Photoinduced periodic grating in cholesteric liquid crystals

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A new nonlinear effect has been observed: A periodic grating forms in a cholesteric liquid crystal when it is illuminated with the beam from an argon-krypton laser. The beam is diffracted by this grating.

Electric and magnetic fields,[1,2] heat,[3] stresses,[4] and temperature gradients[5] are known to cause the formation of two-dimensional periodic structures (square gratings) in cholesteric liquid crystals.

In the present letter we report the observation of a photoinduced grating in a cholesteric liquid crystal. The light beam creates the periodic structure and is diffracted by it as well. It thus becomes possible to use a light beam to study a structure produced by the beam itself, as in the case of the photoinduced Fréedericksz effect.[6]

PROPERTIES OF THE TEST CRYSTAL

We studied a sample cholesteric liquid crystal $L = 110\ \mu\text{m}$ thick in the planar orientation. The liquid-crystal material consisted of "mixture A" (90%) and cholesteryl caprinate (10%). The pitch of the helix is $P = 0.97\ \mu\text{m}$. The temperature interval in which the cholesteric phase exists is essentially the same as the temperature interval in which the nematic phase of the mixture A exists. The upper boundary of this interval is ~72 °C, and the lower boundary is ~0 °C. At 25 °C the parameters of mixture A are $n_e = 1.784$, $n_o = 1.540$ (λ 589 nm), $K_1 = 8.5\times 10^{-7}$ dyn, $K_2 = 7.2\times 10^{-7}$ dyn, and $K_3 = 10.6\times 10^{-7}$ dyn (Ref. 7).

EXPERIMENTAL CONDITIONS

The beam from a Carl Zeiss ILM-120 cw argon-krypton ion laser is focused in the cholesteric liquid crystal by an objective ($f = 270$ nm). The plane of the cell runs

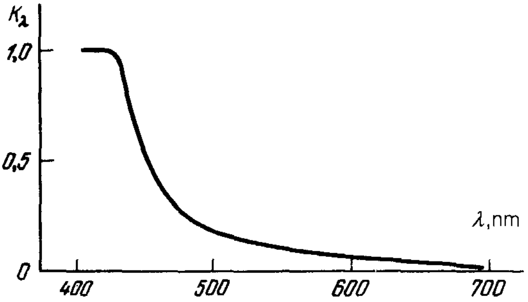

FIG. 1. The absorption coefficient K_λ of the cholesteric liquid crystal versus the wavelength.

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perpendicular to the wave vector of the light incident on the crystal. A double Fresnel rhombus and a quarter-wave plate (at λ 633 nm) produce a linear or nearly circular polarization of the light. The ILM-120 laser makes it possible to produce light at the wavelengths λ 647, 488, and 515 nm. The maximum power of the light at the wavelength λ 647 nm is $P_{\max} \sim 160$ mW, while that in the blue-green region is $P_{\max} \sim 500$ mW (λ 515 nm) and ~ 400 mW (λ 488 nm). The absorption of the test crystal falls off sharply with increasing wavelength (Fig. 1). All experiments were carried out with the liquid crystal at $\sim 21\,^{\circ}\mathrm{C}$.

EXPERIMENTAL RESULTS

A. Appearance of a two-dimensional grating

I. When the crystal is illuminated with a light beam with λ 647 nm, we observe an extremely interesting effect: The diffraction pattern typical of a square grating appears on a screen positioned behind the crystal. Specifically, the pattern has bright spots at the nodes of a square grid (Fig. 2). Significantly, the second-order spots (along the XX and YY directions) are the most intense.

The pattern does not arise instantaneously after the illumination is applied; it instead appears after a delay T_d which depends on the power of the light beam, P.

After an existence time T_e the pattern disappears. The disappearance begins with a blurring of the spots making up the pattern.

The delay T_d decreases with increasing beam power P($T_d \sim 30$ min at $P = 40$ mW; $T_d \sim 10$ min at $P = 60$ mW; $T_d \sim 1$ min at $P = 120$ mW). The time T_e also depends on P: At $P = 80$–100 mW, T_e is on the order of a few minutes, while at $P = 50$–60 mW, T_e is on the order of severals tens of minutes.

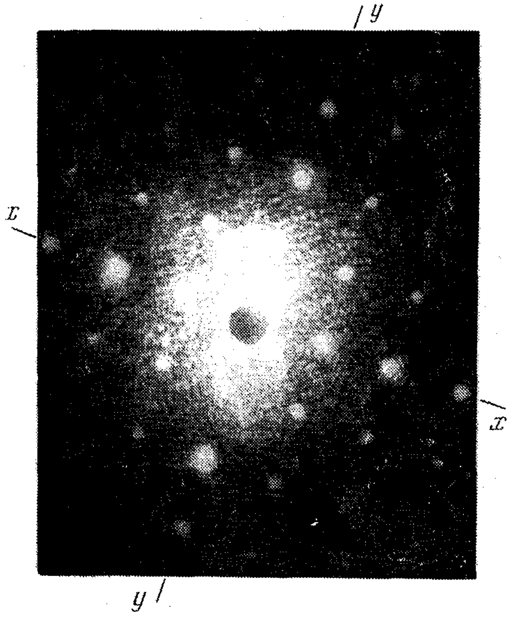

FIG. 2.. Photograph of the pattern of diffraction by a two-dimensional grating produced by a narrow light beam ($P = 100$ mW, $\delta\theta \sim 0.04$ rad). The dark spot at the center of the pattern is a result of the blocking of the beam transmitted by the liquid crystal (to avoid exposure of the photographic film).
λ,nm

The state of the crystal in which the diffraction pattern is observed persists for a rather long time (on the order of several minutes) after the illumination is ended. This point can be demonstrated by blocking the laser beam for a certain time and then resuming the illumination of the crystal, after a reduction of the beam power to $P \sim 1$ mW. (At this power, no distortions of any sort occur in the liquid crystal, and the beam serves as a probe.) If the red beam is replaced by a green or blue beam (λ 515 nm, λ 488 nm) (these wavelengths are strongly absorbed by the crystal) of power $P \gtrsim 5$ mW, however, the diffraction pattern disappears essentially instantaneously, in ~ 1 s; at $P \lesssim 1$ mW, the pattern disappears over a time ranging up to several tens of seconds. A high power in the red line of the laser or an increase in the crystal temperature degrades the conditions for the formation of and the existence of the periodic structure.

The pattern can thus be "written" with a red beam and "erased" with a green or blue beam. The pattern described here appears when the light incident on the cholesteric liquid crystal is either linearly polarized (in an arbitrary direction) or approximately circularly polarized. There are no substantial changes in T_d and T_e here. The polarization of the beam transmitted by the liquid crystal (the zeroth order of the diffraction pattern) is essentially linear (if the incident beam is linear). The plane of polarization is rotated, however. The angle through which the plane of polarization is rotated changes by 20–25° over the time T_d and T_e. Experiments with a wedge-shaped liquid-crystal sample showed that the rotation direction is the same as that which is observed upon a decrease in the thickness of the liquid crystal, i.e.; when the periodic grating forms in the liquid crystal, the angle through which the polarization plane rotates decreases. This result indicates a distortion of the spiral of the cholesteric liquid crystal.

The polarization of the diffraction spots in the XX and YY directions (Fig. 2) is precisely the same as the polarization of the beam transmitted by the liquid crystal.

II. From the angular separation ($\delta\theta$) of the diffraction peaks we can estimate Λ, the period of the photoinduced grating ($\Lambda = \lambda/\delta\theta$). At $L = 110\ \mu$m, it is 15 μm; it decreases with decreasing thickness of the liquid crystal.

For gratings produced by stresses or by a uniform electric field, an expression was found in Refs. 4 and 2 to relate their period to the Frank constants, the pitch of the helix, and the crystal thickness; $\Lambda = (3K_3/2K_2)^{1/4}(pL)^{1/2}$. Using this relation, we find $\Lambda = 13\ \mu$m, in satisfactory agreement with experiment.

Possible reasons for the formation of a grating in a narrow light beam might be a reorientation of the director caused by the electric field of the light beam or the stresses that may arise from a change in the pitch of the helix during heating of the liquid crystal by the laser beam.

Since the grating observed by us is easily destroyed by light which is strongly absorbed by the crystal (λ 515 nm and λ 488 nm), and since a high light power at the wavelength λ 647 nm (at which absorption of the light becomes significant) degrades the conditions for the formation and existence of the grating, it appears that the electric field of the light wave is the more probable cause of the formation of the square grating in the laser beam. Another possibility is that the stress associated with the transverse nonuniformity of the electric field of the narrow light beam plays a definite role in the formation of the square grating.

B. Thermal self-focusing of the light beam

I. A light beam of wavelength λ 488 nm is broadened as it passes through the cholesteric liquid crystal. On a screen behind the crystal we observe the typical pattern of a thermal aberrational self-effect. This pattern consists of two systems of rings with right-hand and left-hand circular polarizations. The divergence and the number of these aberration rings depend on the light power P and the direction of the circular polarization. At $P = 140$ mW, the beam divergence is ~ 0.05 rad.

II. The self-effect of a light beam with a wavelength λ 515 nm is similar, but a given beam divergence is reached at a higher light power.

III. At a power $P = 200$ mW (λ 488 nm) we observe yet another system of equidistant rings, whose intensity is much lower than that of the first two rings.

IV. As can be seen from Fig. 1, light at the wavelength λ 488 nm is significantly absorbed by the test crystal. This absorption naturally gives rise to a thermal self-effect of the beam. Since two normal modes with circular polarization propagate along the axis of the helix in a cholesteric liquid crystal,[1,2] each will produce its own set of rings on the screen. The dependence of the divergence and intensity of the rings on the direction of the circular polarization results from the difference in refractive indices and absorption coefficients for the normal waves which arise in the liquid crystal.

V. The system of equidistant rings which arises with increasing power of the light beam is the result of a diffraction of light by "holes"[8] which arise in the cholesteric liquid crystal due to its heating by the laser beam.

In summary, a narrow light beam can create a two-dimensional grating of distortions of the director field in a cholesteric liquid crystal and can be diffracted by this grating.

This effect is of interest from the standpoint of technical applications: writing and storing information. Information can be written by a red beam and erased by a green beam.

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