Light-induced Fréedericksz transition in an MBBA crystal

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The Fréedericksz effect in a light wave in an MBBA crystal has been studied. The experimental results are compared with the theory of aberrational self-focusing. The Fréedericksz effect has been observed in a circularly polarized light wave. Rotation of the polarization plane has been observed in light beam during self-focusing.

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A Fréedericksz transition caused by the electric field of a light wave was first observed in Ref. 1 in a homeotropically oriented OCBP (octyl cyanobiphenyl) nematic liquid crystal. The transition was accompanied by an intense self-focusing of the light beam which induced the transition. Slightly later, a Fréedericksz transition was observed in an MBBA (*p*-methoxy benzylidene *p*-butylaniline) nematic liquid crystal.[2] A theory for the Fréedericksz transition in a light wave was derived in Refs. 3 and 4; in particular, an aberrational theory of self-focusing of a light beam during this transition was derived in Ref. 4. In the present letter we are reporting a detailed experimental study of the Fréedericksz effect in a well-oriented homoeotropic MBBA crystal under the influence of linearly and circularly polarized light. We will also compare the experimental results with the theory. We will pay particular attention to the polarization of the light transmitted through the crystal.

The experimental arrangement was described in Ref. 2. A freshly prepared, well-oriented, homeotropic MBBA crystal with a thickness ~120 μm was placed at the focus of a beam from an argon laser ($\lambda = 5145$ Å) focused by an objective with $f = 270$ mm. The electric field **E** at the focus was $\sim 10^5$ V/m at an incident power $P = 50$ mW. The elastic constants of the MBBA crystal at $t = 25°$C are $K_1 = 6 \times 10^{-7}$ dyn, $K_2 = 4 \times 10^{-7}$ dyn, and $K_3 = 7.5 \times 10^{-7}$ dyn (Ref. 5). The refractive indices n_e and n_o were measured in the present experiments by the method of Ref. 6 over a broad temperature range, including the corresponding to the nematic phase ($20°\text{C} < t < 46°\text{C}$). At $t = 24°$C we found $n_o = 1.56$ and $n_e = 1.80$. A screen placed behind the crystal and oriented perpendicular to the laser beam displayed the intensity distribution over the cross section of the beam transmitted through the crystal.

In the experiments we varied the power P (and thus the field **E**), the sample temperature t, and the angle (α) between the wave vector (**k**) of the incident light and the director **n**. Both these vectors lay in the horizontal plane.

1. With $\alpha = 0$ the pattern observed on the screen depends on the laser power level, as in the OCBP crystal. At a low beam power level ($P \sim 50$ mW), regardless of

the polarization, the beam transmitted through the crystal is homogeneous over its cross section and has a small divergence. As the power is raised, the beam divergence angle θ increases abruptly to a much larger value at a certain P_{thr}, and the beam acquires a complex structure; rings appear in the plane of the screen. The number of rings, N, increases with increasing power, but at high power levels ($P \sim 100$ mW) the increase slows, and saturation sets in.

2. This threshold is not found in the case of a horizontal polarization and with $\alpha \neq 0$.

3. The rings are not observed at all in the case of a vertical polarization and with $\alpha > 10°$.

4. As in the case of the OCBP crystal, the rings are irregular in shape and slightly prolate: Their dimension along the direction of the field **E** is slightly smaller (~20%) than that in the direction perpendicular to **E**.

5. In the case of a circularly polarized incident beam ($\alpha = 0$), rings are also observed in the MBBA and the OCBP, but at substantially higher power levels than for the linear polarization. The threshold P_{thr} in this case is roughly twice as high. The pattern is unstable near the threshold; it appears and then disintegrates. The period of these cycles is ~1 min for MBBA at $P \sim 100$ mW and ~5 min for the OCBP at $P \sim 150$ mW. Far from the threshold, the pattern stabilizes. For MBBA with $P = 150$ mW we find $N \sim 43$ and $\theta \sim 25°$.

6. The delay time T_d, by which we mean the time which elapses between the beginning of the illumination and the appearance of the ring pattern, ranges from ~10 s to ~10 min, and the time required for the relaxation to a steady-state pattern, T_r, is from ~5 s to ~5 min.

7. The angular divergence of the beam leaving the crystal reaches ~40°, and the number of rings reaches 60, i.e., more than in the OCBP.

8. The temperature of the sample is important: As it is raised, the threshold power, the maximum divergence, and the number of rings all decrease.

9. In crossed polarizers, the rings are extinguished only near the central spot. A rotation of the polarization plane is observed at the outer rings, and this rotation intensifies with increasing distance from the given ring to the center of the pattern (or with increasing beam divergence). Interestingly, the rotation is different at different points on each ring. With horizontally polarized incident light, for example, there is no rotation in the horizontal direction for the outer ring, and the polarization remains horizontal. In the vertical direction in the outer ring, the polarization plane is no longer horizontal, and the angle through which the polarization plane is rotated increases with increasing θ. The maximum rotation angle $\phi_{\max}$ at large values of θ depends on the angle α. At $\alpha = 30°$, we have $\phi_{\max} \sim 45°$, while at $\alpha = 0$ we have $\phi_{\max} \sim 90°$. The polarization plane rotates in opposite directions at the top and bottom points of the outer ring.

10. In the case of circularly polarized incident light, there is a bright spot at the center of the pattern. This spot and the central rings are linearly polarized, and their polarization planes are mutually perpendicular. During the cyclic appearance and

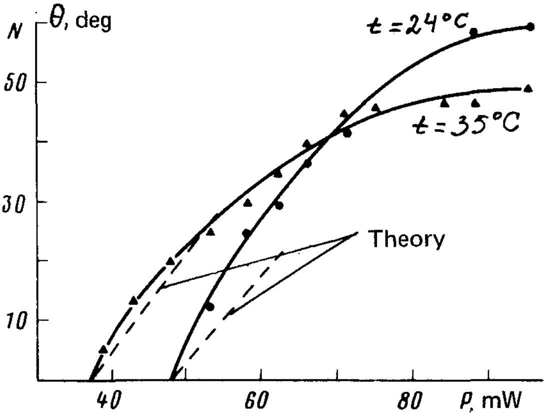

FIG. 1. Experimental and theoretical results on the beam divergence angle θ as a function of the laser power level P at various temperatures.

disappearance of the ring pattern, the directions of the polarization vectors of the spot and of the rings change, but they remain mutually perpendicular.

We may summarize these results as follows: The basic features of the Fréedericksz transition are observed in the MBBA crystal in a light wave, as in the OCBP crystal.[1] Specifically, at $\alpha = 0$ there is a threshold field E_{thr}, and at strong fields saturation sets in. If $\alpha \neq 0$, the threshold disappears. Other manifestations of the Fréedericksz effect are the dependence of the eccentricity of the rings on the direction of the polarization vector and the periodic appearance and disappearance of the ring pattern in the case of the circular polarization (at $P \sim 120$ mW).

Figure 1 shows the experimental results on the divergence angle θ, and Fig. 2 shows the number of observed rings, N, both plotted against the incident power level, for two temperatures of the MBBA sample. Figure 3 shows the P dependence of N for various values of α. Shown for comparison in Figs. 1 and 2 are theoretical curves found from Ref. 4. In order to plot these theoretical curves, we need the dimension of the focus, w; we estimated it to be $w \sim 27$ μm on the basis of the value of P_{thr} at $t = 24°$C. It can be seen from Figs. 1 and 2 that the theoretical curves give a qualita-

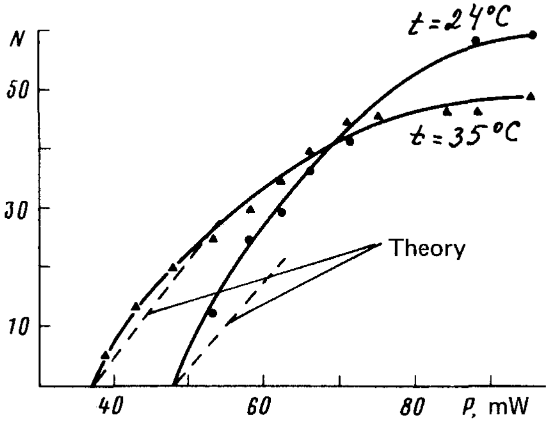

FIG. 2. Experimental and theoretical results on the number of aberrational rings, N, as a function of the laser power level at various temperatures.

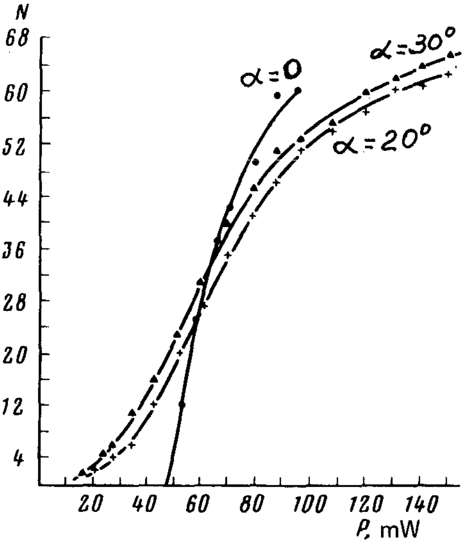

FIG. 3. Number of aberrational rings as a function of the laser power at $t = 23°$C and at various angles α.

tively correct description of the P dependence of N and θ for power levels slightly above the threshold ($P_{\mathrm{thr}} < 1.3\, P_{\mathrm{thr}}$), i.e., in the range in which the theory of Ref. 4 is applicable.

According to Ref. 4, the number of rings in the saturation region, $N_{\max}$, is given by the simple expression $N_{\max} = (n_e - n_o)(L/\lambda)$ in the case $\alpha = 0$, where L is the thickness of the crystal. This number turns out to be 56 and 47 at 24°C and 35°C, respectively. The corresponding experimental values of N are 61 and 50 (Fig. 2).

Why does the polarization plane rotate? In the case $\alpha > 10°$, and with horizontally polarized incident light, an extraordinary wave is excited in the crystal. Since the normal waves propagate independently in an anisotropic medium, each ray emerging from the crystal is a ray of an extraordinary wave.[7] Since the polarization vector of the extraordinary wave lies in the plane defined by the director and the ray direction, the polarization plane will rotate for rays which do not lie in the horizontal plane. Simple estimates put the maximum rotation angle for rays lying in the vertical plane at $\phi_{\max} \sim 50°$ with $\alpha = 30°$; the experimental value is $\phi_{\max} \sim 45°$. The condition for independent propagation of the normal waves is the inequality

$$\frac{2\pi}{\lambda} L\,(n_e - n_o)\ \sin^2\alpha \gg 1,$$

which holds for $\alpha > 10°$ for the MBBA sample of these experiments. At a smaller angle, this condition (for independent propagation of the ordinary and extraordinary waves) is violated.[7] It holds, however, if the ray deflection angle θ is large enough. For $\alpha = 0$, for the rays deflected upward and downward, the polarization of the extraordinary wave leaving the crystal is vertical. In this case, therefore, the rotation of the polarization plane can reach 90°.

When circularly polarized light is incident on the crystal, the director tends to move into the plane in which **E** is rotating. The reorientation of the director can occur in any plane parallel to the beam axis. This case is analogous to a Fréedericksz transition in a homeotropically oriented nematic liquid crystal with a negative dielectric constant when an electric field is applied perpendicular to the walls of the cell.[8] The polarization properties of the circularly polarized light beam transmitted through the nematic liquid crystal confirm the orientational nature of the self-effect: The extraordinary wave which arises in the crystal (its polarization vector lies in the plane in which the director undergoes its reorientation) experiences a self-focusing, while the ordinary wave passes through the crystal without interacting and produces the bright spot at the center of the pattern on the screen.

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