Microcup^{Ò} LCD, A New Type of Dispersed LCD by A Roll-to-Roll Manufacturing Process

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ABSTRACT

Microcup® liquid crystal displays have been prepared by a format flexible, roll-to-roll manufacturing process based on the SiPix Microcup® and sealing technologies. This new type of dispersed liquid crystal display has shown very promising switching characteristics including high contrast, fast response rate, low reorientation field, and negligible hysteresis.

INTRODUCTION

Conventional dispersed liquid crystal systems typically have a broad distribution of size and shape of LC domains(1). The resultant PDLC device often exhibits a transmittance-voltage characteristic curve of low gamma with a reorientation field of 1-10 V/µm and a significant hysteresis. The disadvantages of such a device include low level of multiplexing in passive matrix addressing, slow frame rate, poor reproducibility in gray scale, and trade-off between contrast ratio and operating voltage. An improved system, PELC (polymer encased liquid crystal)(2) in which liquid crystal is enclosed in mono-dispersed latex hollow particles have been disclosed to address the disadvantages associated with the broad size distribution. However the multiple-step synthesis and purification processes involved in the preparation of the PELC system are not straightforward and often quite time-consuming particularly when a dye is used to improve the contrast ratio of displays of thin cell gaps.

High performance, plastic electrophoretic displays manufactured by a format flexible roll-to-roll process based on the SiPix Microcup and sealing technologies has been demonstrated recently(3-5). In the present paper, a new type of mono-dispersed liquid crystal display based on the Microcup roll-to-roll manufacturing process is reported.

ROLL-TO-ROLL MICROCUP^{Ò} LCD MANUFACTURING PROCESS

A schematic process flow is shown in Figure 1. Rolls of Microcup® LCDs have been prepared by for example, (1) coating a UV curable composition on a conductor film, (2) embossing and hardening the Microcups, (3) filling the Microcups with an liquid crystal composition having its ordinary refractive index matched to the isotropic index of the Microcup, (4) sealing the filled Microcups with a sealing layer, and (5) laminating the sealed Microcups with a second conductor film. The resultant LCD roll may be cut (6) to different sizes and formats for different applications. Alternatively, the microembossing step may be replaced by a photolithographic process involving imagewise exposure followed by removing the unexposed areas by a developer.

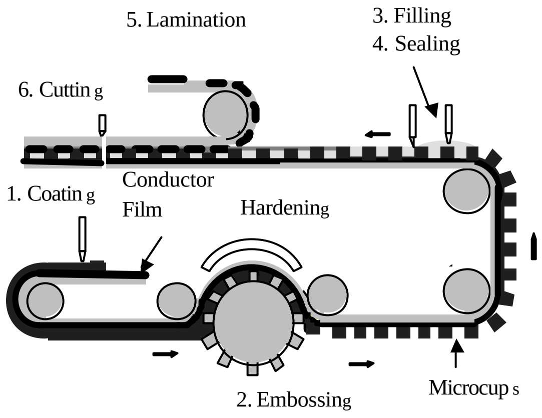
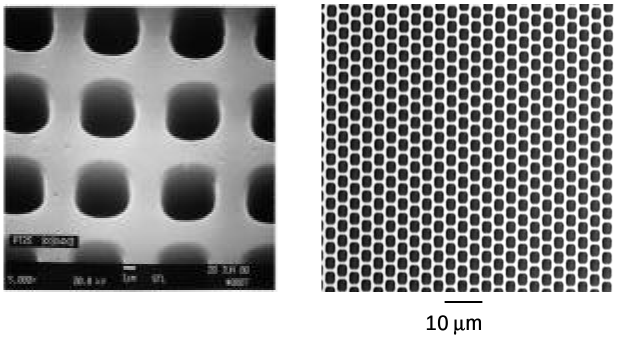


Figure 1. Schematic roll-to-roll process for the Microcup LCD Manufacturing

THE MICROCUP^{Ò}

Two typical arrays having Microcups^{Ò} of substantially uniform shape, size and aspect ratio prepared by the roll-to-roll process are shown in Figures 2a and 2b. Depending on the application, MicrocupsÒ of different shape and size may be prepared by either microembossing or photolithography. Typical diameter of the MicrocupsÒ is in the range of 1 to 10 µm. A cup shape allowing higher contact area between liquid crystal and the cup is preferred. To improve the contrast ratio, a stack of multilayer Microcup arrays may be prepared by a sequential coating, embossing and sealing process or by a transfer lamination process(6,7).


(2a) MicrocupÒ A

(2b) MicrocupÒ B

Figures 2 Micrographs of two typical MicrocupÒ arrays: **Figure (2a)**, SEM of MicrocupÒ (A): 3µm (width and length) x 4µm (depth) x 2.5µm (partition); **Figure (2b)**, Optical micrograph of staggering MicrocupÒ (B): 2µm (width and length) x 3.2µm (depth) x 1.5µm (partition).

THE LIQUID CRYSTAL FILLING AND SEALING PROCESSES

As in the preparation of MicrocupÒ EPDs(3-5), the filling and sealing processes are critical steps of the roll-to-roll Microcup LCD manufacturing. The traditional edge sealing and vacuum filling processes for assembling conventional LCD cells are not useful at all for the MicrocupÒ structure. Directly laminating a conductor film onto the filled Microcups typically results in unacceptable defects such as de-wetting, de-lamination, trapped-in air pocket or void, and non-uniform image quality. To enable the roll-to-roll manufacturing, two high-speed, continuous filling and sealing processes have been developed.

In the two-pass sealing process, Microcups partially filled with a LC composition are over-coated with a sealing layer composition which is optimized to achieve good adhesion to the MicrocupÒ walls and a minimum degree of intermixing with the liquid crystal phase. In the 1-pass filling and sealing process, a sealing composition is pre-emulsified in the liquid crystal composition and filled or coated onto the MicrocupsÒ. The sealing composition is optimized to allow fast phase separation and creaming of the sealing layer to form a contiguous film with acceptable integrity on the top of the filled MicrocupsÒ. In either process, the sealing composition is preferably immiscible with and lighter than the liquid crystal phase.

To achieve an acceptable seamless sealing by either process, at least six critical parameters must be optimized: (1) the density difference between the sealing composition and the liquid crystal composition, (2) the degree of incompatibility between the sealing and the liquid crystal compositions, (3) the surface tension and interfacial tension of all interfaces or surfaces involved, (4) the interaction between the sealing composition and the partition walls, (5) the rheology of both the sealing composition and the liquid crystal composition, and (6) the integrity and physico-mechanical properties of the sealing layer during and after sealing. The 1-pass sealing process is very attractive because of its simplicity. However, the 2-pass process is very useful particularly when the sealing composition is at least partially compatible with the liquid crystal composition. By optimizing the above-mentioned parameters, seamless sealing has been achieved within seconds by either process on a continuous web.

Since a releasing monomer is often used to improve the release of the embossing mold from the MicrocupÒ, a poor wetting of liquid crystal on the MicrocupÒ was found in some combinations of liquid crystal and MicrocupÒ compositions. A corona or plasma surface pretreatment to modify the surface energy of the MicrocupÒ has been found very useful to improve the reproducibility of the filling and sealing processes. Figure 3 shows the effect of methanol plasma treatment of the MicrocupÒ (A) on the quality of the two-pass filling and sealing using Merck E7 as the liquid crystal phase and a 10% solution of a carboxylated acrylic copolymer A in 2-propanol as the overcoat sealing solution. It is evident from Figure 3 that the defect can be dramatically reduced by the surface treatment. A significant increase in contrast ratio of the resultant display was also observed in the surface treated samples.

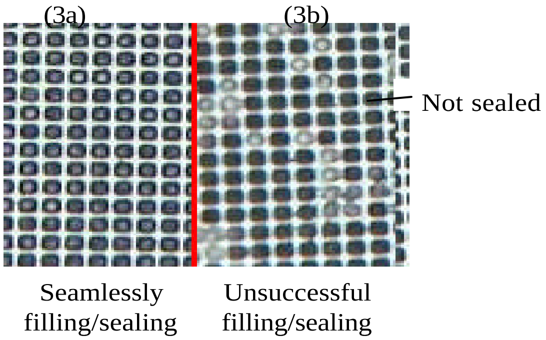


Figure 3 Micrographs of Microcup® arrays filled with Merck E7; (3a) Microcup® treated with methanol plasma; (3b) no surface treatment.

Figure 4A shows the optical response curves of a conventional photo-induced PDLC film containing 30/70 (w/w) of Merck E7/Norland 65 (cell gap: 4.5µm), and Figure 4B shows the curves of a Microcup® LCD having a 4-layer of Microcup® array A (Figure 2a) filled with 3wt% of a dichroic dye, BlueAB2 (Funktionfluid) in Merck BL006 (cell gap= ~16µm), and subsequently sealed by the two-pass process using the same 10% solution of a carboxylated acrylic copolymer A in 2-propanol as the sealing overcoat. The cell gap of the photo-induced PDLC film (4A) was selected so that the LC loading was about the same as that of the 4-layer filled and sealed Microcup® (4B).

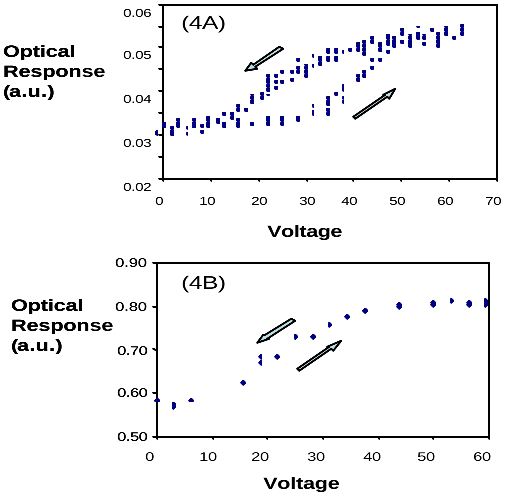
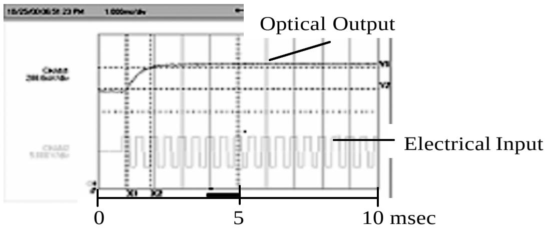


Figure 4 Electro-optical response curves of (4A) a traditional photo-induced PDLC, and (4B) a 4-layer Microcup LC using the Microcup array A of Figure 2a.

The t_{on} and t_{off} of the 4-layer Microcup® LC (4B) at 40V are about 0.5 msec and 11 msec, respectively as shown in Figure 5.

(5a) t_{on} = ~ 0.5 msec



(5b) t_{off} = ~11 msec

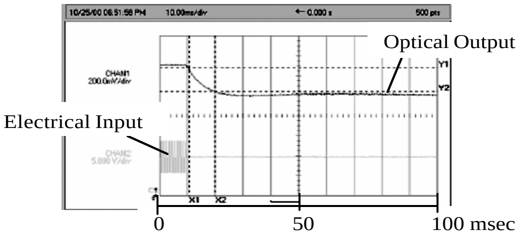


Figure 5 Switching waveforms for the Microcup® LCD (4B) at 40 V and 2KHz. A t_{on} of about 0.5 msec and a t_{off} of about 11 msec are shown in Figures (5a) and (5b), respectively.

Switching rate of the Microcup® LCDs may be further improved via optimization of the Microcup® composition. Incorporation of a low molecular weight polyethylene oxide functional group into the main chain or side chain of the Microcup® polymer network appears to be very effective in enhancing the switching performance. Six UV curable formulations containing various concentration of comonomers, PEGMA (polyethyleneglycol methacrylate) and PEGDMA (polyethyleneglycol dimethacrylate) were coated onto a 5 mil ITO/PET film (OC50 from CPFilm, Martinsville, VA) and embossed under pressure at 90°C to form a series of 3µm (width and length) x 4µm (depth) x 2.5µm (partition) Microcup® arrays. Single layer, filled and sealed Microcup® arrays were prepared using the same liquid crystal composition and sealing layer as described previously in the preparation of the sample for Figure 4B.

As shown in Table 1, significant improvements in both t_{on} and t_{off} may be achieved by incorporating the speed enhancing functional group into the Microcup® network. By optimizing the compositions and structure of the Microcup and LC phases, a threshold voltage of about 3 volts and a clearing voltage of 10~12 volts have been demonstrated. A reorientation field of less than 1 V/µm has also been observed.

Ingredient (parts)	Run# 1	Run# 2	Run# 3	Run# 4	Run# 5	Run# 6
UV oligomer 1	55	50	48	42	40	40
UV oligomer 2	45	45	45	45	45	45
PEGMA	0	5	7	13	15	0
PEGDMA	0	0	0	0	0	15
Photoinitiator 1	1	1	0.4	0.4	0.4	0
Photoinitiator 2	0	0	0	0	0	0.5
Oxygen Scavenger 1	0	0	0.2	0.2	0.2	0
Oxygen Scavenger 2	0.5	0.5	0	0	0	0
t_{on} (msec)	4.0	2.0	0.5	0.9	0.5	0.5
t_{off} (msec)	23.2	12.5	11.0	9.5	23.0	16.0

Table 1. The effect of speed-enhancing comonomers on the t_{on} and t_{off} of single layer Microcup® LCDs.

CONCLUSIONS

A new type of dispersed liquid crystal system, Microcup LCD, has been developed using the SiPix roll-to-roll process. The display has shown negligible hysteresis, fast switching rate, and a reorientation field less than 1 V/µm. Since almost all the compositions of the Microcup®, LC, dye, and sealing layer may be optimized independently, this new type displays provides extremely wide formulation and process latitude. Unlike the PELC system, no complicate synthesis and purification processes is involved in the making of Microcup® LCDs. High performance reflective displays or shutters using uniform cups of various size and shape have been demonstrated with an extremely low manufacture cost. Color Microcup® LCDs may be realized by either laminating a monochrome display onto a color filter, or by sequentially filling and sealing liquid crystal phases comprising R, G, and B dyes in the Microcups(7,8).

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