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Electro-Optical Behavior of Dye Doped Nematic Liquid Crystal

S.P. Yadav, K.Kr. Pandey, A.Kr. Misra and R. Manohar*
Physics Department, University of Lucknow, Lucknow, 226007, India

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We report electro-optical behavior of a dye doped nematic liquid crystal. The dye doped cells have shown some improvement in some parameters important for the display devices such as threshold voltage (V_{th}), splay elastic constant, rotational viscosity and response time. The suppression of screening effect improves the threshold voltage for the doped sample.

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1. Introduction

During last forty years a lot of research and development has been done in the field of liquid crystals (LCs) for their use in display applications. The key features required for this application are flatness, low power consumption, compactness leading to low weight and full color capability [1]. The guest–host liquid crystal displays (GH LCD) [2] that use a LC–dye mixture, have received much attention because of its wide viewing angle, day light readability, high brightness and no requirement of polarizers. Nematic liquid crystals (NLC) are the most commonly used LC materials in the modern display industry [3, 4]. A single LC compound cannot fulfill all the requirements of suitable parameters for the displays. Therefore guest–host mixtures of LCs have been used because of their potential application in displays and other optoelectronic devices [5]. The interest in the liquid crystals as electro-optic and photo-optic materials has increased further when it was realized that the photo-induced effect could be enhanced by an order of magnitude with the addition of minute amounts of absorbing dyes. However the details of the microscopic mechanism involved are still not clearly understood and quite often experimental results still reveal unexpected behaviors [6–9]. The addition of absorbing dyes to NLCs, even in small concentrations, introduces new orienting mechanisms [6]. Dye doped liquid crystalline systems have indeed been the subject of intense studies in recent decades [10–12]. Mixing of carbon nanotubes (CNTs) in LC host is the recent development towards the modification of physical properties of LCs by doping non-mesogenic molecules [13, 14].

The quality of GH LCDs strongly depends on the molecular interaction between the molecules of host liquid crystal and the guest dye. There are many issues that must be considered when designing and analyzing the performances of LCDs. The optimization of the performance of the LCD usually requires extensive knowledge of some essential parameters such as elastic constants of the deformations, rotational viscosity, dielectric anisotropy, optical birefringence and threshold voltages [1, 15].

The first one is the voltage necessary to turn on a pixel in a display. The threshold voltage (V_{th}) is the amount of voltage across the pixel necessary to produce any response i.e. the voltage at which molecules in the central layer start turning on in a display. Liquid crystals with low threshold voltage are advantageous for displays. The possibility of addressing the pixels with lower voltage enables the simplification of the driving electronic circuit. This results in small and low weight of device, which is an important issue for miniaturization of devices. Additionally, the use of lower voltage reduces the power consumption of the device and improves the battery backup.

The equation for the threshold voltage in terms of dielectric anisotropy and elastic constants is [1]:

$$V_{\mathrm{th}} = \pi \sqrt{\frac{k_{11} + (k_{33} - 2k_{22})}{4\varepsilon_0 \Delta\varepsilon}}\,, \tag{1}$$

where k_{11}, k_{22}, and k_{33} are the splay, twist, and bend elastic constants, respectively, $\Delta\varepsilon$ is the dielectric anisotropy of the liquid crystal, ε_0 is the electric constant of air. V_{th} can either be influenced by changing elastic constant or by alerting the dielectric anisotropy.

For strongly anchored planar aligned NLC cell (which generally involves only one elastic constant) the above equation can be written as [16]:

$$V_{\mathrm{th}} = \pi \sqrt{\frac{k_{11}}{\varepsilon_0 \Delta\varepsilon}}\,. \tag{2}$$

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[*] corresponding author; e-mail: `rajlu1@rediffmail.com`

The rotational viscosity and elastic constants k_{11}, k_{22}, and k_{33} are the most important physical properties for the determination of switching behavior of the LCD. Among the five independent components of the viscosity, coefficient of rotational viscosity (γ_1) is the most important factor for the switching action of the LC molecules. γ_1 is associated with rotational viscosity of the liquid crystal molecule around an axis, which is perpendicular to the local director. Its magnitude depends on temperature, intermolecular interactions and the molecular structure of the sample. The relationship between molecular structure and rotational viscosity is in particular of interest because by modifying structure of a liquid crystal, one could tailor a sample of lower viscosity [17]. Splay elastic constant is the proportional constant between the forces i.e. electric field and the deformation of the director fields. The switching time (mainly decay time) of an LCD is proportional to the visco-elastic coefficient (γ_1/k_{11}), the ratio of the rotational viscosity and elastic constant.

It is interesting to study the guest–host effect in NLCs because of their potential applications in displays and other optoelectronic devices. There are various reports concentrating on the electro-optical characterization of LCs [18–20]. We have explored in detail a dye doped NLC for its electro-optical properties. The effect of a dye on the electro-optical properties has been analyzed in terms of threshold voltage V_{th}, dielectric anisotropy $\Delta\varepsilon$, splay elastic constant k_{11}, switching time τ and rotational viscosity γ_1. In the present work an LC material 5CB and dichroic dye SG3 have been used at a varying concentration of 0.5%, 1%, 2% and 3%. The switching waveforms have been obtained for both the pure and the doped LC cell. The results indicate that the various parameters are in good agreement with the known values for 5CB pure cell. Doping of dye in the LC material has lowered the DC threshold voltage and switching time of the cell.

2. Experimental details

2.1. Cell preparation

Two indium tin oxide (ITO) coated glass plates having small conducting areas (25 mm^2) have been used for the preparation of sandwiched type sample holder. Both the electrodes of cells were treated with adhesion promoter and polymer (nylon 6/6) and rubbed unidirectionally to get planar alignment. For homeotropic alignment, glass plates have been treated with lecitin solution (cetyl trimethylammonium bromide in ethyl alcohol). The cell gap has been maintained at 10 μm with the help of mylar spacer [21, 22].

2.2. Dielectric permittivity study

The capacitive and dielectric measurement have been carried out using a computer controlled impedance/gain phase analyzer HP 4194 A. The temperature of the cell has been maintained by a computer controlled hot plate INSTEC Cop. USA [21, 22].

2.3. Electro-optical measurement

The response time has been determined by the optical switching method as shown in Fig. 1. This method uses application of a square wave of frequency 1 Hz and amplitude of 10 V peak to peak to the sample cell. The optical response of the molecules as observed by detector is fed to a storage oscilloscope HM 407 in electrical form. The output wave form is now used to determine the response time. The rise and fall time has been calculated as output wave form reaches the 10% to 90% and 90% to 10% of its maximum value, respectively [23].

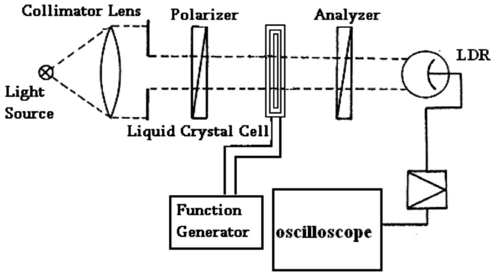

Fig. 1. Setup for measurement of electro-optical parameter.

3. Result and discussion

The experimental results of the threshold voltage and dielectric anisotropy are tabulated in Table.

TABLE

Variation of important electro-optical parameters as function of concentration of dye.

Sample	Threshold voltage V_{th} [V]	Dielectric anisotropy $\lvert\Delta\varepsilon\rvert$	Viscoelastic coefficient γ_1/κ_{11} [$\times 10^{10}$ P/N]
5CB pure	0.70	11.92	15.28
5CB+0.5% SG3	0.65	6.32	14.78
5CB+1% SG3	0.60	0.32	14.29
5CB+2% SG3	0.50	8.01	13.31
5CB+3% SG3	0.40	10.01	13.01

The dielectric anisotropy ($\Delta\varepsilon$) is defined as the difference of the dielectric permittivity in homeotropic aligned cell ($\varepsilon_{||}$) to planar aligned cell ($\varepsilon_{\perp}$). The dielectric anisotropic values are also given in Table. The dielectric anisotropy of the sample shows a fall for 0.5% and 1% dye doped sample as compared to the pure 5CB but an increment in the value has been observed for the doped mixture with 2% and 3% dye. This unusual behavior can be attributed to the dependence of dielectric permittivity on the concentration of guest molecule. It might be possible that addition of dye changes the molecular orientation of the NLC. This molecular alignment of guest host system depends upon the concentration of the dye molecule.

In a dye doped sample, the following interactions between the neighboring molecules may exist in the system:

$$F = F_{\text{lc-lc}} + F_{\text{lc-dye}} + F_{\text{dye-dye}} .$$

At lower concentration of dye in NLC the dye–dye interaction can be neglected. But at higher concentration of dye, this interaction comes into play and becomes dominating. This interaction might cause the nematic molecules to be more ordered for the mixtures with higher concentration of dye molecules, which in turn increases the value of dielectric anisotropy for the mixtures with 2% and 3% of dye. In our case 2% of the dye molecule is the critical value of concentration, where the behavior of dielectric anisotropy has changed. However a more detailed investigation is required to fully understand the phenomena, which requires the study of different NLCs with different dyes.

The threshold voltage as measured from the capacitance voltage plot, is given in Table. The capacitance has been determined with the variation of voltage at strength of 0.05 V for the precise measurement. Two possible causes for the reduction of threshold voltage seem to be the suppression of field screening and the decrease of the anchoring strength. Suppression of the field screening arises from the ion contamination. LC usually contains many ions either from raw materials itself or from added impurities during the cell preparation. This ionic effect influences the physical phenomenon of the LC [24]. The electric bilayer generated by the aggregation of these impurity ions at the polymer surface generates residual voltage and therefore the actual voltage that liquid crystal molecule feels is lower than the applied voltage. However with the addition of the dye, the screening effect has been suppressed due to constrained movement of ions (ions got stuck at the surface of the dye molecules), causing a reduction in the threshold voltage. The anchoring strength also affects the threshold voltage as can be seen by following Eq. [14]:

$$V_{\text{th}} = \frac{\pi\sqrt{k_{11}/\varepsilon_0\Delta\varepsilon}}{1 + 2k_{11}/(w_\theta d)} , \tag{3}$$

where w_θ is the polar anchoring energy and d is the cell gap. The weak anchoring gives rise to lower threshold voltage. The addition of dye influences the interaction of LC/polymide surface. This modification in LC/polymide interface lowers the anchoring strength. Therefore the threshold voltage is also lowered.

Figure 2 shows the variation of splay elastic constant k_{11} with concentration of dye. 0.5% and 1% dye doped sample shows decrement in the value of k_{11} as compared to the pure NLC. However values for 2% and 3% dye doped NLC have higher values than 1% dye doped NLC. All this behavior is attributed to the observed behavior in $\Delta\varepsilon$. The simplified expression for k_{11} can be given as [17]:

$$k_{11} = \frac{V_{\text{th}}^2}{\pi^2}\varepsilon_0\Delta\varepsilon . \tag{4}$$

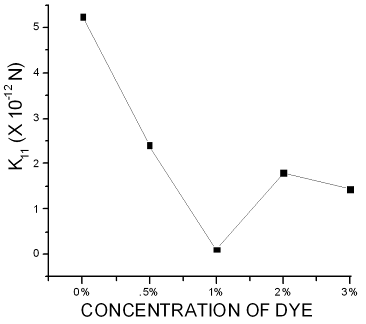

Fig. 2. Variation of k_{11} with the concentration of dye.

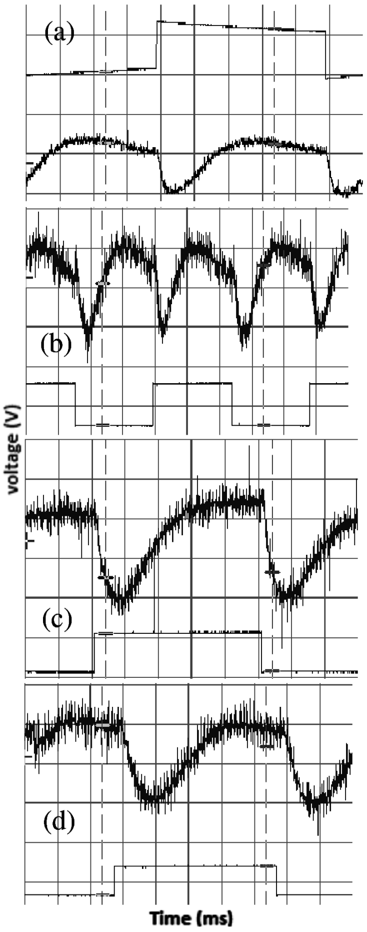

Fig. 3. Response curve for (a) 5CB pure (channel 1 (upper signal) 5.00V/div and channel 2 (lower signal) 0.050V/div), (b) 5CB+1% SG3 (channel 1 (upper signal) 0.020V/div and channel 2 (lower signal) 5.0V/div), (c) 5CB+2% SG3 (channel 1 (upper signal) 0.020V/div and channel 2 (lower signal) 5.0V/div), and (d) 5CB+3% SG3 (channel 1 (upper signal) 0.020V/div and channel 2 (lower signal) 5.0V/div).

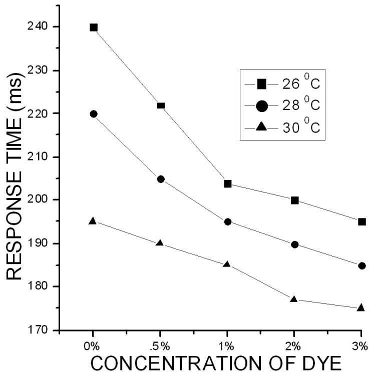

Fig. 4. Variation of response time with temperature and concentration of dye.

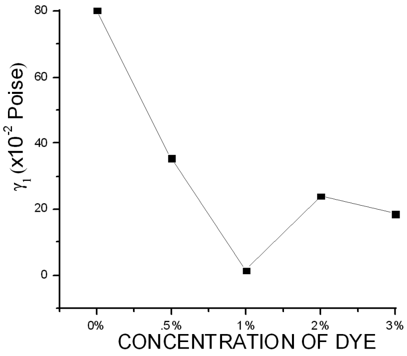

Fig. 5. Variation of rotational viscosity with concentration of dye.

The response time has been calculated by using the response curves, as shown in Fig. 3. The X-axis represents the time scale while y-axis represents the voltage. The square wave shows the input wave applied to the sample holder and distorted signal shows the output wave form. It is clear from Fig. 4 that the value of response time has decreased with the addition of dye. The four dye doped counterparts have slightly lower fall time than its pure NLC. However the rise time does not show any appreciable change. Therefore the total response time has shown improvement with the addition of dye in the pure NLC.

For a strong anchoring in NLCs, the rise and the fall time can be treated separately as

$$\tau_{\rm rise} = \frac{\gamma_1 d^2}{\varepsilon_0 \Delta\varepsilon (V - V_{\rm th})^2}\,, \tag{5}$$

$$\tau_{\rm fall} = \frac{\gamma_1 d^2}{\pi^2 k_{11}}\,. \tag{6}$$

A fall in the response time indicates change in viscoelastic coefficient γ_1/k_{11}. Using $\tau_{\rm fall}$ we have also calculated the rotational viscosity [17]:

$$\gamma_1 = \frac{\tau_{\rm fall} k_{11} \pi^2}{d^2}\,. \tag{7}$$

Figure 5 shows the variation of γ_1 with the concentration of dye. Behavior of γ_1 is almost similar to the behavior of k_{11}. The values obtained for k_{11} and γ_1 for pure 5CB NLC are in good agreement as reported earlier [17].

4. Conclusions

Our preliminary data shows that some of the important properties such as rotational viscosity γ_1, splay elastic constant k_{11}, dielectric anisotropy $\Delta\varepsilon$ and threshold voltage $V_{\rm th}$ show improvement with the addition of dye in pure NLC. Out of the two possible causes for the reduction of threshold voltage, suppression of the screening effect is looking to be more effective, as lowering of anchoring will increase the response time (mainly decay time). But we have observed a slightly decreasing tend for the response time. The viscoelastic coefficient γ_1/k_{11} shows a change for the entire sample. It may be the cause of a slight change in response time.

The observed behavior for elastic constants and rotational viscosity is yet to be explained. However the explanation of underlying mechanism requires more experimental data with different NLC and different dyes including order parameter and anchoring strength.

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References

[1] B. Bahadur, *Liquid Crystals Applications and Use*, Vol. 2, World Sci., Singapore 1991.

[2] G.H. Heilmeier, L.A. Zanoni, *Appl. Phys. Lett.* **13**, 91 (1968).

[3] S. Marino, M. Castriota, V. Bruno, E. Cazzanelli, G. Strangi, C. Versace, N. Scaramuzza, *J. Appl. Phys.* **97**, 013523 (2005).

[4] M. Ohe, K. Kondo, *Appl. Phys. Lett.* **69**, 623 (1996).

[5] R. Muenster, M. Jarasch, X. Zhuang, Y.R. Shen, *Phys. Rev. E* **78**, 42 (1997).

[6] P. Klysubun, G. Indebetouw, *J. Appl. Phys.* **91**, 897 (2002).

[7] I. Janossy, A.D. Llyod, B.S. Wherrett, *Mol. Cryst. Liq. Cryst.* **179**, 1 (1990).

[8] I. Janossy, T. Kota, *Opt. Lett.* **17**, 1183 (1992).

[9] I.C. Khoo, H. Li, Y. Liang, *IEEE J. Quantum Electron.* **29**, 1444 (1993).

[10] A.Y.G. Fuh, M.S. Tsai, C.R. Lee, Y.H. Fan, *Phys. Rev. E* **62**, 3702 (2000).

[11] I. Janossy, S.K. Prasad, *Phys. Rev. E* **63**, 021701 (2001).

[12] H. Yang, H. Yamane, H. Kikuchi, T. Kajiyama, *Liq. Cryst.* **27**, 721 (2000).

[13] H.Y. Chen, W. Lee, *Appl. Phys. Lett.* **88**, 222105 (2006).

[14] W. Lee, J.S. Gau, H.Y. Chen, *Appl. Phys. B, Lasers Opt.* **81**, 171 (2005).

[15] L.M. Blinov, V.G. Chigrinov, *Electrooptic Effects in Liquid Crystal Materials*, Springer-Verlag, New York 1994.

[16] S.Y. Lu, L.C. Chien, *Opt. Exp.* **16/17**, 12777 (2008).

[17] M.L. Dark, M.H. Moore, D.K. Shenoy, R. Shashidhar, *Liq. Cryst.* **33**, 67 (2006).

[18] K. Komorowska, G. Pawlik, A.K. Mitus, A. Miniewicz, *J. Appl. Phys.* **90**, 1836 (2001).

[19] J. Parka, *Opt. Elect. Rev.* **10**, 83 (2002).

[20] M. Ohe, M. Yoneya, K. Kondo, *J. Appl. Phys.* **82**, 528 (1997).

[21] A.K. Srivastava, A.K. Misra, P.B. Chand, R. Manohar, J.P. Shukla, *Phys. Lett. A* **371**, 490 (2007).

[22] R. Manohar, A.K. Misra, A.K. Srivastava, P.B. Chand, J.P. Shukla, *Soft Materials* **5**, 207 (2007).

[23] R. Manohar, S.P. Yadav, A.K. Srivastava, A.K. Misra, K.K. Pandey, A.C. Pandey, P.K. Sharma, *Jpn. J. App. Phys.* **48**, 101501 (2009).

[24] S. Dhara, N.V. Madhusudana, *J. Appl. Phys.* **90**, 3483 (2001).