# Light modulation by a planar-oriented film of a polymer-encapsulated ferroelectric liquid crystal

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Light modulation with the help of a new electrooptic material has been studied. The material is a planar-oriented film of a polymer-encapsulated ferroelectric liquid crystal. The polarization and dynamic characteristics of the material have been studied.

**1.** Ferroelectric liquid crystals (FLCs) presently hold the high-speed response record among known liquid-crystal materials.[1–4] However, several problems are holding up the widespread use of pure FLCs in optoelectronic devices: the need to develop elaborate equipment for fabricating sandwiches with a very small working gap (about 2 $\mu$m wide), the expensive and technologically complex procedures required for producing uniformly oriented monolayers of FLCs, the inability to achieve a sufficient number of shades of gray, etc.

In this letter we propose that planar-oriented films of polymer-encapsulated ferroelectric liquid crystals be used to modulate light.[5] These films combine the advantages of the familiar nematic-based encapsulated films with the high speed of FLCs.

**2.** Planar-oriented polymer-encapsulated FLC films were prepared by a method like that of Refs. 6 and 7, in such a way that the FLC droplets dispersed in polyvinyl acetate were oriented in predominantly one direction in the plane of the film. We selected the well-studied ferroelectric liquid crystal[1–4,8–10] DBC for the encapsulation. The film thickness was $20 \pm 5$ $\mu$m, and the capsule was about 3 $\mu$m in size.

Figure 1 shows a schematic diagram of the test cell. For simplicity, only one of the ensemble of droplets is shown. The $x$ axis runs along the orientation of the encapsulated FLC film. The $zy$ plane coincides with the plane of the smectic layer. The director in the droplets is oriented in the $xy$ plane (the plane of the film) by means of an electric field. The director makes an angle $\theta$ with the $x$ axis. If the angle $\alpha$, between the $x$ axis and the polarization plane of the light, is equal to $\theta$, and if the condition $n_\perp \simeq n_p$, holds, as it does for the particular composite material which we studied, the film will strongly scatter light incident normally on it because of the substantial gradient in the refractive index $(n_\parallel - n_p)$ at the interface between the polymer and the droplet of liquid crystal. Here we are using the approximation of an optically uniaxial FLC,[3] with refractive indices $n_{\parallel,\perp}$ for light polarized, respectively, parallel and perpendicular to the director of the liquid crystal. As the polarity of the electric field is changed (Fig. 1b), the director of the liquid crystal rotates through an angle of $2\theta$. It can thus be seen that in the case $2\theta = 90°$ the film will become essentially transparent, because the refractive-index gradient disappears: $(n_\perp - n_p) \simeq 0$.

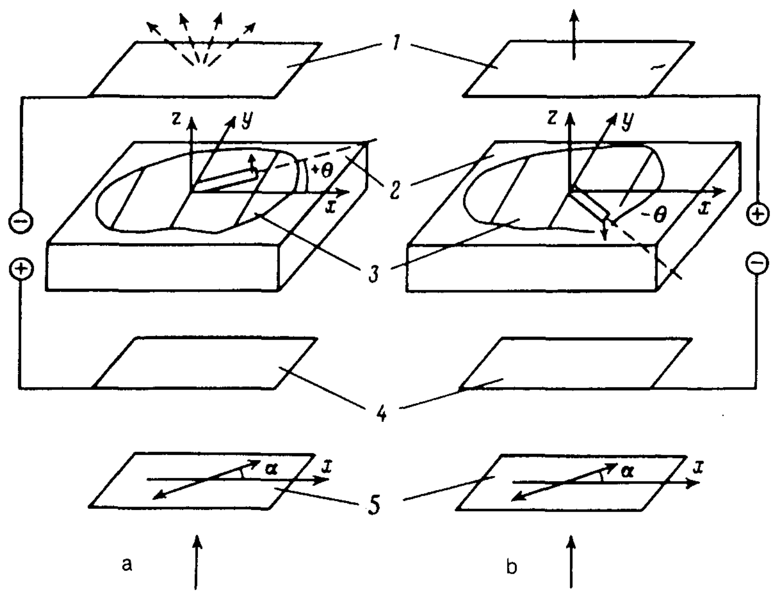

FIG. 1. Schematic diagram of a light-modulating device based on a polymer encapsulated film of a ferroelectric liquid crystal. *1,4*—Glass substrates with transparent electrodes; *2*—polymer film; *3*—droplet of ferroelectric liquid crystal; *5*—polarizer. a) The light is scattered; b) the light is transmitted.

In general, if we think of a plane-polarized light wave as a superposition of two waves, polarized parallel to and perpendicular to the director of the liquid crystal, we can write the difference between the intensities of the transmitted light for the two illustrated orientations of the director (i.e., the modulation amplitude) as

$$\Delta I=I_0[T_\perp \sin^2(\alpha+\theta)+T_\parallel \cos^2(\alpha+\theta)-T_\perp \sin^2(\alpha-\theta)-T_\parallel \cos^2(\alpha-\theta)]$$
$$=I_0(T_\perp T-_\parallel)\sin 2\alpha \sin 2\theta=(I_\perp -I_\parallel)\sin 2\alpha \sin 2\theta, \qquad (1)$$

where $T_{\parallel,\perp}$ and $I_{\parallel,\perp}$ are the transmission coefficients and intensities of the transmitted light polarized, respectively, parallel to and perpendicular to the director. The quantity $I_0$ is the intensity of the incident light. It can thus be seen that the modulation of the light due to the linear electrooptic effect does not occur under the condition $T_\parallel = T_\perp$, which corresponds to the case of a random orientation of the liquid-crystal droplets. In order to maximize the modulation amplitude $(I_\parallel - I_\perp)$, it is necessary to satisfy the condition $\alpha=\theta=45°$.

**3.** The experimental results on the behavior of the modulation amplitude as a function of the angle $\alpha$ shown in Fig. 2 can be described well by expression (1), with maxima reached at angles $\alpha=45°\pm n90°$ $(n=1,2,3...)$.

Figure 3 shows the temperature dependence of the response time $\tau_{\mathrm{ON}}$ and the relaxation time $\tau_{\mathrm{OFF}}$ of the polymer-encapsulated FLC film. The curves of the temperature dependence of $\tau_{\mathrm{ON}}$ for the pure FLC[4,8] and for the encapsulated film are

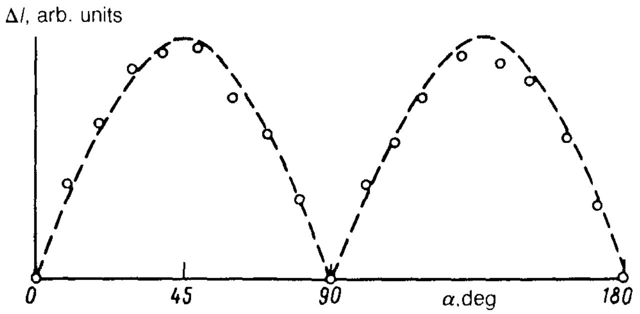

FIG. 2. Light modulation amplitude versus the angle $\alpha$, between the polarization plane of the light and the orientation direction of the encapsulated liquid-crystal film. Circles—Experimental data; dashed curve—calculated from Eq. (1).

identical in shape. It should be noted that the temperature range in which the *CmC** ferroelectric phase exists for a dispersion of DBC in the polymer (55 °C←84 °C) is not the same as that for a pure monolayer of the liquid crystal[9] (75 °C←93 °C). The response time $\tau_{ON}$ for the encapsulated film and that for pure DBC,[8] normalized to the strength of the controlling field, are essentially the same, within the experimental errors.

A curve of more complex shape is observed for the temperature dependence of the relaxation time $\tau_{OFF}$. The shape of the curve near the *CmC*–CmA* phase transition is reminiscent of the temperature dependence of the pitch of the helix, $P_0$, in agreement with the proportionality $\tau_{OFF} \propto P_0^2$ which has been demonstrated previously.[10] The values of $\tau_{OFF}$ for the encapsulated film are comparable in magnitude to the values of $\tau_{ON}$ and much shorter than the relaxation relation time for pure layers of DBC.[10] This

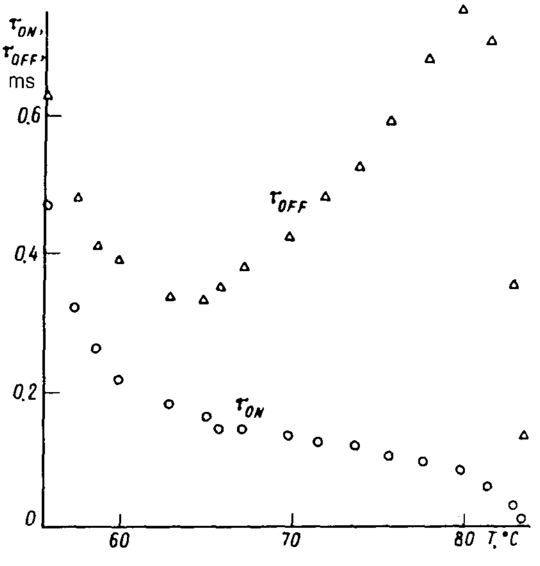

FIG. 3. Temperature dependence of the response time $\tau_{ON}$ (○) and the relaxation time $\tau_{OFF}$(△).

result suggests that forces associated with a surface interaction of the liquid-crystal molecules with the polymer matrix are playing an important role in the dynamics of the linear electrooptic effect and that these forces must be taken into consideration in modeling the process by which the director in a FLC droplet undergoes reorientation.

**4.** The study of the modulation of light by a planar-oriented, polymer-encapsulated FLC film reported in this letter (this is the first such report) thus demonstrates an alternative solution to the problem of developing fast electrooptic devices, on the basis of ferroelectric liquid crystals.

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