The effect of an optical field on the nematic phase of the liquid crystal OCBP

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We have observed a complex structure and an extraordinarily large divergence (30–40°) of an argon-laser beam emerging from an OCBP crystal placed at a focal constriction. The experimental results can be explained by a reorientation of the director in the electric field of the light wave.

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In this letter we report the experimental investigation of the effect of the optical field of an argon laser on the oriented nematic phase of the liquid crystal OCBP (octyl cyanobiphenyl). The radiation of a single-frequency CW argon laser (Spectra-Physics model 170-03) at a wavelength of $\lambda = 5145$ Å and a power of up to 120 mW was focused by a long-distance objective ($f = 210$ mm) on an OCBP crystal. The plane of the cell was perpendicular to the plane containing the wave vector **k** and director **L**. The laser radiation was polarized vertically by a polarizer, and the plane of polarization was rotated by a double Fresnel rhomb. The OCBP samples used were 50 and 150 μm thick. They were placed in a thermostatic cell with a temperature stability of 0.1°C. OCBP is in a nematic phase in the temperature interval $33° \lesssim t \lesssim 40°$C. At $t \lesssim 33°$C it is in a smectic phase; at $t \gtrsim 40°$C, an isotropic phase. Most of the experiments reported in this letter were done at a temperature of $t \simeq 37°$C, which is close to the temperature of the nematic—isotropic-liquid transition. For taking measurements at different angles a between the director **L** and wave vector **k** the cell was placed on a turntable having a vertical axis. A screen was placed at a distance of ~40 cm behind the cell, and the pattern on the screen was photographed. The cell containing OCBP was located at a constriction of the laser beam. The radius of the constriction, as estimated from the divergence of the laser beam in the far field under the assumption that the transverse intensity distribution of the beam was Gaussian, came to 5×10^{-3} cm. The field strength at the center of the beam was then $(2.3\text{–}8.8) \times 10^2$ V/cm at an incident power of 8–120 mW. The parameters of the crystal were $n_0 = 1.53$, $n_e = 1.66$, $\epsilon_{\parallel} = 14$, $\epsilon_{\perp} = 6$ ($t = 37$°C)[1], $K_{11} = 4 \times 10^{-7}$ dyn, and $K_{33} = 7 \times 10^{-7}$ dyn ($t = 34$°C).[2]

The results are set forth below.

1. When the radiation incident on the crystal was horizontally (H) polarized (the **E** vector oscillating in the plane of **k** and **L**) and the angle a was constant, the pattern observed depended on the radiation power P, i.e. on the intensity of the electric field. At low power the transmitted beam was uniform over its transverse cross section, and its divergence was small. As the power was increased, the angular divergence θ of the beam increased sharply and the beam took on a complex structure: rings appeared in the plane of the screen, which was perpendicular to **k**. They increased in number as the

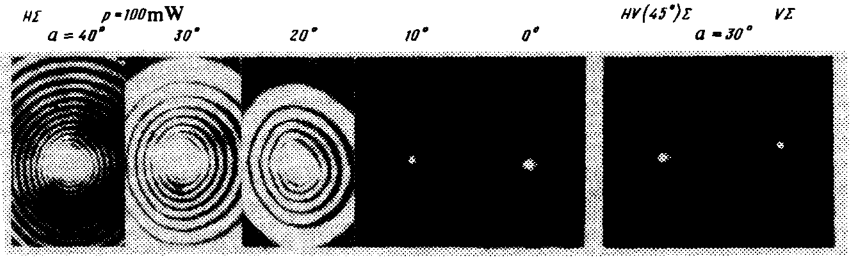

FIG. 1. Dependence of the observed pattern on the angle between the director **L** and the wave number **k** of the incident radiation (in the crystal the angles between **k** and **L** were, respectively 0, 6.5°, 13°, 19°, 24.5°).

power was increased. At powers higher than some threshold value, which was completely determined for each of the angles *a*, the number of rings and, hence, the angular divergence began to grow less rapidly, and the dependence of the angular divergence on the power became weak (Fig. 2).

2. For *H* polarization and a constant beam power *P*, the pattern observed in the plane of the screen depended on the angle *a*. It behaved with increasing angle *a* (0–40°) just as in the case of increasing power: the divergence angle θ increased strongly and the number of rings also increased (Fig. 1).

The rings had an irregular shape: they were larger in the vertical (*V*) direction (perpendicular to the plane of **k** and **L**) than in the *H* direction by 10–40%, depending on the angle *a* and power *P*.

3. The time interval T_d between the start of the illumination and the appearance

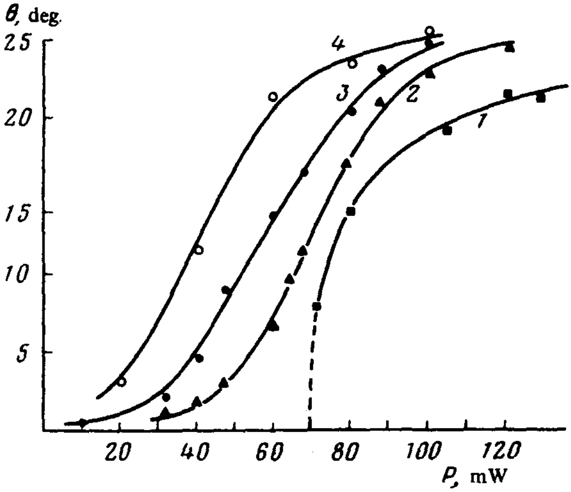

FIG. 2. Angular divergence (for the smaller dimension of the rings) of the transmitted beam as a function of the power of the laser radiation: 1—$a = 0°$, 2—$a = 10°$, 3—$a = 20°$, 4—$a = 30°$.

of the rings (the "delay time") and the time T_{st} required for establishing a stationary pattern depended on the angle a and power P. The smaller the value of a, the larger the value of T_d and the power P at which the rings appeared on the screen, and the smaller the value of T_{st}. In order of magnitude, T_d was between 10 seconds and 2 or 3 minutes, and T_{st} was from 2 to 30 seconds.

At $a = 0$, the ring structure, which was close to the onset of the region where the divergence depended weakly on the power (Fig. 2), arose almost discontinuously (over 2 or 3 sec) at $T_d \sim 30$–40 sec for $P \gtrsim 70$–80 mW. In this case $T_{st} \sim 20$ sec.

4. For V polarization of the radiation incident on the crystal and $a \geqslant 10°$, no rings were observed even at powers of ~200 mW (higher power levels were not used for fear of destroying the crystal). For $5° < a < 10°$ the rings appeared at powers of ~200 mW, but they were not stable: they would appear after $T_d = 30$–40 sec, and in 3 to 5 sec they would collapse; they would reappear after 30–40 sec, and in 3 to 5 sec they would again collapse, etc. At $a = 0$, as in the case of H polarization, the ring structure, which was close to the onset of the region where the divergence depended weakly on the power, arose almost discontinuously (over 2 or 3 sec) for powers $P \gtrsim 70$–80 mW. The rings were also irregular in shape, but in this case they were protracted in the H direction.

5. When the plane of polarization was rotated from H to V, the prolateness of the rings followed the plane of polarization.

6. The central spot of the ring pattern also had a complex structure. Figure 3 shows the nature of this structure and its dependence on the power at $a = 0$, as observed when the crystal was placed between crossed polarizers. The VH and HV patterns were exactly the same at low power. At a power of 104 mW the VH pattern corresponded to the HV pattern rotated by 90°; when the incident radiation was polarized at 45° to the V polarization, the VH pattern corresponded to the HV pattern rotated by 45°.

7. In crossed polarizers, the rings were extinguished only near the central spot, at

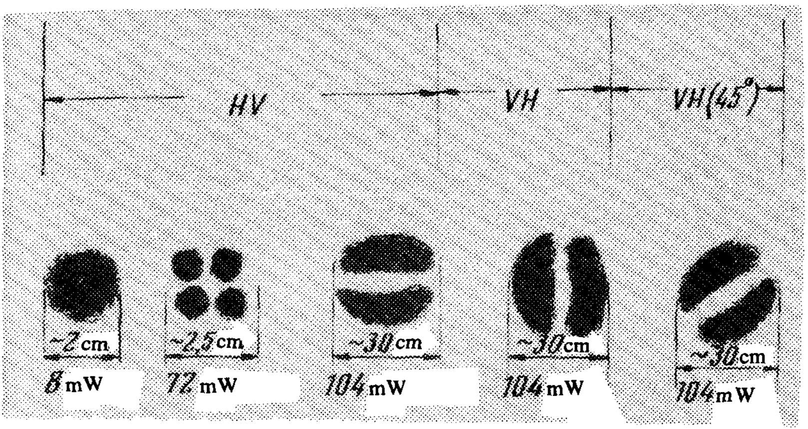

FIG. 3. Shape of the central spot when the crystal was placed between crossed polarizers.

divergence angles $\theta < 5°$. For divergence angles $\theta > 5°$ the rings were only diminished in intensity. This was true for any polarization of the incident radiation.

8. There was an extraordinarily large angular divergence of the beam on emergence from the crystal, reaching 30–40° at large powers. The total number of rings in this case was 25–35.

9. The temperature of the sample had a substantial effect. The ring structure was observed only in the nematic mesophase, and arose the more readily (the threshold power was lower and the number of rings at a given power was larger) the closer the temperature of the sample to the nematic—isotropic-liquid phase transition temperature. The ring structure was not observed in the smectic mesophase or in the isotropic liquid anywhere in the investigated interval of laser powers.

10. When the radiation incident on the crystal was circularly polarized, the ring structure was not observed. At a power of $P \sim 200$ mW there was only a small increase in the angular divergence of the beam.

In our view, all of the results of this experiment can be explained by the reorientation of the director in the electric field of the light wave, in analogy with the Fredericks transition.[3,4] Fredericks transitions are observed in uniform, constant magnetic and electric fields. Our case is more complex, but the basic features of the Fredericks effect can be clearly seen.

First of all, there was a threshold value of the field E_0 ($a = 0$) for $\mathbf{L}\mathbf{k}$ at which the pattern arose discontinuously for any orientation of $\mathbf{E}$ in the plane perpendicular to $\mathbf{k}$ (curve 1 in Fig. 2). Furthermore, this threshold field depended on the thickness of the sample. It was significantly larger in the 50-μm thick sample (by about a factor of three). The time required for establishing the stationary pattern was also comparable to the reorientation times of the director in external fields.[4] For angles between $\mathbf{L}$ and $\mathbf{k}$ of less than 90°, the orientational effect was observed at smaller fields.

Two more facts argue in favor of an orientational mechanism for the effects reported here: 1) the rotation of the prolateness of the rings when the plane of polarization was rotated, and 2) the periodic character of the pattern at some values of the field for small angles a.

As regards the complex structure of the beam and its extraordinarily large divergence, one can say the following. The reorientation of the director leads to a change in the refractive index and, in the general case, to a nonlinear dependence of the refractive index on the field E.[5] The nonuniformity of the field in the transverse cross section of the laser beam causes a radial dependence of the refractive index in the plane perpendicular to the wave vector $\mathbf{k}$. The overall pattern depends on the elastic properties of the crystal and, in general, need not be radially symmetric ($K_{11} \neq K_{22} \neq K_{33}$). Thus the action of the medium on the beam passing through it is extremely complex, and this is reflected in the pattern observed. The ring structure is evidently due to nonlinear aberrations[5,6] occurring as a result of the reorientation of the director, which produces a change in the medium.

A theoretical study of the experimental results reported in this letter is in progress.

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