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## Liquid Crystals

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# Electro-optic effect in polymer-dispersed cholesteric liquid crystals with medium chirality

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We have investigated the electro-optic behaviour of polymer sheets containing small chiral nematic liquid crystal droplets. In previous investigations of polymer-dispersed liquid crystals (PDLC), either non-chiral nematic liquid crystals or cholesteric liquid crystals with very small pitch ($p < \lambda$) have been used. Here we adjusted the pitch $p$ to be below the Mauguin limit, but well above the wavelength, $\lambda$, of the visible range of light; typically we chose $p \approx 2\lambda/\Delta n$. Between crossed polarizers, the sample can be switched from a transparent off state to a dark on state. With respect to non-chiral nematic PDLC films, the transmittance is lower, but the angular dependence is improved.

The optical properties of chiral liquid crystals have been very fully investigated because of their application in electro-optic liquid crystal displays. In particular, the optical behaviour has been very extensively studied in the limits of either low chirality (Mauguin approximation) or very high chirality. For example, chiral nematic liquid crystals with *low chirality* are used in the conventional twisted nematic display [1], where a chiral nematic liquid crystal is sandwiched between two glass plates coated with transparent electrode areas. On both substrates, the director (which describes the average molecular orientation) is anchored parallel to the surface due to suitable surface treatment. The azimuthal angles of this orientation on the bottom and the top plate deviate by 90°, thereby inducing a director field which is twisted by $\pi/2$. When polarized light is transmitted through the sample, the plane of polarization is continuously rotated without the occurrence of any ellipticity, provided that the Mauguin condition is valid, i.e.

$$\lambda \ll \Delta n \cdot p, \tag{1}$$

where $\lambda$ is the wavelength of the light, $\Delta n$ is the birefringence of the liquid crystal, and $p$ is the pitch of its twisted structure. Consequently, the sample appears bright between crossed polarizers. It can be switched to a dark state by applying an external electric field which causes the director to align along the field direction.

Chiral nematic liquid crystals with very *high chirality*, i.e. small pitch $p$, show fundamentally different optical properties. If $p$ is smaller than the wavelength $\lambda$, they

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show selective reflection of circularly polarized light [2]. For normal light incidence, maximum reflectivity occurs at the Bragg wavelength

$$\lambda_0 = n \cdot p, \tag{2}$$

where $n$ is an average refractive index. The optical activity is known to be very high in the vicinity of the Bragg wavelength. The sign of the optical rotation is reversed at $\lambda = \lambda_0$.

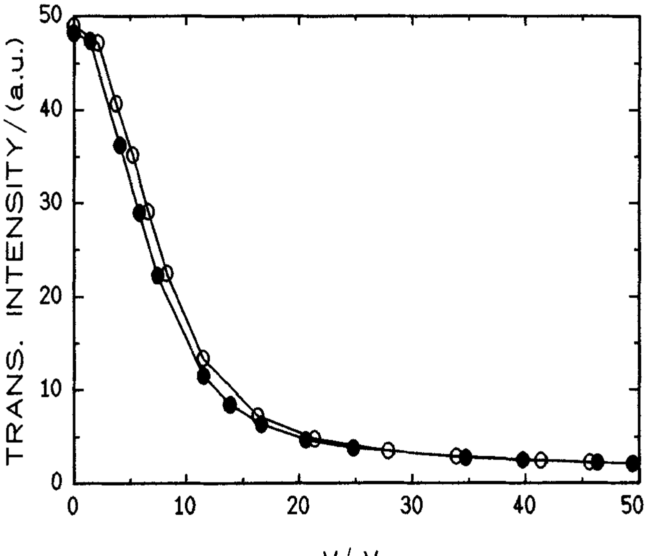
While the former two limits have been very well studied and used for applications, Chanishvili *et al.* [3,4], reported recently on the use of chiral liquid crystals with *intermediate chirality*. They have shown that polarized light transmitted through a chiral nematic layer of thickness $d$ is nearly circularly polarized if the conditions

$$\lambda > \approx \Delta n \cdot p/2 \quad \text{and} \quad p > d, \tag{3}$$

are fulfilled. The remarkable property of the optical behaviour in these limits is that the ellipticity of the transmitted light is independent of the orientation of the liquid crystal. Consequently, the authors were able to build a new display consisting of a chiral nematic liquid crystal with positive dielectric anisotropy sandwiched between crossed polarizers [4]. In comparison with the twisted nematic cell, their device exhibits lower contrast and higher switching voltages, but reasonable switching times. Its main advantages are that the transmission-voltage characteristic shows no oscillations and the liquid crystal cell is very easy to produce, because no surface treatment is necessary.

In the present paper, we report on first attempts to make use of the electro-optic effect studied by Chanishvili *et al.* [4], in polymer-dispersed liquid crystals (PDLC), thereby combining its advanced performance with the advantages of polymer films which contain liquid crystal droplets. The latter systems have been established through the work of Fergason [5] and Doane *et al.* [6]. PDLCs provide an interesting extension to conventional displays due to their capability for use in large area flexible displays and projection displays with high transmission [7,8]. However, PDLC displays suffer from a large angular dependence of their transmittance; thus many efforts, with varying success, have been made to develop devices which are haze-free for non-normal light incidence [9,10]. Here, we demonstrate that the effect claimed by Chanishvili *et al.* [4], can be used in PDLC films. In comparison with non-chiral nematic PDLC displays, our device exhibits a lower brightness at normal light incidence, but a broader angular width of transmittance.

The liquid crystal employed in our experiments consists of the commercial nematic mixture RO-TN 403 from Hoffmann–La Roche (98 per cent by weight) which was chiralized by the addition of 2 per cent of 4-(2-methylbutyl)-4′-cyanobiphenyl (CB15, Merck Ltd., Poole, GB). Using the Cano method [11], an undisturbed cholesteric pitch of $p = 7{\cdot}4\,\mu$m was measured at room temperature. Polymer-dispersed samples were produced by polymerization-induced phase separation using the UV-curable adhesive NOA-65 (Norland). The liquid crystal and the polymer precursor were mixed in a 1:2 ratio and sandwiched between ITO coated glass plates. The sample thickness was controlled by glass cylinders with a diameter of 11 $\mu$m. For the curing process, the samples were illuminated using a 400 W metal-halogen lamp. In order to control the diameter of the droplets, we chose different UV intensities and exposure times, especially 12 mW cm$^{-2}$ (30 s exposure time), 1·2 mW cm$^{-2}$ (5 min exposure time), and 0·12 mW cm$^{-2}$ (50 min exposure time). Previous studies [12] using a similar liquid crystal have shown that the average droplet diameter decreases with increasing UV intensity from a few $\mu$m (0·12 mW cm$^{-2}$) to the sub-$\mu$m range (12 mW cm$^{-2}$).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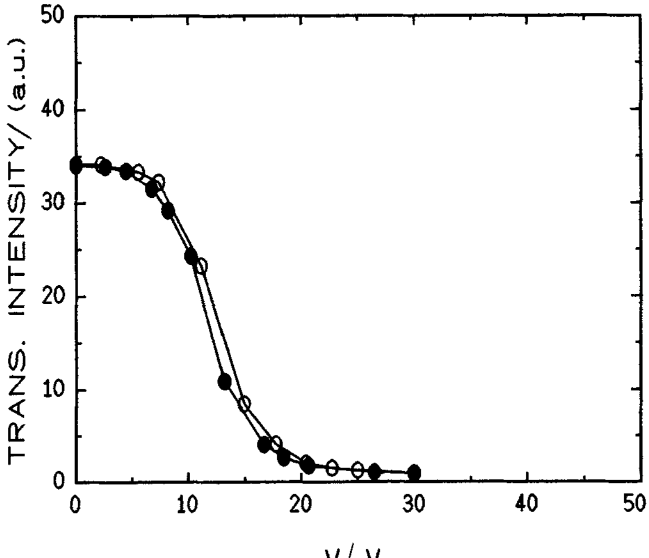
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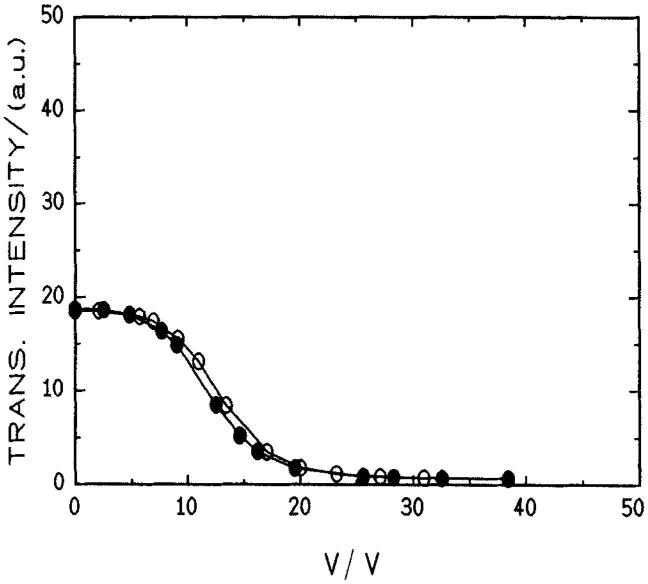


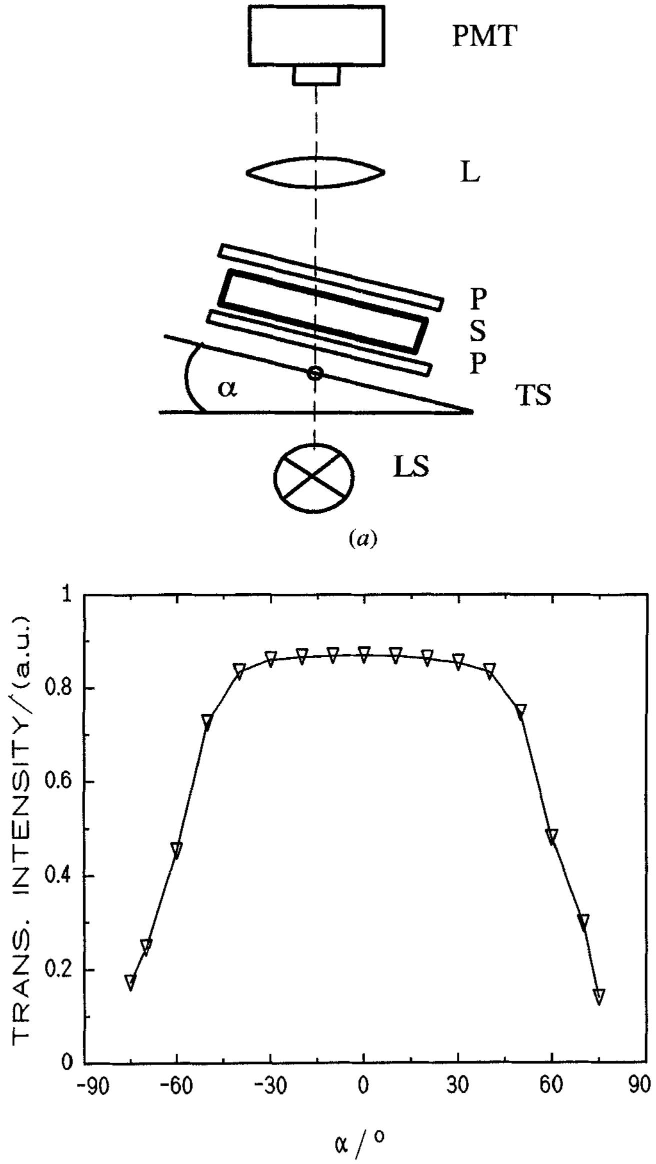
(c)

Figure 1. Transmitted intensity versus applied voltage for increasing (○) and decreasing (●) voltage. The samples were cured with UV intensities (exposure times) of (*a*) 0·12 mW cm$^{-2}$ (50 min), (*b*) 1·2 mW cm$^{-2}$ (5 min), and (*c*) 12 mW cm$^{-2}$ (30 s), respectively. The droplet diameter increases with decreasing UV intensity.

In order to study the optical and electro-optical properties, the cell was placed between crossed polarizers and examined using a polarizing microscope. The transmission of white light from a halogen lamp was measured using a photomultiplier tube connected to the microscope. Alternating voltages (sine, 1 kHz) were applied to the sample; the reported voltages are rms values. In order to study the angular dependence of the transmitted light intensity, we used a tilting microscope stage which allowed us to vary the angle between the surface normal and the direction of light propagation (see figure 2 (*a*)). For this purpose, crossed polarizers were directly attached to the two surfaces of the PDLC sample.

Depending on the UV intensity during the photopolymerization, we obtained liquid crystal droplets with different sizes. In agreement with earlier measurements [12], the lowest intensity (0·12 mW cm$^{-2}$) led to droplet diameters of 4–5 $\mu$m, while the highest UV intensity resulted in droplets of diameters below the spatial resolution of the microscope. If the samples were placed between crossed polarizers and rotated azimuthally, we found little change in the transmitted intensity and no change in the average intensity. This behaviour indicates that the elliptically polarized transmitted light is almost circularly polarized in the field off state.

Figure 1 shows the electro-optic characteristics for three samples cured with UV intensities of 12 mW cm$^{-2}$, 1·2 mW cm$^{-2}$ and 0·12 mW cm$^{-2}$, respectively. When the electric field is applied, the director is reoriented along the field direction, and consequently the transmission decreases (see figure 1). The threshold voltage for samples of 11 $\mu$m thickness increases from $\approx$ 7 V for samples cured with low UV intensity (large droplets) to $\approx$ 12 V for samples cured with high UV intensities (smaller drops, figure 1 (*c*)). The transmitted intensity was found to be higher for the samples



(*a*)

(*b*)

Figure 2. (*a*) Experimental set-up used to measure the angular dependence of the transmission. Crossed polarizers (P) were directly attached to the sample (S). The angle α between the sample surface and the direction of light propagation was measured by means of a tilting stage (TS). [Light source (LS), halogen lamp, L: microscope lens, PMT: photomultiplier tube.] (*b*) Transmitted intensity versus tilting angle α for the sample shown in figure 1 (*a*).

cured with lower UV intensity, i.e., for the larger droplets (see figure 1 (*a*)), than for the samples cured with higher intensity (smaller droplets). Consequently, the samples with large droplet size are very suitable for obtaining high contrast and low switching voltages. However, the sample with medium droplet size (see figure 1 (*b*)) shows a sharper threshold in the electro-optic characteristics.

The advantage of the cholesteric PDLC cells with respect to nematic PDLC samples is a high transmission for non-normal light incidence (see figure 2 (*a*), (*b*)). In comparison with ordinary PDLC films, which provide the possibility of switching between a scattering OFF state and a transparent ON state, our system operates in a 'reverse mode'. Consequently, we may compare our data for the transparent OFF state with reported values [7] for the transparent ON state of conventional PDLC films. With respect to the angular dependence of the transmitted intensity $I(\alpha)$, we find an angular width (defined as the half width at half maximum, HWHM) of $\Delta\alpha_{\mathrm{HWHM}} \approx 60°$. Despite the possibility that differences in the experimental set-up may affect the results, this value is distinctly larger than a typical value of $\Delta\alpha_{\mathrm{HWHM}} \approx 30°$ reported for ordinary PDLC films [7].

Despite the broad angular width of the transmission in our samples, it should be noted that the absolute values of the transmission of nematic PDLC samples for normal light incidence can be higher (in principle up to 100 per cent), because no polarizers are required. In our case, only 50 per cent of the linearly polarized light which hits the sample is transmitted through the analyser.

The results reported above indicate that chiral nematic liquid crystals with pitches in the range between the Mauguin and the high-chirality limit can be utilized for polymer-dispersed liquid crystal films. Similarly to the pure liquid crystal samples studied by Chanishvili *et al.*, our PDLC samples fulfilling the conditions of equation (3) appear bright between crossed polarizers and show little change in the transmitted intensity when they are rotated. The positive dielectric anisotropy of the liquid crystal enables us to switch to a dark state, where the director is uniformly oriented along the field direction.

The well-known non-chiral nematic PDLC films make use of refractive index matching or mismatching of the liquid crystal and the polymer in order to generate the change from a translucent to a transparent state on switching. In contrast to these devices, the effect presented here provides a 'reverse mode' [7, 8]. Unfortunately, our effect requires the use of polarizers and thus cannot be used to achieve the very high transmittance which makes non-chiral PDLC films favourable for projection displays. However, the haze at non-normal light incidence, which is one of the major disadvantages of nematic PDLC displays, is markedly reduced in the transparent state of our systems. Further studies to optimize the parameters, especially to enhance the switching speed of our effect, have to be performed in the future.

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