16- 4: Sliding Plastic Rollable Bistable LCD

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Abstract
We developed a rollable bistable LCD whose substrates are bonded by elastic glue and slide over one other when the LCD is rolled. We produced a 2.5 inch active area, 16x16 pixels prototype and demonstrated multifold bending and rolling of the display in a tube with 2 cm diameter.

1. Introduction
The demand for light weight, thin, shock resistant and inexpensive displays for smart cards, mobile phones, pocket computers, etc. requires substituting the traditional glass LCD for a plastic one [1]. The present use of displays in modern mobiles phones, PDA's and even smart cards does not currently require the displays to bend, thus plastic LCD's of the first generation are usually flat and have a rather low flexibility. However, future market trends require that the second generation plastic LCD's not only bend but should even be rolled into a tube – development of such displays will allow the manufacture of tube-shape computers, mobile phones and pocket computers with relatively large extendable screens.
Physical and chemical properties of plastic substrates differ greatly from the properties of glass ones. Therefore, production of plastic LCD's required development of novel technology and materials. The technology of first generation plastic LCD's includes low temperature deposition of ITO, micro-structured substrates, barrier polymers layers, etc. [2]. Development of the second generation plastic LCD's is a tough technological challenge due to the extremely complicated mechanical stresses exerted on the display when bending.
The technologies developed for 'low-flexible' first generation LCD's is often not valid for second generation 'highly-flexible' or 'rollable' LCD's for the following reasons:
-Low-flexible plastic LCD's are made from rather thick (100 - 200μm) plastic films (usually made from polycarbonate, polyethylene tetraphthalate (PET) polyethylene naphthalate (PEN) polymers), which are not soft and elastic enough to escape spatially modulated transversal deformation of the bent substrates.
-The mechanical properties of ITO electrodes and the polymer substrates are dissimilar – polymer is a relatively elastic and soft material and ITO is an amorphous glass-like rigid matter, thus a fracturing of the electrode structure on the polymer surfaces occurs when the substrates are bent or flexed.
-Highly-flexible LCD's require specialized design for the connection of the electrode pattern to the driving chips and printed circuit board (PCB).
-Low-flexible plastic LCDs are usually sealed around the periphery and spacer beads are glued to both the substrates. When the gap of the cell is maintained by the micro-profiled structure of the substrate, the top of the profiled structure is also tightly sealed to the second substrate. In this case mechanical deformations are concentrated on the edges of the cells and near the spacers when the structure is bent, resulting in a mechanical break of the LCD after relatively few manipulations.
In this paper we report on a new approach for production of highly flexible, second generation plastic LCD's. The main concept of the work was to avoid severe local mechanical deformations of the display by allowing the substrates to slide relatively freely over one other during the bending process.
We fabricated and tested the prototype of a 16x16 pixels. 4 x 4 cm active area bistable sliding cholesteric LCD. The display consists of two 50 μm thick polymer substrates with LC in between. The spacer beads are fixed on only one of the substrates. The LCD cell is sealed over the contour by glue, whose elasticity deformation range is greater than the shift between the substrates at the rolling of the display. During the bending of this LCD, the substrates slide over one other experiencing almost no mechanical stresses owing to the fact that the elastic glue has very low Jung module. We have successfully carried out multifold bending and rolling of the display in a tube with 2 cm radius up to 1000 times without any loss or damage to its electro-optical and mechanical characteristics. The next prototype, of a 160 x160 pixels, 4 x 4 cm active area made with the same technology is currently underway.

2. Results

2.1 Structure and preparation
The schematic structure of the sliding LCD is presented in Figure 1. The substrates were made from 50μm-thick films of PET (DuPont Teijin Films) and prepared by ion cleaning in argon-oxygen plasma. The electrode stripe pattern on the inner surface of the top substrate was formed by deposition of transparent ITO

films by magnetron sputtering of In (95 %) and Sn (5 %) in a gas mixture of Ar (70 %) and O_2 (30 %). The ITO film was formed during 15 min at the density of the magnetron current I = 6 – 8 mA/cm^2 and voltage U = 550 V in the camera with the gas pressure P = 2.6 10^{-3} mPa under the temperature T = 80°C. The film was bombarded by Ar and O ions during the deposition to gain its transparency. The films obtained had the surface resistance R = 20 Ohm/□ and the transparency T_0 = 92 % (λ = 550 nm). The electrode stripe pattern on the inner surface of the bottom substrate was made in black and had the same resistance as the top substrate.

2.2 Performance and testing

The specification of the sliding LCD is presented in the Table and the photo of the prototype can be seen in Figure 2. The displayed image was recorded in the flat state of the LCD. This image was spoiled in the rolled state and electronically recovered or updated after unrolling. It should be noted that the recorded image persisted during bending of the LCD up until about a 2 cm radius. One could also a record of the image during the bending range.

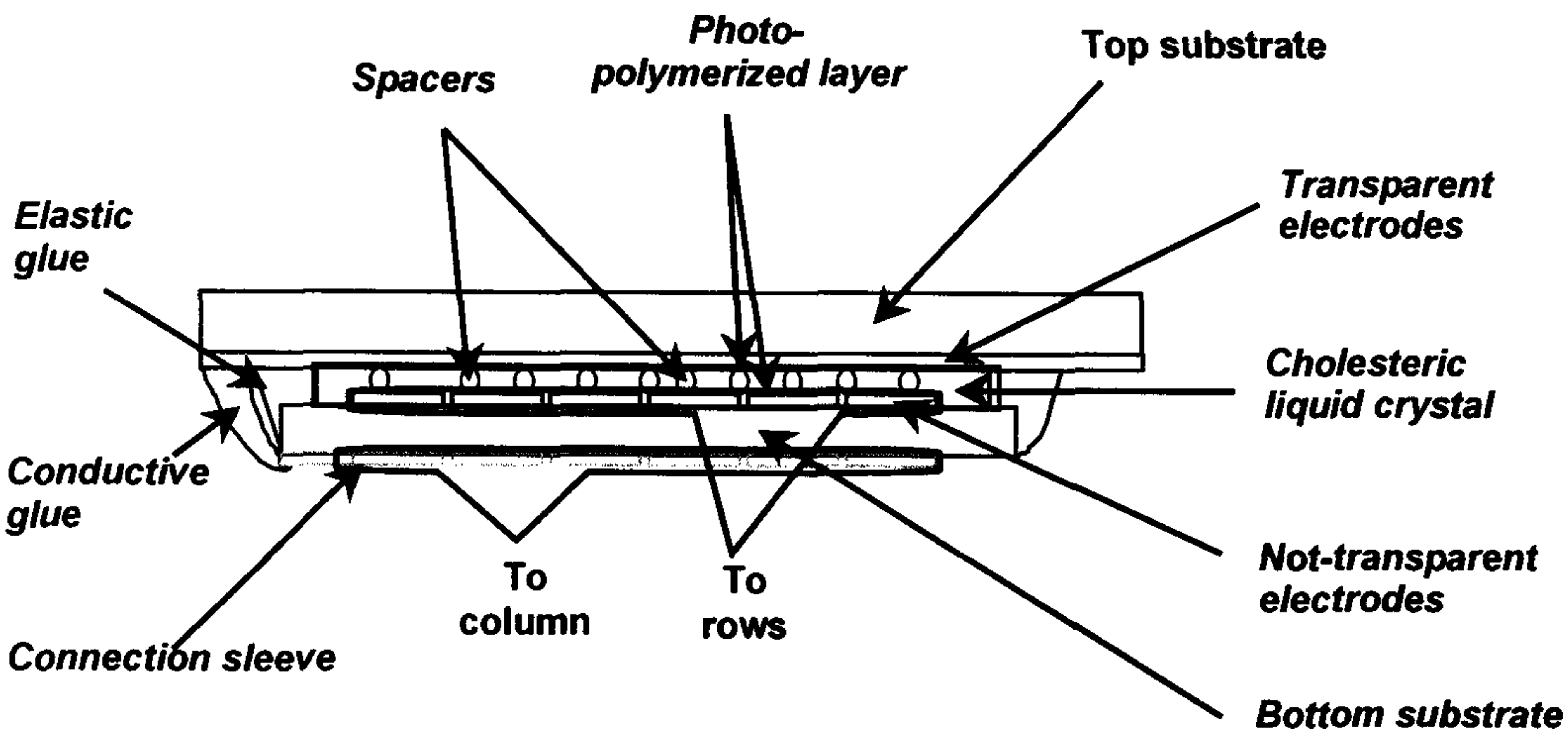

Figure 1: Design of the sliding LCD.

The connector of the electrodes with the PCB was formed on the outer surface of the bottom substrates and joined to the electrode strips by the conductive glue. The outer surface of the bottom substrate was laminated by thin polymer film.
The 4.5μm spherical spacers (Sekisui Chemical) were homogeneously distributed over the bottom substrate by spin-coating of their dispersion in a mixture of UV-curable elastic glue NOA-65 (Norland Products Inc.) with isopropyl alcohol. The following UV-irradiation of the spin-coated layer resulted in fixing of the spacers on the bottom substrate, which surface concentration was about 10^3 cm^{-2}.
Polyurethane based elastic glue DP610 (3M) was deposited over the contour of the bottom substrate using screen-printing technique. Then the substrates were assemble and sealed by pressing them together in a plastic vacuum pocket at 80 °C. The LCD cell was filled with cholesteric LC BL-126 in a vacuum filling chamber and finally sealed with the glue. To increase a contrast of the image, the cholesteric LC was doped by sub-micron ferroelectric particles $Sn_2P_2S_6$

Display mode	Reflective cholesteric bistable mode
Flexibility	Can be rolled in a tube with 2 cm diameter
Operation temperature	-10 ~ 80 °C
Contrast ratio	5:1
LC thickness	4.5 μm
Pixels number	16 x 16
Pixel Size	2.54 x 2.54 mm^2
Driving mode	Dynamic driving scheme [3]
Operating voltage	±17.5 V
Updating time	50 ms
Weight	0.75 g

The tests of the LCD parts and the prototype demonstrated rather high stability to bending. The conductivity of the ITO electrodes did not change after 15,000 manipulations of the substrates in a tube, within the range of the experimental error (< 1%). We have successfully carried out multifold rolling of the display in a tube with 2 cm diameter up to 1000 times without any loss or damage to its electro-optical and mechanical characteristics. We have also not observed any changes in the LC textures that potentially could have appeared due to friction of the spacers over the top

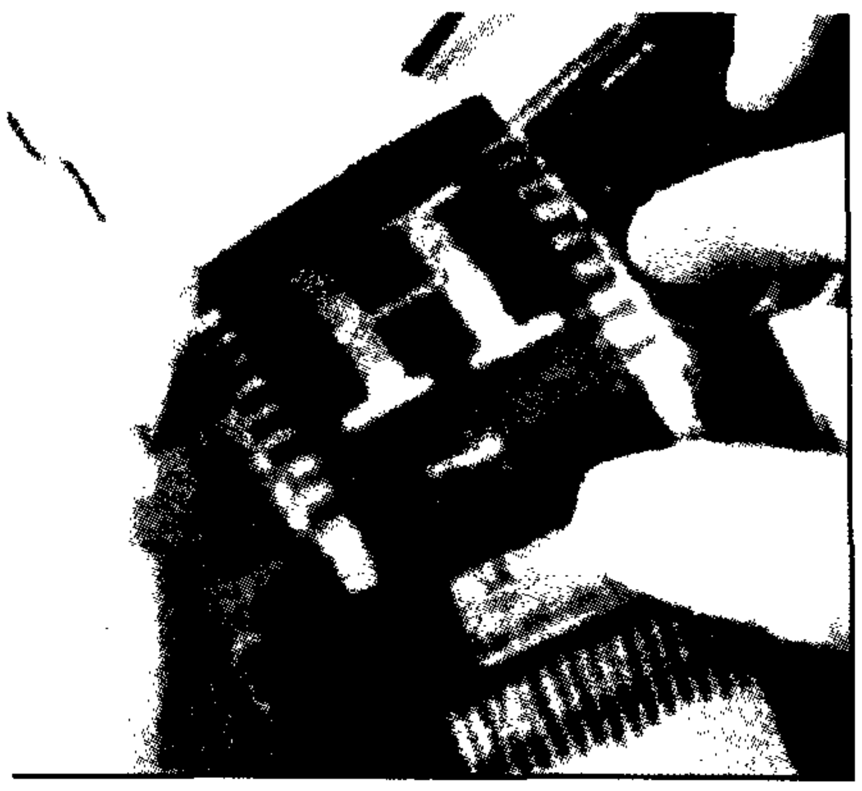

Figure 2: Prototype of 16 x 16 pixels sliding LCD.

substrates. In some instances however, depressurization of the LCD occurred after this number of cycles. Some of the samples kept their properties up to 3,000 bending cycles. We also observed appearance of 'black dots' (up to 0.5 mm diameter) in LC after the LCD manipulation. The appearance of these dots was random; on occasions they appeared after several manipulations cycles and in other cases after hundreds of cycles. Taking into account imperfection of equipment used for the prototype manufacture, we can confirm the high reliability of the sliding LCD.

2.3 Discussion

The specific feature of the sliding LCD is a shift of the substrates over one other when the LCD is bent or rolled. The LC gap does not change essentially while rolling, and the longitudinal shift between initially counter points increases in a linear fashion towards the edge of the substrates. The maximum longitudinal shift between the substrates is achieved along their edges; $\Delta x_{max} = \frac{\pi n}{180^o} d$ (d is the LCD gap, n. is the rolling angle). For instance, at the rolling of the LCD in a tube, $\Delta x_{max} = 2\pi d$. The elastic glue film follows the shift of the substrates during the bending of the LCD (see Figure 3).

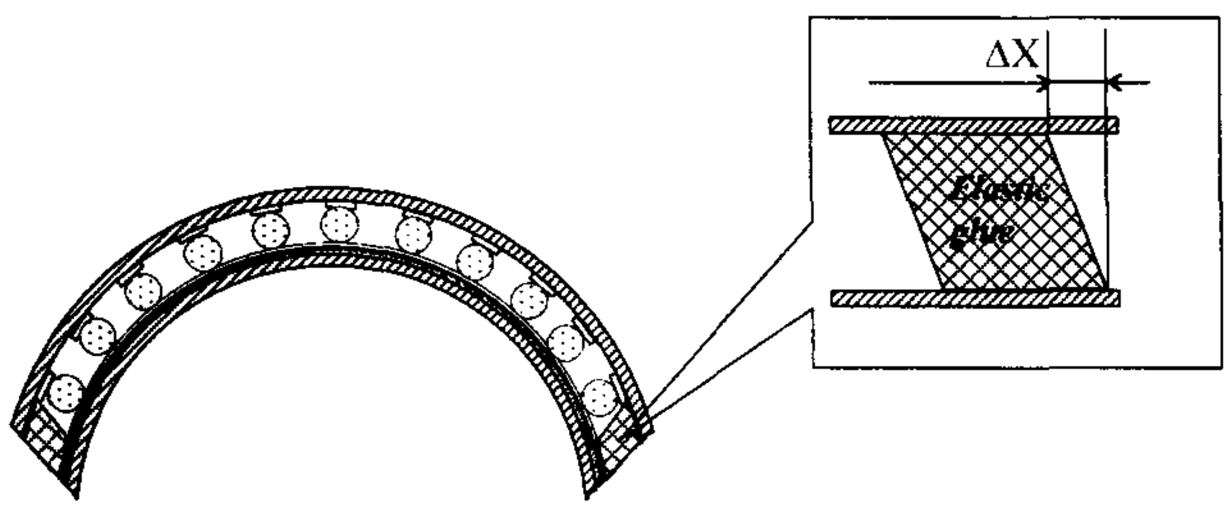

Figure 3: Elastic deformation of sealant in bended LCD.

The expansion of the hermetic glue film during bending and rolling of the LCD alleviates excessive mechanical stress at the edges of the substrates. Unrolling of the LCD results in the back shift of the substrates and the recovery of their initial position, since the elastic range of the glue film deformation is much larger then Δx_{max}. As has been previously mentioned, we did not observe essential changes in the electro-optical characteristics of the device up to 1000 rolling cycles. The only serious problem we have found is the appearance of the 'black dots' after the rolling of the display. In the Ref.4 it was shown that the dark spots are mainly caused by air bubbles that are induced from outside of LCD due to change of the volume inside the display during the bending. Another cause of the dark dots is a gas inherently dissolved in the LC. In the case of the sliding LCD the black dot problem becomes more apparent when the penetration ability of the elastic glue is larger than the common rigid sealant, and the gap between the substrates changes during the bending of the LCD. At the same time we believe that the black dot problem can be solved by choosing a proper elastic sealant, increasing of its film width, previous degassing of the LC and sealant, and by improving a design of the substrates. The manufacturing of the improved 160 x 160 prototype with the pixel size 276 x 276 μm is currently underway.

3. Conclusions

We fabricated and tested the prototype of a 16x16 pixels, 4 x 4 cm active area bistable sliding cholesteric LCD. The main feature of the prototype is the possibility for the substrates to slide over one other during bending and rolling. We successfully carried out multifold bending and rolling of the display in a tube with 2 cm radius up to 1000 times without any loss or damage to its electro-optical and mechanical characteristics. The main problem we observed during the test of the sliding LCD was the appearance of the 'black dots' in the LC. The manufacturing of the 160 x 160 prototype with the pixel size 276 x 276 μm is currently underway.

4. Acknowledgements

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