Nanoparticle-doped polymer-dispersed liquid crystal display

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Polymer-dispersed liquid crystals (PDLCs) represent an important new class of materials for optical device applications. Their valuable advantages such as low operating voltage, high contrast ratio, requiring no extra optical elements (i.e. polarizer), quick electro-optical response, no leakage of materials, simple fabrication, low-cost production and ease of processing make them more popular over other display technologies. Among them, the nanomaterials-doped PDLCs are observed to have superior performance relative to conventional PDLCs materials due to their improved contrast ratio and time response. The present article gives an overview of the various recent approaches involving nanoparticle-doped PDLC techniques which are suitable for the low operating voltage of PDLC, off-axis haze improvement of PDLC, their quick time response, liquid crystal alignment with polymers in PDLC as well as increase in the refractive index. The merits, the various applications in such nanoparticle-doped PDLC display devices, and the advances made in this technology are reviewed.

Keywords: Electro-optical properties, polymer-dispersed liquid crystals, refractive index, nanoparticles.

POLYMER-DISPERSED liquid crystals (PDLCs) represent an important new class of materials for display applications[1–8]. Generally, PDLCs consist of micrometre-sized, birefringent, liquid-crystalline droplets dispersed in an otherwise optically transparent and uniform polymer film. Such PDLC films are easily fabricated using one of a few simple coating procedures. Figure 1 presents a conventional PDLC material device and a nanoparticle-doped PDLC device. These inhomogeneous polymer and liquid crystal (LC) composites have a spatially varying refractive index (Δn) and efficiently scatter light, making them translucent. Light-scattering can be switched-off by applying an electric field across the PDLC film to reorient the LC. Thus in this state the film becomes transparent. An important aspect of the PDLC devices is that they require no extra optical elements (other than optically transparent electrodes) to provide optical contrast. Because little current flows through the film, they consume relatively little electric power. As a result, they are particularly suited for use in large-area devices and are widely used in electrically switchable windows[5].

Compared with ordinary nematic LC devices, PDLC devices have several advantages. In the fabrication of PDLC devices, polarizers are not required; it is possible to reduce power and weight while increasing brightness[9]. Generally, PDLCs are produced by phase separation methods[10]. Phase separation is performed by first creating a homogeneous mixture of polymer and LC; as the two phases separate, LC droplets are formed within the polymer. Phase separations can be induced thermally, known as thermal induced phase separation (TIPS); by polymerization, i.e. polymer-induced phase separation (PIPS); using a solvent, i.e. solvent-induced phase separation (SIPS), or by reaction, i.e. (reaction-induced phase separation) processes. Among these, the most convenient method used for the preparation of a PDLC film is the PIPS of mixtures composed of reactive polymer precursor and LC.

Among these PDLCs, the nanomaterials-doped PDLCs demonstrate better performance relative to conventional PDLC materials due to their improved contrast ratio and time response. Previous studies performed on nanoparticle-doped PDLC films predicted that these particle have positive effects in possible display applications[11–24]. The advantageous features of the usage of monodispersed nanoparticles (MNPs) with PDLCs include: (i) good electro-optic contrast, and (ii) they form a strong network in LC layers, which prevent pouring effects in the cells[23].

Various researchers have utilized different types of nano-composite materials with different concentrations using both physical and chemical methods. Nanostructured materials have been the subject of great research since they demonstrate remarkable physical properties and have potential applications in display technology[24]. In this context, it is interesting to study the role of nanoparticles into the PDLCs morphology and their electro-optical properties. Thus the objective of the present study is to provide an overview of the ongoing and future prospectives of different types of nanoparticle-doped PDLC material devices.

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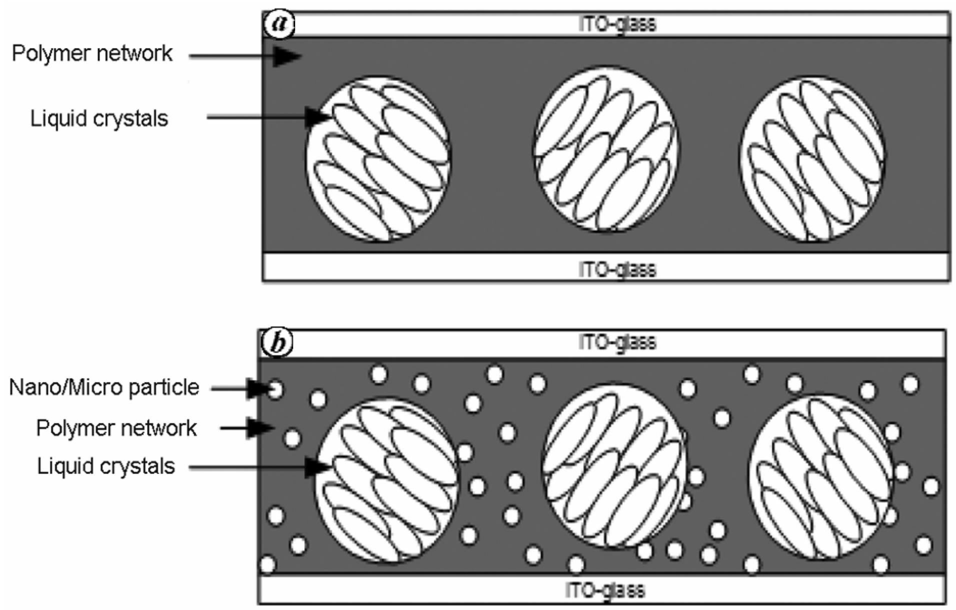

Figure 1. Schematic view of (***a***) conventional polymer-dispersed liquid crystal (PDLC) film, and (***b***) nanoparticle-doped PDLC film.

Advantages of nanoparticle-doped PDLC display technology

Recently, nanotechnologies have made a great impact on the display industry[25]. In a simple PDLC film, orientation of LC clusters located in droplets is controlled by an external electric field which allows matching of the LC and polymer refractive indexes. When LC droplet diameters are in a range of a micrometre, these devices switch from light scattering to transparent states, if their indices are matched. If the LC droplet size reduced to the sub-wavelength scale; it leads to nonscattering state of the film. Thus the film shows electro-optical and polarization insensitivity for a normal incident wave[26].

PIPS fabrication method is usually used in such kinds of biphasic structures. In this method, starting from a homogeneous mixture of monomer and LC molecules, a curing process induces a phase separation and formation of LC droplets. It is generally recognized that the phase separation is usually not complete and that a part of the LC molecules remains trapped in the polymer matrix[27,28]. This partial phase separation and resulting morphologies recently explained using a general Onsager theory of transport, highlighted the role of the initial nucleation phase, and recommended the use of nucleation centres to control LC volume fraction in the droplets[29]. Considering the nanoparticle induction on PDLCs, the nanoparticle-doped method has many advantages. For example, it is much easier than the conventional chemical synthetic methods. This method produces many special electro-optical characteristics, such as frequency modulation response[30], fast response[31], memory effect[32] and low driving voltage[33]. Recently, nanoparticle-induced vertical alignment (NIVA) method has been reported in the LC cell, which is especially suitable for producing flexible plastic LC displays requiring a low temperature process[34,35]. Details of the different nanoparticle-doped PDLCs are discussed in the next section.

Various ongoing PDLC studies performed with nanoparticles

Till date several studies have been performed for the enhancement of electro-optical properties of PDLCs with various types of nanoparticles doped with them. Busbee *et al.*[11] suggested that with a careful selection and design of the components, the LC, monomer, initiator and various organic additives, the switching speed and other optical properties can be optimized for a given application. Nevertheless, there are a number of limitations to an all-organic system[11].

The refractive-index contrast between a typical LC and the polymer contents of a PDLC is generally small. In order to avoid such complexity it desired to include additional inorganic materials into the LC and polymer mixture, that can span a much-larger range of refractive indices to tailor to the periodic refractive-index profile[11]. The introduction of an inorganic material is considered as one of the simplest techniques which is usually performed by controlled addition of nanoparticles into PDLC systems. For this purpose, nanoparticles of various materials can be synthesized in sizes small enough to avoid the addition of light scattering. Further, numerous surface functionalization techniques are also available to control the chemical interaction of the nanoparticles with such types of PDLC systems[11].

Table 1. Detailed characteristics of nanoparticles used for the fabrication of various PDLC composites

Particle type	Particle size/ diameter (nm)	Refractive index	Density	Produced by	Reference
Sb_2O_5 MNP	7–11	1.7	3.78	Nissan Chemicals Industries, USA	13
SiO_2 MNP	10–20	1.46	2.26	Nissan Chemicals Industries, USA	13
TiO_2 MNP	5–10	2.55	4.1	ANP, Korea	13
TiO_2 NP	25–51	2.55	4.1	Nanophase	13
Silica nanoparticles	14	–	–	–	12
Polyhedral oligomeric silsesquioxanes (POSS)	–	–	–	Aldrich	25
TiO_2	15	2.55	–	–	14
Sb_2O_5, SiO_2	7–11, 10–20	–	–	Nissan Chemicals Industries, USA	11
					11
Ag-nanoparticles	10	–		–	62
Au-nanoparticles	14,	–		–	39
	150 nm			Ted Pella, Inc., USA	36
$BaTiO_3$ NP	30–50 nm	–	–	Aldrich	12

MNP, Monodispersed nanoparticle; NP, Nanoparticle.

Moreover, enhancement of the electro-optical properties of LC is dependent on the size, type, concentration and intrinsic characteristics of the nanoparticles used for doping[12]. It is recommended that the nanoparticles should share the similar characteristics with LC molecules and be of a size that would not significantly disrupt the order of the LC. Thus, low doping concentrations (<3% by weight) are usually chosen to yield a more stable and even distribution in the LC, which lowers the interaction forces between particles[12]. It is important to note that in the present work, we have utilized polyhedron-shaped nanoparticles. Moreover in one study it was found that Ag nanoparticles-doped PDLC device showed quicker response than the undoped samples[36]. An important work in LCD and PDLC is the use of polyhedron-shaped ferroelectric nanoparticles (NPs-$BaTiO_3$). These NPs not only improve spontaneous polarization and other vital physical properties of the LC host, but also enhance the electro-optical properties of the LC devices. Also, such utilization of ferroelectric nanoparticles improves the response time. It is considered that nanoparticle-doped LC host, after doping increases in the anisotropic dielectric constants resulted in decreases in the threshold voltage in both electrically controlled birefringence (ECB) and PDLC modes. It is worth noting that part of the NPs-$BaTiO_3$ in the polymer altered the refractive index of the polymer, resulting in a wider viewing angle and also improving the off-axis haze.

Recently, considering the shapes of nanoparticles doped with PDLC systems, two types of nanoparticles, e.g. spherical or rod-like magnetic nanoparticles were studied by Tomašovičová *et al.*[13]. The results obtained from the study predicted that on introducing the magnetic nanoparticles into PDLC, the conductivity (σi) value is increased by more than one order. While in the case of rod-like magnetic nanoparticles, the change in σi is approximately 1.2 times higher than that in the case of spherical magnetic nanoparticles. It was suggested that the shape of the magnetic nanoparticles does not practically influence the change in the value of conductivity. This could be because when the phases are separated, most of magnetic nanoparticles pass to LC in the process of structure formation. The results of studies done by employing several types of nanoparticles into PDLC display are summarized in Table 1.

Yaroshchuk *et al.*[14,15] considered the structural peculiarities and electro-optical performance of PDLCs doped with a small amount of inorganic colloid nanoparticles (Sb_2O_5 and SiO_2). They focused on LC–NP–polymer composites with a high polymer content (φ_P = 30–50 vol%), which was capable to form PDLC morphology. The amount of nanoparticles used in these composites was low (φ_{NP} = 1–2.5 vol%) to minimize deformation of the PDLC structure formed by the polymer and LC. In order to check how NPs are distributed in LC–NP–polymer composites, these specimens were kept in hexane to dissolve and remove LC. Further, these specimens were weighed before and after extraction of LC phase to check the full removal of NPs. After weighing, it was found that the specimen lost weight less than the weight of LC contained in the composite. It was concluded that during phase separation NPs are mainly involved with the polymer phase.

Moreover, nanoparticles can serve as the germs of polymerization. The observed SEM images of PDLC and NP–PDLC are shown in Figure 2. It was concluded that a small amount of NPs does not distort the PDLC morphology of LC–polymer composites. The key point of this study was that doped NPs modify optical uniformity of the polymer. Calculations showed that when the diameter of the spherical particles or their aggregates is above 300 nm, the polymer loses optical uniformity, i.e. the polymer becomes opaque. In contrast, when d = 100 nm, even for 15 vol%, NP loading did not affect the uniformity of the polymer. This work also confirmed that

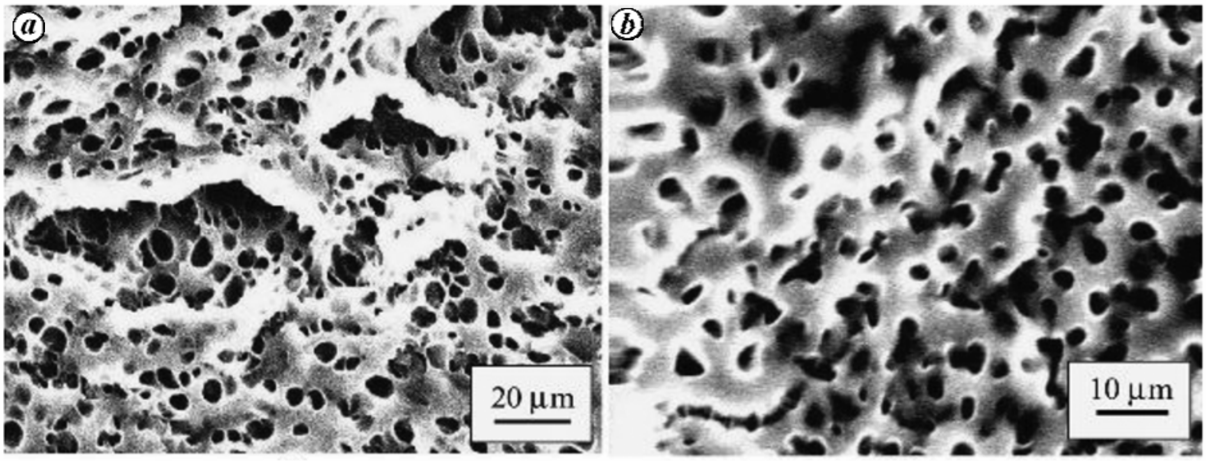

Figure 2. Schematic view of (***a***) SEM images of PDLC without nanoparticles (NPs) (φ_P = 40 vol%), (***b***) PDLC doped with Sb_2O_5 NPs (φ_P = 38 vol%, Sb_2O_5 = 3 vol%). (Reproduced from Yaroshchuk *et al.*[15] with permission from Elsevier Science Ltd, The Netherlands.)

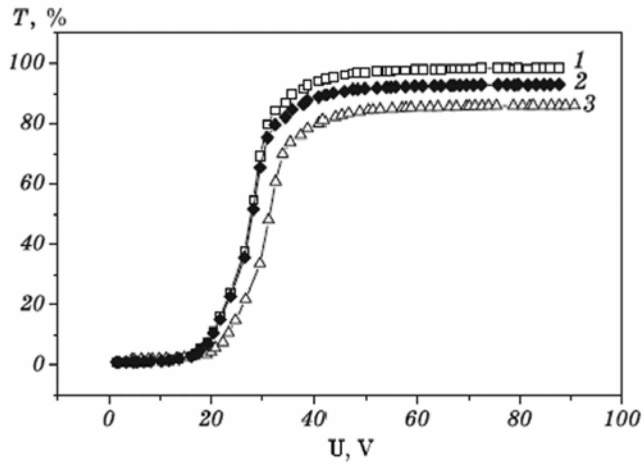

Figure 3. View of the *T*–UV curves for the non-doped and NP-doped PDLC composites. (1) φ_P = 40 vol%; φ_{NP} = 0 vol%; (2) φ_P = 39 vol%; φ_{NP} = 1 vol% (SiO_2 NPs) and (3) φ_P = 39 vol%; φ_{NP} = 1 vol% (Sb_2O_5 NPs). (Reproduced from Yaroshchuk *et al.*[15] with permission from Elsevier Science Ltd, The Netherlands.)

refractive index of the modified polymer linearly depends on NP concentration.

Figure 3 shows transmittance (*T*) versus *U*, *V* curing curves for the LC–polymer (1) and LC–P–NP (2, 3) composites of PDLC morphology. For NP-containing specimens, one can observe an increase in the controlling voltage. This might be caused by the modification of dielectric permittivity of the polymer phase that, in turn, may reduce the effective electric field applied to the LC drops. Further, these studies suggest that doping of the polymer phase with inorganic NP may lead to other improvements in the PDLC, such as enhancement of thermal and mechanical stability of the polymer matrix, and reduction of LC content in polymer[14,15].

Kuo *et al.*[25] produced vertical alignment in LC cells by adding nanoparticles of polyhedral oligomeric silsesquioxanes (POSS) in the LC layer. This letter reports the results of the NIVA in a positive dielectric anisotropic LC cell and its application in hybrid-aligned nematic (HAN) LC cell. In their performed work Figure 4 *a* and *b* shows the polarizing optical microscopic (POM) images of the 20 wt% POSS-filled LC test cell and the LC test cell respectively. It can be seen from Figure 4 *a* that a uniform, dark state is observed from POM. That is, all the LC molecules in LC/POSS mixture were aligned perpendicular to the substrate. On the other hand, a bright picture caused by the random orientation of LC molecules was observed for the samples filled only with LC (Figure 4 *b*). To further understand the orientation of LC in the LC/POSS mixture, the pretilt angles of 20 wt% POSS-filled LC test cells were measured using the Autronic TBA-107. The samples were fabricated with various cell gaps from 10 to 107 μm. These findings are shown in Table 2, which predicted that the pretilt angles were almost kept at 89.6° regardless of the variation in the cell gaps. This study implied that nanoparticle-doped LCs have excellent order and good stability even for large cell gaps.

Rachet *et al.*[26] studied covalently grafted cyanobiphenyl LC molecules at the surface of silica nanoparticles, allowing perfect stability of these particles into the nematic phase. They further compared the electro-optical properties of unmodified and modified LCs. The results clearly demonstrated that LC-grafted nanoparticles act as nucleation centres during the PIPS process leading to a complete phase separation and a premature stop of the growing process, which decreased the size of the droplets. It was found that LC-grafted nanoparticles offer new opportunities to the PDLC community, allowing better diffraction efficiency with thinner films, and then can advantageously decrease addressing voltage and response time of future H-PDLC components.

In later studies, Yaroshchuk *et al.*[16] considered the structural peculiarities and electro-optic performance of LC, colloidal nanoparticle, polymer composites formed by

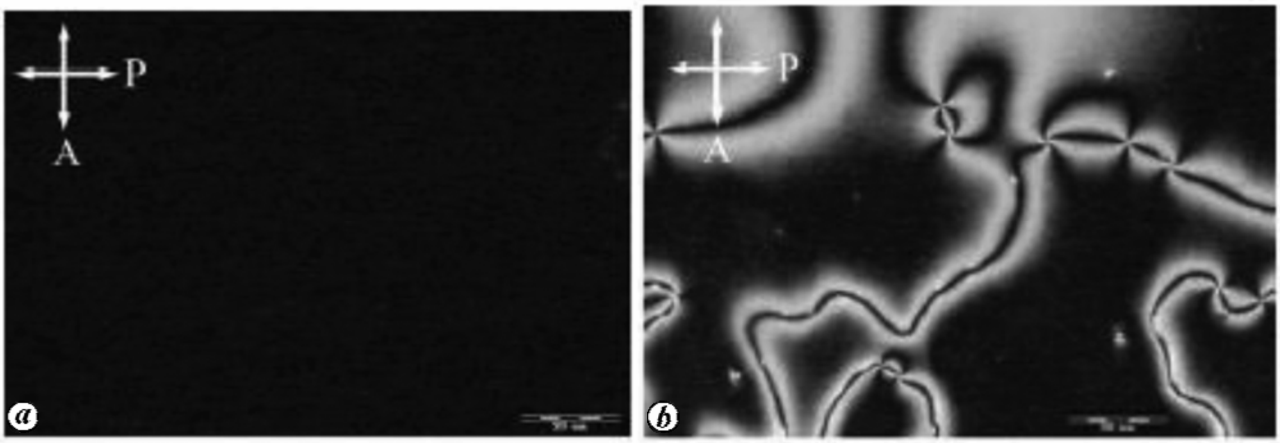

Figure 4. Polarizing optical microscopic views of the (***a***) 20 wt% polyhedral oligomeric silsequioxane filled liquid crystal (LC) test cell and (***b***) LC test cell. Such cells were fabricated by two nontreated ITO-glass substrates and sandwiched between crossed polarizers. (Adopted from Kuo *et al.*[25] with permission from American Institute of Physics, USA.)

Table 2. Summary of pretilt angles of 20 wt% POSS-filled liquid crystal test cells at various cell gaps

Cell gap (μm)	10	52	71	107
Pretilt angle (deg)	89.6	89.57	89.8	89.7

Reproduced from Kuo *et al.*[25] with permission from American Institute of Physics, USA.

photo-induced phase separation. It is important to note that they utilized inorganic nanoparticles for performing such studies. The authors classified these materials into two groups based on polymer morphology. It was observed that in the process of photo-induced phase separation of the LC–NP–prepolymer mixture, the nanoparticles are mainly involved with the polymer, serving as building blocks for the polymer matrix. Mono-dispersed nanoparticle (MNP)-doped PDLCs showed interesting effects, such as colouring, photochromism, and improved angular characteristics of light transmission. Such studies attracted great attention and opened up an interesting field for future studies.

Suzuki *et al.*[17] worked on diffraction efficiency and recording sensitivity in TiO_2 nanoparticle-dispersed methacrylate photopolymer films and recognized that these properties are dependent on the concentration of the nanoparticles. Their findings clarify that such characteristics significantly increase with an increase in the nanoparticle concentration.

In individual studies, Eren San[18] and Qi and Hegmann[37] used fullerene C60, C70, single-walled and multi-walled carbon nanotubes (CNTs). Here, graphene sheets were doped to nematic LC host in the same percentage. Interestingly, fullerene balls were found to be the best compatible material for optical characteristics and reorientation of LC molecules, while the carbon nanotubes experience some reorientation in LC media, and graphene layers are good barriers to preserve reorientation. For the improvement of photo-refractivity, dye[19], fullerene[20,21] and nanotubes were used as doping materials in various works.

Fullerene is well adopted to the above-mentioned doped LC objectives and there have been several reports on fruitful LC–fullerene combinations[22,23]. LC–fullerenes are generally prepared in C60 and C70 forms, and charge carriers arising by optical effects are of critical effect in various LC applications. In the same way, CNTs are another group of modern materials of research in physics, chemistry and materials science. They are in either single-walled or in multi-walled morphologies. Also, CNT-doped structures are of great interest due to their several practical and scientific applications[24,38]. Once the CNTs are produced, they are in the form of bundles and a medium is required for their conservation without bundling. Here the LC is used as a medium. An additional carbon-based material is the graphene sheet, which is considered as a promising candidate for various applications[18].

Ding *et al.*[39] studied the photorefractive effect in a CdS nanoparticle-sensitized polymer composite. This study confirmed that the CdS colloidal particles had a nanoscale size and quantum confinement effect, adopting transmission electron microscopy and UV–Vis absorption spectroscopy. Further, this study clarified that the addition of CdS nanoparticles as a photo-sensitizer in poly(N-vinylcarbazole) (PVK) significantly enhances the photoconductivity because of the high photocharge generation quantum efficiency and high charge transport to the conducting polymer.

Zhu *et al.*[36] studied the electro-optical properties of PDLC fabricated by doping Ag nanoparticles. They found that such novel material exhibits a unique electro-optical response characteristic that is sensitive to frequency modulation of the applied voltage. They observed that nano Ag-doped PDLCs demonstrate faster response time to burst square voltage waveforms than the undoped sample, and the deviation of the two rise times can be as high as 50%.

Similarly, the effect of SiO_2 nanoparticles on the electro-optical properties of PDLC films was reported by Li *et al.*[40]. In this work, PDLC films were prepared by UV light-induced polymerization of photopolymerizable monomers in nematic LC/monomers/SiO_2 nanoparticles composites. The observed results predicted that with the adjustment of the SiO_2 nanoparticles content, the refractive index ratio of the LC and polymer could be modulated, and the electro-optical properties of the polymer matrix/LC/SiO_2 nanoparticles composites can also be optimized. Further, this study suggested that the doping of SiO_2 nanoparticles composites is promising for LCD and other electro-optical applications.

Recently, by doping the gold nanoparticles (of 14 nm diameter) into PDLC films, a significant improvement in their electro-optical properties has been reported[41]. In this work, the addition of ~ 0.02 g Au NPs in concentration lowered the threshold voltage by almost 50% and increased the relative transmission with the applied field. This study suggests that surface plasmon excitations at metal/dielectric interfaces in the composite material may contribute to the build-up of local electric fields in PDLCs containing Au NPs.

Koenig *et al.*[42] reported that darkfield microscopy can be used to track the trajectories of chemically functionalized gold nanoparticles in nematic LCs, thus leading to measurements of the diffusion coefficients of the nanoparticles in the LCs. For this study gold nanoparticles with nominal diameters of 150 nm and 4-phenyl-4′-cyanobiphenyl (5 CB) as LC were used. Further, the spacing between the two glass slides was established using a 12 μm thick film of Mylar. The findings reveal that the diffusion coefficients of the nanoparticles dispersed in the LC are strongly dependent on the surface chemistry of the nanoparticles. The evaluated results provide insights into the effects of surface chemistry, defect structures, and local ordering of LCs on nanoparticle mobility in LCs that are of fundamental importance[42].

The same research group has studied the interactions of synthetic LCs and viruses supported on nanostructured surfaces[43]. The aim of the work was to understand how the structure of the virus impacts the orientational order within the contacting LC.

The phenomenon that doping of a nematic liquid crystal with nanoparticles made of gold or semiconductors (e.g. CdSe or CdTe) can fundamentally change its electro-optical properties has been observed and reported by Hegmann and co-workers[44–46]. They reported that in the samples where the molecules of the pure LC align parallel to the glass substrate due to a polyimide alignment layer the respective nanoparticle dispersions may show a homeotropic alignment[46]. When the voltage is applied to the sample, the dispersion behaves seemingly like a LC with negative dielectric anisotropy. Such a dispersion switches from homeotropic to non-homeotropic alignment; however, their experimental findings prove a positive dielectric anisotropy for the nanoparticle/LC dispersion[45]. They further extended this work by studying such unusual switching behaviour using the electro-optical characteristics[46]. Some valuable works in this category are reported in the literature[37,45,47–52].

Considering the advantageous features of nanoparticles, Yoshida *et al.*[53] proposed a simple and robust method that can drastically simplify the procedure to fabricate metal NP–LC suspensions. It was claimed that such suspensions can be fabricated by sputter depositing the target material on the host LC. In their work, gold nanoparticles were dispersed in the host LC known as 5CB or E47 (Merck). The results obtained from the study indicated that gold NPs are highly dispersed in the LC host and affected the microscopic orientation of the LC molecules, even though the NPs were not coated with stabilizers or capping agents. Further their proposed method was applied to other LC materials, which resulted in NPs with different diameters. Their findings provide a strong evidence that improved electro-optical properties can be expected in LC devices with NPs dispersed by the sputter doping method.

de Silva *et al.*[54] studied the influence of nanoparticle doping on the lyotropic liquid crystalline phase of the industrial surfactant Brij ®30 ($C_{12}E_4$) and water, that were doped with spherical polyoxymetalate nanoparticles and were of smaller size than the characteristic dimensions of the host lamellar phase. Their results predicted that the shear viscosity, yield stress and instantaneous elastic modulus of the lamellar phase systematically decreased with increasing POM nanoparticle doping fraction. Further from the X-ray data they concluded that the nanoparticles remained encapsulated within the multilamellar vesicles (MLV) membranes, which further clarified that this technique was cheaper for the encapsulation of metallic nanoparticles within surfactant vesicles.

Employing nanoparticles in the display industry, Fuh *et al.*[55] proposed a useful and simple technique for the dual LC alignment configuration which was based on the nanoparticle-doped polymer films, and its application in phase gratings and single-cell-gap transflective LCDs. POSS as nanoparticles were utilized for this approach, and the experimental findings indicated that the UV-cured, nanoparticle-doped polymer film can induce vertical alignment onto the substrate. This study proposed that such an approach is highly promising and can be employed in fabricating the colourless optical devices, including LC Fresnel lenses, viewing-angle-dependent LCDs, etc.

Woo[56] studied the effect of ferroelectric nanoparticles on the electro-optical characteristics of PDLC display. For this study, two types of nanoparticles, i.e. normal nanoparticles (melamine formaldehydes, Sb_2O_5 and TiO_3) and ferroelectric nanoparticles ($SrTiO_3$ and $BaTiO_3$) were studied. The results obtained suggested that the haze value largely increases at the off-state and CR decreases with the increase in ferroelectric nanoparticle inclusion. Further, the SEM images obtained verified the PDLC morphology, that the nanoparticles are embedded in the polymer matrix, which may further influence the alignment of LCs with voltage.

Applications of nanoparticle-doped PDLC display

Masutani *et al.*[57,58] studied nanoparticle-embedded polymer-dispersed LCs for paper-like reflective display. They mixed TL213 nematic liquid crystal and PN393 UV curable pre-polymer, adding small amounts of 8 μm spacer with powdered melamine formaldehyde nanoparticles, and sandwiched the solution between a hydrophilic glass substrate and anti-sticking substrate. The electro-optical properties of the transmittance cell for nanoparticles showed a reduction of on-state transmittance with increase in nanoparticle concentration because of the refractive index mismatch between the LC and nanoparticle. Furthermore, they measured reflectivity and contrast ratio dependency against the viewing angle, which were found to be smaller when the D-PDLC cells were doped with 5% nanoparticles, with incident light being 30°. A paper-like display was fabricated using nanoparticle-embedded D-PDLC frontplanes and 3.8′ diffuse reflector backplanes. The authors claimed that nanoparticles added a small diffusion to the on-state of the D-PDLC display, which reduced its metallic glare and its viewing angle dependency (Figure 5).

Figure 5. Nanoparticle-doped PDLC on 3.8 inch test panel with patterned ITO. A white paper is placed at the back of the panel with black laser-printer text for visual comparison. (Reproduced from Masutani *et al.*[57] with permission from Society for Information Display, USA.)

Further studies showed that fullerene-doped PDLC could also be applied in the LC display technique for recording holograms and for laser optical limiting (OL) devices. Holographic grating and OL have been reported in fullerene-introduced PDLCs based on polyimide 6B (PI6b), COANP and C60-N-(4-nitrophenyl)-(L)-prolinol (NPP) compounds in the nano-, pico- and femtosecond regions[59]. The results predict that fullerene-doped PDLC systems could be applied for OL at the incident laser density in the range 0.3–0.4 J cm^{-2}.

A study performed on the holographic diffraction grating properties of layered double hydroxides (LDHs)-dispersed methacrylate photo-induced polymer films is reported in ref. 60. Similarly, a work on the conventional H-PDLC has been performed[61]. Here, TiO_2 as a nanoparticle was doped to the H-PDLC film for the study of real-time grating formation, diffraction efficiency, and electro-optical properties of the film[61]. The results predicted that with the addition of TiO_2, the induction and polymerization period became longer compared to the TiO_2-free polymer. However, the doping of TiO_2 raised the formulation viscosity. Accordingly, it resulted in slow grating formation, low saturation diffraction efficiency, and large decay time of the film.

Summary and conclusion

The developments in nanostructured particles and nanocomposite materials have a large impact on LC and PDLC display research. The present study provides a technical overview of nanocomposite materials-doped PDLC display. Due to their improved characteristics such as contrast ratio, time response, memory effect and low driving voltage, nanomaterials-doped PDLCs predict better performance than the conventional PDLC materials. Therefore, in recent times, nanoparticle-doped PDLCs enjoy wide acceptance among the display community.

In this review, we have briefly described some of the previous studies, which provided different types of nanoparticles with advantages therein to prepare the nanostructured particles doped into PDLC films. Various results obtained by adopting several types of nanoparticles doped in PDLCs have been also discussed. Further, a detailed analysis and summary have been carried out on the latest research advancement made in the development of nanostructured particles and nanocomposite-based PDLC display. This study also demonstrates some useful applications of such nanoparticle-doped PDLCs, e.g. the role of nanostructured particles in the emerging field of E-paper fabrication technology and nanoparticle-doped H-PDLC grating.

As the nanostructure-based PDLC films became more demanding and complex, more scientific methods for the fabrication of nanostructured PDLC materials will be required. These techniques along with new nanotechnological approaches could be utilized in LC and PDLC displays, and their applications in display research. Increasing interest in the field of nanotechnology, especially in the nanoparticle composites has led to the rapid development of low driving voltage PDLCs with improved processability, contrast ratio and functionality. Several studies related to nanostructure-based PDLC display are in progress.

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ACKNOWLEDGEMENTS. We thank the respective publishers/authors for permission to reproduce Figures 2–5 and Table 2 taken from Elsevier Science Ltd, The Netherlands, and American Institute of Physics, and Society for Information Display, USA.

Received 24 May 2011; revised accepted 21 November 2011