Dielectric and Electro-Optical Properties of Ceramic Nanoparticles Doped Liquid Crystals

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Received January 18, 2016; Accepted February 5, 2016

Liquid crystals are important materials because of their applications in display technology and many other scientific applications. Different mixtures of liquid crystals and their doped samples have gained interest because a single liquid crystal compound cannot fulfill all the required parameters for the display application. The doping can be accomplished with dyes, polymers, or composite nanoparticles among other substance. The addition of nanoparticles can modify the physical properties of the host liquid crystal and enhances the performance of electro-optical devices. The present study is focused on investigations of possible changes in dielectric and electro optical properties of liquid crystals caused by doping with ceramic nanoparticles. Including smaller nanoparticles were found to be better candidates for use in suppressing the unwanted ion effects in liquid crystal displays.

Keywords: Nematic liquid crystals, Dielectric properties, Electro-optical properties, Nanoparticles

1. INTRODUCTION

Liquid crystal displays (LCDs) have been developed over the past 50 years ago and have become the dominant in the display market [1,2]. LCDs are widely used in our daily life - smart phones, tablets, PCs, and large panel televisions. The uses of liquid crystals in different devices depend upon various properties like dielectric constant, dielectric anisotropy birefringent behavior, or optical transmittance. LCDs are known for high electro-optic performance as well as low power consumption devices [3,4]. Liquid crystals exhibit very high electro-optic and thermo-optic effects due to high birefringence [5] and large dielectric anisotropy [6].

Much research has been done in the field of liquid crystals (LCs) for their use in display application. The key features required for most display application are flatness, low power consumption and full color capability. Instead of synthesizing a large number of high quality LC compound, doping particles into LCs is a potentially cost effective way to attain these important features. The doping of nano particles into liquid crystal has emerged as a fascinating area of research to the application point of view [7-10]. Liquid crystal dispersions containing various types of nano particles have been developed in the recent years [11,12]. Commonly used doping particles include metallic nano particles [13,14], semiconducting nano particles [15,16], ferroelectric nano particles [17,18], carbon-related nano particles [19,20] and inorganic nanoparticles [21]. Each type of these nano particles has its own effect on alteration of the LC material properties. There does not exist a general theory which could be satisfactorily applied to all nanomaterial doped LCs, possibly because of different physical and chemical properties of nanomaterials. The same kinds of nanomaterials prepared by two different methods have given different results when dispersed in the same LC [22]. The interaction between nanomaterials and LCs depends upon the various factors like nature of dispersing materials, refractive index of nanomaterials and LCs, shape and
size of nanomaterials, concentration of nanomaterials into LC host, density, physical and chemical properties and applied electric field parameters [23-25]. Dispersion of nanoparticle in LCs has shown considerable improvement in the existing properties of LC material, exhibiting many special characteristics such as frequency modulation, enhancement of the dielectric anisotropy and birefringence, reduced threshold voltage and induced vertical alignment [26-32]. Recently, the modifications of the physical properties of liquid crystals by doping nanoparticles have received much attention for the enhancement of the performance of LC electro-optical devices. The present study reviews the enhancement in the dielectric and electro-optical properties of LCs doped with ceramic nanoparticles.

2. PROPERTIES OF DOPED NEMATIC LIQUID CRYSTALS

The least ordered mesophases is the nematic phase where the molecules have only the orientational order. This orientational order allows nematic LCs to possess anisotropic physical properties. Nematic LCs are in the focus of intense interdisciplinary investigations of supermolecular systems. In recent years there has been continually growing interest in physical effects caused by addition of ceramic nanoparticles to nematic LCs [33,34].

Leonid O. Dolgov et al. investigated electrooptic properties of nematic LC E7 filled with two types of silica nanoparticles [35]. The nanoparticles of first type, aerosil (A) were prepared by high-temperature hydrolysis of chlorosilanes. The second type of LC was based on monodisperse silica nanoparticles prepared by hydrolysis and controlled precipitation of tetraethylorthosilicate in alcohol. The typical transmittance versus voltage curves for the suspensions of E7-A and E7-MNP are shown in Figure 1a and 1b respectively. In the initial state the samples were characterized by the initial transmittance T0. With increasing applied voltage, the transmittance of both the samples reached a saturation value (Tsat) as shown in Curve 1. Curve 2 represents variations in transmittance with decrease in voltage. As the voltage decrease to zero, the system turns to the state with residual transmittance (Tm).

The results demonstrated that the preparation method strongly influences the structure and properties of LCs filled with nanoparticles. Chemically active monodisperse silica particles, existing only in the form of colloidal solutions, demonstrated enhanced aggregation and even reactive merging when they are mixed with LCs. To make LC-monodispersed nanoparticle (MNP) composites attractive for applications, a highly dispersed state of the solid phase should be stabilized. These results were found useful for the development of new composites based on the variety of fillers supplied by modern nanotechnologies.

S.M. Weiss et al. demonstrated tunable photoluminescence from erbium doped LCs infiltrated into porous silicon microcavities at 1.55 μm by thermal actuation [36]. Extinction ratios of 10 dB were found achievable in microcavities with quality factors of 200. Further optimization of the porous silicon morphology, oxide thickness, and surface alignment agents allowed thermal tuning over a 40 nm bandwidth within the erbium emission spectrum.

Fumiaki Haraguchi et al. reported the reduction of threshold voltage of twisted nematic LC devices by doping the nanoparticles of MgO and SiO2 [37]. The results were explained by inserting the experimentally determined values of elastic constants (k_{eff}) and dielectric anisotropy (∆ε) in the formula

\[ V_0 = \pi \sqrt{\frac{k_{eff}}{\Delta \varepsilon}} \]

Where elastic constant (k_{eff}) is directly proportional to the square of order parameter and dielectric anisotropy (∆ε) is directly proportional to the order parameter. Threshold voltage decrease approximately as the square root of order parameter as the order parameter decreases due to the existence of appropriate nanoparticles.

Lara Scolari et al. fabricated a device based on a photonic crystal fiber infiltrated with liquid crystals doped with BaTiO3 nanoparticles and compared the measured transmission spectrum with the one achieved without dopant [38]. The threshold voltages for doped and undoped liquid crystals in a silica capillary and in a glass cell were also measured as a function of the frequency of the external electric field.

Figure 2(a) and 2(b) show the measured transition for both pure E7 and nanoparticle-doped E7 as a function of the frequency of the external field.

The threshold voltage as a function of frequency was found similar in glass cell and in silica capillaries.

Wei-Ting Chen et al. studied the transient current and the voltage dependent transmittance in twisted nematic liquid crystal cells doped with ZnO, TiO2, and SiN nanoparticles [39]. The addition of insulating nanoparticles lead to a reduction of the transported ion concentration and the threshold voltage while

Fig. 1. Transmittance versus voltage curves for two types of suspensions: (a) E7-A300 and (b) E7-SiO2 monodispersed nanoparticle.

Fig. 2(a). Measured transition threshold at different frequencies for nanoparticle-doped E7 and pure E7 in a glass cell.
simultaneously producing a high voltage holding ratio (VHR) value. Figure 3 shows the threshold voltages at different doping concentrations and ZnO, TiO₂, and Si₃N₄ nanoparticles doped LC cells possess lower threshold voltages compared to undoped LC cells. Guest dopants interaction with ion impurities the screening effect to be less effective and allowed the LC molecules to experience a relatively larger effective voltage within the cell.

The lower transient current found in the doped cells indicates that doping insulating nanoparticles into the LC cell has the ability to decrease the moving-ion density, and was thus found to suppress the undesired field-screening effect and contributes to a reduction of the threshold voltage. The voltage holding ratio of the doped cells which is maintained higher than 95% indicates that these insulating nanoparticles do not decrease the resistivity of the LC cell. Hence, this doping method was found to improve the electro-optical characteristics in nematic LC cells.

J.F. Blachat et al. synthesized BaTiO₃ ferroelectric nanoparticles by a simplest solid methodology and showed that a few millings was sufficient to obtain nanoparticles of approximately 150 nm in diameter, suitable for LC applications [40]. Electro-optic measurements were performed with pure and nanoparticles doped nematic LC (5CB). The presence of nanoparticles resulted in a decrease in the switching time and an increase in the restoring switching time. These results were assigned to a strong dipole/dipole interaction between LC molecules and ferroelectric nanoparticles.

Chen-Yu Tang et al. investigated the electrical properties of nematic LC doped with anatase TiO₂ nanoparticles by means of dielectric spectroscopy [41]. Low-frequency dielectric spectroscopy between 10⁻² and 10³ Hz was used to investigate the space-charge polarization. The results indicate that the ionic concentration, the diffusion constant and activation energy were reduced in the nematic LC E44 doped with TiO₂ nanoparticles, implying that doped cells would suffer less ionic effect than the pure cells. Although the activation energy was decreased in a nanoparticle doped LC cell, the dopant yields a positive effect on the performance of the LC device over the wide temperature range studied. Thus, doping anatase nanoparticles into LC was found to be a potentially cost-effective and simple method to improve the device performance.

Saurabh N. Paul et al. dispersed a low concentration (0.5 wt %) of ferroelectric nano-powder of barium titanate (BaTiO₃) in 4-(trans-4-n-hexylcyclohexyl) nematic liquid crystal othiocyanato-benzoate (6CHBT) [42]. The temperature and frequency dependent relative dielectric permittivity and loss were investigated and relaxation frequency and activation energy of an observed relaxation mechanism along with the electro-optical parameters such as threshold voltage, switching voltage of the pure as well as nano system dispersed with LC. Figure 4 shows that dielectric anisotropy decreases due to dispersion of barium titanate mainly because of the decrease in the longitudinal component of the dielectric permittivity. The dielectric anisotropy Δε′ of the dispersed sample decreases by 20% as compared to the pure 6CHBT sample.

It was also observed that due to the dispersion of barium titanate, isotropic to nematic transition temperature of 6CHBT decreases by about 0.5 °C and transition enthalpy is reduced by 24%. The activation energy corresponding to the flip-flop motion of the molecules about the short axes of the barium titanate dispersed 6CHBT sample is marginally reduced compared to the pure sample and that the threshold voltage of 6CHBT increases due to dispersion of barium titanate.

Alexander Lorenz et al. investigated simple nematic mesogen 5CB doped with milled barium titanate nanoparticles with X-ray scattering [43]. Doping with barium titanate nanoparticles of 9 nm diameter led to the formation of crystallites. The pure and doped samples were studied at a temperature of 28 °C. The pure 5CB showed a typical diffraction pattern of oriented nematic LCs as shown in Fig. 5(a). Nematic LCs showed two diffuse peaks in the wide-angle region. The position of these peaks corresponded to the average intermolecular separation in the direction perpendicular to the molecular long axis. Additionally, two narrower
peaks appear in the small-angle region. The position of the narrow small-angle peaks corresponds to the average intermolecular separation in the direction parallel to the molecular long axis. In contrast to the pure 5CB, the doped sample showed segregation into a phase separated white substance at the bottom of the capillaries. Both the segregated substance and the more transparent upper region were studied separately. No significant difference between the scattering from the upper region of the sample and the scattering from the pure sample could be discerned. In contrast, X-ray diffraction patterns of the white region of the doped LC (Fig. 5(b)) differed considerably from diffraction patterns of the pure LC.

Yukihide Shiraiishi et al. prepared cyclodextrin (CyD)-capped silica ($\text{CyD-SiO}_2$) nanoparticles and poly (cyclodextrin) (PCyD)-capped silica ($\text{PCyD-SiO}_2$) nanoparticles [44]. The average diameter of $\text{SiO}_2$ nanoparticles capped by $\alpha\text{CyD}$, $\beta\text{CyD}$, $\gamma\text{CyD}$ and PrCyD were 9.4, 8.4, 10.6, and 6.4 nm, respectively. The nanoparticles were dispersed in LC, 4'-pentyl-4-cyanobiphenyl to form a novel twisted nematic LC device. The response time of this twisted nematic LC device in the presence of $\text{PrCyD-SiO}_2$ nanoparticles was observed to be faster than that in its absence.

Yong-Seok Ha et al. investigated the properties of nematic LC device doped with titanium nanoparticle [45]. The electro-optic properties of LCs were found to change according to Ti nanoparticle doping concentration. As the Ti nanoparticle concentration increased, lower threshold voltages and faster response times were obtained. Therefore, LC performance was verified by changing the nanoparticles concentration to improve electro-optic characteristics. The results of Ti nanoparticles doping in nematic LC showed high performance optical properties necessary for LCD devices.

M.R.Hakobyan et al. observed that ferroelectric nanoparticles could produce enhanced changes in the physical properties of a LC host [46]. In the process they also presented the preparation of LC-ferroelectric nanoparticle composites using other ferroelectric nanoparticles so as to improve the physical properties of the host LC. They used a number of LC-particle composites that used either BaTiO$_3$ or Sn$_2$P$_2$S$_6$ ferroelectric nanoparticles, and reported that ferroelectric nanoparticles dispersed into the single-component LC behaved as a molecular dipole and could either increase or, in some cases, decrease the resulting order parameter of the LC mixture. The variations in order parameter ranged from 10% to 20% depending on the LC-particle mixture used for the measurement. The typical temperature dependence of the order parameter of unmodified 5CB and the three dispersions are shown in Fig. 6.

In the samples made with BaTiO$_3$ particles of 11 nm and 50 nm diameters, the increase of the clearing temperature $\Delta T_{NI} \approx 4.5$ and 2.5 $^\circ$C respectively was observed and a clear increase of the average order parameter in the dispersion was found. Similarly in the sample made with Sn$_2$P$_2$S$_6$ particles in the same particle size range (11 nm diameter), the increase in the clearing temperature $\Delta T_{NI} \approx 4$ $^\circ$C and an average increase in order parameter in the dispersion was found.

O. Köysa et al. investigated the effect of Fe$_3$O$_4$ nanoparticles doped into E63 coded LC with 0.1 wt% in a wide range of frequency, bias voltage, and illumination [47]. The frequency, bias voltage, and illumination level dependence of the electrical and dielectric properties of pure E63 and doped mixture (E63-Fe$_3$O$_4$) had been investigated using the current-voltage ($I$-$V$) and admittance spectroscopy ($C$-$V$ and $Glo$-$V$) data in the frequency range of 10 kHz - 1 MHz at room temperature. The increment in current with Fe$_3$O$_4$ doping was due to the metallic nature of the Fe$_3$O$_4$ nanoparticles. The current switching voltage of reorientation was shifted to lower voltage values as a result of Fe$_3$O$_4$ doping. Similar behavior was also observed with increasing illumination level.

The transient currents and voltage-transmittance (V-T) characteristics of the LC suspensions containing different sizes of TiO$_2$ nanoparticles have been measured and discussed by Tsu-Ruey Chou et al. [48]. Figure 7 represents the current-voltage characteristics of doped and undoped samples. The current peaks observed from -2 to 2 V were related to the mobile ions in the LC layer. Similarly, this current peak was suppressed by the doped TiO$_2$ nanoparticles and the peak value of the cell with smaller nanoparticles was lower than that of the cell with larger nanoparticles.

The experimental results illustrated that doping TiO$_2$ nanoparticles into nematic LCs leads to a reduction in the moving-ion...
density. The amount of the reduced impurity ions related to the size of doped TiO$_2$ nanoparticles. Under similar doping concentrations, TiO$_2$ nanoparticles with a smaller average particle size were found to be more effective in trapping the impurity ions.

U.B. Singh et al. prepared composites of nematic LCs and ferroelectric barium titanate (BaTiO$_3$) nanoparticles (NPs) and the alignments of NPs in the host medium had been demonstrated [49]. Effect of NPs doping on various display parameters of nematic LCs, namely, threshold voltage, dielectric anisotropy and splay elastic constant had been studied using electro-optical and dielectric studies. The composites were shown to improve electro-optical characteristics. The dielectric anisotropy was found to increase and the threshold voltage required to switch the LC molecules from planar to homeotropic configuration was substantially reduced by the presence of the NPs. The frequency bandwidth was also observed to increase for the composites. This phenomenon could be utilized to enhance the usable frequency bandwidth of nematic LCs which has low relaxation frequency.

Nina Podoliak et al. investigated the impact of ferroelectric nanoparticles on the basic parameters of LCs using two different nematic LCs, TL205 and 18523 [50]. The dielectric constant measurements and electro-optic study showed that the ferroelectric nanoparticle doping causes a significant increase of the dielectric anisotropy and also reduces the splay elastic constants. Both of these effects were lead to a decrease in the threshold voltage up to a factor of 1.5-1.8. The increase of dielectric constants originated from the particles ferroelectric nature, while the decrease of the elastic constant resulted from a dilution of the LC host with dopants. Investigation of the LC switching behavior in twisted cells was used to estimate dynamic parameters, such as rotational viscosity for the suspensions. An increase in the rotational viscosity by a factor of 3.2 was observed for the suspensions.

3. PROPERTIES OF DOPED CHIRAL NEMATIC LIQUID CRYSTALS

A cholesteric LCl has a a helical structure and is known as a chiral nematic LC. These materials organize in layers with no positional ordering within layers, but a director axis which varies with layers. The variation of the director axis tends to be periodic in nature. The period of this variation is known as the pitch (p). Unique properties of cholesteric LCs are conditioned by a supramolecular helical structure [51-55]. If the helical pitch is comparable to the wavelength of light a distributed optical feedback results in selective light reflection and giant optical activity. Effective control of the helical pitch value by external fields makes chiral nematics extremely promising for uses in photonic and electro-optic devices, such as photonic crystals [56], light shutters and switches [57], and adaptive laser optics and lasing [58].

A. Glushchenko et al. reported the influence of sub-micron ferroelectric particles on optical, dielectric and electro-optical properties of cholesteric LCs [59]. Introduction of an ultra small fraction of ferroelectric nanoparticles into the cholesteric matrix had been found to be a promising non-chemical method of improvement of electro-optical characteristics of different LC cells. A low fraction of the ferroelectric particles led to the broadening of the reflection band, essential decreasing of the driving voltage for switching between bistable textures and increasing the steepness of the switching.

Figure 8 shows that the maximum of the Brag selective reflection band at 40°C had been shifted towards shorter wavelengths ($\Delta \lambda_{\text{max}} \approx 27$ nm), and the halfwidth of the Bragg band had been increased ($\Delta \lambda_{\text{c}} \approx 36$ nm, $\Delta \lambda_{\text{col}} \approx 39$ nm).

These changes are the result of the strong effect of the ferroelectric particles on the optics and dielectric properties of the LC matrix.

O.Kurochkin et al. studied the effect of ferroelectric nanoparticles into a cholesteric matrix [60]. The most impressive impact of the ferroelectric nanoparticles was the 45% decrease of the driving voltage in a cell filled with cholesteric nanocolloids. The drop of the driving voltage was caused by a strong increase of the effective dielectric anisotropy of the nematic matrix, which was the basic component of the cholesteric compound.

A large decrease of the threshold voltage of the transition from the planar texture to the homeotropic one was observed as shown in Fig. 9.

The results reported clearly show the promise of ferroelectric LC nanocolloids for various applications. In particular, these novel materials they offer a unique way for an effective tuning of the dielectric, optical and electro-optic properties of LC materials in a non-synthetic way that offers a new direction for the development of advanced anisotropic meso-materials.

4. PROPERTIES OF DOPED FERROELECTRIC LIQUID CRYSTALS

Ferroelectric LCs consist of chiral rod like molecules whose long axes are, on the average, not perpendicular to the smectic layer plane [61,62]. These materials have various applications in display and other electrooptic devices because of their low-oper-
ating voltage and fast response time \[63\]. Spontaneous polarization, tilt angle, azimuthal angle, switching time and rotational viscosity, etc. are the important parameters of ferroelectric LCs \[64,65\]. To improve the various parameters which are crucial for their use in display devices and other useful applications, efforts have been made by different research groups \[66,67\]. Introduction of different nanoparticles can improve important material parameters of ferroelectric liquid crystal systems.

A. Mikulko et al. studied various dielectric and electrooptic properties of a ferroelectric LC mixture doped with BaTiO$_3$ nanoparticles \[68\]. Electro-optic studies showed slightly lower spontaneous polarization, faster response time and relatively higher coercive voltage for the nanocomposite as compared to the pure ferroelectric LC mixture. Dielectric measurements revealed a lower relative dielectric permittivity for the nanocomposite.

A slight decrease in magnitude of spontaneous polarization for the barium titanate nanocomposite in comparison to the pure ferroelectric LC mixture was observed as shown in Fig.10. This difference could result from the antiparallel dipole-dipole correlation between the molecules of the ferroelectric LC mixture and the BaTiO$_3$.

The relative dielectric permittivity was found to be lower for the BaTiO$_3$/ ferroelectric LC nanocomposite than for the pure sample as shown in Fig.11. Based on this result it was assumed that the dipole moments of ferroelectric nanoparticles combine antiparallelly to dipole moments of ferroelectric LC molecules. This corresponds to a lower macroscopic spontaneous polarization and a lower dielectric permittivity.

Neeraj and K.K. Raina dispersed silica (SiO$_2$) nanoparticles in different wt/wt% ratios in a novel room temperature ferroelectric LC mixture \[69\]. The dielectric properties of the ferroelectric LCs were found strongly influenced by silica nanoparticles. At low frequency, dielectric permittivity was observed to decrease gradually with an increase in silica concentration in the SmC$^*$ phase. Typical behavior of the dielectric loss ($\varepsilon'$) as a function of frequency in SmC$^*$ phase is shown in Fig.12. Two losses peaks corresponding to low and high frequencies respectively were observed, indicating two relaxation modes. The first loss peak corresponds to the phase fluctuations in the azimuthal angle. Dielectric loss was observed to decreases with increase in silica concentration in the frequency from 50 Hz to 1 kHz. It was also noticed that for various SiO$_2$ concentrations, the decrease in loss varied from 30% to 80% as compared to the undoped sample.

The influence of bismuth ferrite (BiFeO$_3$) nanoparticles on the electro-optical and dielectric properties of an orthoconic antiferroelectric LC mixture was investigated by S. Ghosh in planar cells \[70\]. The dispersion of nanoparticles in the orthoconic antiferroelectric LCs lead to modifications of response time, spontaneous polarization, rotational viscosity and voltage required for switching the molecules between two ferroelectric states in the antiferroelectric phase while the tilt angle was found to remain almost the same after doping. A strong local electric field was produced due to the large ferroelectric dipole moment of the nanoparticles which induced dipole moment to the neighboring LC molecules and reinforced the polarization realignment under electric field.

The sensitivity of LC was also enhanced in the BiFeO$_3$- orthoconic antiferroelectric LC composite due to the large induced dipole of the LC molecules.

T. Joshi et al. observed that the doping of alumina nanoparticles (AL-NPs) has suppressed the undesired ionic effect in ferroelectric liquid crystals \[71\]. The pure and AL-NPs doped ferroelectric LC cells were analyzed by means of dielectric spectroscopy and electrical resistivity/conductivity measurements. Fig.13 shows the variation of dielectric permittivity $\varepsilon'$ of pure and 1 wt% AL-NPs doped ferroelectric LC material with frequency at different temperatures. It was observed that the value of $\varepsilon'$ for AL-NPs doped material decreased as compared with that of the pure material. The decrease in $\varepsilon'$ could be understood by the fact that it is directly related to the net charge stored within a LC cell which acts as a capacitor. The presence of ions in ferroelectric LC material can contribute largely to $\varepsilon'$ in the low-frequency regime resulting in the higher values of $\varepsilon'$. Dielectric loss spectra confirmed the disappearance of the low-frequency relaxation peak, which appears due to the presence of ionic impurities in the ferroelectric LC materials. The reduction of ionic effects has been attributed to the strong ad-
sorption of ionic impurities on the surface of AL-NPs. This study would be helpful in minimizing the undesired ionic effects of LCD devices.

P. Malik et al. prepared and studied dispersed LC materials consisting of silica nanoparticles doped into ferroelectric LC in smectic C* phase [72]. Dielectric permittivity decreases with increase in the silica concentration. Relaxation frequency was found to increase with increasing silica concentration and temperature in the smectic C* phase and decreases as it approaches the SmA phase. The decrease in permittivity is due to the strong anchoring forces that develop between higher concentrated silica and ferroelectric LC molecules.

P. Kumar et al. investigated the dynamic properties of a ferroelectric LC mixture doped with silica nanoparticles using polarization current reversal method [73]. The effect of temperature and bias field on the switching responses of silica-ferroelectric LC composites with different silica concentrations (0.01, 0.02, 0.05 and 0.1 wt %) were studied and compared. Various electrooptic properties of the ferroelectric LC mixture were found to change according to the silica nanoparticles concentration. At a 0.1 wt% silica nanoparticle doping concentration, the ferroelectric LC cell showed the best electro-optic properties, such as low threshold and driving voltage, improved optical contrast and a low tilt angle. Tilt angle was slightly higher in 0.01% silica sample as compared to other silica samples shown in Fig. 14. These results suggest that SiO₂ nanoparticles affect the ferroelectric LC molecules alignment in ferroelectric LC -SiO₂ composites which may be explained on the basis of anisotropic interactions between silica nanoparticles and LC molecules.

The Fig. 13 shows the variation of contrast ratio (CR) as a function of reduced temperature in various samples. It decreases with increase in temperature up to SmC* to SmA transition temperature. This is due to the reason that upon heating, there is an increase in the disorder of ferroelectric LC molecules which in turn reduces the contrast between on and off states. Figure 15 shows that contrast ratio increases with increase in silica concentration.

A. Choudhary et al. presented the results based on the electrooptic and dielectric properties of silica nanoparticles doped ferroelectric liquid crystal in SmC* phase [74]. Switching time, spontaneous polarization and rotational viscosity decreased with increase in silica concentration. An improvement in switching time after doping the silica particle was assumed due to the enhancement in anchoring energy that existed between silica nanoparticle and ferroelectric LC. The dielectric permittivity and dielectric strength was noticed to decrease with increase in the concentration of silica nanoparticle in SmC* phase and relaxation frequency and was found to increase with increase in the silica concentration and temperature in SmC* and decreases as we approach towards transition temperature.

P. Ganguly et al. presented the results pertaining to faster electro-optic response time and improved photoluminescence of BaTiO₃ nanoparticles doped ferroelectric LC [75]. Increase in photoluminescence intensity and simultaneous reduction of response time had been achieved for an optimal BaTiO₃ nanoparticles doping of 0.2 wt %. Those were attributed to the large dipole moment of BaTiO₃ that couples effectively with that of ferroelectric LC molecules. Figure 16 shows the behavior of spontaneous
polarization (Ps), response time (T_{R}) of pure and BaTiO₃ NPs doped FLC samples with applied voltage at room temperature.

The value of spontaneous polarization of BaTiO₃ nanoparticles doped samples were observed to be increased slightly compared to the pure ferroelectric LC material and showed strong dependence on the concentration of the BaTiO₃ nanoparticles (Fig. 16(a)). The value of spontaneous polarization increases initially with the concentration of BaTiO₃ nanoparticles (up to 0.5 wt. %) and then reduces to a lower value comparable with that of pure ferroelectric LC (0.7 wt. %). However, the variation of spontaneous polarization of BaTiO₃ nanoparticles composites showed the same trend as that of pure ferroelectric LC material. The modifications in the spontaneous polarization values of BaTiO₃ nanoparticles / ferroelectric LC composites indicated that BaTiO₃ nanoparticles possesses larger dipole moment and hence polarization, which coupled effectively with ferroelectric LC molecules, resulting in enhancing the net spontaneous polarization values.

The response time (SR) was found to decrease in 0.2 wt. % BaTiO₃ nanoparticles doped ferroelectric LC as compared to that of pure ferroelectric LC material (Fig. 16(b)). However, the response time increases by further increasing the concentration of the BaTiO₃ nanoparticles. It is thus noteworthy that 0.2 wt. % concentrations of BaTiO₃ nanoparticles were found optimum in enhancing the photoluminescence intensity and at the same time reducing the response time of the ferroelectric LC material.

A. Rudzki et al. investigated the influence of the size of harvested barium titanate nanoparticles on the properties of ferroelectric LCs nanocolloids by electro-optical and dielectric methods [76]. The spontaneous polarization and the switching time were found to decrease for the LC nanocolloids compared to nondoped ferroelectric LC mixtures of different dipole strengths. This dependence was stronger for small particles (9 nm diameter) with the same concentration in weight.

S. K. Gupta et al. studied the effect of titania nanoparticles on the dielectric and electro-optical properties of ferroelectric LCs [77]. Different dielectric and electro-optical measurements were conducted to explore the charge transportation and polarization mechanism in the titania nanoparticles doped ferroelectric LC system. Doping of titania nanoparticles showed reduced DC conductivity, attributed to the trapping of free charges by titania nanoparticles at the surface. Polarization had been found to increase at low fields indicating reduction of field screening effect in doped ferroelectric system. The response time study with applied electric field shows that the titania NPs have reduced the response time to very low values at small electric fields have reduced the response time to very low values at small electric fields. This study would be helpful in minimizing the slow response problems and the grey level shift in LC devices which arise due to ionic effects.

5. CONCLUSION

Above study shows that combination of liquid crystal technology and ceramic nanotechnology resulted in the development of new display materials to improve the performance of liquid crystal displays. The small inclusion of ferroelectric nanoparticles to a ferroelectric liquid-crystalline mixture affects some physical properties of the mixture without disturbing the molecular structure of the ferroelectric liquid crystal helix. Inclusion of nanoparticles was also found to increase the DC conductivity anisotropy of the composite systems which could be utilized in the device applications such as conductivity switch. The rotational viscosity and response time were found to reduce in the doped cell because strong electric field is produced due to the large ferroelectric dipole moment of the nanoparticles and induces dipole moment to the neighboring liquid crystal molecules to reinforce the polarization realignment under electric field. Charge transfer between liquid crystal molecules and nanoparticles weakens the interlayer and intermolecular interaction in the host liquid crystal. Smaller nanoparticles were found to be better candidates for one to use in order to suppress the unwanted ion effects in liquid crystal displays. We believe that these results will be useful for the development of new composites based on the variety of fillers supplied by modern nanotechnologies.

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