Integration and Modeling for Ink-Jet Printing of Cholesteric Liquid Crystal in a Roll-to-Roll System

Wanda W. W. Chiu*, Wei-Hsun Huang, Chen-Chu Tsai, Chih-Jian Lin, Cheng-Yi Wang, Kevin Cheng*; Industrial Technology Research Institute; Hsinchu, Taiwan 310, R. O. C.

Abstract

Flexible substrates are becoming more important in printed electronics and displays. The era of ink-jet fabrication is coming because of its low cost, high throughput and the feasibility of manufacturing on flexible substrate. Its innate non-contact characteristic and digitalization of patterning make it a bright star for future manufacturing. In this paper, a bi-stable flexible electronic display has been evaluated based on the roll-to roll ink-jet printing technology with a photographic film coating technique assistant. This roll-to-roll continuous process, where the mechanical design follows the Normal Entry Law (NEL) with a different roller type, was surveyed in order to optimize the web spreading. This included factors like friction, roller porosity, roller diameter, speed; and the roller layout. In addition, we estimate the manufacturing running cost to be about 666 NT for a continuous 10.4" Ch-LC R2R ink-jet printing fabrication. In this paper, we successfully demonstrate a 4.1", bi-stable color Ch-LC display by ink-jet printing with the contrast ratio being about 9:1, in QVGA resolution.

Introduction

Cholesteric liquid crystal was chosen as the operating material because such materials do not require alignment layers or polarizing films. Furthermore, cholesteric liquid crystals can be applied to birefringent substrates, such as common extruded polyester, without affecting optical performance. Cholesteric material holds a reflective, planar (P) state or a clear, focal-conic (FC) state indefinitely without a field. The bi-stable states can be achieved using passive matrix addressing [1], which eliminates the need for an active matrix plane. In prior studies, Kodak was to combine photographic and electronic materials and processes to create low-cost, large-area displays. Technology selection was based on a preference for a minimum number of simple, room-temperature processes. They demonstrated that Cholesteric polymer-dispersion displays a 22% reflectance and a 6:1 contrast ratio. The displays have memory, and are flexible as well as pressure insensitive. It can be re-written for hundreds of thousands of cycles using passive matrix addressing, where the Gelatin and its associated processing have proven useful in electrically driven displays [2-3].

Differing with Kodak's coating process; we developed the ink-jet printing process to deposit red, green and blue cholesteric liquid crystal; a single layer of color Ch-LC display is realized on a single substrate. It emphasizes the atmospheric process and fabricates on only a single substrate. It is introduced in Fig.1.

The challenges of roll-to-roll for fabricating a Ch-LC display mentioned by McCollough Charles [4] mainly concern its resolution and yield ratio compromise. Low resolution is easier in pulling the yield ratio up to a high rate; for example, it could be over 90% in resolution with 25 ppi. But the yield ratio decreases rapidly with high resolution. In 50 ppi, only a 70% yield ratio is expected for a 14"*19" Ch-LC display. The lack of control of the misalignment caused by excessive screen stretch or dimensional change in the support as a result of internal moisture content, is a major failure mode for this kind of segmented displays.

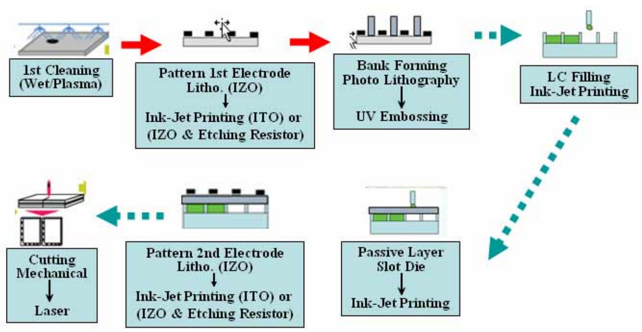


Figure 1. Process flow of color Ch-LC display

Cost Assessment

After a comparison with traditional sheet-by-sheet processing for cholesteric liquid crystal display, the material running cost of a roll-to-roll for color Ch-LC display was estimated. Specifically, a diagonal 10.4", aspect ratio 4:3, QVGA resolution panel, is made from a roll-to-roll line with substrate length 1000 ft, by ink-jet printing speed of 0.5 m/s. The replacement time for changing the roller assumes 1 hr for each substrate roller. The average product speed is about 22 sec/panel, or equal to the throughput of 3900 panels/day. The materials for dispensing the liquid crystal cost about $NT 128/panel, substrate cost is about $NT 63/panel; processing cost includes the passive layer, and indium-tin oxide (ITO) patterning, while the photo bank forming is about $NT 453 /panel. As for the print head maintenance, the average cost is about $NT 22/panel. The total material running cost is about $NT 666/panel, though this does not include the equipment and operation fees.

Ink-Jet Printing of Liquid-Crystal

Capillary injection is a conventional method for liquid crystal filling in the LCD industry, but it is a time-consuming process. In recent years, the one drop filling process has been widely used due to the short tact time requirement; however, it is not suitable for pixel-deposition or for the high precision volume control process because of its large dot size. Here we use an inkjet printing system, designed by ourselves, DTC/ITRI, to develop a new process for discharging Ch-LC with good control. This is shown in Fig 2(a)-(c). The solution for the printing issues of the high viscosity Ch-LC is shown in Fig. 2(a). The yield rate of this printing process can reach 95% and the volume variation can be smaller than 2% of the total discharging quantity. Therefore this method is suitable for a display application with a color pattering of Ch-LC and when there is a demand for high precision control for LC quantity. Fig. 2(c) is a prototype for ink-jet printing of color Ch-LC at 4.1”. With QVGA resolution, the contrast ratio is about 9:1.

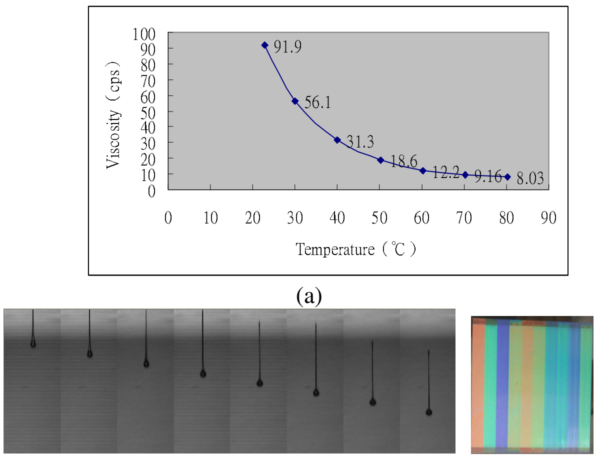


Figure 2. The image of the printing drop for Ch-LC (a) Viscosity of Ch-LC operation at different temperature (b) Jetting Observation (c) Ink-jet printing of color Ch-LC, in 4.1”, QVGA.

System Architecture & Optical Alignment

The main stage of coloring Ch-LC in red, green, and blue adopts the ink-jet printing technology. Its concept design is indicated in Fig. 3. Four printing head modules, in order, are for red, green, blue and passive layer patterning. The flexible substrate moves at a steady speed on the stage to pass the aforesaid four modules. Each module could be composed of two heads or more depending on the resolution and substrate width need. For reducing the acoustic streaming effects which degenerate the jetting quality beneath the substrate, a suction flow channel was designed. In this stage it has suction openings covering the full area. Each suction opening connects to a linking passage provided inside the stage where it then connects to a vacuum pump. This design will ensure the minimizing of the acoustic streaming effects and will keep the substrate delivery in a flat and low vibration.

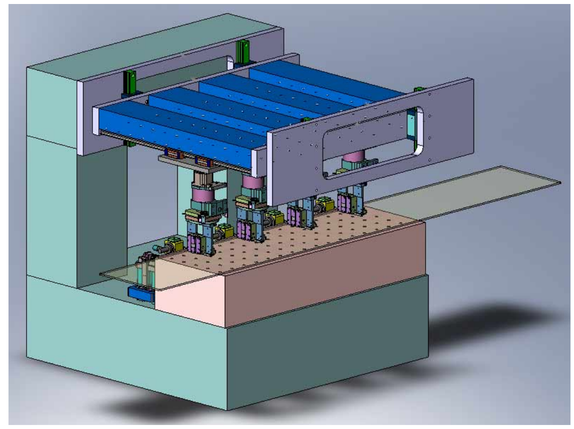
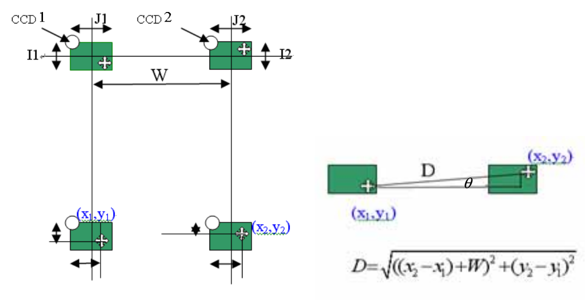


Figure 3. The system of roll-to-roll inkjet printer.

In general, a completed process includes the surface cleaning, patterning process, and post curing processes. Most common curing processes like thermal curing or UV curing will deform the substrate. Therefore, it is necessary to have a high resolution optical system in order to detect the elongation. Fig. 4 is two optical sensing devices used to examine the coordinates of alignment mark location to verify the deformation of the substrate. After calculation, the position shift and rotation can easily be identified, as shown in Fig. 5.



(a) (b)

Figure 4 (a) I1,I2,J1,J2: CCD, resolution(640X480). (x1,y1) (x2, y2): the coordinate of the alignment mark 1 and the alignment mark 2, W: the distance between CCD1 and CCD2. (b) D: the distance between alignment 1 and alignment 2.

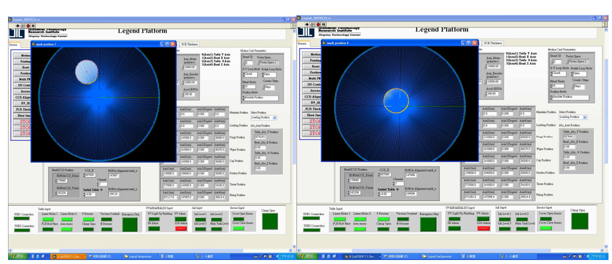


Figure 5. User operation interface for aligning substrate deforming.

Substrate Deformation Concerns

Thermal Expansion

Flexible substrates are neither dimensionally nor thermally stable. To ensure precision registration of the different layers in the final device, the substrate distortion must be compensated and controlled. Such distortion arises from exposure to elevated temperatures, mechanical stresses from handling, changes in surface material compositions, and moisture absorption.

The most important thermal properties of the flexible substrate are dimensional stability and thermal expansion. The dimensional instability (thermal shrinkage) of flexible substrates is a kind of irreversible dimensional change. When the substrate is exposed to a high temperature, the internal stress induced by the manufacturing process is relaxed, resulting in a permanent deformation. This dimensional instability makes the deformation prediction more difficult. To improve the dimensional stability, a pre-annealing process can be performed in order to release the internal stress in the substrate by exposure to high temperatures and minimal web tension. It is important to note that the thermal shrinkage is a slow process that takes several minutes or several hours to make the dimensional change stable. In addition, the thermal shrinkage could be anisotropic due to the polymer chains becoming oriented along the direction of the machine rolling process during the manufacturing of the film. As listed in Table 1, the heat shrinkage in the machine direction (MD) is different from that in the transverse direction for APO, PET and PEN.

Unlike the dimensional instability, the behavior of the natural thermal expansion is more predictable. This property is expressed by the coefficient of the thermal expansion (CTE) of the material. For multi-layer devices, any mismatch in thermal expansion coefficients during thermal cycling could cause thermal stress and film cracking.

Tension Force

When the substrate is subjected to a tensile force, it will be elongated along the tensile direction and shrink in the transverse direction. Hence this is an anisotropic deformation, typically named a Poisson ratio. According to Hooke's law, a substrate with a larger Young's modulus has a smaller deformation. If the coefficient of thermal expansion of the deposited material mismatches that of the substrate, the internal stress will cause the substrate to expand or shrink.

Moisture Inflation

Humidity could cause an expansion of the flexible substrate. This deformation is reversible. To prevent unwanted deformation of the substrate, the humidity should be controlled. Compared to glass, the deformation of flexible substrates is usually large and anisotropic. To ensure high precision alignment, anisotropic distortion compensation is necessary. For a completed process, a post baking or environmental drying system should be considered. Table 1 is the most common used flexible substrate, and in Fig. 6, it is a measurement for the PC (Polycarbonate, T_g~215℃, Teijin Co., Model SS120-B30) and PET (Polyethersulfone, T_g~223℃, Sumitomo Bakelite Co., Model Sumilite FST-X014D) substrates, in order to observe its variation due to the heating process applied. The result indicated that both PC & PET will have dimension extension because of the heating process, and will experience a gradual shrinkage change with cooling time. After a one day natural cooling process, the substrate will recover to nearly its original dimension, and the PC substrate will have less variation than that of PET. This implies that for a roll-to-roll design, there should be a carefully designed cooling stage following a heating stage, in order to speed up the waiting time for obtaining satisfactory substrate variation which will meet requirements.

Table 1: Properties of plastic and glass (TEIJIN)

Property	PC	SP-PC	PES	PAR	APO	PET	PEN	Glass
Production Process	Solvent-cast		Extrusion	Solvent-cast	Solvent-Cast or Extrusion	Extrusion		Fusion
Density	1.20	1.20	1.37	1.2	1.1	1.40	1.43	2.2-2.6
Total Transmittance (%)	92	90	88	-	92-95	88-92	85-90	93
Haze (%)	0.2	0.2	0.3	0.5	0.2	0.5	0.6	0.1
Reflective index	1.59	1.62	1.65	-	1.51-1.53	1.66	1.70	1.45~
Retardation (nm)	10	1	7	15	5	large	large	1
Photo elasticity rate	72	45	69	-	-4	large	large	-
Glass Transition Temperature (℃)	155	215	223	215	171	100	170	-
Coefficient of Thermal Expansion (Ppm/℃)	75	73	60	61	-	20-30	20	1>
Heat shrinkage (%)	0.05 @ 130℃2hr	0.01 @ 180℃2hr	-	0.03@ 130℃2hr	MD:0.01 TD:0.1 @130℃2hr	MD:1.0 TD:0.5 @150℃2hr	MD:0.5 TD:0.1 @150℃2hr	0
Young's modulus (Gpa)	2.2	2.8	12	-	2.1	5.4	6.0	Large
Water Vapor Transmittance Rate (g/m²/day 40℃100%RH)	50	30	105	-	1	9	2	-
Water Absorption Coefficient (%)	0.2	0.3	-	0.4	0.1-0.4	0.5	0.4	-

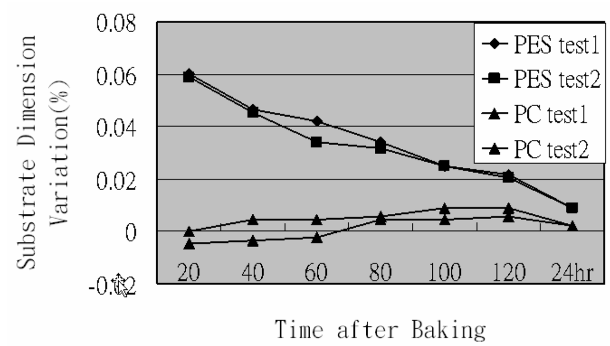


Figure 6. Substrate dimension variation after heat process

Dynamic Delivery Controller

Having an accurate web tension and velocity control is the crucial issue in delivering the flexible substrate of a color Ch-LC display which directly affects the quality of the end product. If the tension is inappropriate during web spreading, it will cause flexible substrate buckling, wrinkling, or even breakage [5]. Normally web tension should be set at 10%-25% of the web's yield strength and should be kept within 10 % of this value during the system's steady running state [6].

In this consideration for the Ch-LC ink-jet printing process, we become concerned if the deformation of the flexible substrate is over 30 μm because this causes the RGB Ch-LC to land in the wrong position on the substrate and thus to be wrongly mixed. For example the yield strength of PET base flexible substrate is 3% of Young's module (5.4 GPa) and the Poisson's ratio is 0.24 [7]. By Hook's law there will be a 12 μm longitudinal deformation with a 127 μm thickness, an 8 inch length and a 6 inch width PET film suffering from 2% of the longitudinal tension changes.

In order to satisfy process requirements, the web-tension should be kept in a specific range: within a 2% steady state error. Fig 7 is the schematic of a roll-to-roll system for delivering the flexible substrate which is controlled by a pc-based web controller. In order to satisfy the requirements of the Ch-LC ink-jet printing process, the system should precisely control the delivery speed of 0.5 m/sec and a 2% steady state error of web tension.

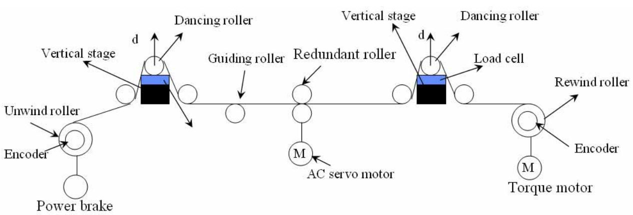


Figure 7. The schematic of R2R system

The web controller includes the well tuned tension and velocity regulation unit. The block diagram for the control flow is demonstrated in Fig 8. The tension regulator measured web-tension by the load cell, and fine tuned the tension at a specific value real-time by controlling the vertical stage in order to change the displacement of the active dancer roller. If the compensation for web-tension is out of the active dancer roller handling, the tension regulator will transmit a signal to the velocity regulator to modulate the torque of the rewind roller in time to prevent error. The diameter of the unwind and rewind rollers changes over time. With the increase of the winder roll diameter, inertia increases exponentially to the 4^{th} power of diameter [8]. The velocity regulator, in order to keep the web delivery velocity and tension in the specific range that modulates the torque of the rewind roller driven by the torque motor, follows the diameter changes.

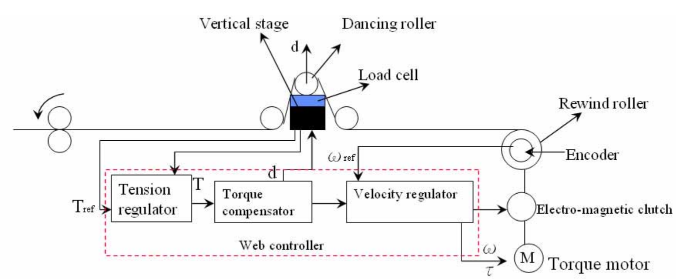


Figure 8 The block diagram of control flow

Conclusion

In this article, a roll-to-roll ink-jet printing system is introduced for bi-stable Ch-LC color display. It successfully demonstrates a 4.1”, bi-stable color Ch-LC display by ink-jet printing with a contrast ratio of about 9:1 in QVGA resolution. We discuss key issues like the substrate deformation, especially for the thermal processes which cause the elongation. Typically, the PES will give a larger expansion than does the PC; therefore, the latter is more suitable for the display substrate. In addition, this article discusses the design principle for highly accurate delivery which consists of three feedback loops: the torque regulator, the torque compensator, and the velocity regulator. In the near future, we will focus on control rules design, and the adoption of the fuzzy controller into this R2R system.

References

[1] Doan, J., Yang, D-K., U.S. Patent 5,251,048, “Method and Apparatus for Switching an Electronic Display,” (1993).

[2] Stanley W. Stephenson, David M. Johnson, John I. Kilburn, Xiang-Dong Mi, Charles M. Rankin, Robert G. Capurso, “Development of a Flexible Electronic Display Using Photographic Technology”, SID, section 16:3, 2004.

[3] Stanley W. Stephenson*, Xiang-Dong Mi, David M. Johnson, J.I. Rangel, J. Silbermann, “Electro-Optical Cholesteric Sheet Writing”, SID, section 27:3, 2006.

[4] G. Thomas McColloughCharles, M. Rankin, MeganL. Weiner, “Roll-to-rollmanufacturing considerations for flexible, cholesteric liquid-crystal display (Ch-LCD) media”, Journal of SID, Vol.14, N.1, 25-30, 2006

[5] KEE-HYUN SHIN, Tension Control: Atlanta, GA, TAPPI Press, 2000.

[6] Weixuan Liu, E. J. Davison, “Servomechanism controller design of web handling system.”, IEEE Translations on control systems technology, Vol. 11, NO. 4, JULY 2003

[7] William E. Hawkins, The plastic film and foil web handling guide: Boca Raton, Florida, CRC press, 2003

[8] Zhijun Liu, “Dynamic analysis of center-driven web winder controls”, Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE

Author Biography

Wanda W. W. Chiu received her Masters’ degree in Mechanical Engineering from National Cheng Kung University in 1996. She is now a deputy manager in the Printing Science Department of the Industrial Technology Research Institute at Taiwan. Her work is primarily leading the industrial ink-jet printing processes and system integration. Her research interest covers the opto-mechanical system development, and she specializes in ink-jet printing control and flow architecture design.

Kevin Cheng received his B.S. degree in Mechanical Engineering from the University of Tamkang in Taiwan in 1992 and a Ph.D. in Aeronautics & Astronautics from National Cheng Kung University in 1998. He is now a printable science department deputy director in the panel integration division II / Display Technology Center of Industrial Technology Research Institute in Taiwan. His work is primarily leading the ink-jet printing technology into printed display and electronics development.