Polymer dispersed liquid crystal composite films-droplet orientation and optical responses

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Abstract | Polymer dispersed liquid crystals (PDLCs) constitute an important class of novel materials in which liquid crystal droplets are dispersed in an appropriate polymer matrix. The opto-electric switching in these materials is achieved by matching the refractive index of the liquid crystal with that as the polymer matrix. In this paper, preparation and characterization of PDLC films of nematic and Ferroelectric liquid crystals in various polymers are described. PDLC films with a dichroic dye dissolved in the liquid crystal possess a controllable absorbance and a controllable scattering as well. This combination can be used to produce high contrast displays. This attractive feature is attributed to the molecular orientation in dispersed liquid crystal droplets and the optical transmission of dichroic PDLC cells exhibiting a remarkable dependence on the droplet morphology. It is found that the viscosity and concentration of the dichroic dye influence the LC droplet size and low dye concentration, samples show improved contrast ratio with reduced threshold voltage.

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1. Introduction

P.G de Gennes, a pioneer in the field of liquid crystal proposed in 1979 that a polymer-liquid crystal gel (consisting of a low molar mass nematic liquid crystal and thermoplastic) can form composite materials and show better electro-optic properties[1]. Fergason exploited this idea in 1984 and patented an encapsulated liquid crystal display having good mechanical and electro-optic properties. Doane et. al (1986) carried out detailed experimental work and proposed several theories to support the ideas of de Gennes and Fergason. These flexible composites were thereafter named as polymer dispersed liquid crystals (PDLCs). Recently PDLC[2–12] and polymer stabilized LC (PSLC)[13–14] have been widely studied and applied intensively in the field of display devices.

They essentially consisting of nematic liquid crystal droplets of micron or sub-micron size embedded in a polymer matrix, PDLCs have rather dramatic light scattering properties. Optical effects in this system are based on light scattering, the magnitude of which can be controlled by an external field, temperature, or directional deformation of the polymer matrix which changes the LC orientation. Theoretical analysis of light transmission, scattering, and birefringence in PDLC has played an important role in the development of flat-panel and projection displays. A thin film of this material can switch between a translucent and a transparent state in presence of an electric field due to the refractive index matching. This laid the concept of an electronic window using liquid crystals.

As the interest in this subject grew, researchers used dispersions of cholesteric and ferroelectric liquid crystal materials. This gave rise to coloured and faster switching displays, retaining the polymer

Figure 1: (a) A dye-doped NLC droplet (b) Liquid crystal cell in presence of electric field.

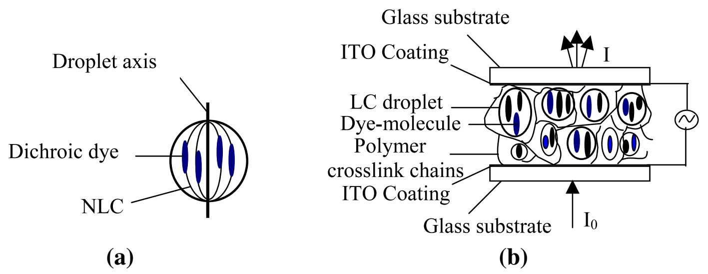
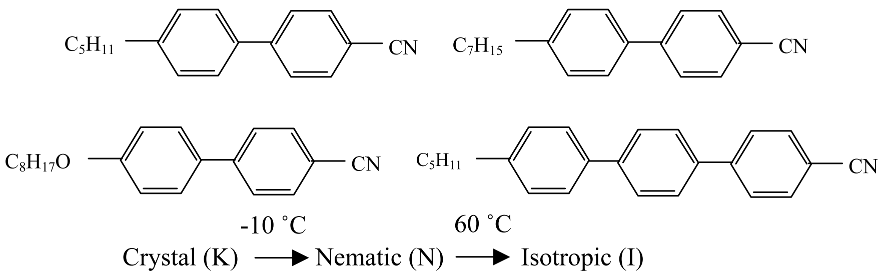


Figure 2: Molecular structure of the components and phase sequence of nematic liquid crystal mixture (E7)[33].



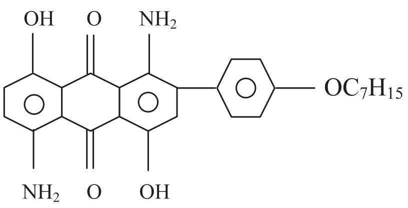
character of the film. Kitzerow et.al in 1992 reported that the dispersion of ferroelectric liquid crystals in a polymer matrix also shows non linear electro-optic behaviour[15]. These polymer dispersed ferroelectric liquid crystals (PDFLCs) showed both the advantages of traditional PDLC films as well as submicrosecond-switching time. However for their electro-optic applications, uniform alignment of the layer normal in the smectic phase is essential[16]. Depending on the helix pitch either a bistable switching or a continuous variation of the transmission can be achieved by electric fields.

However due to their low contrast ratio the use of PDLC and PDFLC for display devices is limited and many studies have been carried out to overcome the problems. Generally, to improve the contrast ratio, the use of dichroic dye-doped liquid crystal was proposed[17–19]. Some dichroic dyes show the attractive property of photo-isomerization using light. As a result, investigation of this phenomenon has been focused on the manufacture of photo-controllable devices which have a high contrast ratio[20–23]. We also know that the scattering effect of the film in the OFF state depends on the LC droplet size[22–23]. Thus for a constant dye concentration, the UV intensity should be optimized to obtain a suitable droplet size such that the transmittance in the Off state can be minimized to improve the contrast ratio. Moreover by controlling the concentration of dye, it should be possible to improve the optical efficiency and reduce the operating voltage of dichroic PDLC.

The orientation of the elongated dye molecule is governed by the nematic director configuration inside the droplet. Therefore, the dye absorbance is modulated by the alignment of the nematic director with an external field. In the OFF-state, we assume random orientation from droplet to droplet along the symmetry axes of the bipolar droplets resulting in random orientation of the dye molecules. The extinction coefficient is therefore averaged over all droplets and is equal to the isotropic extinction coefficient of the dye. In the ON state, the droplet the director and the dichroic dye molecules in the droplet are aligned normal to the surface of the film (Fig. 1) and the dye extinction coefficient is equal to the perpendicular extinction coefficient. Dichroic dye that is dissolved in the polymer binder will be unaffected by the external field and remain randomly oriented. Therefore, only the dye dissolved in the nematic droplet will exhibit dichroic properties and enhance the contrast of the film.

Recently it was demonstrated that a small amount of a dye dissolved in NLC can enhance the

Figure 3: Molecular structure of anthraquinone dye molecule.



reorientation by almost two orders of magnitude[24]. The explanation proposed by Janossy[25] is connected with the electronically excited metastable states appearing in the molecules of absorbing dye. The interaction of dye molecule with the LC molecules is different in its excited and ground states. The Janossy model is suitable for the reorientational bulk effect. A surface driven reorientation effect as a result of the light action on the bulk of a light-sensitive NLC-azo dye mixture was reported by Voloschenko and co-workers and explained to be due to the adsorption of dye photo-transformed molecules onto the aligning photopolymer surface[26]. Simoni and co-workers have pointed that the observed huge reorientational effect in a LC-dye mixture is due to light-induced modifications and the surface-induced nonlinear effects[27]. Their investigations about the diffraction efficiency revealed the basic role of light-induced adsorption and desorption of the dye molecules onto the boundary surfaces[28–29].

2. Materials

In the existing work, the liquid crystal mixtures used in our experiments were commercially available nematic liquid crystal mixture (E7)[30], ferroelectric liquid crystal mixture (ZLI-3654)[31]. An optical adhesive UV curable polymer NOA-65 (Norland, NJ)[32] was used as the matrix element in the preparation of PDLC, PDFLC and DPDLC films. The blue anthraquinone dichroic dye used in the experiments was obtained from Rollick, Switzerland. The molecular structure of the nematic liquid crystal mixture E7 and dichroic dyes are shown in Figs. 2, 3 respectively. Some of the physical parameters for the liquid crystals E7 and ZLI-3654, the NOA 65 polymer and the dichroic dyes are listed in Tables 1–4 respectively.

3. Preparation of samples and experimental

PDLC, PDFLC and DPDLC, films were prepared using the polymer induced phase separation (PIPS) method. In order to refractive index matching between the polymeric matrix and the LC is very important. In order to design an electrically-activated switch, it is necessary to choose the refractive index of the polymer matrix n_p matching with the ordinary refractive index of the LC n_o so that the effective refractive index of the LC droplets n_{eff} is larger than n_o in the OFF state (the film is opaque) while $n_{\mathrm{eff}} = n_o \approx n_p$ in the ON state (the film is transparent). Generally, the typical value of the effective refractive index n_{eff} is $n_o \leqslant n_{\mathrm{eff}} \leqslant n_p$for the PDLC samples.

In this experiment, the UV curable polymer NOA 65, nematic E7 and FLC ZLI3654 were taken in a fixed 1:1 (LC: polymer) wt./wt. ratios in a vial. This homogenous mixture (LC-polymer) was heated to isotropic temperature of the LC by placing them in a vacuum oven to obtain good mixing and simultaneously shaken rapidly to ensure proper dispersion. For the preparation of DPDLC, NLC/FLC was mixed with 0.125%, 0.25%, 0.50% and 1.0% (wt./wt.) of dichroic dye and then dispersed into the polymer material in 1:1 ratio by weight.

The mixture was then filled between two ITO coated glass substrates by capillary action after heating the material to its isotropic temperature. The cell gap was controlled by a Mylar spacer of thickness 10 μm. The sample cells were sealed by an optical adhesive and exposed to UV light (intensity $\sim$ 2 mW/cm^2) for about an hour at

Table 1: Physical properties of nematic liquid crystal

Materials	Phase sequence	Refractive index
Nematic liquid crystals	Crystal $\xrightarrow{-10^\circ\mathrm{C}}$ Nematic $\xrightarrow{60^\circ\mathrm{C}}$ Isotropic	n_e= 1.7464 n_o= 1.5211

Table 2: Physical properties of FLC material

Materials	Properties	Values
Ferroelectric liquid crystal mixture (ZLI-3654)	Phase sequence	K-30 °C SmC* 62 °C SmA76 °C Ch 86 °C I
	Tilt angle at 20 °C	25 °
	Spontaneous polarization (nC/cm^2)	29
	Switching time (μsec)	44
	Pitch (μm)	3

Table 3: Physical properties of UV curable NOA 65 polymer

Physical Properties	NOA- 65 Polymer
Polymer viscosity at 25°C (CPS)	1000
Refractive index of cured polymer	1.52
Tensile (Psi)	1500
Modulus (Psi)	2000

Table 4: Physical properties of anthraquinone dichroic dye

Properties	Value
Solubility %	100
Colour	Blue
$\lambda_{\max(nm)}$	630

room temperature. The sample was placed in a hot stage coupled to a controller (Model TP 94 and THMS 600) and then cooled down to room temperature @ 0.1°C per min. Uniform dispersion of dye doped LC droplets in the polymer matrix were viewed at a magnification of 10X/50X through Olympus polarizing microscope (Model BX-51P) fitted with charge coupling device (CCD) camera and interfaced with a computer. The opto-electric responses were studied by applying an electric field to the sample using a function generator (Philips FG-8002) and detected using a photo-multiplier tube (Model RCA 931-A). The data were acquired using digital storage Oscilloscope (Tektronix Model TDS 2024) interfaced to a computer.

4. Spontaneous polarization

The spontaneous polarization is the macroscopic polarization, which the sample attains due to the coupling of the molecular polarization P with the electric field E within the smectic layer, the sample gets poled and attains a macroscopic polarization. At this stage, the helix of the FLC in PDFLC mixture confined in the cell of a particular thickness unwinds, the macroscopic polarization becomes non-zero and the sample gets spontaneously polarized. This polarization was determined by applying a symmetric triangular wave (50 Hz frequency) and separating the resistive and capacitive term from the polarization term by drawing a base line. The polarization peak is directly associated with dipole reorientation, corresponding to the switching between uniform stable states. Every reorienting dipole imparts a charge impulse and contributes to the polarizing reversal peak. Thus the peak incorporates total contribution of reorientation dipoles while switching between uniform states. The area under the peak is a measure of the spontaneous polarization, given by

$$P_s = \frac{A(i \times t)}{R(\text{Area of Sample})} \tag{1}$$

Where $A(i \times t)$ is the area under the curve measured by integrating the polarization peak in terms of voltage and time[34,35]. The magnitude of P_s in the ferroelectric phase of PDFLC films decrease with

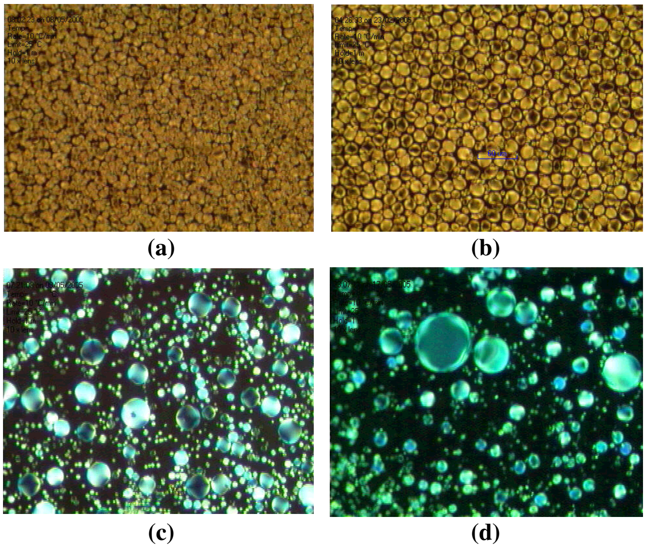
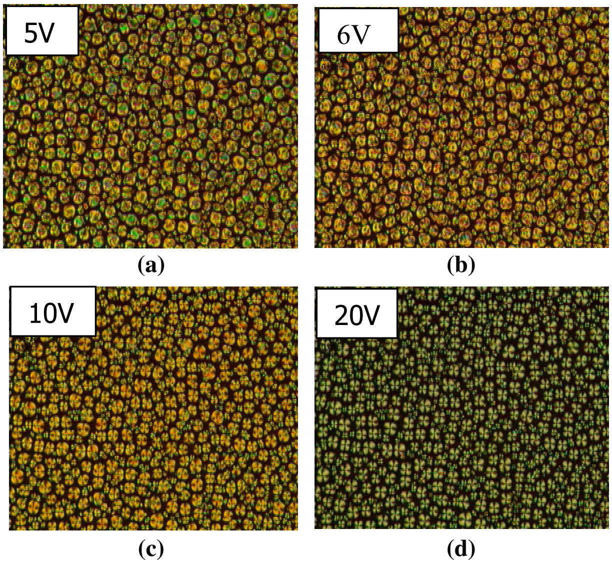

(a) (b) (c) (d)

Figure 4: Droplet morphologies of NOA dispersed nematic liquid crystals (Noa65+E7+B2) with varying dye contents. (a) Without dye (b) 0.25%, (c) 0.5% and (d) 1.0%, Microscopic textures were viewed at a magnification of 10X.

Figure 5: Droplet orientation of dichroic (0.25% dye) polymer dispersed liquid crystal under electric field.



the rise of temperature and finally becomes zero at T_c^* obeying the power law

$$P_s = P_o(T_c - T)^{\beta} \tag{2}$$

The critical exponent β should be 0.5 as predicted by the mean field theory.

5. Principle of DPDLC device

We consider a nematic liquid crystal in which dye molecules have been randomly dispersed [Fig. 1]. The ordinary and extra-ordinary refractive indices of the dichroic NLC are n_0 and n_e, respectively. Out side these droplets is the cured polymer in the solid state with refractive index $n_p \approx n_{0.}$ In the OFF state, the random orientation of the symmetry axes of the droplets results in random orientation of the dye molecules. Therefore, when the film is thin or the scattering effect is not too much, the extinction coefficient is averaged over all droplets and approximates the isotropic extinction coefficient of the dye.

In order to increase the brightness of the dichroic PDLC film, the dye concentration should be relatively low, and the film should be thin (We assume that there is no correlation between absorption and scattering). According to Beer's law[36], the extinction coefficient (γ)

$$\gamma = \alpha + \beta \tag{3}$$

Where α and β reflect the scattering and absorption coefficient of the film respectively. The

Figure 6: Morphology of DPDFLCs with dye concentration (wt %) of 0.125% (b) 0.25% (c) 0.5% and (d) 1.0%, respectively.

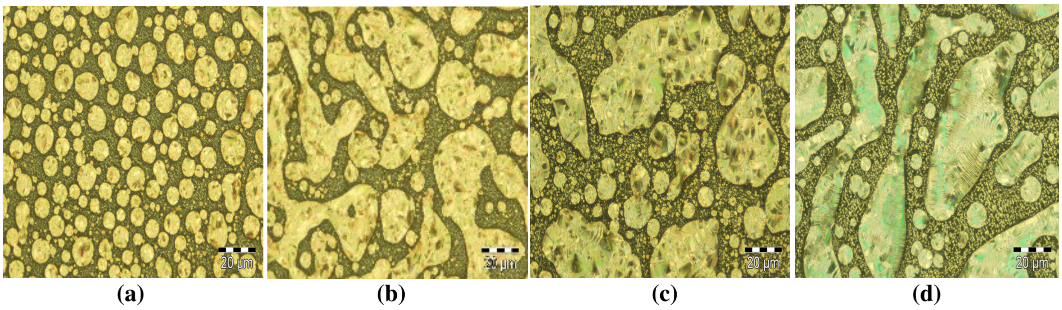
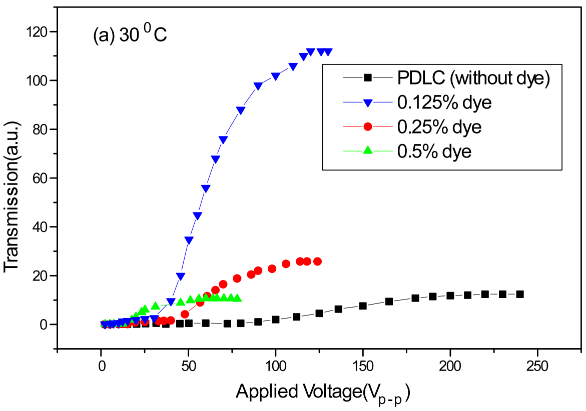


Figure 7: Dye concentration dependence transmission as a function of applied voltage of dichroic PDLC films at temperature 30°C.



Off-state transmittance (T) can be written as

$$T = \frac{I_t}{I_0} = e^{-(\alpha+\beta)d} \tag{4}$$

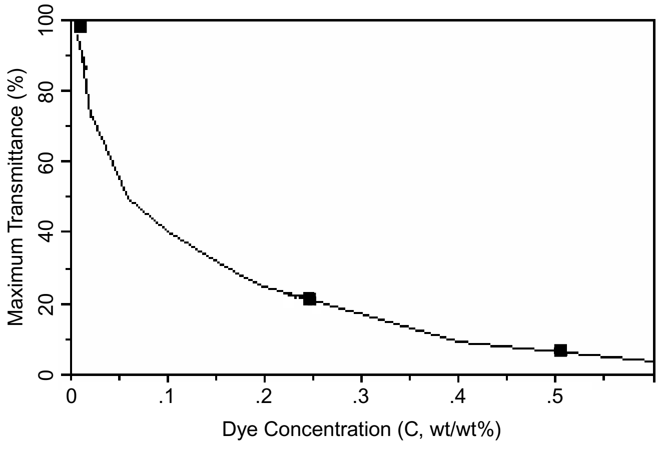
Where I_0, I_t are the incident and transmitted light intensity and d is the sample thickness. α is a function of the liquid crystal droplet size and curing temperature. Since polymer and liquid crystal molecules hardly absorb any visible light, the absorption of a PDLC film results entirely from the dye. Therefore, the absorption coefficient β is

$$\beta = \varepsilon x l \tag{5}$$

Where ε and x are the dye extinction coefficients and dye, concentration respectively, and l is the ratio of the distance traveled by light and the film thickness (d). For normal incidence, $l > 1$ because of the scattering. For thin film $l \approx 1$ (the scattering effect is small). Then, according to Beer's law, the OFF-state transmittance of the PDLC film will be

$$T = \frac{I_t}{I_0} = e^{-(\gamma d)} \tag{6}$$

Figure 8: The relationship of the maximum transmittance vs dye concentration at the ON state at 30°C. The line is a fit to the theoretical expression.



In the ON-state, [Fig. 1(b)], the symmetry axes of the dye-doped NLC droplets move in only one direction, the dye molecules absorb the light only slightly, and because $n_p \approx n_0$, the largest portion of the incident light I_0 is transmitted through the dye-doped PDLC film. The path length of light is just the thickness of the film because there is no scattering.

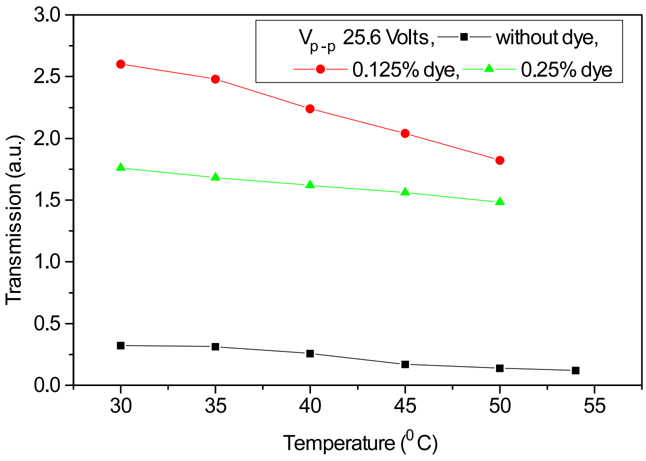
6. Results and discussion

6.1. *Droplet morphology*

The droplet morphology and phase behaviour of the dichroic dye doped polymer dispersed nematics liquid crystal (PDNLC) without dye and with 0.125%, 0.25%, 0.5% and 1% (wt./wt.) of dichroic dye respectively, were studied as a function of temperature as shown in figure 4. It is seen that the liquid crystal droplet size in the lower dye concentration ($\leqslant 0.25\%$) films is relatively smaller (in the range of ~10–15 μm) and more uniformly distributed forming spheroidal bipolar configuration (fig. 4b) than higher dye concentration samples (fig. 4c–d). It may be due to the less free volume available for the dispersed low dye concentration droplets in the polymer matrix[37]. Further it was clear from the UV-VIS absorbance that the dye in the films absorbs UV light and absorbance increases with the increase of dye concentration, which reduced the UV curing intensity resulting in an increase of the droplet size[38]. The lower UV cure rate results in a slower freezing of the PDLC once phase separation is induced, allowing more time for the liquid crystal to form larger droplets. It is reasonable to assert that the degree of polymerization, when the drops first form, is an important determiner of drop growth and eventual film morphology. Drop growth requires diffusion of liquid crystal material towards and diffusion of monomer and polymer away from the drop, and movement of the drop boundary in to the polymer rich region. Further with increasing the dye concentration the DPDLC mixture moves closer to the phase boundary resulting in less developed polymer matrix when phase separation occurs and more time liquid crystal to form large droplets.

At 0.5% dye concentration, the molecular orientations depict the combination of several other

Figure 9: Temperature dependence of transmission for PDLC and dichroic PDLC films at fixed applied voltage.



configurations [bipolar, axial, radial and toroidal (or collapsed)] which appear simultaneously.

We believe that torodial LC droplet form spontaneously by collapse of polymer shell covering the LC droplet thus forming a torodial cavity in the film[37]. The dye molecules absorbed at the polymer/LC interface may weaken the polymer shell, causing it to collapse under certain condition. A reduction in interfacial energy can cause an increase in the fraction of torodial LC droplets. Several groups reported the formation of torodial LC droplets in PDLC and DPDLC composite films[39–41].

Figure 5 shows the influence of external field on the droplet morphology at room temperature.

It can be seen that dichroic LC droplets have a bipolar configuration and their bipolar axes are randomly distributed inside polymer matrix. A model for the LC director field in a spheroidal PDLC droplet is shown in Fig. 1. In this configuration the director field is anchored parallel at the interface. The director field possesses cylindrical symmetry, with the symmetry axis defined by two point defects which lie at the opposite ends of the droplet. Most polymers tend to induce a parallel alignment of the nematics so that bipolar droplets are generally found in PDLC films. The optical axis orientation, corresponding to the average nematic director alignment, varies randomly from droplet to droplet with no applied field. Upon application of an electric field across the film, we observed a bulk distortion of the LC droplet at low applied field. The rotation of bipolar axes is associated with the individual droplets, [Figs. 5(b,c)] in such a way that the bipolar axes tend to align along the direction of the applied field. However, at higher voltage ($\sim$20 V_{p-p}) the LC droplets exhibits a well defined Maltese type crosses [Fig. 5(d)].

Further PDFLC material doped by dichroic dye was obtained by the variety of the starting composition. As shown in Fig. 6 optical microscopicopy depicts that FLC droplets in DPDFLC are droplets in higher, not uniform as in the case of nematic LC dispersion, however the low dye concentration sample showed uniformity and comparatively smaller size of the droplets. The non-uniformity of FLC droplets in higher dye concentration DPDFLC may be due to the inherent property of FLC materials. The phase changes of PDFLC material can be seen from table 5, with an

Figure 10: (a) Dye dependence transmission characteristics of DPDFLCs as a function of the applied voltage at 50 Hz (b) dye dependence contrast ratio of DPDFLCs at an applied voltage 30 V_{p-p}, at room temperature.

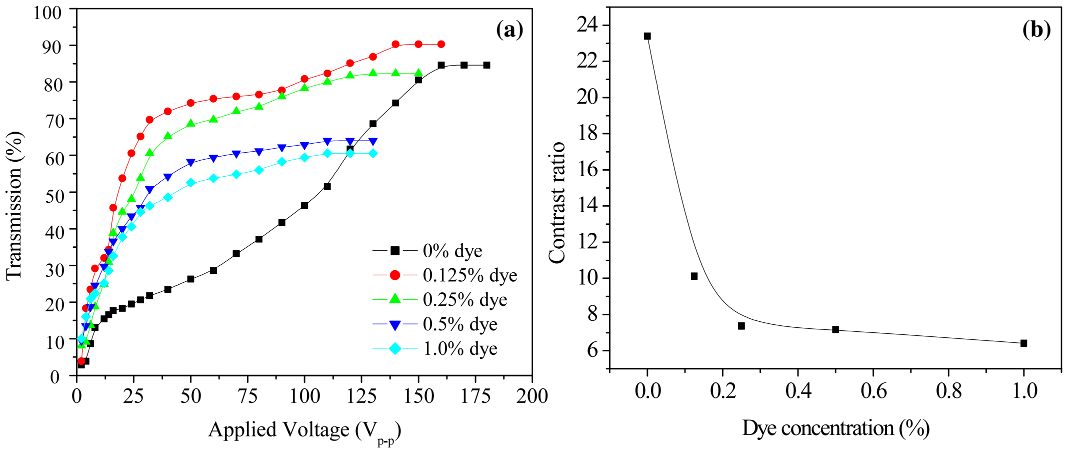
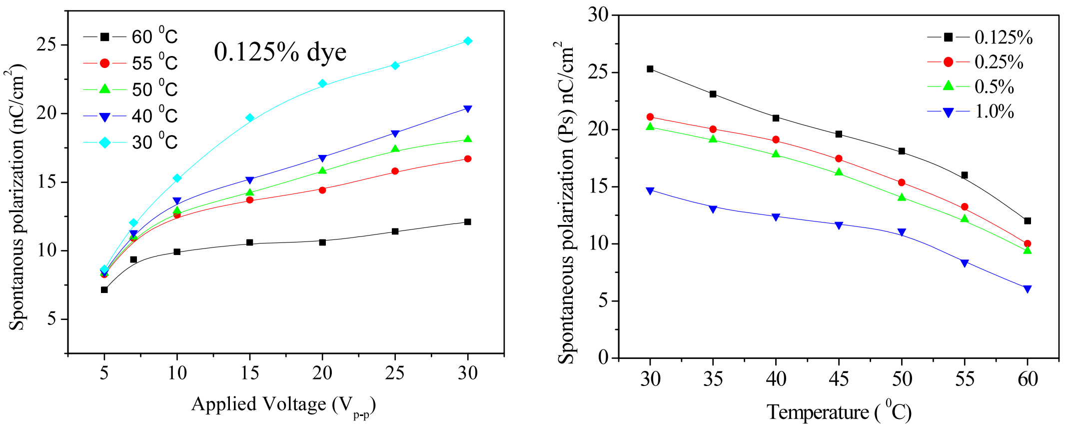


Figure 11: Influence of bias voltage on spontaneous polarization of (a) 0.125 % and (b) temperature dependence spontaneous polarization of all DPDFLCs at a constant bias voltage 30 V_{p-p}.



increase in isotropic temperature about 9–10°C above the isotropic transition temperature of the FLC. The increase in dichroic dye concentration in DPDFLC results in decreased isotropic temperature as compared to PDFLC. We believe that this difference in the transition temperature may be due to some ionic impurities arising from dye molecules when dissolved in LCs. The light absorption of the dye molecules at higher concentration may also contribute to lowering the T_{N-I}[37].

Fig. 6 shows the morphologies of films in the voltage off state. We found that in low dye concentration (0.125%) DPDFLC material consists of FLC domains dispersed in polymer matrix are smaller in size and comparatively more uniformly distributed, as shown in fig. 6(a). This may be due to the partial solubility and better mutual interaction of polymer-FLC systems for low weight % of dichroic dye. It was also found from our results that the smaller the domain size in DPDFLC systems, the better is the electro-optic response.

6.2. *Electro-optic and contrast ratio*

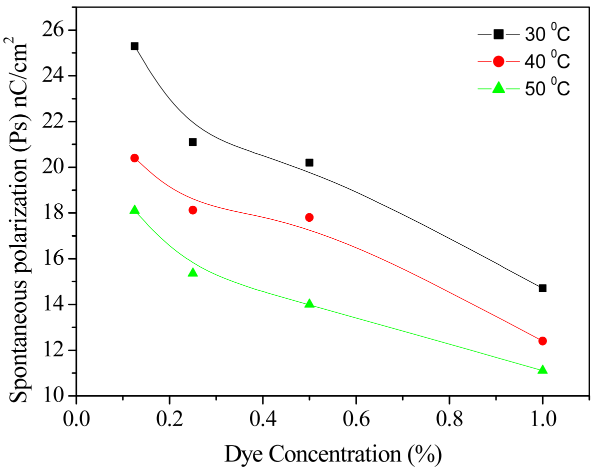
The light transmission of PDLC and Dichroic PDLC films with different dye fractions was measured as a function of the applied voltage at 50 Hz for obtaining the value of threshold voltage and contrast ratio, as shown in fig. 7. It was also observed that among DPDLC films with increasing dye concentration the transmission decreases. The transmission decrease in dichroic PDLCs is due to the large light absorbance of the anthraquinone dye molecules dissolved in PDLC[37]. The lower concentration dye doped samples give better transmission than higher dye concentration samples due to minimum light absorbance and having more uniform structure of liquid crystal micro droplets. From the measured transmittances of the films, the dye extinction coefficient can be obtained using eqs. (3). By least square fitting of the experimental data, we find that the straight line was least squares fit to the experimental data[37]. The relationship between the maximum transmission of the films and the dye concentrations is shown in Fig. (8). The line is a fit to the theoretical expression.

Fig. 7 indicates that the driving Voltages from minimum transmission ($T_{\min}$) to maximum transmission ($T_{\max}$) for these dichroic PDLC films are different. This finding implies that the value of

Table 5: Transition temperature of all the dichroic DPDFLC samples

Samples	SmC* to SmA Transition (T$_C$*A° C)	SmA to N* Transition (T$_C$*A° C)	N* to Isotropic Transition (T$_N$*I°C)
NOA65/ZLI- 3654	64	80	96
NOA65/ZLI-3654/B2 (0.125%wt)	62	76	92
NOA65/ZLI-3654/B2 (0.25%wt)	62	76	89
NOA65/ZLI-3654/B2 (0.5%wt)	62	74	87
NOA65/ZLI-3654/B2 (1.0%wt)	62	74	86

Figure 12: Influence of dye concentration on spontaneous polarization at a constant bias voltage 30 V_{p-p}.



threshold voltage V_{th} is approximately 8 V/μm for pure PDLC (without dye), where as the threshold voltages are approximately 4 V/μm, 2 V/μm and 1 V/μm for 0.125%, 0.25% and 0.5% dye doped PDLC respectively. This finding is expected because these films are made of the same PDLC material and by the same process except for the dye concentration. It depicts that as dye concentration increases, the threshold voltage decreases. The possible explanation may involve the Janossy effect. Janossy et al.[42] reported that a small amount of anthraquinone dye dissolved in nematics liquid crystal to make it light absorbing can greatly enhance the orientational optical nonlinearity of the material and found that photo-excited anthraquinone dye molecules induced a positive torque, thereby reducing the optical Freedericksz transition. The contrast ratios of the DPDLC samples were also measured as a function of the applied voltage. The contrast ratio increases with increasing applied voltage, reaches a maximum and then maintains the constant value. The PDLC film with 0.125 wt% dye content has higher contrast ratio under same applied electric field[37].

The experimental results show that the maximum transmission decreases with increase in temperature as shown in fig 9. One conceivable reason for this unusual behaviour may be the temperature dependence of the refractive indices of the polymer matrix and the LC droplets. In principle, the on-state transmission of PDLC films depends strongly on the difference between the effective refractive index of the droplet, n_{eff}, and the refractive index of the polymer matrix, n_p. Because n_{eff} approaches the ordinary refractive index of the liquid crystal, n_o, at saturating voltages, a high degree of transparency in PDLC films is achieved only when n_p is equal to n_o. Therefore, if the degree of refractive index mismatching between the polymer matrix and the LC droplets depends considerably on temperature, the maximum transmission is also expected to show corresponding temperature dependence. The maximum transmission decreases with the increase of temperature because the index matching condition gets poorer.

The DPDFLC system depends on the birefringence of liquid crystals and takes advantage of the bistable mode in which switching occurs between 2θ[43], yielding the dark and bright states. When an applied field interacts with an FLC molecule, the molecule tends to be orientated in the direction of +Ps (dark state). If the field is inverted, then the FLC molecule is reoriented in the direction of −Ps (bright state).

Fig. 10(a) shows the dye dependence of light transmission characteristic of DPDFLCs as a function of the applied voltage at a frequency of 50 Hz, for exploring the value of threshold voltage and effect of dye. The maximum transmission of DPDFLCs decreases with increasing concentration of the dye whereas the threshold voltage decreases but DPDFLC with 0.125% dye has better transmission than the PDFLC and 90% transmission is achieved at dye concentration 0.125% with a threshold voltage ~ 1.57 V/μm where as the transmission is 82% for PDFLC with a threshold value ~ 11.0 V. The contrast ratio is calculated from the transmission values of the dark and the bright states. Fig. 10(b) shows the relationship between the contrast ratio and the dye concentration at room temperature at an applied voltage 30 V_{p-p}. The results reveal that the low dye concentration DPDFLC has a higher contrast ratio.

6.3. *Polarization switching and response time*

The polarization (Ps) and response time of the DPDFLCs of different dye concentration were calculated as a function of applied voltage for 0.125%, 0.5% and 1.0% (wt/wt). As shown in fig. 11(a), with increase in the applied voltage, the spontaneous polarization increases sharply initially due to unwinding of helix and shows the same trend for all DPDFLCs in the smectic C* phase. The polarization with switching with respect to temperature at different dye concentration was measured and is given in fig 11(b), it is observed that the value of Ps decreases with increase in temperature. These trends of DPDFLCs can be explained on the basis of intra-molecular rotations and inter-molecular interactions in the presence

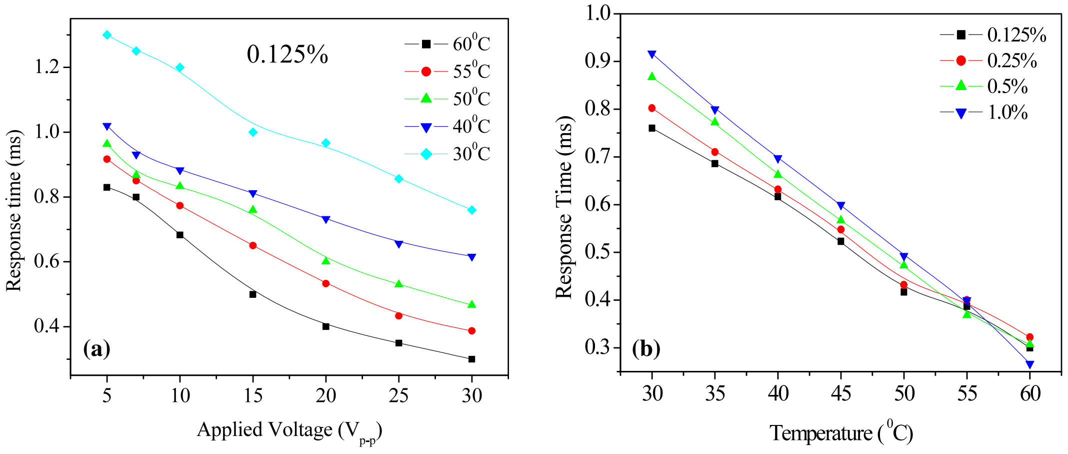


Figure 13: Influence of bias voltage on response time of (a) 0.125% DPDFLC at different temperatures and (b) temperature dependence response time of all DPDFLCs.

of dye molecules in the system. The decrease in the Ps value with increase in the temperature may be due to the weak P-E (polarization- electric field) coupling and P-θ (polarization-tilt angle) coupling in dichroic FLC.

Further the dye dependence of Ps was also measured as shown in fig 12. It was found that DPDFLC containing low dye concentration shows higher polarization value. At a constant applied voltage 30 V_{p-p} at 30 °C, the DPDFLC containing 0.125% dye possess Ps ~ 25.3 nC/cm^2, whereas the value is ~ 14.7 nC/cm^2 for 1.0 % concentration of dye. It suggests that the dichroic dye affects the FLC molecular alignment and phase separation in DPDFLC. The higher value of Ps in low concentration of DPDFLC may be due to the induced helical unwinding in the system due to the orientation of ferroelectric liquid crystal molecules in the preferred direction of dye molecules in the DPDFLC. The decrease in Ps value with increasing the dye concentration may due to the weak phase separation and changed phase transition temperature because the optical tilt angle varies with temperature and optical tilt angle decreased with increasing the dichroic dye concentration[44].

Fig. 13(a) shows the relationship between response time and the applied voltage for a fixed square-wave ac voltage on the DPDFLCs containing 0.125% concentration of dichroic dye. The response time decreased with the applied field strength. Fig. 13(b) shows the response time as a function of temperature for all DPDFLCs. It was found that DPDFLC with low dye (0.125%) has faster response as compared to higher dye concentration PDFLCs. With an increase of dye concentration in DPDFLC the viscosity of the FLC in the polymer matrix is increased and hence the slower response.

7. Conclusions

- LC domains in these DPDLC films are predominantly in the bipolar configuration. Effect of electric field on these films has been found to strongly influence the LC droplet orientation.
- Low dye concentration DPDLC shows improved optical responses e.g. higher transmission, higher contrast ratio. Higher dye content also results in a lower value of clearing temperature.
- Use of dye leads to reducing threshold voltage for switching the material from a scattered to transparent state. The threshold voltage V_{th} is approximately 8 V/μm for pure PDLC where as the threshold voltages is as low as 1.7 V/μm with anthraquinone dye doped PDLC.
- The increase in dichroic dye concentration in DPDFLC results in decreased isotropic temperature as compared to PDFLC. It may be due to some ionic impurities arising from dye molecules when dissolved in LCs and due to light absorption of the dye molecules at higher concentration. It was also found that smaller the domain size in DPDFLC systems, the better is the electro-optic response.
- The maximum transmission of DPDFLCs decreases with increasing concentration of the dye where as the threshold voltage decreases but DPDFLC with 0.125% dye transmit has better transmission than the PDFLC and 90% transmission is achieved

with a threshold voltage of ∼ 1.57 V/μm where as the transmission is 82% for PDFLC with a threshold value of ∼ 11.0 Volt. The results reveal that the low dye concentration DPDFLC has a higher contrast ratio.

- It was found that DPDFLC containing low dye concentration shows higher polarization value. The DPDFLC containing 0.125% dye possess Ps ∼ 25.3 nC/cm^2 at a constant applied voltage 30 V$_{p-p}$ at 30 °C which is unexpectedly 3.5 times more than Ps ∼ 7.23 nC/cm^2 of PDFLC.
- Droplet size is a significant factor to control the opto-electronic properties of these PDLC and PDFLC systems. The materials may find suitability and promise as functional electronic materials for flexible display technology.

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