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High-performance, in-plane switching liquid crystal device utilizing an optically isotropic liquid crystal blend of nanostructured liquid crystal droplets in a polymer matrix

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ABSTRACT

A light scatter-free, transparent, thermally stable, optically isotropic liquid crystal mixture was achieved among three different mixtures of liquid crystal E7: Norland Optical Adhesive 65 with concentrations 30:70, 40:60, and 50:50 wt%. The 50:50 wt% mixture exhibited the best performed optically isotropic state when exposed to ultraviolet light of intensity 150 mW/cm² for droplet formation. The high intensity ultraviolet light curing process induces nano-sized liquid crystal droplets in the polymer matrix of average droplet size 218 nm, characterized by scanning electron microscope. The analyzed result shows an excellent contrast ratio (CR) equal to 1574 at the normal direction and a high CR at a wide viewing angle. The magnitude of Kerr constant in these nano-sized PDLC was $\sim 7.36 \times 10^{-10}$ mV⁻², which was more than ~ 330 times that of a conventional Kerr material such as nitrobenzene. Unprecedented fast rising and falling times of approximately 385 μ s and 1.1 ms, respectively, were achieved for the device. This high-performance material also eliminated the long-term hurdle of hysteresis to make it a promising candidate for next-generation display and photonic technologies.

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1. Introduction

In the last 20 years, liquid crystal displays (LCDs) have been very successful in flat panel display markets due to phenomenal improvements in electro-optic (E-O) performance and reduction in production costs. In addition, the size of LCDs range from small mobile displays to large televisions helps to dominate it in the display market [1]. Requirement of an alignment layer increases the product cost and slows the response time of these displays. Fast response time is essential for three-dimensional LCD applications and field sequential color displays using red (R), green (G), and blue (B) light emitting diodes (LEDs) without noticeable color breakup [2]. Sequential RGB colors would eliminate the commonly used spatial color filters which in turn enhances light efficiency and resolution density by $\sim 3 \times$. Recent advancement of next-generation LCDs with a fast response time [3] and wide viewing angle without an alignment layer have been reported based on an

optically isotropic LC (OILC) mixture, especially the blue phase liquid crystal (BPLC), which is optically isotropic in nature and have sub-millisecond order grey–grey response time. However, thermally stable polymer-stabilized blue phase (PSBP) suffers from high operating voltage and hysteresis [4–5]. Another novel, parallel approach for improving the response time without an alignment layer is to design nanostructured OILCs with polymer/LC blends. Haseba et al. produced an OILC via in situ photo polymerization by cross-linking monomers in the isotropic phase of a chiral nematic LC [6]. Recently, nano-sized, polymer-dispersed LC (PDLC) materials have been reported [7–8]. An ultraviolet (UV)-curable monomer was mixed with a nematic liquid crystal and cured under an appropriate intensity and wavelength of UV light. Droplet size can be controlled by the polymerization kinetics i.e. faster curing rate smaller liquid crystalline domains and vice versa [9–10]. The droplet size also depends on the polymer content, wherein increasing the polymer content domain size reduces beyond the limit of Rayleigh optical scattering so that the composites become optically isotropic [11]. The intent of this report is to investigate nanostructured PDLC, which is completely optically isotropic, scattering free and its E-O characteristics, such

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as voltage-dependent transmittance (V - T), hysteresis in V - T , response time, and viewing angle, under a two-domain in-plane switching (IPS) electrode [12–13].

2. Experimental

The precursors used for PDLC formation were a commercially-available eutectic nematic liquid crystal mixture E7 (Merck), UV light curable photopolymer (Norland Optical Adhesive 65, NOA-65), and photo initiator (Irgacure-651). The phase sequence of the E7 mixture was Crystalline -10 °C Nematic $+61$ °C Isotropic. E7 has a birefringence (Δn)=0.217 and dielectric anisotropy ($\Delta\epsilon$)=+14.4. Although three different mixtures with different concentrations of LC: NOA-65 were prepared, 30:70, 40:60, and 50: 50 wt %, the 50:50 wt% mixture exhibited the best optically isotropic state. The mixture was heated to approximately 70 °C, which was sufficiently greater than the clearing temperature of E7, and then injected into a sandwich-type, two-domain IPS glass cell with a 2.7 μm gap. The electrode width (w) and electrode distance (l) were 3 μm and 7 μm , respectively. The cells were irradiated with a 365-nm UV light source for 1 min. The UV light intensity was optimized to produce the optimal OILC film. When the cell

was exposed to an intensity of 150 mW/cm^2 for polymerization, it exhibited a more transparent state compared to the cell exposed to an intensity of 100 mW/cm^2 .

3. Results and discussion

Fig. 1(a) shows the cell exposed to a UV light intensity of 150 mW/cm^2 for droplet formation. The cell was placed above the “CBNU” phrase written on a dark paper. The cell showed a relatively clear black background without light scattering compared to the cell exposed to a UV light intensity of 100 mW/cm^2 (Fig. 1(b)), which exhibits significant light scattering due to the larger droplet, reducing the transparency of the cell. The Rayleigh-Gans (RG) approximation for light scattering in PDLC system assumes that light scattering is minimum if $kD/2 \ll 1$ for an incident wavelength λ , where $k=2\pi n_p/\lambda$ is the magnitude of the wave vector of the incident radiation inside the polymer matrix, and D is the diameter of the LC domain, [14]. Specifically, minimum scattering can be achieved when D is much smaller than λ . This model was appropriate for submicron-sized scattering particles and accurately describes the scattering properties of very small nematic droplets and small polymer crystallites. The average scattering cross-section was also related to the droplet size within the film via the following equation:

$$\sigma_{\text{avg}} \propto \frac{D^6}{\lambda^4} \quad (1)$$

Our fabricated LC cell contains nano-sized droplets, so D is very small and fourth power of D is very very small, for that reason light scattering negligibly small. We have obtained excellent transparent OILC film due to above mentioned reason and the picture is shown in Fig. 1(a).

The textures of the cell were imaged using a polarizing optical microscopy (POM) system fitted with a Nikon DXM1200 digital camera. Temperature-dependent, electric field-induced optical switching was observed under POM by placing the cell inside a temperature controller (Linkam, TMS-94) and applying voltage using a waveform generator (Tektronix, AFG3022) connected to an

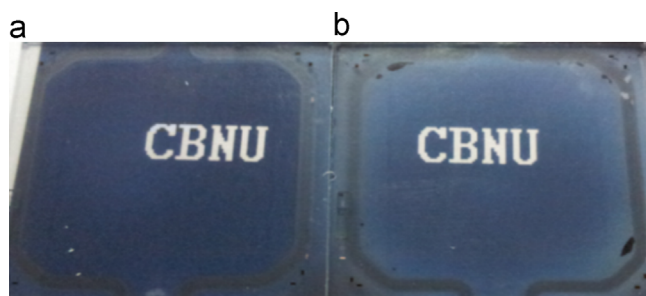


Fig. 1. Macroscopic images of the OILC cells under UV exposure. (a) High intensity (150 mW/cm^2) and (b) low intensity (100 mW/cm^2). The cell exposed weaker UV light shows noticeable light scattering such that the dark background looks sky-blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

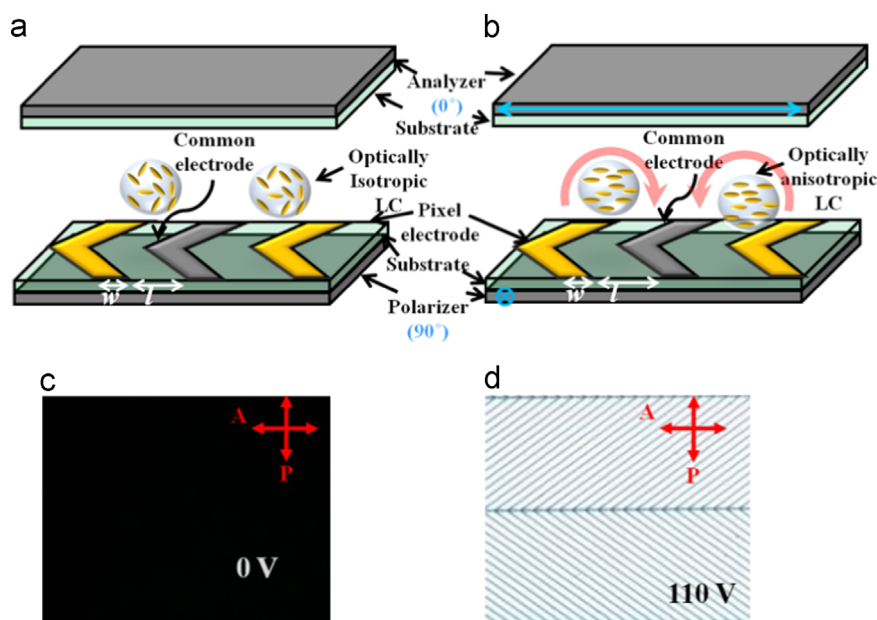


Fig. 2. Schematic diagram of the two-domain IPS cell. LCs are oriented randomly in nano-sized LC droplets in the “off” state (a), and LCs in the droplets reorient along the field direction in the “on” state (b). Actual POM textures of the cells during the “off” and “on” states are shown in (c) and (d), respectively.

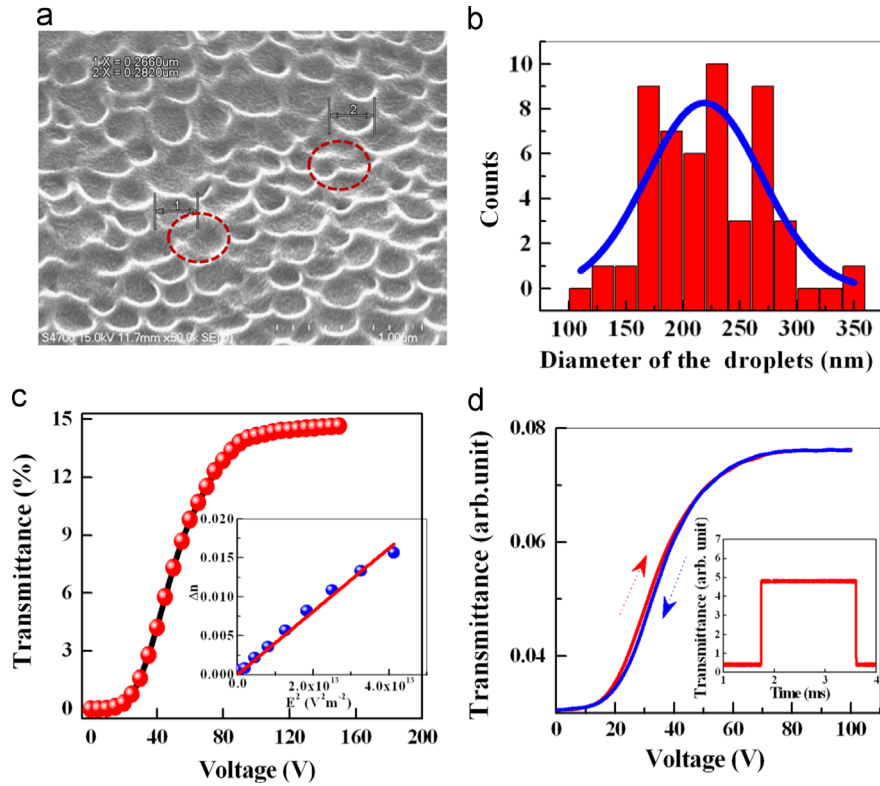


Fig. 3. SEM image of the nano-sized polymer templates (a), histogram of droplet sizes (b), V - T graph (inset Δn_{ind} vs. E^2) (c), and hysteresis graph (inset response time graph) (d).

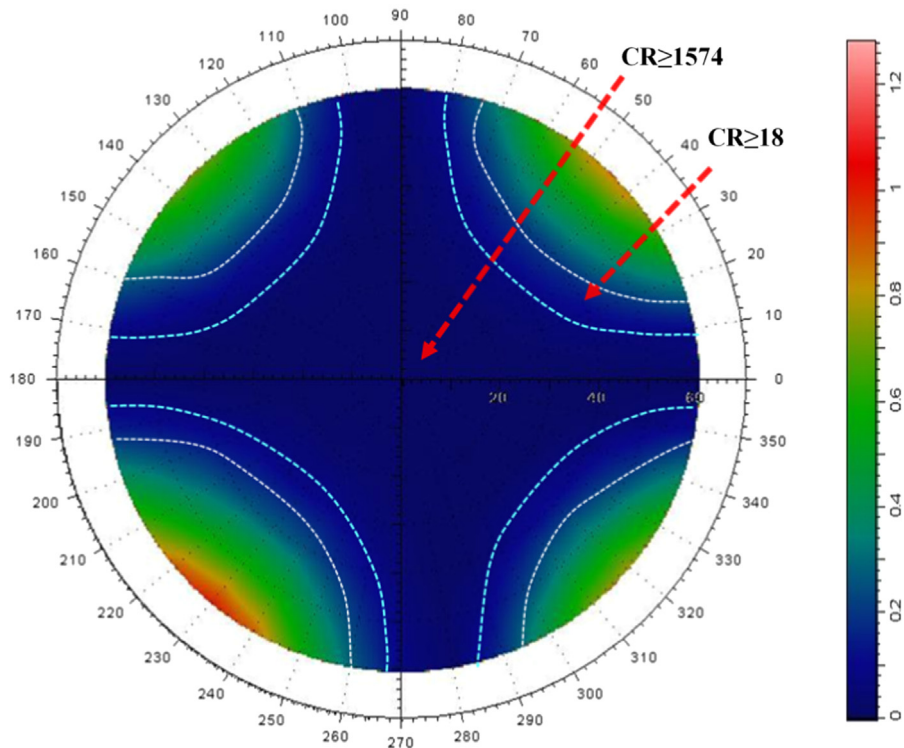


Fig. 4. Iso-contrast ratio contour for different viewing angles of the nano-PDLC cell.

amplifier. The applied voltage was a square waveform with a frequency of 1 kHz. As shown in Fig. 2(c), the POM image exhibited a clear dark state as the cell was placed between crossed polarizers. At a bias voltage of 100 V, the cell exhibited an

excellent white state (as shown in Fig. 2(d)). Transmittance was generated by induced birefringence associated with reorientation of LC in the nanostructured polymer matrix, as schematically explained in Fig. 2(a) and (b).

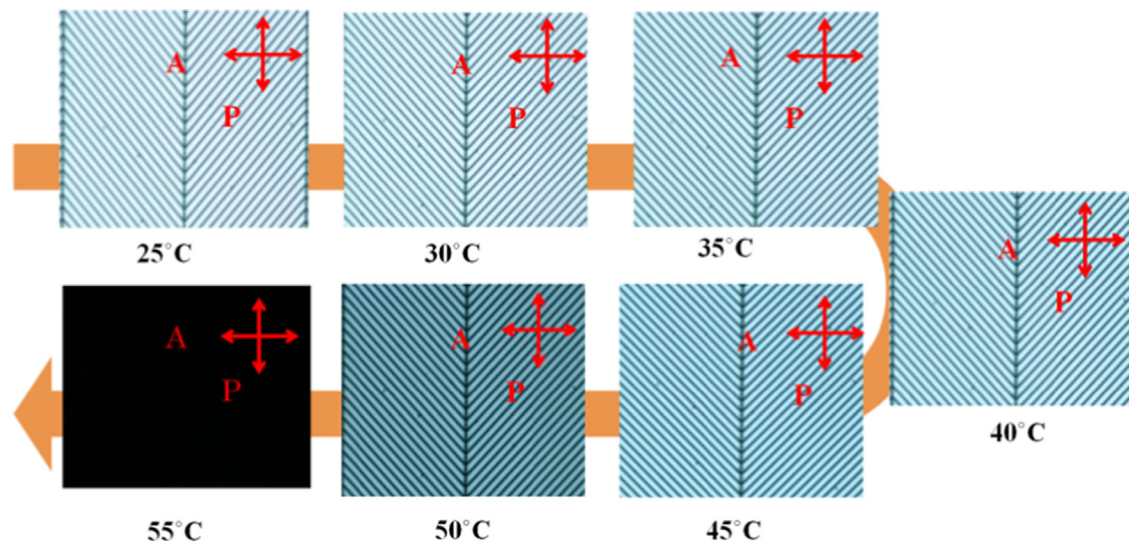


Fig. 5. Temperature-dependent POM image of the OILC cell in the presence of an electric field.

After the polymer matrix was separated and dried, it was sputtered with gold and observed under a scanning electron microscope (SEM, JSM-6701F, JEOL, Japan). Fig. 3(a) shows the SEM image of the droplets in a polymer matrix, and Fig. 3(b) shows the statistical histogram of the size distribution. The average size, ~ 218 nm, was extracted by fitting the distribution with a Gaussian function (blue line). The result confirms nano-sized LC droplets much smaller than that of the incident wavelength. The E-O characteristics of the cell were also measured. Fig. 3(c) shows the V - T curve at room temperature, in which the transmittance increases with increasing amplitude of the signal and tends to saturate at voltages greater than 80 V. The quadratic E-O Kerr effect can be expressed by [15]:

$$\Delta n_{ind} = \lambda K E^2, \quad (2)$$

where Δn_{ind} is the induced birefringence, λ is the probe wavelength (550 nm), and E is the electric field. The inset graph in Fig. 3(c) shows the plot of Δn_{ind} with squared electric field (E^2), and the magnitude of K in these nano-sized PDLC was $\sim 7.36 \times 10^{-10} \text{ mV}^{-2}$, which was more than ~ 330 times that of a conventional Kerr material such as nitrobenzene, $K = 2.2 \times 10^{-12} \text{ mV}^{-2}$ [16]. Fig. 3(d) depicts a negligibly small hysteresis, which may be due to a nano-sized nematic LC droplet captured by the polymer matrix in droplets so that the LC returned to their original position after the electric field was withdrawn. In comparison to PSBP, which suffers from large hysteresis due to electrostriction [17], this OILC system will be more advantageous for a high-frame rate display device. The inset picture in Fig. 3(d) shows the transmittance change with respect to time, from which unprecedented fast rising and falling times of approximately 385 μs and 1.1 ms, respectively, were extracted. Fig. 4 shows the viewing angle characteristics of the nano-PDLC cell, and the viewing angle was evaluated by plotting the iso-contrast contour at $\lambda = 550$ nm using LCD-1000S (Otsuka electronics, Japan). The analyzed result shows an excellent contrast ratio (CR) equal to 1574 at the normal direction and a high CR at a wide viewing angle too. It is worthy to mention that CR was greater than 10 even at 170° in the vertical and horizontal directions. This excellent CR is due to the minimum dark level of ~ 0.00081 , which is remarkable.

The switching temperature range was confirmed by observing the textures under POM at 100 V. Fig. 5 indicates proper switching has occurred even up to 54°C , a few degrees below the clearing temperature. This robust thermal stability is highly desirable for display and photonic applications which is a drawback for OILC like BP.

4. Conclusions

An LCD device with fast response time, high contrast ratio, small hysteresis, wide viewing angle, and wide temperature range was developed using nanostructured PDLCs. Electro-optics of nano-sized PDLC in two domain IPS cell is unique concept with respect to high CR and wide viewing angle display devices. Very small hysteresis of the mixture is very interesting and can remove motion blur for fast response display devices. The proposed OILC mixture and device are expected to be applicable to light-modulated display and photonic devices.

Acknowledgments

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