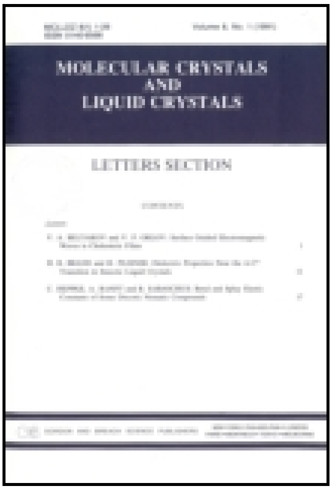

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Droplet Size Dependent Electro-Optical Properties of PDLCs with One Plastic Substrate

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We established the accurate LC droplet size control technique based on membrane filtering method, and based on the technique fabricated emulsion type PDLC cells with various LC droplet size distribution configuration such as single LC layer with different droplet sizes, the combination of different droplet sizes both inside layer and layer by layer, and investigated the electro-optical properties of them. In this paper, we discuss in detail on the electro-optical properties of the emulsion PDLC with various droplet size distribution and layer configuration.

Keywords PDLC; emulsion method; flexible display; transparent display; one substrate

1. Introduction

Polymer dispersed liquid crystal (PDLC) is made up with droplets of the nematic liquid crystal (LC) dispersed in a polymer matrix. Due to the mismatching and matching of the refractive indices of LC and polymer, PDLC can be switched from an opaque OFF state to highly transparent ON state. These interesting optical properties make PDLC being studied extensively and applied to various electro-optical applications for decades [1–5]. Recently PDLC has become attractive for the transparent flexible display applications such as smart window, digital signage and public display because of high transmittance and high light shading as well as high mechanical stability.

For high performance PDLC applications, various attempts have been done so as to improve the scattering efficiency [6–9]. However, most tries resulted in the decrease of the transmittance due to usual trade-off relation between the scattering efficiency and transparency. Electro-optical properties of PDLC were influenced by various parameters such as refractive indices of the LC and the polymer, droplet size distribution, concentration of the LC, film thickness, surface interaction between the LC and the polymer.

We focused on the droplet size distribution dependence on the electro-optical properties of PDLC based on emulsion method. The LC droplets are made before cell assembly in the emulsion method [10–11]. To investigate the droplet size distribution dependence, the accurate LC droplet size control is essential, but most emulsion PDLC studies used stirring method to form the LC droplets, so it was hard to get uniform sized droplets.

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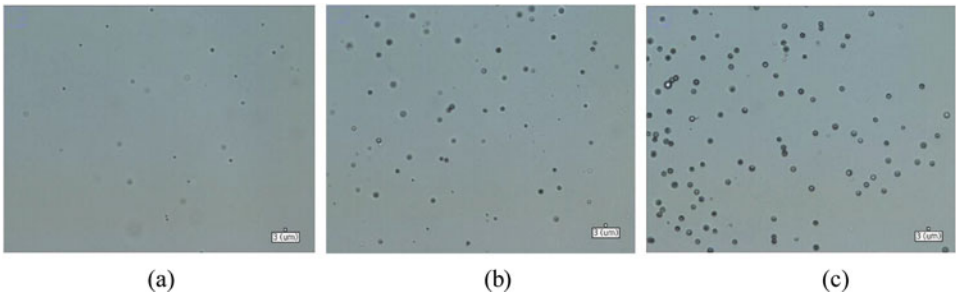

Figure 1. Optical microscopic image of the LC droplet dispersed PVA solution with LC droplets extracted though membrane filter with pore size of (a) 0.2 um, (b) 0.6 um, (c) 1.0 um.

We established the accurate LC droplet size control technique based on membrane filtering method, and based on the technique fabricated emulsion type PDLC cells with various LC droplet size distribution configurations, particularly multi layered PDLC film with combination of various size distributions. The multi-layer coating did not make any visible boundary, which is significant advantage of our emulsion PDLC process.

In this paper, we discuss in detail on the electro-optical properties of the emulsion PDLC with various droplet size distribution and layer configuration.

2. Experimental

Materials used in this experiment are nematic LC mixture (SLC9023, ne = 1.768, Δn = 0.251, from Slichem), PVA-205 (having the degree of polymerization of 500 and the saponification rate of 88 mol%, n = 1.51, from Kuraray Co., Ltd.), Benzyl methacrylate (Photo curable monomer, stabilized with MEHQ, n = 1.511 to 1.516, form Wako Pure Chemical Industries, Ltd.), Heptadecafluorodecyl acrylate (Photo curable monomer, stabilized with MEHQ, n = 1.3350 to 1.3370, from Tokyo Chemical Industry Co., Ltd.) and 2,2-Dimethoxy-2-phenylacetophenone (Photo initiator, from Tokyo Chemical Industry Co., Ltd.).

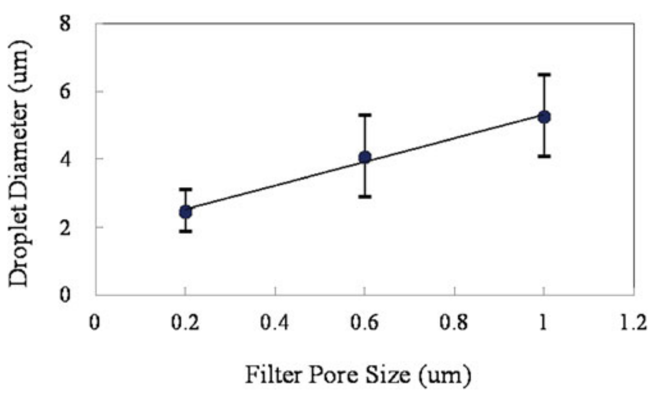

Figure 2. The droplet size distribution of the LC droplet dispersed PVA solution measured by Image J program for membrane filter size of (a) 0.2 um, (b) 0.6 um, (c) 1.0 um.

Table 1. Representative E-O properties of single layer PDLC film with droplet size of (a) 2.5 um, (b) 4.1 um, (c) 5.3 um

	T_L (%)	T_H (%)	CR	V_{90}(V)
(a)	8.7	81.9	9	76
(b)	30.5	82.3	3	50
(c)	44.1	82.7	2	47

PVA-205 was dissolved into de-ionized water at 40°C to prepare a 10 wt% aqueous solution of PVA-205. After PVA-205 was dissolved completely, the LC mixture was dispersed in PVA solution through membrane filter where LC droplet was extracted from uniform sized pore by air pressure injection. In present work, we used 0.2 um, 0.6 um and 1 um pore size of membrane filters respectively.

When all of the LC mixture was dispersed in PVA solution, PVA solution turned to creamy white LC emulsion. Then the LC emulsion was knife-coated on a poly carbonate (PC) film and PVA solution was coated on the LC emulsion layer for surface flatness and protection. Using the three emulsions with different sized LC droplets, we fabricated not only single layer but also multi-layer film, which consisted of single size droplets or combined droplets.

For one plastic substrate PDLC film, insulation layer and electrode layer also were knife-coated on the PDLC film. To find the weight ratio of LC and PVA which has optimum electro-optical properties cell, weight ratios of SLC9023 and PVA205 were set at 60:40 (LC60), 50:50 (LC50) and 40:60 (LC40). PDLC films with photo cured monomer were also fabricated by the above method.

We measured the size of LC droplets which extracted though 0.2 um, 0.6 um and 1 um pore size of membrane filters by optical microscopy and Image J program. The thickness of emulsion layer after drying it was measured by Nanoview using the principle of optical interference and reflection. Electro-optical properties of PDLC films such as transmittance, *T*, driving voltage, *V90* and contrast ratio, *CR* were observed using a luminance colorimeter named BM-7 and EOMS-250 program.

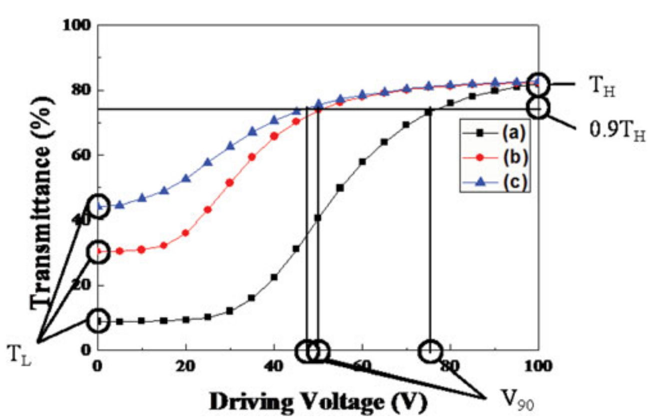

Figure 3. Transmittance-Voltage curve of single layer PDLC film with LC droplet diameter of (a) 2.5 um, (b) 4.1 um, (c) 5.3 um.

Table 2. Representative E-O properties of multi-layer PDLC film with different droplet size and different layer thickness: (a) 2.5 um, 8un, (b) 2.5 um, 16 um, (c) 2.5 um, 24 um, (d) 4.1 um, 8 um, (e) 4.1 um, 16 um, (f) 4.1 um, 24 um, (g) 5.3 um, 8 um, (h) 5.3 um, 16 um, (i) 5.3 um, 24 um

	T_L (%)	T_H (%)	CR	V_{90} (V)
(a)	8.7	81.9	9	76
(b)	8.3	65.7	8	84
(c)	5.1	44.9	9	93
(d)	30.5	82.3	3	50
(e)	14	77.6	6	73
(f)	8.7	67.8	8	86
(g)	44.1	82.7	2	47
(h)	23.7	76.6	3	75
(i)	15.8	72.1	5	77

3. Results and Discussion

3.1 LC Droplet Size Distribution Dependence on Electro Optical Properties

The LC droplet size was controlled with the membrane filter pore size as a dominant parameter and with viscosity of LC and PVA, stirring speed of magnetic bar, PVA concentration, the air pressure and the injection time of membrane filter as additional parameters.

Figure 1 shows the optical microscopic image of the LC droplet dispersed PVA solution, which were extruded through membrane filters with pore sizes of 0.2 um, 0.6 um and 1.0 um. The droplet size distribution measured by Image J program is shown in Figure 2. The average sizes of droplets corresponding to the pore size of 0.2 um, 0.6 um and 1.0 um were 2.5 um, 4.1 um and 5.3 um respectively. The result revealed that narrow LC droplet size distribution could be achieved by using our method.

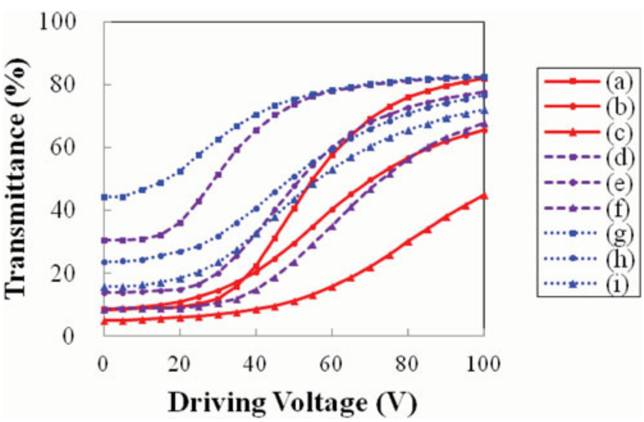

Figure 4. Transmittance-Voltage curve of multi- layer PDLC film with different droplet size and different layer thickness: (a) 2.5 um, 8un, (b) 2.5 um, 16 um, (c) 2.5 um, 24 um, (d) 4.1 um, 8 um, (e) 4.1 um, 16 um, (f) 4.1 um, 24 um, (g) 5.3 um, 8 um, (h) 5.3 um, 16 um, (i) 5.3 um, 24 um.

Table 3. Representative E-O properties of single layer PDLC film with single layer with (a) 4.1 um LC, (b) 5.3 um LC droplets, (c) mixture of 5.3 um and 4.1 um LC droplets

	T_L (%)	T_H (%)	V_{90} (V)
(a)	30.5	82.3	50
(b)	44.1	82.7	47
(c)	36.4	84.1	43

Transmittance to voltage characteristics for PDLC cells with three different sized LC droplets was observed (Figure 3). Scattering efficiency, in other words contrast ratio, of the PDLC cells was the highest for the cell with smallest droplets in the range of 2.5 um to 5.3 um. The lowest and highest transmittance, TL and TH, contrast ratio (TH/TL) and driving voltage for 90% of TH, V90 shown in the figure were summarized in Table 1.

The electro-optical properties of the PDLC cells with three different sized LC droplets depending on LC layer thickness were investigated (Figure 4). The thickness of the PDLC layer was set 8 um, 16 um and 24 um, corresponding to the number of LC coating layer, one, two and three respectively. It was found that the multi-layer coating did not make any visible boundary in this experiment, which is significant advantage of our emulsion PDLC process, particularly for the forming of multi-layer with different LC droplet sizes. In the range of droplet size and LC layer thickness, thinner thickness for small droplet cell and thicker thickness for large droplet cell provided better performance from the view point of transmittance and contrast ratio, which was summarized in Table 2.

We investigated the LC droplet size distribution dependence on the electro-optical properties of the emulsion PDLC. Figure 5 showsthe V-T curves of the emulsion PDLC cells with droplet size of 4.1 um, 5.3 um and the emulsion PDLC cells consisting of the two kinds of LC droplets. The PDLC cell with mixed LC droplets showed better performance

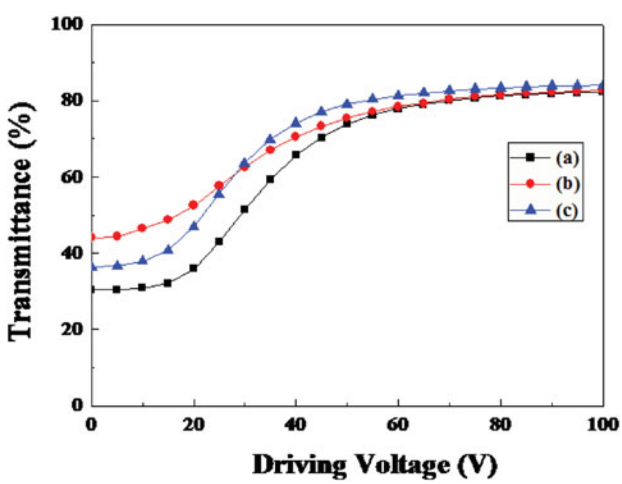

Figure 5. Transmittance-Voltage curve of single layer PDLC film with single layer with (a) 4.1 um LC, (b) 5.3 um LC droplets, (c) mixture of 5.3 um and 4.1 um LC droplets.

Table 4. Representative E-O properties of double layer PDLC film with LC droplet sizes: (a) 4.1/4.1 um, (b) 4.1/5.3 um, (c) (5.3+ 4.1)/(5.3+ 4.1) um, (d) 5.3/5.3um

	T_L (%)	T_H (%)	V_{90} (V)
(a)	14	77.6	73
(b)	19.9	79.9	62
(c)	18.4	77.8	62
(d)	23.7	76.6	75

Table 5. Representative E-O properties of single layer PDLC cells with LC droplet size of 4.1 um. LC-PVA concentration ratio: (a) 40–60 wt%, (b) 50–50 wt%, (c) 60–40 wt%

	T_L (%)	T_H (%)	CR	V_{90} (V)
(a)	31	82	3	50
(b)	18	78	4	53
(c)	15	77	5	56

Table 6. Representative E-O properties of PDLC emulsion with droplet size of 4.1 um (a) without and (b) with photo curable polymer

	T_L (%)	T_H (%)	CR	V_{90} (V)
(a)	18	78	4	53
(b)	6	77	13	40

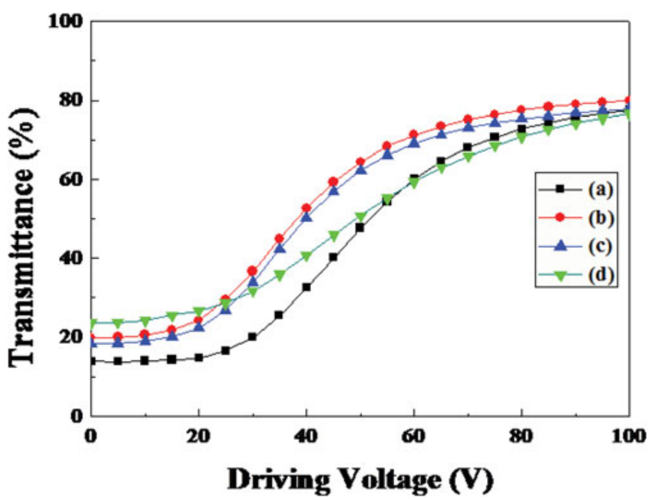

Figure 6. Transmittance-Voltage curve of double layer PDLC film with LC droplet sizes: (a) 4.1/4.1 um, (b) 4.1/5.3 um, (c) (5.3+ 4.1)/(5.3+ 4.1) um, (d) 5.3/5.3 um.

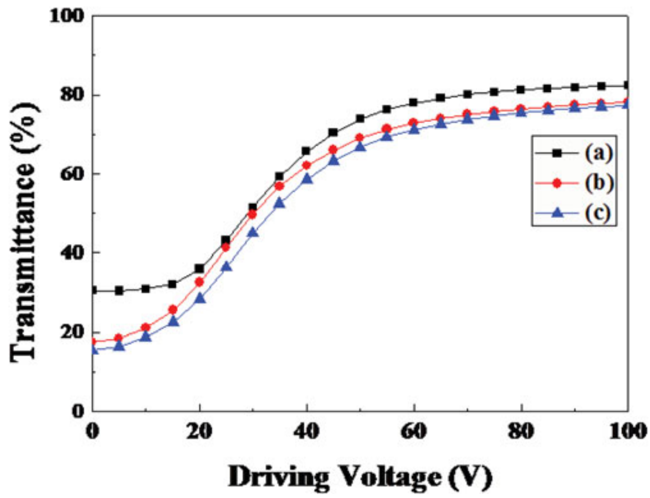

Figure 7. LC and PVA concentration ratio dependence on the transmittance of single layer PDLC cells with LC droplet size of 4.1 um. LC-PVA concentration ratio: (a) 40–60 wt%, (b) 50–50 wt%, (c) 60–40 wt%.

in transmittance and driving voltage than each single layer PDLCs, which was summarized in Table 3.

In order to investigate the electro-optical properties of the emulsion PDLC cells consisting of stacked LC layers which have different LC droplets in each layer, we made four kinds of PDLC cells with droplet size combination of double layers such as (a) 4.1um/ 4.1 um, (b) 4.1um/ 5.3 um, (c) (4.1 um + 5.3um)/ (4.1 um + 5.3 um) and (d) 5.3 um/ 5.3 um. The result shows in Figure 6. The PDLC cells with different size combination, (b) and (c) showed better performance in transmittance and driving voltage than those with the same size combination, (a) and (d), which was summarized in Table 4.

3.2 Scattering Efficiency Depending on LC and PVA Concentration Ratio

In our experiment for the emulsion PDLC cells with LC and PVA concentration ratio in between 40:60 and 60:40, the scattering efficiency increased as LC concentration ratio increased, but it was not greatly changed in case of LC concentration larger than 50%.

3.3 Improvement of E-O Properties by Adding Photo Curable Monomer into LC Emulsion

As an approach to improve the electro-optical properties of the emulsion PDLC in our system, we tried to add photo curable monomers into LC emulsion as reported by Ono [12]. We made photo curable monomer doped emulsion PDLC cells with 4.1 um sized LC droplets, and compared the E-O properties of them with those of the emulsion PDLC cells without photo curable monomer. We obtained much improvement in scattering efficiency and driving voltage as shown in Fig. 8 and Table 6. As described by Ono it can be analyzed that the improvement of the driving voltage by adding a proper amount of fluorinated acrylate reduces the anchoring energy at interface between LC and PVA. The reason

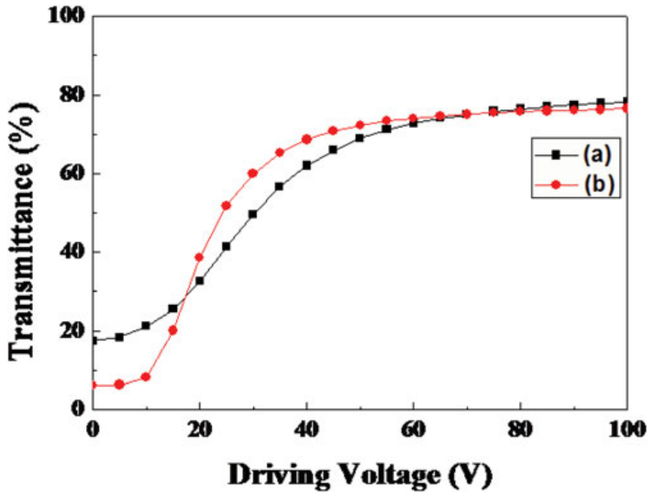

Figure 8. Transmittance-Voltage curve of PDLC emulsion with droplet size of 4.1 um (a) without and (b) with photo curable polymer.

why the scattering efficiency increased as photo curable monomer doped is not clearly understood yet, so that further research is needed.

4. Conclusion

We established the accurate LC droplet size control technique based on membrane filtering method, and based on the technique fabricated emulsion type PDLC cells with various LC droplet size distribution configuration such as single LC layer with different droplet sizes, the combination of different droplet sizes both inside layer and layer by layer, and investigated the electro-optical properties of them.

For the emulsion PDLC cells with LC droplet size of 2.5 um, 4.1 um and 5.3 um we obtained the following results: (1) Scattering efficiency was the highest for the cell with smallest droplets. (2) Thinner thickness for small droplet cell and thicker thickness for large droplet cell provided better performance from the view point of transmittance and contrast ratio. (3) The PDLC cell with mixed LC droplets showed better performance in transmittance and driving voltage than each single layer PDLCs. (4) The PDLC cells with different size combination showed better performance in transmittance and driving voltage than those with the same size combination.

It is expected that high performance PDLC could be achieved applying the above method and results incorporating other approach such as doping photo curable monomer into LC emulsion that was proven effective in our experiment.

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