Development of Single Substrate Flexible LCD Using Deformable Polarizer

Toru Umemoto[1], Kosuke Takae[1], Kazuki Kawamidori[1], Takashi Kamijo[1], Kazuya Miwa[1], Junichi Nagase[1], Takahiro Ishinabe[2], Yosei Shibata[2], Hideo Fujikake[2]

e-mail: toru.umemoto@nitto.com
[1] Nitto Denko Corporation, Osaka, Japan
[2] Department of Electronic Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan
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ABSTRACT

We developed ultra-thin flexible LCD using novel deformable polarizer. The LCD was constituted of optically isotropic LCs located between a single substrate and 10μm deformable polarizers. The LC material was investigated to achieve excellent optical & electrical properties as well as bending performance by optimizing its composition and thickness.

1 Introduction

Flexible liquid crystal displays (LCDs) have been studied in recent years, and they have many advantages such as thinness, light-weight, and impact resistance [1]. In particular, single-substrate LCD without opposed substrate is more attractive for flexible displays because of its thinner structure (Fig. 1b).

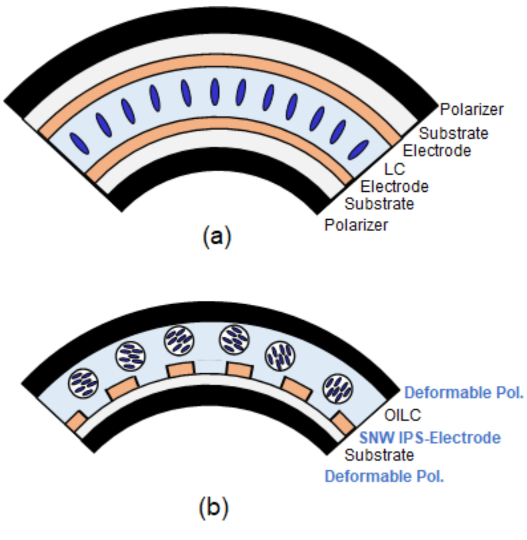

Fig. 1 Schematic structure of flexible LCDs

In a previous study [2], it was reported that the single-substrate LCD could achieve high contrast images by utilizing both polarizer and optically isotropic LCs (OILCs) in which the nano-sized LC droplets are dispersed in the polymer matrix [3, 4]. However, both high contrast images and high flexibility have not been achieved yet because conventional polarizers are generally thick.

To achieve them at the same time, more flexible and thinner polarizer is required. As reported in SID 2021 [5], we achieved novel deformable polarizer, which has remarkable flexibility through new stretching process. Besides, thickness of the polarizer could reach to only 10um by replacing protection film to coating protective layer (Fig. 2).

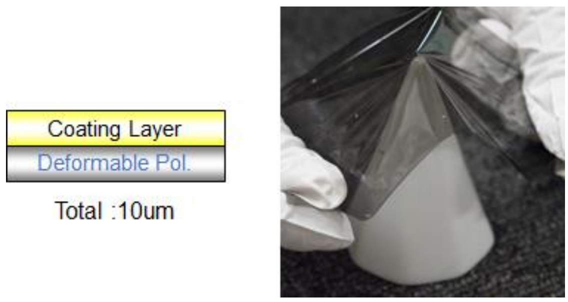

Fig. 2 Configuration & photograph of the deformable polarizer

Thus, we could develop ultra-thin flexible LCD by integrating OILC coated directly on a single substrate with bendable electrodes and the deformable polarizer. When utilizing polarizer, we must consider depolarization caused by scattering from each constituent material located below polarizer to avoid contrast degradation. OILC is an especially important material to determine transparency of the flexible LCD. In addition, OILC works as self-supported material to keep cell gap and bonding material to adjacent layers.

In this paper, we have investigated appropriate OILCs for the single substrate LCD to achieve both high contrast images and excellent flexibility. Then, we evaluated electro-optical and bending performances of the fabricated flexible LCD.

2 Experiment

2-1. Preparation of OILCs

To prepare the mixtures for OILC compound, we used 5CB (Tokyo Chemical Industry) as nematic liquid crystal. Four kinds of UV light curable monomers;

trimethylolpropane triacrylate (TMPTA; Tokyo Chemical Industry), 2-ethylhexyl acrylate (ETA; Tokyo Chemical Industry), Dipentaerythritol Hexaacrylate (DPHA; Tokyo Chemical Industry), and Ethoxylated glycerin triacrylate (EGTA) were prepared. Additionally, small amount of photo-initiator (Irgacure907; BASF) was added. The mixture ratio and monomer components in this report are shown in Table 1.

Table 1. OILC mixture compositions & concentrations

Sample#	5CB (wt%)	TMPTA (wt%)	DPHA (wt%)	EGTA (wt%)	EHA (wt%)	Irg.907 (wt%)
#1	47	52			0	1
#2	47	42			10	1
#3	47	32			20	1
#4	47	12			40	1
#5	47		32		20	1
#6	47			32	20	1

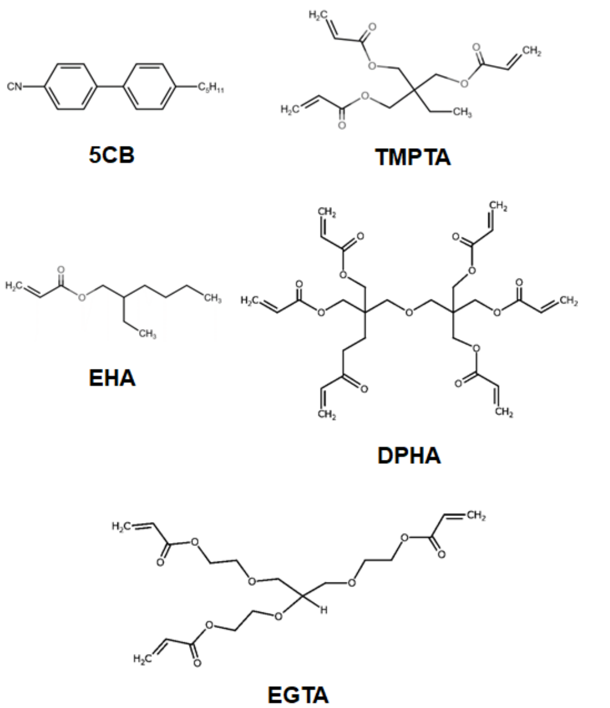

Fig. 3 LC & monomer materials

Glass cell for evaluation of OILCs was fabricated by combining a comb-shaped indium tin oxide (ITO) electrode glass for in-plane switching (IPS) mode on the bottom side and bare glass on the top side with various cell gap between 3um ~ 15um. The OILC mixtures were respectively injected into the empty glass cells with capillarity action, and 365nm UV light was exposed to the cells for 30 seconds at 60°C. The UV intensity was 120 mW/cm^2.

After photopolymerization, optical haze of these cells was measured by haze meter (HM-150; MURAKAMI COLOR Research Laboratory Co., Ltd.), and a voltage-transmittance measurement was carried out.

2-2. Fabrication of flexible LCD

According to previous study [5], we prepared deformable polarizer with a thickness of 10um. Beside this, we formed bendable IPS electrodes on the 25um thick cycloolefin substrate by coating the silver nano-wire (SNW) to electrically control the birefringence of OILCs. The resistance was 50Ω/□. The SNW layer was partially etched by a laser ablation machine with a Galvano mirror. The wavelength of the laser was 355nm. The electrode width (w) and electrode distance (l) were set to be 12.5um.

Figure 4 shows a fabrication procedure of flexible LCDs. The SNW electrode film and the deformable polarizer were attached with 8um gap, and the edge area was sealed by the UV curable sealant. OILC mixture was injected into the empty cell with capillarity action. UV photopolymerization was carried out under the same condition as glass cell. Another deformable polarizer was laminated on the backside of substrate film through an optically clear PSA.

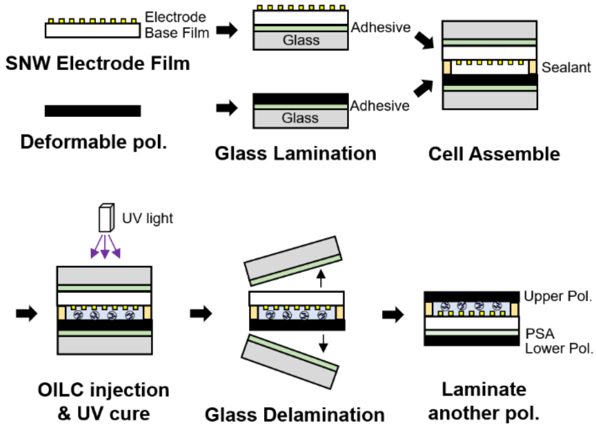

Fig. 4 Fabrication process of Flexible LCD

3 Result and Discussion

3-1. Evaluation of OILCs

Table 2 is an evaluation result of the OILCs in Table 1. It was confirmed that haze tends to increase with an addition of EHA monomer. Sample #4 ~ #6 were hazy (≥1.0 %), especially sample #5 had strong haze (13.7 %). Therefore, we confirmed that EHA concentration should be small from a viewpoint of depolarization. On the other hand, the trend of transmittance in on-state at 150 V were opposite from that of haze. The more the concentration of EHA increased, the higher the transmittance became for these samples except sample #4. EHA is mono-acrylic monomer, which has slower reaction speed than other multi-acrylic monomers. Usually, the slow reaction results in spare polymer network. Thus, LC domain size of the sample with rich EHA is bigger [6]. We guess that the bigger domain caused this phenomenon because LC molecules easily aggregate with weak anchoring energy in the domain.

Table 2. Optical properties of OILCs

Sample#	Thickness (um)	Haze (%)	T% @150V (%)
#1	6	0.4	5.0
#2	6	0.5	13.7
#3	6	0.7	17.9
#4	6	1.5	1.1
#5	6	13.7	26.4
#6	6	1.0	11.5

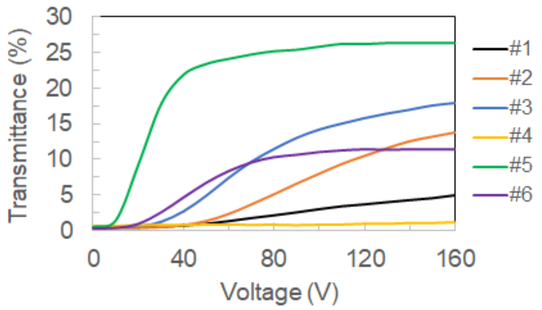

Fig. 5 Electro-Optical performance of OILCs

Next, we investigated thickness effect of the OILCs. The cell gap of sample #3 was varied between 3um ~ 15um. While the cell gap and haze were in proportion to each other, the transmittance change in the V-T curves reached a peak at 10um and didn't increase any more at 12um (Fig. 6). The saturation probably came from IPS mode because lateral electric field from comb-shaped electrode couldn't reach to the top substrate if the cell gap is too thick. Then, LC molecules around the top side didn't electrically align. In this study, we selected 8um as a proper gap to achieve excellent contrast and electro-optical property.

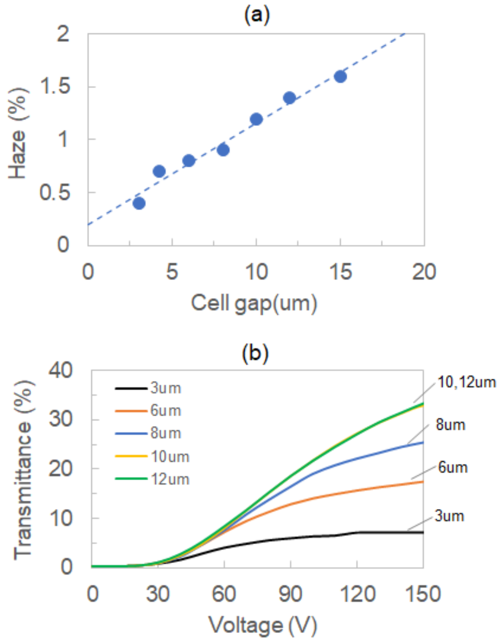

Fig. 6 Cell gap effect to haze & V-T curve

3-2. Evaluation of single substrate flexible LCD

The flexible LCDs integrated with SNW electrode film and deformable polarizer were fabricated. We used three different OILCs as shown in Table 3.

As a result, the LCD with OILC #5 showed extremely low contrast in off-state because of its depolarization caused by strong haze (Fig.7b). On the other hand, the LCD with OILC #6 delaminated after fabrication process (Fig. 7c). Although EGTA, which has ethoxylate soft chains was expected as more flexible polymer than TMPTA and DPHA, the OILC including EGTA was not enough strong as self-supported material. Consequently, this result indicated that OILC #3 was an appropriate material for the flexible LCD.

Table 3. Evaluation result of flexible LCDs

LCD#	OILC#	Gap (um)	Depolarization	Delamination
a	#3	6	O Good	O Good
b	#5	6	X Bad	O Good
c	#6	6	O Good	X Bad

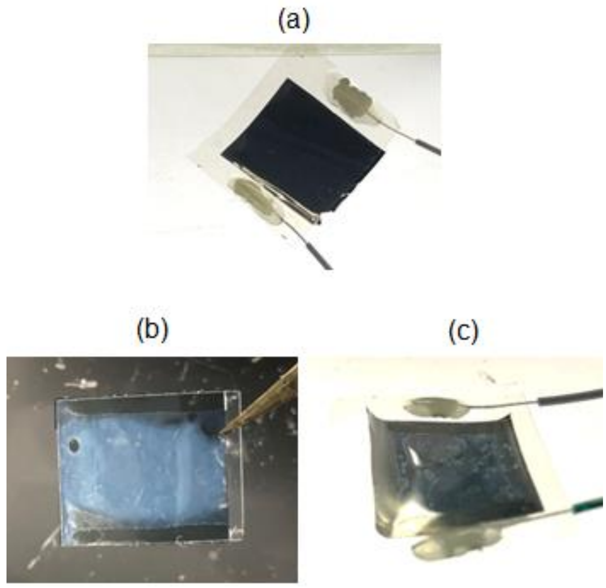

Fig. 7 Appearance of flexible LCDs with (a) OILC #3, (b) OILC #5, (c) OILC #6

Figure 8 is the flexible LCD prepared under optimized condition. We selected OILC #3 with a cell gap of 8um. The total thickness was 60um. The flexible LCD could reversibly switch between off-state and on-state. In addition, it could keep brightness even during the bending process without any delamination, wrinkle. The minimum radius of curvature was 1 mm.

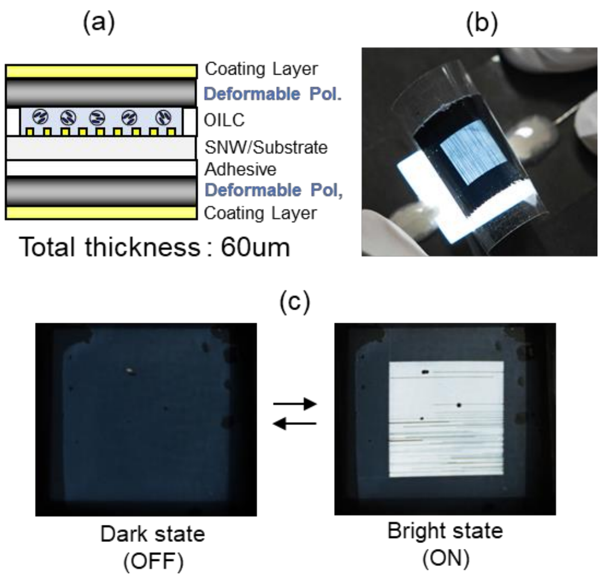

Fig. 8 Switching test of the flexible LCD
(a) Configuration of the fabricated LCD,
(b) Curved state, (c) Dark & Bright images

Figure 9 shows that electro-optical performance of the optimized flexible LCD. The transmittance increases with an increase of applied voltage, and the maximum transmittance was 30% (The maximum value of the transmittance of this device is theoretically 50% considering the comb-shaped electrode).

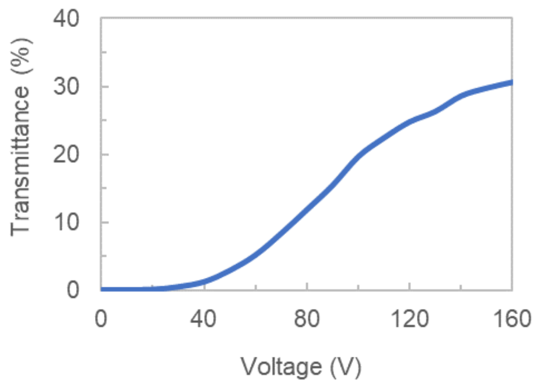

Fig. 9 Electro-Optical performance of the fabricated flexible LCD

4 Conclusions

We have developed a novel ultra-thin flexible LCD by integrating optically isotropic LCs coated directly on a single substrate and deformable polarizer. In this study, we investigated the effects of mixture concentration and monomer compositions of OILCs to obtain high optical properties and strong mechanical strength. We found that concentration of EHA, which is a mono-acrylic monomer determined optical haze and transmittance during applying voltage. Additionally, it became clear that the types of multi-acrylic monomer also affected those parameters and mechanical property. After optimization of the OILCs, the flexible LCD could achieve low haze less than 1% without obvious depolarization, and 30% high transmittance as well as enough mechanical strength without any delamination. Then, we experimentally confirmed that the novel LCD could reversibly switch even during the bending process in a small radius of curvature. It is expected to apply this technology to various applications such as flexible, rollable, or wearable displays.

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