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ORIGINAL PAPER

CARBON NANOTUBE DOPED LIQUID CRYSTALS

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Abstract. *Liquid crystals are unique functional soft materials where the direction of alignment can be easily controlled by external fields or by suitably treated surfaces. This simplicity of control has made liquid crystals very attractive materials for applications, particularly as the active medium in displays. These properties open a route for inclusion of carbon nanotubes in liquid crystals where the host's liquid crystalline phase gives an ordering effect on the carbon nanotubes doped into it. This ordering of carbon nanotubes significantly enhances the liquid crystals electro-optic properties and other physical parameters. In this review paper we have briefly reviewed the research on dispersion and alignment of carbon nanotubes liquid crystalline phases.*

Keywords: *Liquid Crystals, Electro-Optical, Carbon Nanotubes.*

1. INTRODUCTION

Liquid crystals (LCs) are anisotropic fluids that represent an intermediate state between the solid and the liquid. Liquid crystal phases share some of the properties of both isotropic liquids and crystalline solids. While the molecules in these phases exhibit some positional and orientational order. The most common technological application of LCs is liquid crystal display (LCD). Apart from applications in the area of displays LCs are found in the field of surfactants and detergents, membranes, high strength polymers, photonics, thin films, semiconductors, artificial muscles, thermal, chemical and electrical sensors, etc. [1]. To optimize the performance of a LCD, it usually requires previous knowledge of physical parameters of the LC mixture, such as the elastic constants of deformation, dielectric and optical anisotropies, conductivity and rotational viscosity. The various types of nanomaterials such as metallic nanoparticles, quantum dots, carbon nanotubes (CNTs) have been doped into LCs to enhance electro-optical properties of LCs, to improve memory effect, photoluminescence, to enhance electrical conductivity, fast response, etc.[2- 9]. Amongst several particles, CNTs are very attractive because they have anisotropic shape LCs and they interact with LC molecules strongly. They show high conductivity along the tube length but very low conductivity across the diameter.

Mixing CNTs into LC hosts was found one of the attempted approaches to modify the physical properties of LCs along with CNT alignment in LC matrix. LCs have the long range orientational order rendering them to be anisotropic phases. If CNTs can be well dispersed in LC matrix, they will in general align with their long axes along the LC director and minimize distortions of the LC director field. Dispersion of CNTs in LCs can offer us a cheap, simple, adaptable and effective means of controlling nanotube orientation on macroscopic scale with no limitations on nanotube type.

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CNTs, the fourth allotrope of carbon, after diamond, graphite and fullerene, are one dimensional, well ordered all-carbon hollow cylinders of graphite having a high aspect ratio. Usually CNTs are classified in two categories based on their structure and dimensions: single-walled carbon nanotubes (SWNT), which consist of one layer of cylindrical graphene and have diameters from 0.4–2.0 nm and lengths in the range 20–1000 nm; and multi-walled carbon nanotubes (MWNT),

Which consist of several concentric graphene sheets and greater diameters in the range of 1.4–100 nm and lengths from 1 to a few microns. The conductivity of SWNTs can be either metallic or semiconducting; while in MWNTs it is always metallic. All SWNTs and MWNTs are synthesized using catalysts; hence metal nanoparticles are likely to be present along with carbon particles such as graphite, amorphous carbon etc. Carbon nanotubes are chemically exceptionally inert and basically insoluble. The combination of superlative mechanical, thermal and electronic properties displayed by SWNTs and MWNTs make them ideal for a wide range of applications, such as, conductive and high-strength composites, catalyst supports in heterogeneous catalysis, energy-storage and energy-conversion devices, field emitters, transistors, sensors, tips for scanning probe microscopy and molecular wires [10-16].

The first report on doping of carbon nanotubes in LCs was given by Lee and Chiu in the year 2001 after one decade of CNTs discovery, who observed self diffraction by gratings in nematic LCs doped with multiwalled carbon nanotubes.

Having molecular structure similar to CNTs, LCs perfectly include CNTs into own structure. Particularly, the liquid crystalline orientational order can be imposed on CNTs so that aligned ensembles of these particles can be attained [17]. CNTs have brought a number of improvements to LC layers used in electrooptic devices [18]. The LC doping by CNTs reduces response time [19,20] and driving voltage [21] etc. The LC-CNTs systems are not limited to nematic matrices. A series of exceptional LC-CNTs composites based on thermotropic and lyotropic materials with different LC mesophases has been developed and characterized.

The present paper is focused on remarkable dielectric, electro-optical and micro-structural characterstics of LC-CNTs dispersions, their correlation and mutual influence.

2. CNTS IN NEMATIC LIQUID CRYSTALS

Nematic liquid crystal displays (LCDs) are widely employed as an essential component in modern display devices due to their attractive features such as flatness, low power consumption and full colour capability [22]. MWCNTs exhibited diverse electrical stretching behavior in nematic liquid crystals (NLC) depending on nanotube surface state.

Lynch and Patrick in 2002 achieved high degree of CNT alignment along the nematic director field by taking the advantage of self-assembly properties of nematic liquid crystals and then removing the LC by vacuum suction leaving the CNTs alignment intact [23]. Khoo *et al.* have observed an extremely large electrooptically induced photorefractive effect in nematic liquid crystals doped with SWNTs and explained the basic mechanisms and conditions necessary for such nonlinearities [24].Dierking *et al.* have studied the alignment and reorientation of doped carbon nanotubes in LC cells under electric and magnetic fields along with the change in the conductivity of the LC cell upon reorientation of the CNTs with the liquid crystal director field [25, 26]. Voltage-dependent transmittance and capacitance under ac and dc electric field showed that the residual dc related to an image sticking problem in LCDs was greatly reduced due to the ion trapping by CNTs following strong charge transfer from the adjacent LC molecules [27]. Similarly under applied ac voltage the electro-optical properties of CNT doped TN-LCD cells were rectified by reducing the driving voltage and rise time [28]. Huang *et al.* have studied the electro-optical characteristics of twisted nematic (TN) mode and chiral homeotropic liquidcrystal mode cells filled with +ve and –ve dielectric anisotropy liquid crystals doped with CNTs [29]. The improved electro-optical characteristics of the cells were attributed to the viscosity of the LC mixture. MWNTs were found superior additives to SWNTs which was attributed to metallic character of MWNTs [30].

Dierking et al. also obtained parallel alignment of nanotubes by dispersion in a nematic liquid crystal [31]. Exploiting the supportive reorientation of LCs, the overall direction of the nanotube alignment could be controlled both statically and dynamically by the application of external fields. They demonstrated that the self-organizing properties of LCs could be employed to unidirectionally orient carbon nanotubes of the single wall, as well as those of the multiwall type and determined a nanotube orientational order parameter of approximately *S*=0.9 for the MWNTs. The reported investigations also confirmed an electrically steered OFF–ON splanar geometryd and ON–OFF shomeotropic geometryd switch based on LC–nanotube.

Local deformation of LC director induced by translational motion of carbon nanotubes under in-plane field was studied in a CNT-doped nematic LC cell [32]. The CNTs were well aligned with the LC director, when a critical ac field was applied; the CNTs began translational motion between the electrodes as a result of electrophoretic motion thereby causing deformation of local director field. The minute addition of CNTs also suppressed the undesired field screening effect and increased the charge mobilities in the presence of a strong field which was due to the parallel alignment of both the long axis of CNTs and the nematic director along the electric field [33] The influence of CNTs on the elastic constant was studied and it was found that CNTs increase the effective elastic constant of the LC-CNT dispersions [34].

Chi-Yen Huang investigated the electrooptical properties of a CNT doped twisted nematic (TN) LC cell [35]. Experimental results have shown that the doped CNTs increase the effective elastic constant of LC–CNT dispersion. Using a small amount of CNT dopant, the field-on response time of the LC cell was found nearly invariant whereas the threshold voltage of the cell was increased due to the increase in the elastic constant of LC–CNT dispersion. At a higher CNT concentration, the contribution of the dielectric anisotropy of LC–CNT dispersion to the reduction in the rise time was significant.

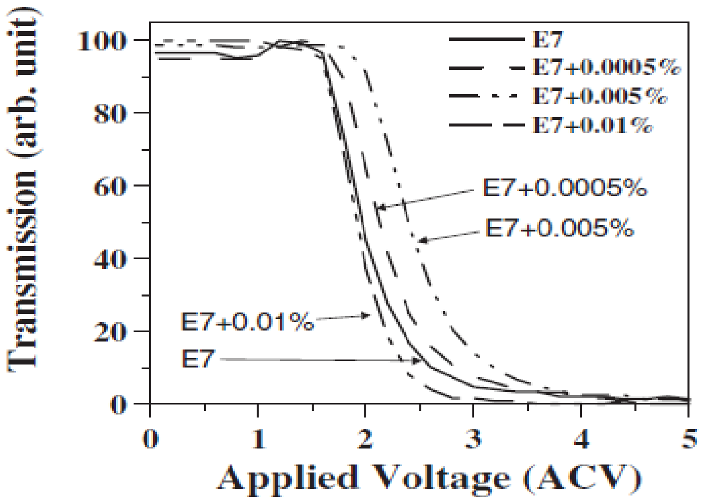

Figure 1. Measured transmission curves for TN cells as function of ac applied voltage at various CNT concentrations.

The field-off response time of the cell was also found to decreases with increasing CNT concentration due to the increase in elastic constant and the slight increase in viscosity of LC–CNT dispersion. Fig. 1 shows the measured transmission curves for the TN cells as a function of applied ac voltage at various CNT concentrations. It is clear from the figure that initially threshold voltage of the cell increases with CNT concentration, and then decreases rapidly with increasing CNT concentration.

Fig. 2 shows the measured dielectric anisotropy of the LC–CNT dispersion as a function of CNT concentration. As shown in the figure, dielectric anisotropy increases slightly and is nearly invariant when the CNT concentration is below 0.005 wt %, and then increases noticeably when the CNT concentration exceeds 0.005 wt %. The increase in the threshold voltage is accredited to the increase in the effective elastic constant when the CNT concentration is below 0.005 wt %. When the CNT concentration is 0.01 wt %, the dielectric anisotropy of LC–CNT dispersion increases markedly and significantly decreases the threshold voltage of the cell.

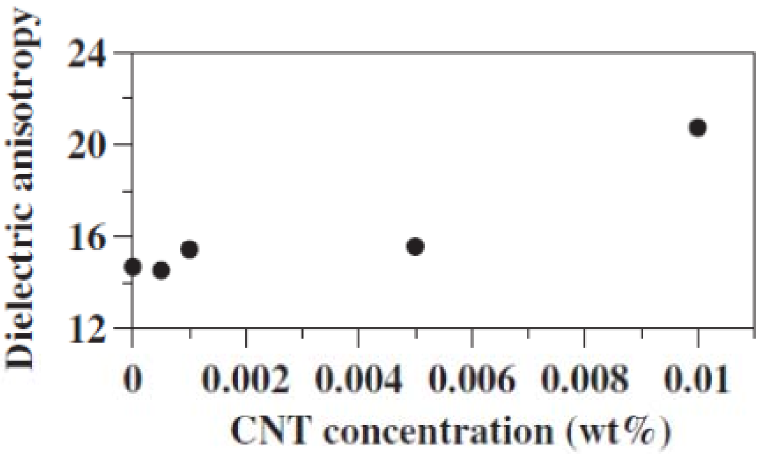

Figure 2. Measured dielectric anisotropy of LC–CNT dispersion as function of CNT concentration.

Hui-Yu Chen et al. developed a model based on the dielectric displacement current to describe the electric field dependence of the response and to yield a rotational viscosity that was found to decrease with increasing concentration of carbon nanotubes [36]. It has been shown that doping with nanotubes can effectively reduce the dc driving voltage and improve the switching behavior of a twisted nematic-LC cell.22 Dierking *et al.* have also studied the reorientation dynamics of CNTs in LC medium [37] Very interestingly, Cervini *et al.* have aligned MWNTs by a pattern assisted method using a homeotropically aligned liquid crystalline monomer that was consequently polymerized to a rigid polymeric material which led to retention of the orientation of both the mesogens and more outstandingly the nanotube [38] This should be a promising route towards achieving composite materials with novel functionality or enhanced properties due to the presence of aligned CNTs at adequate concentration.

Shin-Ying Lu and Liang-Chy Chien reported SWCNT doped LC materials which show considerable improvement in the response time for optical controlled birefringence cells [39]. Four different types of LCs were chosen to mix with CNTs and they demonstrated similar results in improving the response time. Experimental results show that CNTs have changed the property of alignment layer, causing the increase in anchoring energy for one order.

O. Yaroshchuk et al. demonstrated the effect of electro-optic memory in CNTs doped LC s and modern trends in optimization of the composites for practical use [40]. Electro-optic memory of LC–CNTs suspensions could be enhanced by doping small amount of chiral agent. The developed samples gave actual application prospect to the memory type LC-CNTs composites, especially in the information displaying and storage systems based on the LC materials.

Bo-Ru Jian et al. investigated temperature-dependent electrical properties of dilute suspensions of CNTs in NLCs under the condition of null biased voltage [41]. The experiment was carried out in the frequency range of 10^{-1}–10^{5} Hz and temperature range of 303–353 K. It was found that the activation energy for ionic diffusion is slightly higher and the diffusion constant significantly smaller in the suspensions. The effect of temperature on the mobile-ion concentration and diffusion constant, in both pure and CNT-doped NLC is displayed in Fig. 3. Figure reveals that the ion concentration of pure NLC is relatively independent of the temperature, whereas the ion concentration of CNT-doped NLC is lower than that of the pure sample in the mesophase [15, 16]. As temperature gets higher, the ion has enough energy to transport and the mobile-ion concentration of CNT-doped E7 rises.

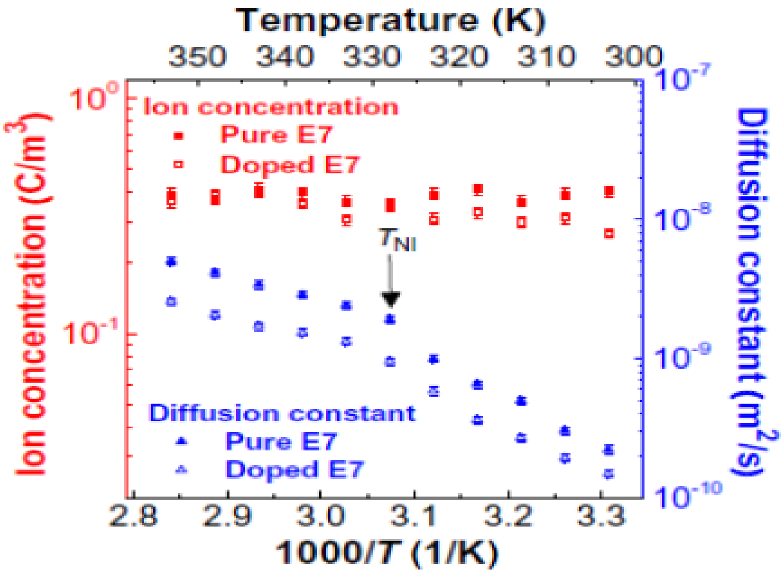

Figure 3.Temperature dependence of the diffusion constant and concentration of the ion impurities.

These results were found highly reproducible due to the homogeneity and stability of the Suspensions.

Nihan Kaya studied the effect of SWNTs on two different NLCs (E8 and ZLI-1132) separately doped with three different dyes (1,2-, 1,4- and 2,6-diaminoanthraquinone) [42]. When CNTs in a small amount were added to the dye mixtures as co-dopant, the increases in order parameters (S) were observed in mixtures with low S values.

Florin Marius Ion et al. presented results of carbon nanotubes electro-optical effect in NLC cells under an applied dc voltage [43]. It was observed that nanotubes insertion in the LC changes dielectric anisotropy, viscosity, threshold voltage and electro optical switching speed significantly. The ON and OFF response time was also found to increase with increasing concentration of NTs.

Fig. 4 represents the electro optical response of a cell with NLC (E7) doped with different MWNT concentrations .

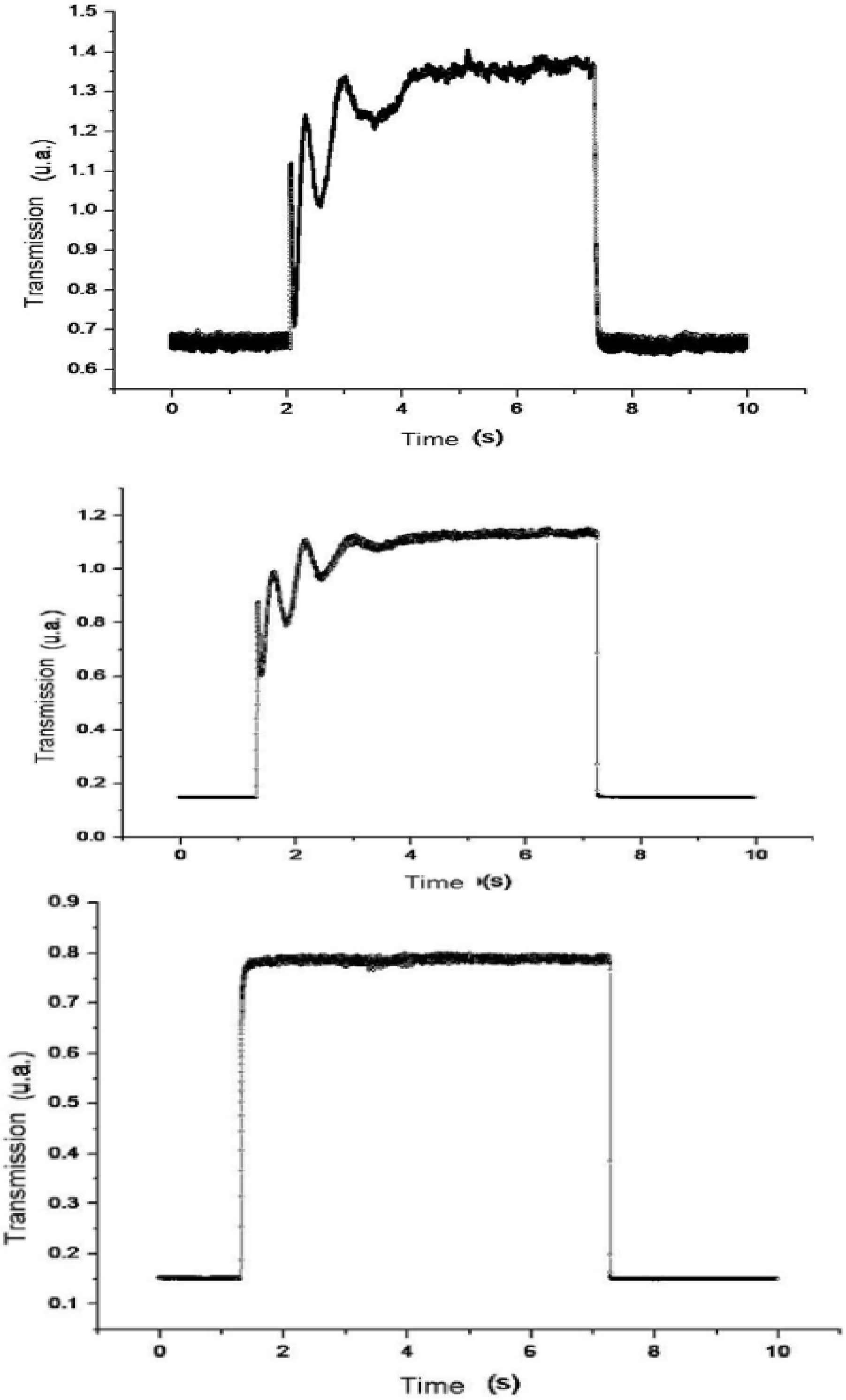

Figure 4. The form of electro-optical response of cells with NLC (E7) having different MWNT concentrations: A) *c* = 0.001%; B) *c* = 0.005%; C) *c* = 0.01%.

L. Dolgov et al. observed irreversible electro-optical response for NLC (EBBA) doped by MWCNTs near the percolation threshold of the MWCNTs (0.02÷0.05 wt. %) which was caused by irreversible homeotropic-to-planar reorientation of LC in an electric field [44]. This mechanism was established by the absence of memory in the EBBA/MWCNT composites, whose original structure was fixed by a polymer. The observed effect recommended new operation modes for the memory type and bistable LC devices.

Feng-Ching Lin et al. investigated the dielectric polarizations induced by impurity ions in both high- and low-resistivity nematic liquid crystals on adding CNTs as a dopant [45]. The former exhibited no distinct change in the low-frequency (< 102 Hz) dielectric spectrum; whereas the later showed dramatic decrease in dielectric constant in that the CNTs extremely trapped the impurity ions in the NLC of high ionic content. Consequently, the dopant raised the voltage holding ratio by 26% and prolonged the lifetime of the cell. They also investigated ionic behaviors in the low-resistivity NLC confined in cells with three different configurations.The diffusion constant of the ions in homeotropic cells was found to be the greatest, and the dc conductivity, determined by the diffusion constant, was also higher in the homeotropic ones. By contrast, the dielectric relaxation was obviously observed in the low-resistivity NLC rich in impurity ions. Those experimental results suggested that CNTs as a dopant can effectively suppress the ion effect in the low-resistivity NLC, thereby promoting the voltage holding ratio substantially. In addition, the impact of the dopant on the low-frequency dielectric spectrum was found very pronounced for the NLC host as shown in Fig.5. From this figure it is clear that, after doping 0.05-wt% CNTs in NLC, the dielectric permittivity (ε') decreases in the low-frequency region and the relaxation frequency shifted to the lower frequency. The CNTs as an additive in the ion-rich nematic host effectively trapped mobile ions [5] give rise to the decline in space-charge polarization.

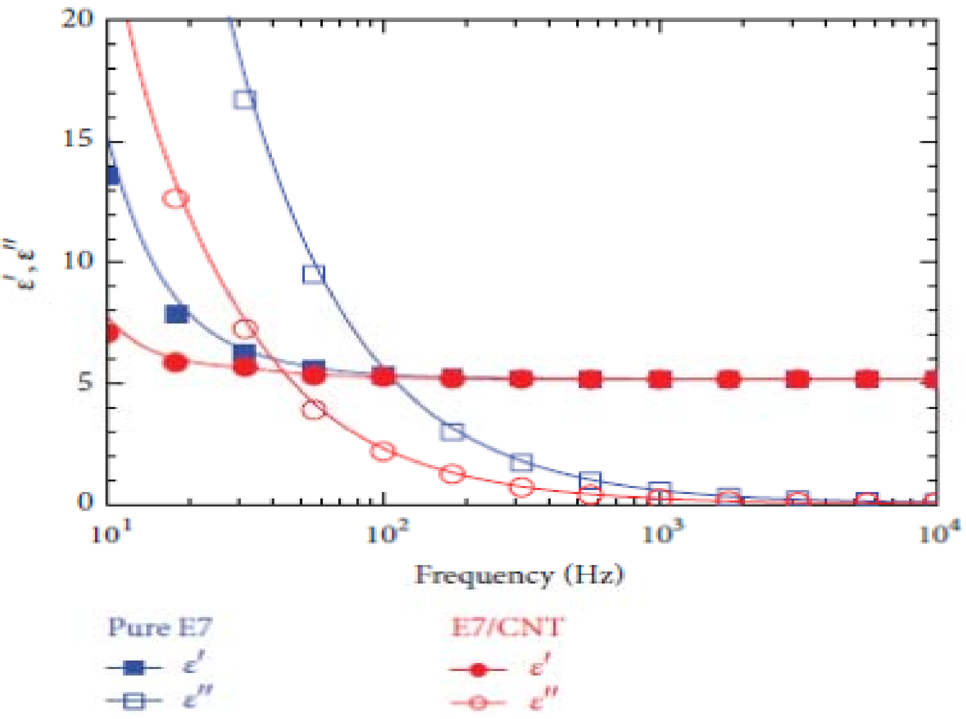

Figure 5. The dielectric spectra of pure and 0.05 wt% CNT-doped NLC in homogeneous cells at 303K.

Nasreen Raheem Jber et al. studied electric properties of NLC, N-(4`-methoxybenzylidene)-4-n-butylaniline (MBBA) doped with different concentrations MWCNTs at room temperature [46]. The dielectric permittivity and conductivity of LC-CNTs cell was observed higher than that of pure LC cell with increasing concentration of CNTs more than 0.05 wt %.

Amanda García-García et al. prepared cells of liquid crystal doped with high aspect ratio multi-walled carbon nanotubes and studied their characteristic impedance at different frequencies and excitation voltages [47]. For MWCNT-doped LC cells, the measurements reveal dominant resistor behavior at mid-range frequencies. The impedance magnitude was found to decrease with the voltage applied to the doped LC cell, and increase in the frequency range at which the resistor behavior dominate. The effect wass not reversible as the resistor behavior persists when the exciting voltage was brought back to values below the threshold voltage.

3. CNTS IN FERROELECTRIC LIQUID CRYSTALS

Ferroelectric liquid crystals (FLCs) are special types of LC materials possessing spontaneous polarisation and layered structure and are well known for their good optical contrast, low threshold voltage, memory effect, fast response etc. Most of the reported work has been focused on NLCs and twisted NLCs. The doping of CNTs in FLCs is rarely reported in literature. However, few studies have been found on CNTs doped FLCs materials.

A small amount (0.05% & 0.1% wt. /wt.) of MWCNT doped ferroelectric liquid crystal (FLC) sample cell were prepared and studied by P. Malik et al. A decrease in dielectric permittivity (~40%) in 0.1% CNT doped FLC sample was found over 0.05% doped sample [48]. The relaxation frequency of goldstone mode was found ~ 119-161Hz and 116-182Hz respectively for 0.1% and 0.05% CNT doped cells.

The temperature dependence of dielectric permittivity (ε') at varying frequencies in both samples are shown in fig. 6. Fig. 6(a) shows that dielectric permittivity (ε') increased up to 62°C in SmC*. The value of dielectric permittivity is more predominant at low frequencies (500Hz, 1 KHz). However at higher frequencies, no significant variation in dielectric permittivity was observed. It may be assumed due to that at higher frequencies, LC dipoles have not sufficient time to align themselves with the direction of field.

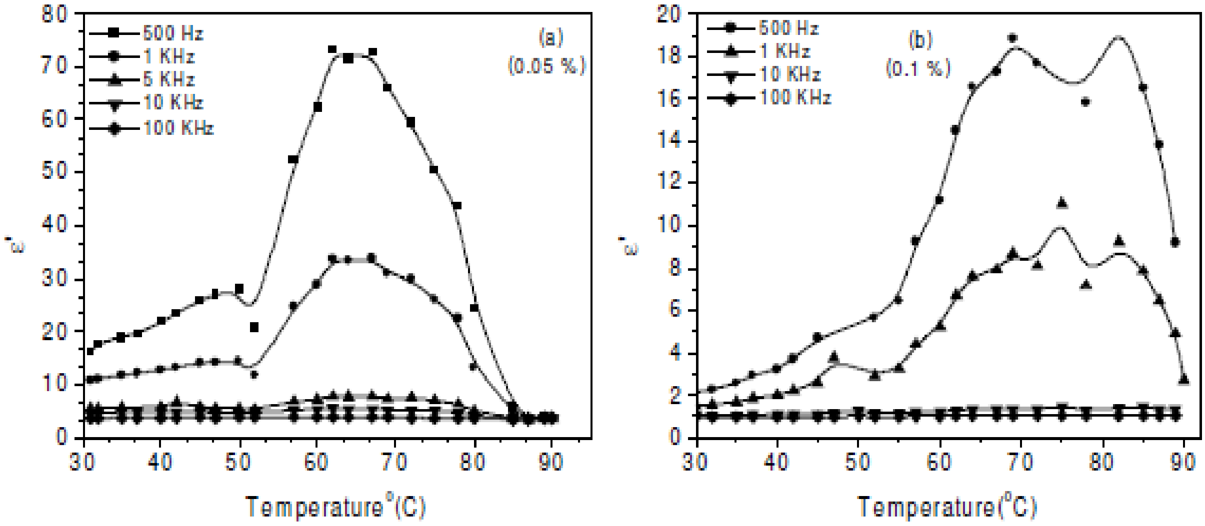

Figure 6. Temperature dependence on dielectric permittivity (ε') at varying frequencies for (a) 0.05% (b) 0.1% CNT doped FLC sample.

The frequency dependence on dielectric permittivity (ε') at different temperatures is shown in fig.7. It is clear that for 0.05% doped FLC sample cell, ε' increases from 31^{0}C to 62^{0}C and after that permittivity continuously decreases. Similarly for 0.1% doped FLC cell, permittivity increases from room temperature 31^{0}C to 75^{0}C i.e. almost up to SmA phase and after that permittivity decreases.

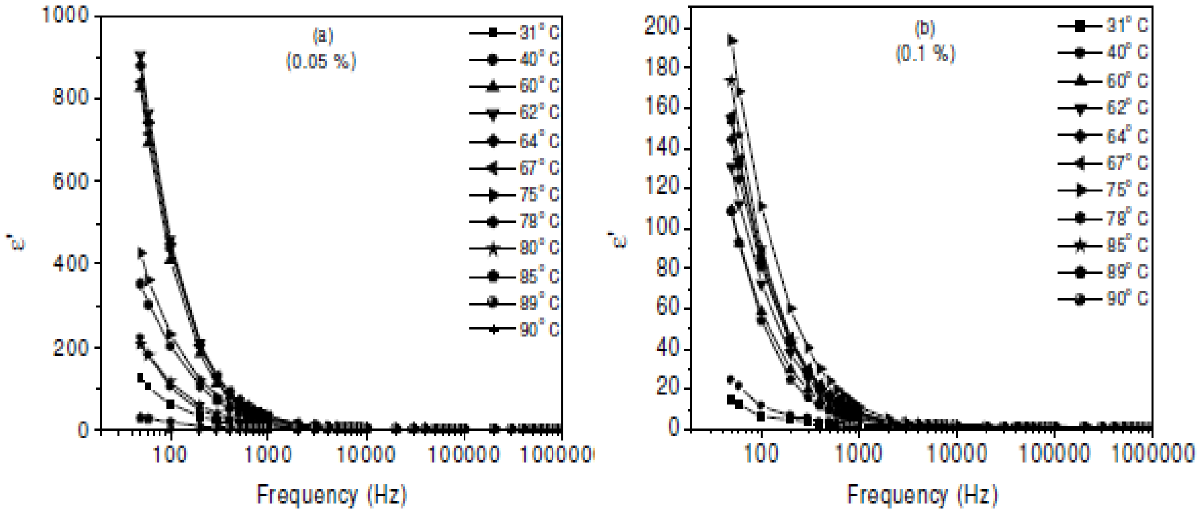

Figure 7. Frequency dependence of dielectric permittivity (ε') at different temperatures (a) 0.05% (b) 0.1%

J. Prakash et al. observed fastness of response in CNTs-doped helix FLC (DHFLC) which had been attributed to the decrease in rotational viscosity and increase in anchoring energy [49]. The increase in conductance in doped cells had also been observed.The experimental results provide the fundamental concept to develop electrooptic applications of LC device by incorporation of nanoscale material. The change in tilt angle and the spontaneous Polarization with applied voltage for pure and CNTs-doped DHFLC material has been shown in fig 8(a) and fig 8(b) respectively. Figure shows that there is a substantial difference in tilt angles of pure and CNTs-doped DHFLC cells below the certain voltage i.e., the threshold voltage of around 2 V. The value of the tilt angle in CNTs-doped DHFLC cell is less compared to the pure one below threshold voltage. But after threshold voltage, the tilt angle saturates almost the same in both cases. Fig. 8(b) clearly indicates that the value of the spontaneous polarization in CNTs-doped DHFLC cell is less compared to the pure one. The change in tilt angle and spontaneous polarization confirmed the change in rotational viscosity.

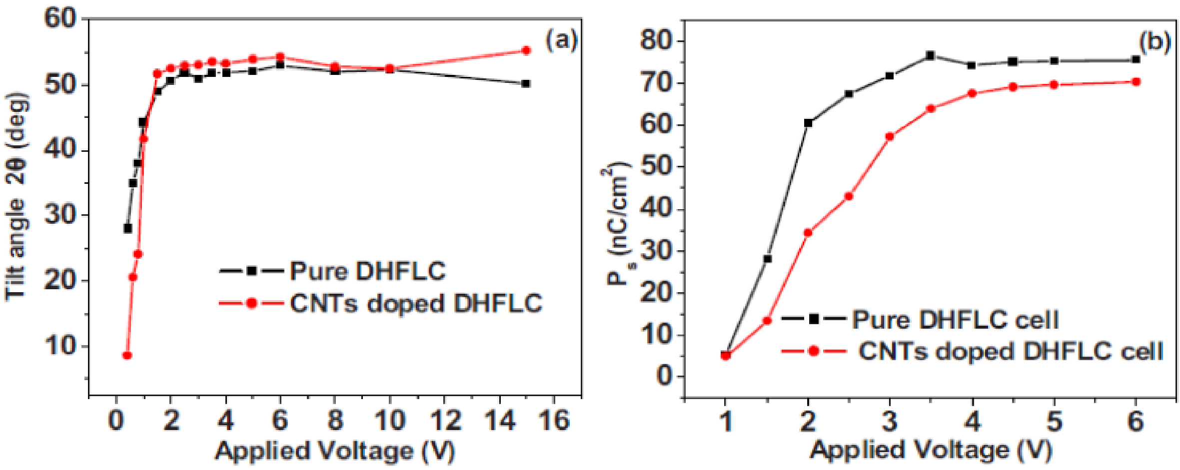

Figure 8. Behavior of (a) the optical tilt (2θ) and (b) spontaneous polarization (Ps) with applied voltage for strongly treated pure and CNTs-doped DHFLC cells at room temperature.

Fedor V. Podgornov et al. investigated the influence of the chiral SWCNTs on the dielectric and electrooptic properties of a FLC mixture [50]. It was demonstrated that even a small amount of chiral SWCNTs affect greatly the performance of FLC cells. The most outstanding result was the decrease of the rise time as well as the real and imaginary part of the dielectric permittivity of the FLC/CNTs with respect to that of the undoped sample. The reduction of the electrooptical response time could be explained by trapping of the impurity ions on the surface of the carbon nanotubes due to delocalized π-electrons which results in satisfactory decrease of ion density in nanodispersions and lead to the decrease of the dielectric losses.

Srivastava et al. presented switchable grating based on chiral SWCNT doped FLCs and found that these gratings have very high diffraction efficiency and may find application in many devices [51]. Sood N et al. studied the effect of CNTs on the dielectric properties of the deformed helix FLC mixture FLC-6304, in different LC phases [52]. The authors observed that the inclusion of CNTs significantly affected the dielectric parameters in the chiral smectic C phase with an inversion of the effect near the transition to, and in, the chiral smectic A phase.

Praveen Malik et al. prepared and studied MWCNTs doped FLC (KCFLC10R) thin films in different (0.00, 0.01 and 0.03 wt./wt.%) ratios [53]. In doped sample, fastening of switching time, an increase in spontaneous polarization and decrease in rotational viscosity than pure FLC sample was noticed. A reduction in permittivity and in dc conductivity with increasing MWCNTs concentrations was also observed.

Typical temperature dependence on spontaneous polarization (Ps) at 10 V (50 Hz) in 0.00%, 0.01% and 0.03% doped samples is shown in Fig. 9. It can be seen from Figure that doping of MWCNTs in FLC increases the Ps~30% as compared to pure FLC sample. This increase in Ps might be due to the increase in ion concentration which induces more dipole moment in MWCNTs doped FLC cells.

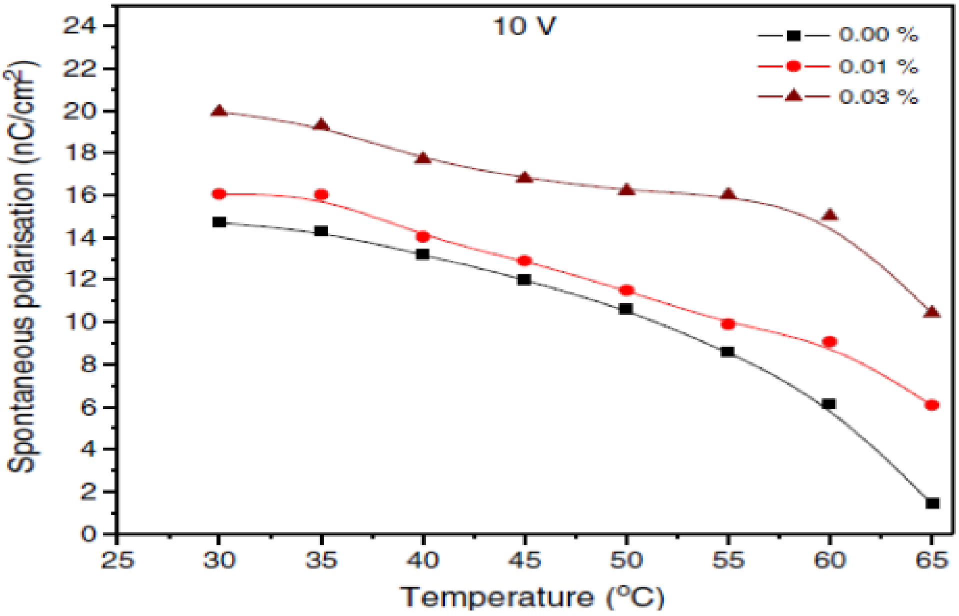

Figure 9. Typical temperature versus spontaneous polarization for pure and MWCNTs doped samples at 10 V (f=50 Hz).

Fig. 10 shows the response time (τs) behavior as a function of temperature in pure and doped samples. It was found that response time decreases with increasing the concentration of MWCNTs in FLC mixture. This fastening of response time was assumed due to the ion trapping of MWCNTs in FLC material.

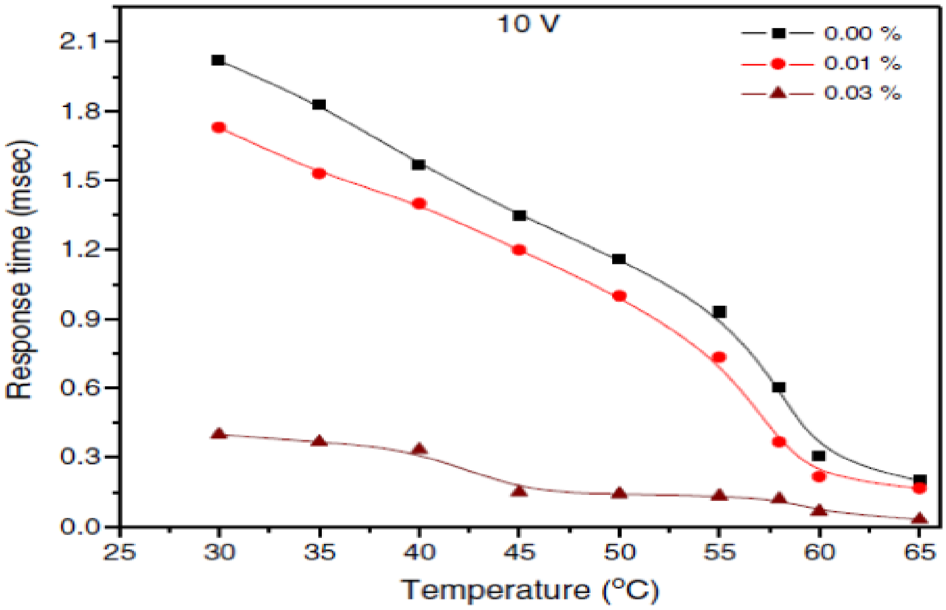

Figure 10. Temperature dependence on response time for pure and MWCNTs doped samples.

The corresponding change in rotational viscosity is also presented in Fig. 11. The decrease in rotational viscosity in doped samples was due to requirement of higher torque, which is directly proportional to effective electric field in the doped sample cells than pure FLC cell.

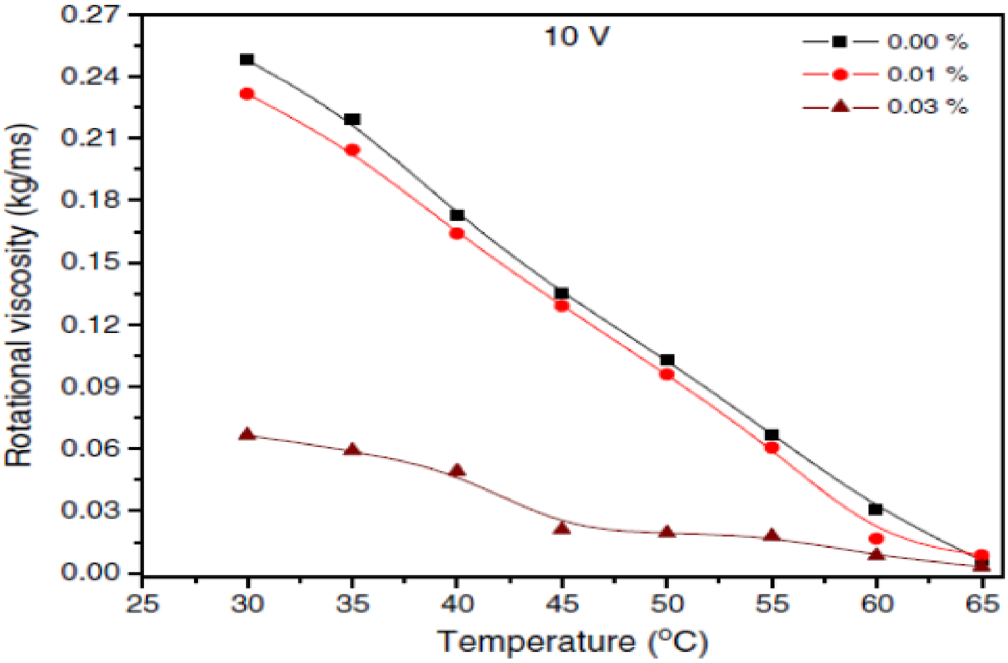

Figure 11. Variation of rotational viscosity with temperature for pure and MWCNTs doped samples.

Nitin Sood et al.studied the effect of CNTs on the dielectric properties of the deformed helix FLC mixture (FLC-6304) in different LC phases [54]. The dielectric permittivity and dielectric strength of the CNT doped LCs was found to reduce appreciably compared with that in the pure LC cell, at lower temperatures. With a rise in temperature, the addition of CNTs result in a steady inversion of effect near the transition temperature and continued into the SmA* phase. The effect of CNT doping on the dielectric parameters were accredited to an increase of elastic energy.

Shashank Tripathi et al. characterized a newly synthesized FLC material, (LAHS 22) using dielectric relaxation spectroscopy and polarization optical microscopy [55]. The observed improvement in the dielectric and electro-optical properties of the FLC material has also been studied with concentration of GNPs-decorated MWCNTs in FLC material. An increase in dielectric parameters, spontaneous polarisation and rotational viscosity of the FLC material has been observed in GNPs-decorated MWCNTs doped FLC system. Fig. 12 shows the behavior of dielectric loss factor with frequency for pure and GNPs decorated MWCNTs doped FLC material at room temperature. The observed dielectric relaxation was due to Goldstone mode associated with the phase fluctuations of the FLC molecules [36]. It is clearly reflected that the dielectric loss factor increases for GNPs-decorated MWCNTs doped FLC system. The increment in dielectric loss factor was due to the fact that MWCNTs are conducting in nature so that they offer higher loss for the GNPs-decorated MWCNTs doped FLC system [12] and hence increase the dielectric loss factor of the doped system. Fig. 13 shows the rotational viscosity as a function of applied voltage for pure and GNPs-decorated MWCNTs doped FLC material at room temperature. As shown in the figure, the rotational viscosity in the GNPs-decorated MWCNTs doped FLC material has been increased as compared to that of pure FLC material. The increment could be explained as follows.The rotational viscosity is related to the rotation of molecules. The MWCNTs produce obstruction to the rotation of the nearby FLC molecule in the doped system. These obstruction s may cause the distortion of director of FLC material and hence to increase the value of rotational viscosity to increase.

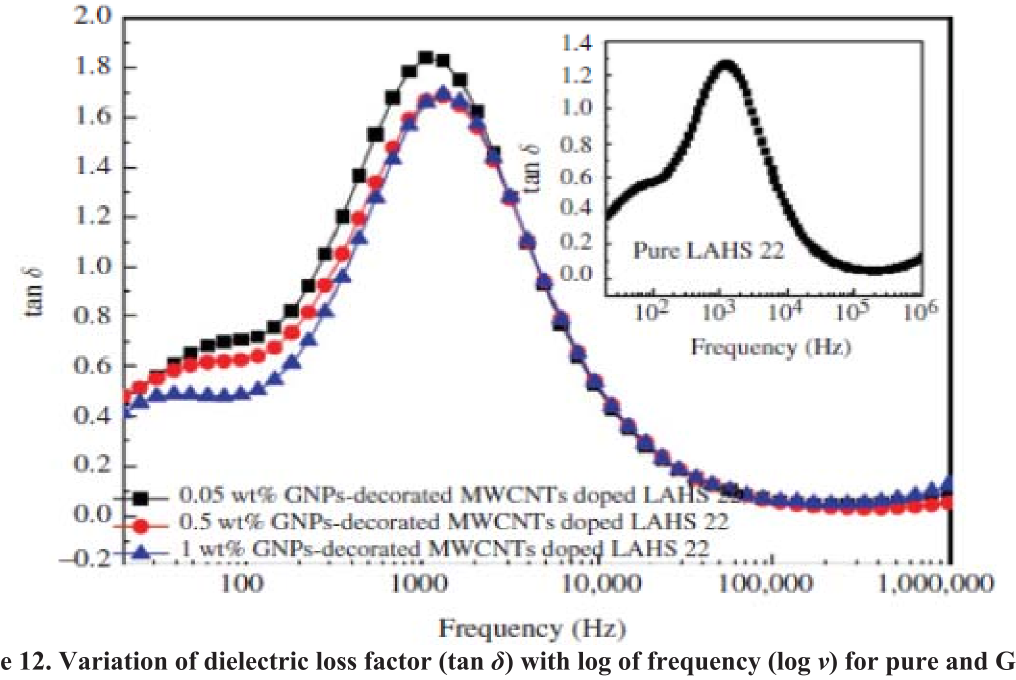

Figure 12. Variation of dielectric loss factor (tan δ) with log of frequency (log ν) for pure and GNPs-decorated MWCNTs doped LAHS 22 at room temperature.

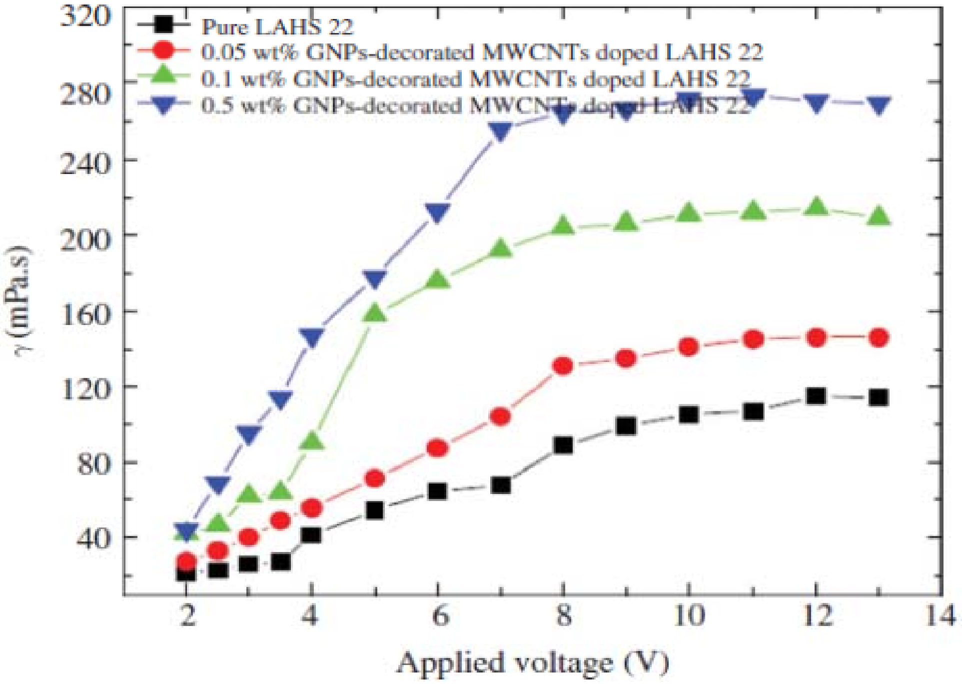

Figure 13. Behaviour of the rotational viscosity (*γ*) with applied voltage for pure and GNPsdecorated MWCNTs doped FLC cells at room temperature.

Neeraj and K.K. Raina investigated the role of CNTs and their interaction with the high polarization FLC molecule [56]. The CNTS were functionalized with carboxyl group (-COOH) before dispersion in order to enhance their stabilith y in the liquid crystal medium. The various CNTS doped FLC thin film composites show enhanced dielectric strength and dielectric permittivity values as compared to the undoped sample. The variation of ac conductivity (σ_{ac}) as function of frequency at different CNT concentration is shown in fig 14. It is clear that at 1 k Hz frequency, σ_{ac} for 0.02% CNT-FLC composite is approximately 46% higher than the undoped FLC and decreases as the CNT concentration increases to 0.1%.

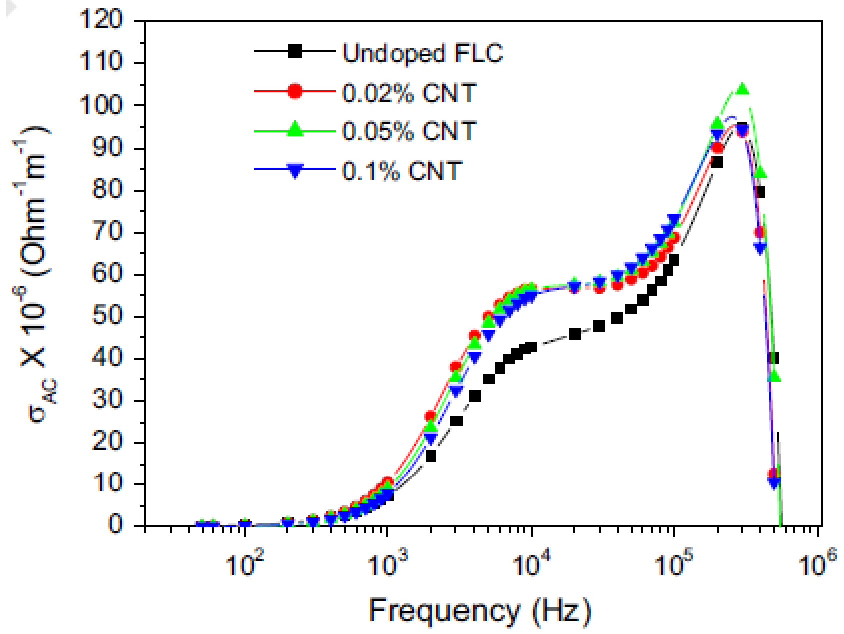

Figure 14. Variation of ac conductivity with frequency at fixed temperature (-5^{0}C).

4. CNTS IN LYOTROPIC LIQUID CRYSTALS

There are very less examples of insertion of CNT into lyotropic liquid crystals. However, as lyotropic liquid crystals are water based and common in biological and living systems, it could be very interesting to use CNT-lyotropic LC mixtures for biotechnological applications. Dispersion of individual nanotubes in thermotropic liquid crystals is not straightforward due to the bundling and aggregation of CNTs even for mild concentration of CNTs. On the other hand, in the case of lyotropic LCs, a considerable amount of SWCNTs (up to 0.2 wt.%) can be dispersed and aligned.[57,58].The lyotropic LC-CNT composites can be prepared in two different ways. By preparing an isotropic low-surfactant concentration of CNTs and then that can be made liquid crystalline by adding more surfactant or it can be added to an already prepared lyotropic LC sample. The insertion of SWCNTs into lyotropic liquid crystalline phases for various concentrations was first investigated in 2006 by Weiss et al. [59]. They observed that both the supramolecular (d-spacing) and macroscopic (viscosity) properties of the lyotropic LC increaseSwith increase of CNT concentration in the composite. Lagerwall et al. have aligned SWCNTs in the lyotropic NLCs formed by both rod shaped and disc shaped micelles [60]. Their polarized Raman spectroscopy measurements indicated that the nanotubes are aligned along the LC director and allowed the determination of the order parameter.

Jiang et al. have dispersed CNTs in a lyotropic LC formed in room-temperature ionic liquids [61]. They also observed that the *d*-spacing as well as the viscosity of the medium was increased with increase in nanotube concentration. Notiv-Roth et al. dispersed SWCNTs in CTAB/water lyotropic liquid crystal system and bserved that CNTs incorporate into ordered lyotropic liquid crystalline phase while preserving the native *d*-spacing [62]. Moussa et al. reported high orientational ordering of SWCNTs when dispersed in a nematic chromonic liquid crystal which was a new class of water-based lyotropic LC[63].

5. CONCLUSIONS

- We have described recent developments of CNTs-LC mixtures which confirm that further and multidisciplinary research efforts are well worth in this field.
- Several methods and successes have been achieved at the laboratory scale. The phase behaviour of CNTs doped LCs is found in good agreement with well-established theories.
- Control of nanotube alignment has been recognized to play a vital role in developing the practical techniques in the utilization of individual nanotube properties in the macroscopic assemblies.
- The intrinsic self assembling nature in the liquid-crystalline phase is promising in achieving such macroscopic nanotube alignment. As the LCs are highly responsive to the external forces, the applied fields could appreciably improve the nanotube alignment in the liquid-crystalline phase.
- A lot of theoretical work is still requisite to have better understanding of CNT and LC interactions.

REFERENCES

[1] Demus, D., Goodby, J., Gray, G. W., Spiess, H.-W., and Vill V., (Eds.), *Handbook Of Liquid Crystals*, Vol. 1–3 Wiley-Vch: Weinheim, 1998.

[2] Kaur, S., Singh, S. P., Biradar, A. M., Choudhary, A., Sreenivas, K., *Appl. Phys. Lett.*, **91**, 023120, 2007.

[3] Prakash, J., Choudhary, A., Kumar, A., Mehta, D. S., Biradar, A. M., *Appl. Phys. Lett.*, **93**, 112904, 2008.

[4] Kumar, A., Prakash, J., Mehtas, D. S., Biradar, A. M., Haase, W., *Appl. Phys. Lett.*, **95**, 023117, 2009.

[5] Holt, L. A., Richard, B. J., Stephen, E. D., Andrew, B., Gordon, S., *J Appl Phys.,* **103**, 063712, 2008.

[6] Josh., T., Kumar, A., Prakash, J., Biradar, A. M., *Appl Phys Lett.*, **96**, 253109, 2010.

[7] Hirsts, L. S., Kirchhoff, J., Inman, R., Ghosh, S., *Proc. Spie,* **7618**, 76180f, 2010.

[8] Kumar, A., Prakash, J., Khan, M. T., Dhawan, S. K., Biradar, A. M., *Appl Phys Lett.*, **97**, 163113, 2010.

[9] Prakash, J., Choudhary, A., Mehta, D. S., Biradar, A. M., *Phys Rev E.* **80**, 012701, 2009.

[10] Iijima, *S., Nature (London)*, **354**, 56, 1991.

[11] Martel, R., Schmidt, T., Shea, H. R., Hertel, T. Avouris., P, *Appl. Phys. Lett.*, **73**, 2447, 1998.

[12] Rueckes, T., Kim, K. Joselevich, E., Tseng, G. Y., Cheung, C. L., Lieber, C. M., *Science*, **289**, 94, 2000.

[13] Kong, J., Franklin, N.R., Zhou, C., Chapline, M.G., Peng, S., Cho, K., Dai, H., *Science*, **287**, 622, 2000.

[14] Yu, X., Rajmani, R., Stelson, K. A., Cui, T., *Sens. Actuators A*, **132**, 626, 2006.

[15] Baughman, R.H., Zakhidov A. A., De Heer, W.A., *Science*, **297**, 787, 2002.

[16] Zheng, M., Jagota, A., Semke, E.D., Diner, B. A., Mclean, R.S., Lustig, S. R., Richardson, R. E., Tassi, N. G., *Nat. Mater.*, **2**, 338, 2003.

[17] Dierking, I., Scalia, G., Morales, P. & Leclere, D., *Adv. Mat.*, **16**(11), 865, 2004.

[18] Qi H., and Hegmann, T., *J. Mater. Chem.*, **18**(28), 3288, 2008.

[19] Huang, C. Y., Hu, C. Y., Pan, H. C., and Lo. K.Y., *Jpn. J. Appl. Phys.*, **44**(11), 8077, 2005.

[20] Chen, H. Y., Lee, W. and Clark, N. A., *Appl. Phys. Lett.*, **90**(3), 033510-1, 2007.

[21] Lee, W., Wang, C. Yu & Shih, Yu-Cheng., *Appl. Phys. Lett.*, **85**(4), 513, 2004.

[22] Lee, W., Gau, J. S., Chen, H. Y., *Appl. Phys. B: Photophys. Laser Chem.*, **81**, 171, 2005.

[23] Lynch M. D., Patrick, D. L., *Nano Lett.*, **2**, 1197, 2002

[24] Khoo, C., Ding, J., Zhang, Y., Chen, K. and Diaz, A., *Appl. Phys*. Lett., **82**, 3587, 2003.

[25] Dierking, Scalia, G., Morales P. and Leclere, D., *Adv. Mater.*, **16**, 865, 2004.

[26] Dierking and San, S. E., *Appl. Phys. Lett.*, **87**, 233507, 2005.

[27] Baik, I.S. Jeon, S. Y., Lee, S. H., Park, K. A., Jeong, S. H., An K. H. and Lee, Y. H., *Appl. Phys. Lett.*, **87**, 263110, 2005.

[28] Lee, W. and Shih, Y. C., *J. Soc. Info. Dis.,* **13**, 743, 2005.

[29] Huang, C. Y., Hu, C. Y., Pan, H.C. and Lo, K.Y., *Jpn. J. Appl Phys.,* **44**, 8077, 2005.

[30] Chen H. Y. and Lee, W., *Optical Review*, **12**, 223, 2005.

[31] Dierking, Scalia, G., Morales, P., *Journal of Applied Physics,* **97**, 044309, 2005.

[32] Baik, I.-S. Jeon, S. Y., Jeong, S. J., Lee, S. H., An, K. H., Jeong, S. H. And Lee, Y. H., *J. Appl. Phys.*, **100**, 074306, 2006.

[33] Chen H.Y. Lee., A., *Appl. Phys. Lett.*, **88**, 222105, 2006.

[34] Huang, C.Y., Pan H.-C. and Hsieh, C.-T., Jpn. *J. Appl. Phys.,* **45**, 6392, 2006.

[35] Huang, C. Y., Pan H. C. and Hsieh, C. T., *Japanese Journal of Applied Physics,* **45**, 6392, 2006.

[36] Chen, H.Y., Lee, W., Clark, N. A., *Applied Physics Letters,* **90**, 033510, 2007.

[37] Dierking, Casson K., And Hampson, R., *Jpn. J. Appl. Phys*., **47**, 6390, 2008.

[38] Cervini, R., Simon, G.P., Markovic, M. G., Matisons, J. G., Huynh C. and Hawkins, S., *Nanotechnology*, **19**, 175602, 2008.

[39] Lu, S. Y. and Chien, L. C., *Optics Express,* **16**(17), 12777, 2008.

[40] Yaroshchuk, O., Tomylko, S., Dolgov, L., Semikina, T., Kovalchuk, O., *Diamond & Related Materials,* **19**, 567, 2010.

[41] Jian, B. R., Tang, C. Y., Lee, W.*, Carbon*, **49**, 910, 2011.

[42] Kaya, N., *Liquid Crystals*, **38**(1), 1, 2011.

[43] Ion, F. M., Berezovski, C., Berezovski, R., Heimann, G., Moisescu, M., *Romanian Reports in Physics*, **64**(4), 1011, 2012

[44] Dolgov, L., Yaroshchuk, O., Tomylko, S., Lebovka, N., *Condensed Matter Physics*, **15**(3), 33401, 2012.

[45] Lin, F. C., Wu, P. C., Jian, B. R., And Lee, W., *Advances In Condensed Matter Physics*, Article ID 271574, 2013.

[46] Jber, N. R., Rashad, A. A., Shihab, M. S., *J. of Mole. Struc.,* **1043**, 28, 2013.

[47] García, A. G., Vergaz, R., Algorri, J F., Quintana, X., and Otón, J. M., Beilstein, J., *Nanotechnol*., **6**, 396, 2015.

[48] Malik, P., Chaudhary, A., and Raina, K. K., *Asian Journal of Chemistry*, **21**(10), S095, 2009.

[49] Prakash, Choudhary, A., Mehta, D. S. and Biradar, A. M., *Physical Review E*, **80**, 012701, 2009.

[50] Podgornov, F. V., Suvorova, A M., Lapanik, A V., Haase, W., *Chemical Physics Letters*, **479**, 206, 2009.

[51] Srivastava, A. K., Pozhidaev, E. P., Chigrinov, V. G., Manohar, R. *Appl Phys Lett*., **99**, 201106, 2011.

[52] Sood, N., Khosla, S., Singh, D., Bawa, S. S., *Liq. Cryst.,* **39**, 1169, 2012.

[53] Malik, P., Chaudhary, A., Mehra, R., Raina, K.K., *Journal of Molecular Liquids,* **165**, 7, 2012.

[54] Sood. N., Khosla. S., Singh. D., Bawa. S. S., *Liquid Crystals*, **39**(10), 1169, 2012.

[55] Tripathi, S., Prakash. J., Chandran, A., Joshi, T., Kumar, A., Dhar, A. & Biradar, A. M., *Liquid Crystals*, **40**(9), 1255, 2013

[56] Neeraj, Raina K. K., *Physica B*, **434**(1), 126, 2014.

[57] Lagerwall, Scalia G., *J. Mater. Chem*., **18**, 2890, 2008.

[58] Schymura, S., Kuhnast, M., Lutz. V., Jagiella. S., Weglikowska., U. D., Roth S., Giesselman, F., *Adv. Funct. Mater*., **20**, 3350, 2010.

[59] Weiss, V. R., Thiruvengadathan, Regev O., *Langmuir*, **22**, 854, 2006.

[60] Lagerwall, Scalia, G., Haluska, M., *Adv. Mater*., **19**, 359, 2007.

[61] Jiang W., Yu B., Liu W. and Hao, J., *Langmuir*, **23**, 8549, 2007.

[62] Notiv-Roth E., Yerushalmi-Rozen R., Regev O., *Small*, **4**, 1459, 2008.

[63] Moussa, N., Blanc C., Zamora-Ledezma, C., Lavrentovich, O. D., Smalyukh, I., Islam, M.F., Yodh, A. G., Maugey, M., Poulin, P., Anglaret, E., Nobili, M., *Liq. Cryst*., **40**, 1628, 2013.