and a spherical lens is obtained. The dependence of the focal ring radius on the voltage is shown at fig. 6a.

The experiments show that microlens focal length is negative. The dependence of focal length on voltage is shown at fig. 6b. When the reorientation is not yet started the focal length is equal to an infinity. At the values of voltage when the phase profile is linear the focal length is equal to the infinity too. Hence the dependence of the microlens focal length on the voltage must have a minimum.

Hereby the homeotropical - aligned LC-microlens is diverging lens and its focal length can be controlled by the applied voltage on the electrode. This property can be used for many applications. The researching of the phase retardation profiles shows that there is the plateau at low voltage. The similar plateau have been described at the reference 5. The best optical property is shown to be obtained at the cell with ratio of hole diameter to the cell thickness L/d from 5 to 12. The value from 5 to 10 was predicted theoretically for homogeneous-aligned microlens[5].

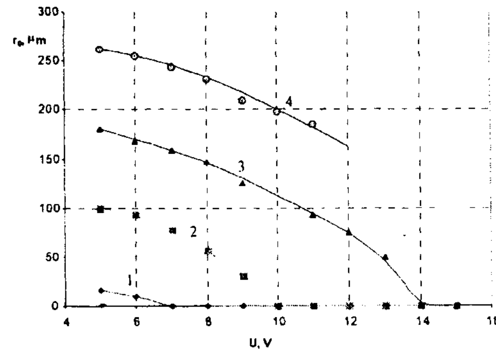


FIGURE 6a. The dependence of the focal ring radius on the voltage (1 - L/d=3.4, 2 - L/d=7, 3 - L/d=11.5, 4- L/d=15)

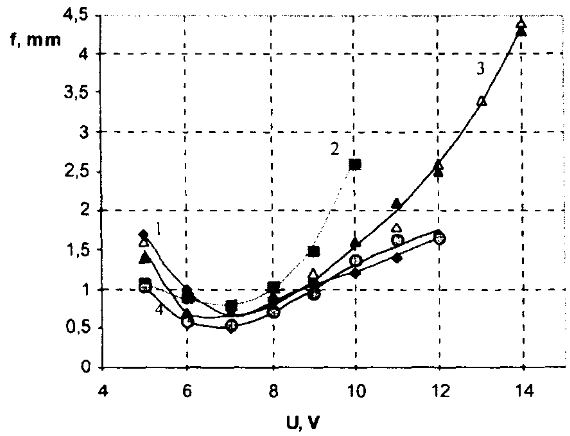


FIGURE 6b. The dependence of the focal length on the voltage (1 - L/d=3.4, 2 - L/d=7, 3 - L/d=11.5, 4- L/d=15)

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