



## MINI REVIEW

### Enhancing Liquid Crystal Properties through Nanoparticle Doping: A Mini Review

BHASKAR KASHYAP<sup>1</sup>, AYUSHI SAINI<sup>1</sup> and ARSHI RASTOGI<sup>\*1</sup>

Department of Chemistry, K.L.D.A.V. (P.G.) College, Roorkee-247667, India

\*Corresponding author: E-mail: arshirastogi@gmail.com

Received: 14 December 2023;

Accepted: 10 January 2024;

Published online: 28 February 2024;

AJC-21544

Liquid crystals doped with nanoscale particles have recently acquired popularity, improving their capabilities and applications. The impact of doping metallic and metal-oxide nanoparticles as well as other nanoparticles in liquid crystals is presented in this brief review. Silver nanoparticles (Ag NPs) have an effect on phase transitions, molecular alignment and electrical properties such as threshold voltage and response time. The optical tilt and electro-optical characteristics of gold nanoparticles (Au NPs) are improved. Metal-oxide nanoparticles such as MgO, ZnO, Al<sub>2</sub>O<sub>3</sub>, CuO and SiO<sub>2</sub> enhance dielectric properties, mitigate screening effects, increase birefringence, and reduce light leakage. Doping carbon nanotubes (CNTs) influences impedance, optical transmittance and electro-optical properties. The review aims to study the effects of nanoparticle doping on liquid crystal features such as phase transitions, molecular alignment, electrical and optical properties, dielectric behavior, and impedance. A better understanding of these modifications can lead to more applications for liquid crystal in areas such as sensors, displays, optoelectronics, and photovoltaics.

**Keywords:** Liquid crystals, Nanoparticles doping, Silver nanoparticles, Gold-nanoparticles, Metal-oxide nanoparticles.

## INTRODUCTION

Since their discovery in 1888, liquid crystals (LCs) have continuously captivated researchers due to their unique electro-optical properties, which play a crucial role in various optical and photonic applications such as liquid crystal displays, attenuators, tunable polarizers, spatial light modulators and photonic sensors [1]. Various types of smart windows, including electrochromic, photochromic, thermochromic, suspended particle and liquid crystal (LC) devices, have been documented for their ability to regulate the transmission of sunlight and solar heat [2,3]. A series of transitions between a disorganized liquid and a well-defined crystalline solid is possible. Plastic crystals, polymers and liquid crystals are among these transitional phases. When the temperature of a solid sample is elevated to 145.5 °C, it undergoes a change into a hazy liquid state, whereas at 178.5 °C, the substance transforms into a translucent liquid as the temperature rises. The turbid liquid changes colour, going from red to vivid blue-violet to pale blue.

Lehmann created the name liquid crystal in 1900 after earlier referring to them as “flowering crystals” in 1889 and

“crystalline solids” in 1890 [4]. Liquid crystal is so termed because it has features that are common to both solids and liquids. It has dielectric, electrical and optical anisotropy (direction dependency) like crystalline solids, but also fluidity and molecular mobility like isotropic liquids. Based on these findings, researchers are combining liquid crystals with nanotechnology to develop a new technology. Due to their unique scientific features and numerous uses, liquid crystals containing nanoscale particles have garnered attention in recent decades.

Recent studies have revealed that combining nanomaterials with liquid crystals has increased application and benefits beyond what each sector offers alone. This fascinating breakthrough has improved modern optoelectronic devices, products and technologies [5]. This study investigates the impact that doping liquid crystals with nanoparticles of metal and metal oxide has on the properties of the liquid crystals. Silver nanoparticles doped in liquid crystals are attractive because of their conductivity, chemical stability and nanoscale properties. They affect phase transitions, molecular alignment and electrical properties such as threshold voltage and turn-on/off timings [6,7]. Similarly, doping of gold nanoparticles (Au NPs) have

been widely studied in liquid crystals as the optical tilt and electrooptical properties has been enhanced. Moreover, gold nanoparticles can improve material alignment, light leakage and liquid crystal threshold voltage [8].

Metal-oxide nanoparticles, such as MgO, ZnO, Al<sub>2</sub>O<sub>3</sub>, CuO and SiO<sub>2</sub>, have a significant impact on the electro-optical and dielectric properties of liquid crystals. These nanoparticles improve the dielectric constant, screening effect, birefringence and light leakage in liquid crystals [9,10]. Carbon nanotube (CNT) doped in liquid crystals impact impedance, optical transmittance and electro-optical characteristics. CNT alignment and disentanglement in liquid crystals increases their mechanical [11], electrical [12-14] and optical properties [15]. Doping liquid crystals with QDs, particularly cadmium selenide (CdSe) and cadmium telluride (CdTe) QDs enhances the dielectric anisotropy [16], threshold voltage and switching time [17]. Thus, doping liquid crystals and investigating their effects will develop the field and improve its application in sensors, optoelectronics, photovoltaics and displays.

The objective of this review is to examine the effects of introducing metallic nanoparticles (*e.g.* silver and gold), metal-oxide nanoparticles and other nanoparticles into liquid crystals. Moreover, the impact of nano-particle doping on many aspects of liquid crystals, including phase transitions, molecular alignment, electrical characteristics, optical properties, dielectric properties and impedance were also studied.

### Doping of various nanoparticles in liquid crystals

**Doping of Ag NPs in liquid crystals:** Silver nanoparticles are popular and extensively utilized metallic nanoparticles due to their conductivity, chemical stability, strong calorimetric effects at the nanoscale and applications in medicine [18,19]. Vimal *et al.* [6] reported that adding silver nanoparticles to pure ferroelectric liquid crystal had a significant impact on phase transitions, molecular alignment and several other aspects of liquid crystal behaviour. Singh *et al.* [7] doped Ag NPs in a nematic liquid crystal and found that an increase in temperature occurred during the transition from the nematic to isotropic phase, which also decreases the threshold voltage required for this transformation. Yan *et al.* [20] prepared the polymer stabilized liquid crystal (PSLC) devices supplemented with surfactant sodium dodecyl sulfate (SDS) and found that Ag NPs with a size range of 15-20 nm. According to the experimental findings,  $V_{10}$  (voltage for 10%) and  $V_{90}$  (voltage for 90%) significantly decrease in the presence of Ag NPs at a concentration of 0.05 wt.% compared to the PSLC devices without doping. The results are specifically lower than the undoped device. In addition, the PSLC device with 0.05 wt.% Ag NPs doping, has a surprisingly quick turn-on time of just 2 min, which is only 10% as quick as the turn on time observed in the undoped device. Also, the PSLC device turn-off time is reduced by 32% with 0.05 wt.% Ag NPs doping. Significantly, the inclusion of Ag NPs has little effect on the frequency response of PSLC device. All of the current findings suggested that Ag NPs doping can increase the electro-optical performance of PSLC devices, which will widen their applicability, particularly when rapid switching devices like adaptive optics components are considered. An

alteration in photoluminescence was observed after doping with Ag NPs as reported by Katiyar *et al.* [21], which indicated that the intensity of photoluminescence varied between composites and pure *n*-octyloxycyanobiphenyl. However, the addition of silver nanoparticles leads to a reduction in the photoluminescence intensity of pure liquid crystal. This quenching of luminescence in the composites is directly influenced by the quantity of silver nanoparticles present.

**Doping of Au NPs in liquid crystals:** Researchers have consistently paid close attention to gold nanoparticles because of their fascinating properties, which include the behaviour of individual particles, size-dependent electronic, magnetic and optical properties (quantum size effect), and their numerous applications in biology and catalysis [22]. As a result, several techniques have been used to create such nanoparticles.

The optical and electro-optical properties of FLC mixture doped with gold nanoparticles, have been studied by Kaur *et al.* [8]. Surprisingly, when the FLC mixture was doped with gold nanoparticles, the optical tilt noticeably increases by five times. This enhancement is still feasible with a very low applied voltage of just 0.1 V. Another most common properties are thermo- and electro-optical property of PLCFs (photonic liquid crystal fibre) doped with Au NPs, which are studied by Siarkowska *et al.* [1]. The effect of the dopant on the characteristics of the PCLF was directly evaluated using four different concentrations of gold nanoparticles (0.1, 0.3, 0.5 and 1.0 wt.%). The experiment conducted in the presence of an external electric field confirm that Au NPs lower the switching time as well as the threshold voltage in PLCFs. Both doped and undoped liquid crystals (LCs) were subjected to the measurement of birefringence and the findings showed a high degree of conformity with numerical calculations [23].

**Doping of metal-oxides nanoparticles in liquid crystals:** The incorporation of metal oxide nanoparticles into liquid crystals has gained significant interest in study due to the multiple improvements that are induced in their properties. The conductivity of metal-oxides nanoparticles varies due to their different oxidation states and the presence of lattice defects.

**Doping of magnesium oxide nanoparticles (MgO NPs):** A variety of advantageous qualities are exhibited by magnesium oxide, also known as magnesia, an alkaline earth metal oxide with oxygen vacancies on its surfaces and edges. The ability of these vacancies to enhance charge transfer between the substrate and adsorbate enhances the catalytic activity of material [24]. It has been reported that the use of MgO NPs as a doping agent can improve the electro-optical properties of ferroelectric liquid crystals (FLCs) [25]. MgO NPs were doped at various concentrations and the results showed a noticeable improvement. A reduction in reaction time, an increase in elastic constant values, a decrease in polarization, and an improvement in performance were some of the modifications that have been accomplished [25].

**Doping of zinc oxide nanoparticles (ZnO NPs):** Both piezoelectric and semiconducting properties are exhibited by ZnO nanoparticles, moreover being non-toxic, they are powerful oxidizers. Such materials are diversely utilized in nano generators, optoelectronics, electronics, gas, chemical and

biological sensors. Additionally, they find applications in cancer detecting biosensors, ultrasensitive DNA sequence detectors, drug administration systems, biomedical imaging, high-efficiency solar cells, field emitters and UV photodetectors [26,27]. The alignment of the material to a nearly defect-free state was enhanced by adding 1% by weight of ZnO NPs to ferroelectric liquid crystal cells, which also results in the enhancement of the optical contrast and reduced light leakage centers [9]. Chen *et al.* [10] found that ZnO NPs in nematic liquid crystals (NLCs) reduced the screening effect, it happens when electric fields are insulated by decreasing transient current. This decreased ion density suppressed the undesirable field-screening effect and thereby lowering the threshold voltage ( $V_{th}$ ).

#### **Doping of aluminium oxide nanoparticles (AlO NPs):**

Aluminium nanoparticles exhibit exceptional sensitivity, quick responsive to changes in humidity, swift recovery, remarkable dielectric properties and high thermal, mechanical and chemical stability. Aluminium nanoparticles find applications in the improvement of catalysts, powering small devices, enhancing the structural materials for aerospace, automotive and petroleum sectors as well as facilitating rapid optical sensing and switching technologies. Doping AlO NPs mitigates the influence of ions in ferroelectric liquid crystals (FLCs), which inherently exhibit favourable characteristics such as high optical contrast, a low threshold voltage ( $V_{th}$ ), memory retention capability and rapid responsiveness [28]. The process of adsorption effectively eliminates ionic impurities from the FLC/AlO NPs system. Examination of FLCs containing AlO NPs revealed that the unwanted ionic contaminate within the FLCs were effectively sequestered by the defect sites on AlO NPs surface. The incorporation of AlO NPs into KCFLC7S (a ferroelectric nematic liquid crystal) and KCFLC 10S materials caused a discernible change in the dielectric loss profiles and resistance/conductivity investigations, demonstrating a significant reduction in the presence of ionic contaminants. The absence of dielectric loss factor ( $\tan \delta$ ) fluctuations proved that the ferroelectric liquid crystal (FLC) sample was free of ionic contaminants. Furthermore, the lack of ionic influence in the KCFLC 7S material was demonstrated by contrasting the pure FLC material with the doped FLC material, as evidenced by higher electrical resistance values observed across different temperatures.

**Doping of copper oxide nanoparticles (CuO NPs):** Mishra & Gupta [29] altered the electrical, scattering of light, optical, photo-voltaic and magnetic characteristics of polymer-dispersed liquid crystal (PDLC) system by introducing copper oxide nanoparticles (CuO NPs). At different temperatures, the dielectric characteristics of PDLCs doped with CuO NPs reveal a considerable frequency dependency ( $f < 102$  Hz), with a noticeable and quick rise in the dielectric constant of sample. This result shows that the inclusion of CuO NPs into PDLC material improves its performance in electrical and electronic devices.

**Doping of silicon dioxide nanoparticles (SiO<sub>2</sub> NPs):** SiO<sub>2</sub> nanoparticles exhibit favourable qualities such as biocompatibility, minimal toxicity, thermal resilience, crystalline structure, porous nature, chemical inertness and optical clarity [30,31]. These nanoparticles are also used as catalysts and in the fields of electronics, sensor technologies and energy production.

Dolgov & Yaroshchuk [32] studied NLC E7 injected with two different SiO<sub>2</sub> NPs. So, when these with identical mass, shape and material were introduced into the host NLC, they exhibit varying electro-optical properties depending on their manufacturing process. Researchers used the composites LCA and LC-monodisperse nanoparticles (LCMNP) to distinguish them. When compared to the proportion of monodisperse nanoparticles (MNPs) in the LC-MNP suspension, the LCA suspension exhibited its highest memory efficiency at a significantly reduced wt.% of Comp-A. Unlike the wt.% of MNPs in the LC-MNP suspension, the LCA suspension showed its highest memory efficiency at a considerably lower wt.% of Comp-A. The adverse consequences of magnetic nanoparticle (MNP) doping, which included the creation of SiO<sub>2</sub> micro crystallites and a deterioration in the sample's electro-optic performance, were considerably exacerbated by the combination of these two processes. However, by adding a network of polymers to magnetic nanoparticle liquid-crystals (LC-MNP) suspensions, these drawbacks were lessened.

Chaudhary *et al.* [33] presented the electro-optic and dielectric properties of SiO<sub>2</sub> nanoparticles introduced into a ferroelectric liquid crystal (FLC) in the smectic phase. They observed that the switching time, spontaneous polarization and rotational viscosity all decrease as silica concentration increases, moreover, a reduction in changeover time was also observed. The enhanced anchoring energy between the SiO<sub>2</sub> nanoparticles and the FLC was responsible for these changes in many metrics [34]. Furthermore, there was a direct correlation between the temperature and the relaxation frequency, as well as the concentration of SiO<sub>2</sub> nanoparticles in the smectic phase. However, as the temperature approached the critical point, the relaxation frequency decreased.

#### **Doping of carbon-nanotubes (CNTs) in liquid crystals:**

Due to their cylindrical tube shape, carbon nanotubes, a kind of carbon derivative, possess the most efficient electric-conductive property. The tubular design facilitates unrestricted movement of electrons or radiation within the tubes. The random orientation and entanglement of CNTs reduces their anisotropic properties. Garcia *et al.* [12] incorporated high aspect ratio multi-walled carbon nanotubes to liquid crystals in an experiment. They investigated the characteristic impedance of doped liquid crystals at different frequencies and excitation voltages. The magnitude of impedance reduces as the voltage applied to the doped liquid crystal cell increases. Furthermore, the frequency range where resistor behaviour becomes dominant widens. When influenced by any disturbance, the reorientation of the director in nematic liquid crystal causes a considerable change in the transmission of light through the material. The variation in optical transmittance (denoted as  $T_0-T$ , where  $T_0$  represents the transmittance of an undisturbed liquid crystal cell and  $T$  represents the transmittance of an LC/CNT suspension) is currently established to indicate the degree of alignment of CNTs within the liquid crystal. A distinct, gradual shift in optical transmittance is found at the transition from the nematic to the isotropic phase [13,14]. In the nematic phase, the difference between  $T_0$  and  $T$  values is substantial, indicating a high transmittance, but it is significantly lower in the isotropic phase.



This result clearly shows a structured and organized arrangement of CNTs within the nematic phase of suspension.

Yadav *et al.* [35] investigated the doping of carbon nanotubes in liquid crystals (LCs) using optical characteristics with the goal of using them in optical devices. They evaluated the photoluminescence of NLC-CNT composites as well as pure NLC at wavelength of 385 nm. These spectra consist the maximum at 422 nm, but the photoluminescence intensity of pure NLC is very much lower than the CNTs doped mixer NLCs. Huang *et al.* [36] reported the electro-optical properties of the CNT-doped liquid crystals. The dielectric anisotropy and viscosity of the LC-CNT combination change, when anisotropic carbon nano solids are added. Thus, it affects the switching and threshold voltage of a liquid crystal device. However, as the LC-CNT mixture viscosity and absolute dielectric anisotropy grow, the threshold voltage, fall time and delay time increase. The threshold voltage drops significantly in positive nematic host samples due to enhanced absolute dielectric anisotropy. The rise, fall and delay times increase as the concentration of doped carbon nanotubes (CNTs) in these samples increases due to the increased viscosity of LC-CNT mixture.

Lee *et al.* [15] examined the electro-optical (EO) characteristics of 90° twisted nanotubes-LC cells under DC voltage. The investigation of 90° TN-LC cells doped with CNTs, alongside neat and C60-doped counterparts, revealed enhanced electro-optic performance when subjected to a biased dc voltage. The incorporation of CNTs had a positive influence on TN-LC cells, indicating their potential as substitutes for traditional materials in the development of liquid crystal photonic devices. Notably, there were no significant drawbacks observed in the introduction of CNTs into liquid crystal hosts with a standard LCD cell gap. The study also underscored the diminished degradation in 6 μm thick cells compared to 25 μm thick films, emphasizing the potential stability of CNT-doped TN-LC cells in practical LCD configurations. These findings contribute to the progression of electro-optic capabilities in liquid crystal devices, paving the way for future technological advancements. Veverick *et al.* [11] examined the effects of (multiwall carbon nanotubes) MWCNT or MWCNT/Fe<sub>3</sub>O<sub>4</sub> doping in a nematic liquid crystal. Doping caused a strong link between the electric and magnetic moments of CNTs and the director's liquid crystal molecules. In 6CHBT, (4-(4-hexylcyclohexyl)isothiocyanatobenzene) liquid crystal doped with CNTs, the magnetic moments of the nanotubes aligned parallel to the molecules. However, the strength of external magnetic and electric fields affected the liquid crystal director's orientation away from the carbon nanotubes. Thus, a combination of electric and magnetic fields might alter the orientation of liquid crystal molecules in doped samples, which is not possible in pure liquid crystals. Doping also affected liquid crystal magneto-optical characteristics. These findings could be used as nano-sensors or magneto-optical devices in electronic systems in the transport industry.

**Doping of quantum dots in liquid crystals:** Quantum dots (QDs) have distinct properties, such as their ability to be processed in solution, the capacity to modify band gaps and quantum confinement, which make them well-suited for various

applications such as lasers, photovoltaics, solar cells and optoelectronics [37]. Cadmium selenide (CdSe) and cadmium telluride (CdTe) quantum dots due to their uniformity and size dependent photoluminescence resulting from the quantum confinement effect, have been used in conjunction with the nanocomposites of nematic liquid crystals (NLCs) [16]. One potential approach to precisely control the arrangement of quantum dots within the nematic liquid crystal matrix is to introduce QDs doping in such NLC. Kumar *et al.* [17] found that 5PCH (*trans*-4-pentyl-alkyl(4'-cyanophenyl)hexane) liquid crystal and CdSe nanoparticles aligned well upto 2 wt.%. The 5PCH CdSe nanocomposites have a lower alignment threshold voltage than pure 5PCH. Additionally, the dielectric anisotropy of NLC was increased by CdSe quantum dots, which resulted in an improvement in the electrical responsiveness of material. CdSe quantum dots did not significantly lower the nematic-isotropic (NI) transition temperature, which indicates a phase change in the liquid crystal. Quantum dots align with the average direction of NLC molecules in CdSe QD-NLC nanocomposite systems with improved dielectric anisotropy. This alignment shows a QD-NLC interaction that could improve the orientation order of nanocomposite and found that addition of CdSe QDs to NLC at the surface improves orientation order. These CdSe QD-NLC nanocomposite systems can help design new LC-based optoelectronic devices.

In another study on nematic LC-QD composites, the optical and electro-optics studies showed that the alignment and electro-optical properties of LC-QD mixtures depend on size, capping agent and CdSe content [38]. Polarized optical microscopy (POM) revealed that different QD concentrations in Felix-2900-03 oriented N-LC molecules in distinct ways. In Felix-2900-03, a 2 wt.% CdSe QDs combination promoted a vertically oriented (homeotropic) alignment of N-LC molecules, resulting in the well-known birefringent stripe patterns between plain glass slides and planar electro-optic cells. In planar cells and plain glass slides, doping samples with 1% CdSe generated homeotropic alignment. These QDs aggregated on surfaces and in bulk over 1 wt.%, leading to the induced homeotropic alignment. The V<sub>th</sub> (threshold voltage) and K11 (elastic constant) were lowered in all LC-QD composites.

Kumar & Sagar [39] investigated the effect of varying concentrations of CdSe quantum dots with sizes of 2.3 and 3.5 nm that were capped with a mixed-monolayer of trioctylphosphine (TOP) and octadecyl amine [40] on the liquid crystal phase behaviour of a triphenylene derivative (H<sub>4</sub>TP). Quantum dots exhibit quantum confinement phenomena and have a configurable bandgap due to their nanoscale dimensions, allowing precise absorption of certain light wavelengths for efficient solar energy capture. Their high absorption coefficient allows them to catch significant solar energy even in thin layers. numerous exciton generation (MEG) increases solar performance even more by creating numerous electron-hole pairs from a single photon. Furthermore, the solution processability of quantum dots makes them compatible with low-cost large-scale manufacturing methods such as inkjet printing, enabling the manufacture of flexible and lightweight solar cells with a wide range of practical applications.

Praseetha *et al.* [41] studied the non-linear optical (NLO) properties of two liquid crystal materials in their native liquid crystal state and after doping with quantum dot particles. ZnS quantum dots with an average size ranging from 2 to 5 nm was employed as a dopant and it was prepared using a chemical co-precipitation process. The dopant was then characterized in terms of linear optical and microstructural properties. The study found that when both liquid crystal materials were doped with ZnS quantum dots, their NLO behaviour improved. This enhancement can be attributed to the combined effects of excited state absorption (ESA), two-photon absorption (TPA) and the molecular director's collective reorientation. The samples exhibited a self-defocusing effect during the examination of non-linear refraction (NLR). The Janosky effect as well as some form of charge transfer between the guest and host molecules, can be linked to the rise in NLR observed in the doped system. The researchers also investigated the optical limiting features of the LC-QD devices and determined that the optical power limiting effect was caused by the doped system's improved NLO properties. The optical limiting threshold for the 5PCH-ZnS system was suggested to be 1.99 J/cm<sup>2</sup> and 3.043 J/cm<sup>2</sup> for the 5CB-ZnS system, respectively. These results showed that the doped systems outperform a wide range of other optical materials that are routinely employed as effective optical limiters.

The observed improvement in the NLO and optical limiting capabilities of the examined system illustrates its potential as a useful tool for optical power limiting in nano photonics and optoelectronics applications.

Kumar *et al.* [42] discovered an increase in the intensity of photoluminescence (PL) and a shift in the spectral energy band of ferroelectric liquid crystal (FLC) when it was doped with ZnS quantum dots in their investigation. The source of this phenomena has been traced to changes in the refractive index of FLC molecules produced by variable quantum dot concentrations. These findings point to a possible path forward in the development of adaptive optoelectronic devices capable of producing emission colours that can be modified or changed. In summary, the effects on the properties of liquid crystals that are caused by the deposition of different types of nanoparticles are summarized in Table-1.

### Conclusions

The doping of metallic and metal-oxide nanoparticles in liquid crystals has demonstrated considerable influence on the characteristics and behaviour of the liquid crystal materials. It has been discovered that doping silver nanoparticles in liquid crystals affects phase transitions, molecular alignment and electrical properties such as threshold voltage and turn-on/off

TABLE-1  
THE EFFECTS ON LIQUID CRYSTAL PROPERTIES THROUGH VARIOUS TYPES OF NANOPARTICLES DOPING

Nanoparticle type	Effects on liquid crystals	Ref.
Silver nanoparticle	<ol style="list-style-type: none"> <li>1. Impact on phase transitions and molecular alignment</li> <li>2. Increase in temperature for phase transition</li> <li>3. Decrease in threshold voltage for phase transition</li> <li>4. Decrease in turn-on time and turn-off time</li> <li>5. Little effect on frequency response</li> </ol>	[6,7,18-21]
Gold nanoparticle	<ol style="list-style-type: none"> <li>1. Increase in optical tilt</li> <li>2. Enhancement of electro-optical properties</li> <li>3. Improvement in material alignment and optical contrast</li> <li>4. Reduction in threshold voltage</li> </ol>	[8,22,23]
Magnesium oxide	<ol style="list-style-type: none"> <li>1. Improvement in electro-optical characteristics</li> <li>2. Reduction in reaction time, increase in elastic constant values</li> <li>3. Drop in polarization, improvement in performance</li> <li>4. Alteration of dielectric properties</li> </ol>	[24,25]
Zinc oxide	<ol style="list-style-type: none"> <li>1. Improvement in material alignment and reduction in light leakage</li> <li>2. Decrease in threshold voltage and screening effect</li> <li>3. Impact on birefringence</li> </ol>	[9,10,26,27]
Aluminium oxide	<ol style="list-style-type: none"> <li>1. Reduction of ionic effects and improvement in electrical resistance</li> <li>2. Absorption of ionic impurities</li> <li>3. Influence on dielectric loss spectra and resistivity/conductivity Influence on electro-optical characteristics</li> </ol>	[28]
Copper oxide	<ol style="list-style-type: none"> <li>1. Modification of electrical, light scattering and optical properties</li> <li>2. Increase in dielectric constant and improvement in performance</li> </ol>	[29]
Silicon dioxide	<ol style="list-style-type: none"> <li>1. Different electro-optical characteristics based on creation process</li> <li>2. Change in switching time, polarization and dielectric constant</li> <li>3. Variation in relaxation frequency</li> </ol>	[21,32-34,36]
Carbon nanotubes	<ol style="list-style-type: none"> <li>1. Change in impedance at different frequencies and voltage</li> <li>2. Alignment and disentanglement affect mechanical</li> <li>3. Variation in photo-luminescence intensity</li> <li>4. Impact on switching and threshold voltage</li> <li>5. Suppression of back-flow effect and increase in fall time</li> <li>6. Increase in rise, fall and delay time</li> </ol>	[11-15,35,36]
Quantum dots	<ol style="list-style-type: none"> <li>1. Enhance the dielectric Anisotropy</li> <li>2. Altered threshold voltage and Elastic constant value</li> <li>3. Exhibits shorter switching period</li> </ol>	[16,17,37-42]

times. Doping with gold nanoparticles improved optical tilt and electro-optical properties in a variety of liquid crystal combinations. Doping metal-oxide nanoparticles in liquid crystals with magnesium oxide (MgO), zinc oxide (ZnO), copper oxide (CuO), aluminium oxide (Al<sub>2</sub>O<sub>3</sub>) and silicon dioxide (SiO<sub>2</sub>) has improved the electro-optical properties, dielectric properties and reduced undesirable effects such as screening and light leakage. Doping liquid crystals with carbon nanotubes has resulted in changes in impedance, optical transmittance and better electro-optical characteristics. Overall, nanoparticle doping in liquid crystals offers a promising route for modifying and increasing the properties of liquid crystal materials for a variety of applications including optoelectronics, sensors, photovoltaics and displays. Further investigation of various nanoparticle doping tactics and their impact on liquid crystal behaviour will help to advance the subject and broaden the range of potential applications.

#### CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

#### REFERENCES

1. A. Siarkowska, M. Chychlowski, D. Budaszewski, B. Jankiewicz, B. Bartoszewicz and T.R. Wolinski, *Beilstein J. Nanotechnol.*, **8**, 2790 (2017); <https://doi.org/10.3762/bjnano.8.278>
2. C. Granqvist, *Solar Energy Mater. Solar Cells*, **99**, 1 (2012); <https://doi.org/10.1016/j.solmat.2011.08.021>
3. X. Xia, Z. Ku, D. Zhou, Y. Zhong, Y. Zhang, Y. Wang, M.J. Huang, J. Tu and H.J. Fan, *Mater. Horizons*, **3**, 588 (2016); <https://doi.org/10.1039/C6MH00159A>
4. H. Kelker, *Mol. Cryst. Liq. Cryst.*, **21**, 1 (1973); <https://doi.org/10.1080/15421407308083312>
5. J. Prakash, S. Khan, S. Chauhan and A.M. Biradar, *J. Mol. Liq.*, **297**, 112052 (2020); <https://doi.org/10.1016/j.molliq.2019.112052>
6. T. Vimal, S.K. Gupta, R. Katiyar, A. Srivasrava, M. Czerwinski, K. Krup, S. Kumar and R. Manohar, *J. Appl. Phys.*, **122**, 114102 (2017); <https://doi.org/10.1063/1.5003247>
7. U.B. Singh, R. Dhar, R. Dabrowski and M.B. Panday, *Liq. Cryst.*, **40**, 774 (2013); <https://doi.org/10.1080/02678292.2013.783136>
8. S. Kaur, S. Singh and A. Biradar, *Appl. Phys. Lett.*, **91**, 023120 (2007); <https://doi.org/10.1063/1.2756136>
9. T. Joshi, A. Kumar, J. Prakash and A.M. Biradar, *Appl. Phys. Lett.*, **96**, 253109 (2010); <https://doi.org/10.1063/1.3455325>
10. W. Chen, P. Chen and C. Chao, *Mol. Cryst. Liq. Cryst.*, **507**, 253 (2009); <https://doi.org/10.1080/15421400903053602>
11. M. Veveriřik, P. Bury, P. Kopěanský, M. Timko and Z. Mitróová, *Procedia Eng.*, **192**, 935 (2017); <https://doi.org/10.1016/j.proeng.2017.06.161>
12. A. García-García, R. Vergaz, J.F. Algorri, X. Quintana and J.M. Otón, *Beilstein J. Nanotechnol.*, **6**, 396 (2015); <https://doi.org/10.3762/bjnano.6.39>
13. G.S. Chilaya and L.N. Lisetski, *Mol. Cryst. Liq. Cryst.*, **140**, 243 (1986); <https://doi.org/10.1080/00268948608080157>
14. N. Lebovka, T. Dadakova, L. Lysetski, O. Melezhyk, G. Puchkovska, T. Gavrilko, J. Baran and M. Drozd, *J. Mol. Struct.*, **887**, 135 (2008); <https://doi.org/10.1016/j.molstruc.2007.12.038>
15. S.Y. Jeon, S.H. Shin, S.J. Jeong, S.H. Lee, S.H. Jeong, Y.H. Lee, H.C. Choi and K.J. Kim, *Appl. Phys. Lett.*, **90**, 121901 (2007); <http://dx.doi.org/10.1063/1.2714311>
16. B. Kinkead and T. Hegmann, *J. Mater. Chem.*, **20**, 448 (2010); <https://doi.org/10.1039/B911641A>
17. J. Kumar, R.K. Gupta, S. Kumar and V. Manjuladevi, *Macromol. Symp.*, **357**, 47 (2015); <https://doi.org/10.1002/masy.201400185>
18. R.M. Crooks, M. Zhao, L. Sun, V. Chechik and L.K. Yeung, *Acc. Chem. Res.*, **34**, 181 (2001); <https://doi.org/10.1021/ar000110a>
19. C.L. Haynes, A.D. McFarland, L. Zhao, R.P.V. Duyne, G.C. Schatz, L. Gunnarsson, J. Prikulis, B. Kasemo and M. Käll, *J. Phys. Chem. B*, **107**, 7337 (2003); <https://doi.org/10.1021/jp034234r>
20. X. Yan, Y. Zhou, W. Liu, S. Liu, X. Hu, W. Zhou and D. Yuan, *Liq. Cryst.*, **47**, 1131 (2020); <https://doi.org/10.1080/02678292.2019.1641754>
21. R. Katiyar, K. Agrahari, G. Pathak, T. Vimal, G. Yadav, K.K. Panday, A.K. Mishra, A. Srivastava and R. Manohar, *J. Theor. Appl. Phys.*, **14**, 237 (2020); <https://doi.org/10.1007/s40094-020-00374-5>
22. L. Dykman and N. Khlebtov, *Chem. Soc. Rev.*, **41**, 2256 (2012); <https://doi.org/10.1039/c1cs15166e>
23. P. Lesiak, D. Budaszewski, K. Bednarska, M. Wójcik, P. Sobotka, M. Chychlowski and T.R. Wolinski, *Proc. SPIE Non. Opt. Appl. X*, **10228**, 102280N (2017); <https://doi.org/10.1117/12.2263978>
24. J.A. Rodríguez and M. Fernández-García, *Synthesis, Properties and Application of Oxide Nanomaterials*, Wiley-Interscience, A John Wiley & Sons Inc. (2007).
25. A. Chandran, J. Prakash, K.K. Naik, A.K. Srivastava, R. Darbowski, M. Czerwinski and A.M. Biradar *J. Mater. Chem. C*, **2**, 1844 (2014); <https://doi.org/10.1039/C3TC32017K>
26. Q. Zhang, C. Xie, S. Zhang, A. Wang, B. Zhu, L. Wang and Z. Yang, *Sens. Actuators B: Chem.*, **110**, 370 (2005); <https://doi.org/10.1016/j.snb.2005.02.017>
27. H.J. Zhang and H.M. Xiong, *Curr. Mol. Imaging*, **2**, 177 (2013); <https://doi.org/10.2174/22115552113029990012>
28. T. Joshi, J. Prakash, A. Kumar, J. Gangwar, A.K. Srivastava, S. Singh and A.M. Biradar, *J. Phys. D: Appl. Phys.*, **44**, 315404 (2011); <https://doi.org/10.1088/0022-3727/44/31/315404>
29. K.G. Mishra and S.J. Gupta, *Adv. Appl. Sci. Res.*, **2**, 212 (2011).
30. D. Sriamulu, E.L. Reed, M. Annamalai, T.V. Venkatesan and S. Valiyaveetil, *Sci. Rep.*, **6**, 35993 (2016); <https://doi.org/10.1038/srep35993>
31. T. Yu, K. Greish, L.D. McGill, A. Ray and H. Ghandehari, *ACS Nano*, **6**, 2289 (2012); <https://doi.org/10.1021/nn2043803>
32. L.O. Dolgov and O.V. Yaroshchuk, *Colloid Polym. Sci.*, **282**, 1403 (2004); <https://doi.org/10.1007/s00396-004-1151-y>
33. A. Chaudhary, P. Malik, R. Mehra and K.K. Raina *Phase Transitions* **85**, 244 (2012); <https://doi.org/10.1080/01411594.2011.624274>
34. G.C. Yang, S.J. Zhang, L.J. Han and R.H. Guan, *Liq. Cryst.*, **31**, 1093 (2014); <https://doi.org/10.1080/02678290410001712541>
35. G. Yadav, K. Agrahari and R. Manohar, *J. Dispers. Sci. Technol.*, **42**, 707 (2021); <https://doi.org/10.1080/01932691.2019.1710184>
36. C.Y. Huang, H.U. Chao-Yuan, H.C. Pan and K.Y. Lo *Japanese J. Appl. Phys.*, **44**, 8077 (2005); <https://doi.org/10.1143/JJAP.44.8077>
37. S.K. Nayak, M. Amels-Cortes, M.M. Neidhardt, S. Beardsworth, J. Kirrese, M. Mansueto, S. Cordier, S. Laschat and Y. Molard, *Chem. Commun.*, **52**, 3127 (2016); <https://doi.org/10.1039/C5CC09110A>
38. J. Mirzari, R. Sawatzky, A. Sharma, M. Urbanski, K. Yu, H-S. Kitzerow and T. Hegmann, *Emerging Liq. Cryst. Technol. VII*, **8279**, 827913 (2012); <https://doi.org/10.1117/12.909022>
39. S. Kumar and L.K. Sagar, *Chem. Commun.*, **47**, 12182 (2011); <https://doi.org/10.1039/C1CC15633K>
40. G. Zlateva, Z. Zhelev, R. Bakalova and I. Kanno *Inorg. Chem.*, **46**, 6212 (2007); <https://doi.org/10.1021/ic062045s>
41. K.P. Praseetha, E. Shiju, K. Chandrasekharan and S. Varghese, *J. Mol. Liq.*, **328**, 115347 (2021); <https://doi.org/10.1016/j.molliq.2021.115347>
42. A. Kumar, J. Prakash, A.D. Deshmukh, P. Silotia and A.M. Biradar, *Appl. Phys. Lett.*, **100**, 134101 (2012); <https://doi.org/10.1063/1.3698120>