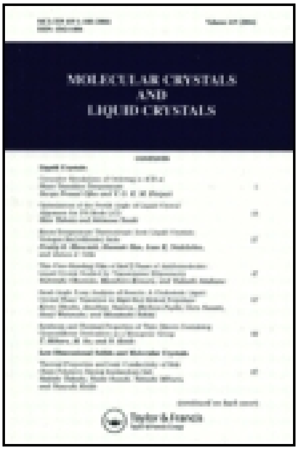

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Orientational interaction of a light beam and nematic liquid crystals subjected to an external electrical dc field has been studied. It is shown that the intensity distribution in the aberrational pattern appeared in the cross section of the transmitted beam can be highly asymmetric, unlike the conventional, rather centrally symmetric, ring system. The director-field distortion produced by the combined action of light and dc fields is independent of the light polarization. The results are explained by the surface photorefractivity.

Keywords: dc electric field; light self-action; nematic liquid crystals; optical nonlinearity; photorefractive effect

INTRODUCTION

The light-induced perturbation of the NLC director field produced due to the direct action of the light field on the induced dipoles or due to changing intermolecular forces is rather axially symmetric.

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Correspondingly, a rather symmetric system of the aberrational rings appeared in the cross-section of the light beam transmitted through an orientationally nonlinear NLC layer [1–4]. The influence of the external ac field results only in an increase (or decrease) of orientational nonlinearity [5,6].

In [7], it was first found that the aberrational pattern of the light beam passed through an NLC sample subjected to external dc field can be quite different. In this paper, we present the basic properties of the light self-action in dc-field-affected NLCs and discuss the formation of the aberrational pattern in this case.

EXPERIMENTAL

Experiments were performed on nematic material ZhKM-1277 (mixture of cyanobiphenyls and esters) and ZhKM-1277 doped with methyl red (MR, 0.1 wt%) or rhodamine 6G (R6G, 0.05 wt%). Planar alignment (ZhKM-1277 with the thickness $L = 50\,\mu m$, ZhKM-1277 + 0.1% MR ($L = 100\,\mu m$) and ZhKM-1277 + 0.05% R6G ($L = 100\,\mu m$)) was produced by buffing thin ($\sim$500–1000 nm) polyimide layers deposited on glass plates, which were previously coated with electroconductive indium tin oxide layers (ITO). Homeotropic alignment (ZhKM-1277 and ZhKM-1277 + 0.05% R6G with $L = 100\,\mu m$) was achieved by the deposition of thin ($\sim$50 nm) films of chromium stearylchloride.

The samples were illuminated by a focused light beam ($f \sim 18$ cm). The light sources were argon lasers (LASOS LGK 7872 GL or ILA-120 (Carl Zeiss)) emitting radiation with $\lambda = 515$ or 488 nm), argon-krypton laser ILM-120 (Carl Zeiss) ($\lambda = 647$ nm), and solid state laser LASOS GL-V6 ($\lambda = 532$ nm). The angle α of the light incidence on an NLC cell could be changed by rotating the cell about the vertical axis (for definiteness, the angle α is taken positive for counterclockwise rotation and negative in the opposite case). The plane of the liquid crystal layer was vertical; the unperturbed director $\mathbf{n}_o$ was in horizontal plane (in this geometry the horizontal polarization of the light beam corresponds to extraordinary wave; the vertical polarization, to the ordinary wave). The direction of the linear polarization of the incident beam could be changed by a double Fresnel rhomb. The aberrational pattern developed in the transmitted beam was observed on the screen placed behind the LC cells.

RESULTS AND DISCUSSION

At normal incidence of a horizontally polarized light beam (with the power $P = 1$–10 mW), on planar ZhKM-1277 sample, the aberrational

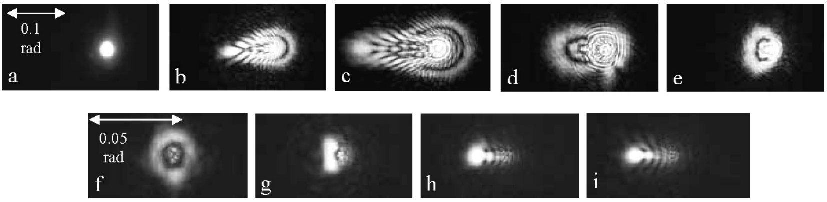

FIGURE 1 Dynamics of the aberrational-pattern formation in the cross-section of a light beam (P = 5 mW, $\lambda = 515$ nm, $\alpha = 40^{\circ}$) passed through (a–e) the planar or (f–i) the homeotropic sample of NLC ZhKM-1277 subjected to dc field (U = 2 V). Time interval between consecutive snapshots is 10–20 s.

pattern was only observed when dc voltage (U $\sim$ 2 V) was applied to the LC cell. In this case, a ring-shaped pattern of the aberrational self-defocusing was first formed during $\sim$1 min and then collapsed slowly during $\sim$10 minutes.

At oblique incidence of the light beam the aberrational pattern is much more complex. The dynamics of its formation (started after application of dc voltage to the LC cell) is shown in Figures 1a–e. First, a pattern somewhat similar to a petal is formed. The latter is elongated along the horizontal line. Then, the second (rather ring-shaped) pattern is additionally formed; its center coincides with the center of the light beam before switching on the voltage. The sign of the self-action for this system was negative (self-defocusing), as was determined by small shift of the NLC sample with respect to the light beam [8]. Finally, both patterns merge into one ring system with lesser divergence. The dimension of the aberrational pattern increases with U and P (Fig. 2).

The efficiency of the light-beam self-action was found to increase with decreasing the wavelength. For example, at U = 2 V and P = 4 mW no aberrational pattern was observed at $\lambda = 647$ nm; at $\lambda = 515$ and 488 nm the horizontal divergence of the pattern was about 0.2 and 0.4 rad, respectively.

The direction of the beam deflection (that is, the direction from the center of the second system to the "petal" center) changes with the sign of applied voltage U or the sign of the angle of incidence α. The deflection direction for one certain set of U and α is shown in Figure 3.

With planar ZhKM-1277 + 0.05% R6G sample, we also observed the development of a highly asymmetric complex aberrational pattern. Different results were obtained with planar ZhKM-1277 + 0.1% MR sample. In this case, one ring-shaped (although with a certain degree of asymmetry) pattern was only observed (Figs. 4a–c).

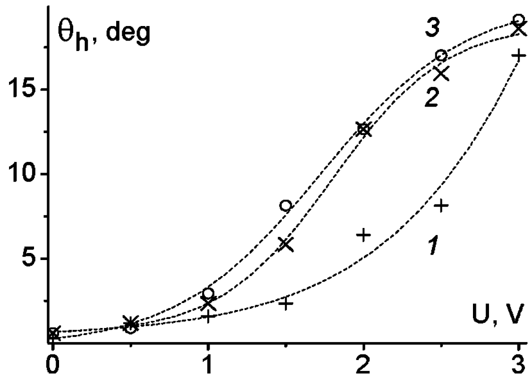

FIGURE 2 Dependence of the maximum divergence θ_h of the aberrational pattern (corresponding to its full horizontal dimension) in the cross-section of the light beam ($\lambda = 515\,\mathrm{nm}$, $\alpha = 40^\circ$) passed through the planar ZhKM-1277 sample for various beam powers P = (1) 2, (2) 5, and (3) 10 mW.

For homeotropic samples ZhKM-1277 and ZhKM-1277 + 0.05% R6G, we also observed highly asymmetric patterns with complex dynamics (see an example in Figs. 1f–i). However, the beam divergence was less than in the case of planar samples.

An important feature of the aberrational patterns in a light beam transmitted through the NLCs affected by dc field is the fact that the aberrational pattern (having a horizontal polarization (e-wave)) is almost independent of the polarization of the incident beam. Specifically, the rotation of the incident-beam polarization vector results simply in a decrease in the intensity of the pattern and in the appearance of a bright vertically polarized spot (corresponding to the ordinary wave passed through the crystal). This is illustrated by Figure 4 for

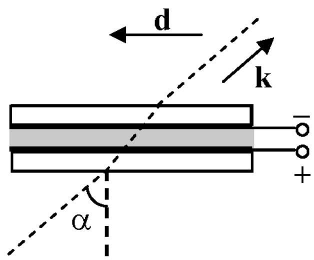

FIGURE 3 Geometry of the light-beam deflection: **k** is the light wave vector, α is the angle of incidence, and **d** is the vector indicating the direction of the beam deflection.

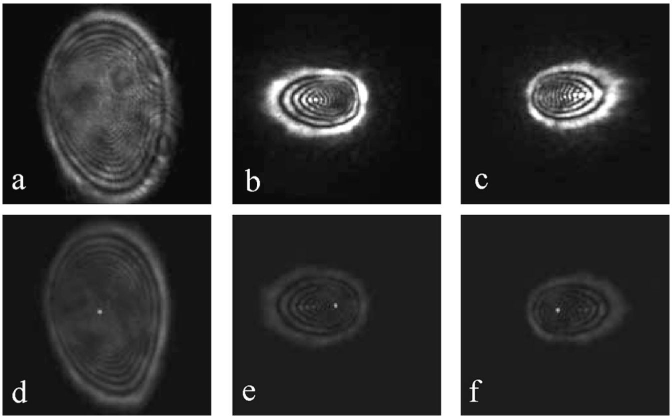

FIGURE 4 Aberrational pattern in the cross-section of a light beam ($P = 2\,\text{mW}$, $\lambda = 515\,\text{nm}$) passed through the planar sample ZhKM-1277 + 0.1% Methyl Red subjected to dc field: (a, d) $\alpha = 0^\circ$, $U = 2.8\,\text{V}$; (b, e) $\alpha = 60^\circ$, $U = 2\,\text{V}$; and (c, f) $\alpha = -60^\circ$, $U = 2\,\text{V}$. Snapshots (a–c) were taken for the horizontal polarization of the incident light (extraordinary wave); snapshots (d–f), for the polarization vector rotated by a small angle ($\sim 15^\circ$) from the vertical direction (the ordinary wave with small "admixture" of the extraordinary one).

planar sample ZhKM-1277 + 0.1% MR. It should be emphasized that such a behavior is quite different from the conventional self-action of light, in which case the aberrational-pattern size decreases with decreasing the intensity of the extraordinary-wave component of the incident light.

The value of the optical nonlinearity estimated from the aberrational pattern was 2 orders of magnitude higher than the "giant" optical nonlinearity [4].

Let us discuss the experimental results. First, we notice that the above phenomena are of orientational (and not of thermal) nature. This is evident from the absence of any aberrational pattern without dc field. Then, the independence of the aberrational-pattern shape on the incident-beam polarization suggests that the light self-action is due to the surface photorefractivity (the generation of ions in the NLC bulk would depend on the light polarization because of the absorption dichroism).

Therefore, we can assume that the mechanism responsible for the above self-action consists in the partial eliminating of dc electric field screening by the ions present in the nematic materials [9].

The existence of screening in our experiment was confirmed by the measurement of the dependence of the phase variation on applied

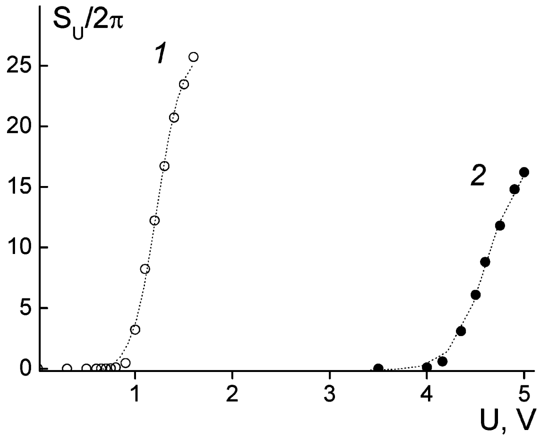

FIGURE 5 The dependence of the phase variation S_U (normalized to 2π) on (1) ac and (2) dc voltage U applied to the planar ZhKM-1277 sample.

ac and dc electric fields performed using a standard optical technique (Fig. 5). One can see from this figure that the Freedericksz transition threshold for dc field is about four times higher than for ac field.

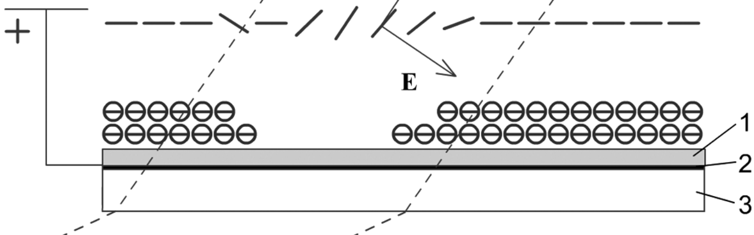

FIGURE 6 Schematic of the light beam interaction with NLC subjected to dc field: (1) polyimide layers, (2) ITO layers, (3) glass plates; **E** and **k** are the electric field and the wave vector of the light-beam, respectively; line segments in the middle of the NLC layer indicate the director orientation.

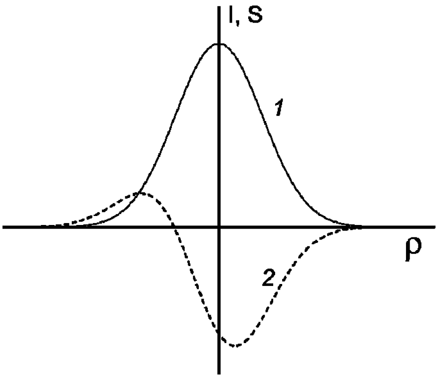

FIGURE 7 (1) Intensity profile I(ρ) of the incident light beam and (2) the nonlinear phase shift profile S(ρ) produced due to the director field distortion.

The mechanism of the light influence on the dc field screening is most likely related to the photoemission of electric charges from the polymer coating, occurred in the presence of ions at the polymer surface. The contribution of the light-induced conductivity in the bulk of polymer is also possible.

The asymmetry of the pattern is due to the transverse spatial shift between the intensity and the phase profiles in the transmitted beam [10–12]. This shift stems from the difference of the light-induced processes at the anode and the cathode, which results in the different degrees of the screening elimination. Possible director field distortion responsible for the asymmetric aberrational pattern and the respective phase profile are shown in Figures 6 and 7. The influence of the doping dyes on the light self-action may be due to their deposition [13] on the polymer layers.

CONCLUSIONS

Thus, we have found that the aberrational pattern in the cross-section of a light beam transmitted through planar and homeotropic NLCs subjected to external electric dc field can be highly asymmetric. The shape of the aberrational pattern is sensitive to the polarity of the applied dc voltage and depends on the doping agents. The light-induced director reorientation, responsible for this light-beam self-action, is independent of the light polarization. The related orientational nonlinearity is 2 orders of magnitude higher than the "giant" orientational nonlinearity of NLCs. The self-action of the light-beam in NLC subjected dc field is explained by surface photorefractivity.

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