Research Trends of Flexible Liquid Crystal Displays

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***Abstract* – Nowadays, preparing for next generation display devices, flexible display technologies are widely studied and developed. Due to the use of the flexible substrates, there exit several kinds of obstacles to be solved. In this paper, we will introduce various kinds of flexible display mode, related issues and our works in order to overcome some obstacles.**

Index Terms* – *Flexible Display, Display mode, e-paper, Plastic, LCD,.

I. Introduction

For the past 10 years, flat panel display (FPD) technology has been greatly advanced and at last exceeds the market of cathode ray tube(CRT) displays, which reflect the evolution of trends from heavy and large displays to slim and light displays. Nowadays preparing for new generation and replacing the glass substrate by plastic substrate, flexible display devices are widely and extensively studied for the purpose of use in applications such as smart cards, PDA, head mount displays and all kind of mobile display because of their lighter weight, thinner packaging, flexibility, ruggedness and reduced manufacturing cost through continuous roll processing [1].

Currently, there are two ways of development of flexible displays according to type of applications. One is approach as paper, and the other is approach as display which can show moving images like the conventional FPD. Fig. 1 shows various kinds of applications of flexible displays such as wearable display, personal health indicator, smart card or sign boards.

In developing the flexible displays, there are many kinds of obstacles to be solved such as substrates itself due by flexibility, process conditions and display modes. Most of the flexible displays, the plastic is used as substrates since plastic is transparent, rugged and flexible. But its glass transition temperature is low, it is needed to use low temperature of fabrication processes. In this paper, we will introduce briefly flexible display modes, especially flexible liquid crystal display modes and technical trends. And we will give perspective of market trends and concluding remarks.

II. Flexible Display Modes

Many kinds of display modes such as OLED (Organic Light Emission Diode), EPD (Electrophoretic display) and LCD (Liquid Crystal Display) are extensively studying for the purpose of application to flexible displays. Fig 2 shows the various kinds of prototypes of flexible display modes.

First let us consider the flexible display as paper. For the application of flexible displays as paper, bistable reflective display modes are commonly used since bistability means maintaining the display information although the external power is turned off and reflective display can use the environmental light, for example sunlight, which minimize the power consumption. Let us briefly introduce the display modes suitable for this application.

- Bistable Reflective flexible display mode

The one of the well-known mode of this application is EPDs developed by E-ink. EPD use ink particles embedded in thin films (Fig.3). The ink particles are positive and negative charged, respectively, and according to the polarity of external electric field, each charged particles with black and white

Fig 1 **Various examples of flexible display applications**

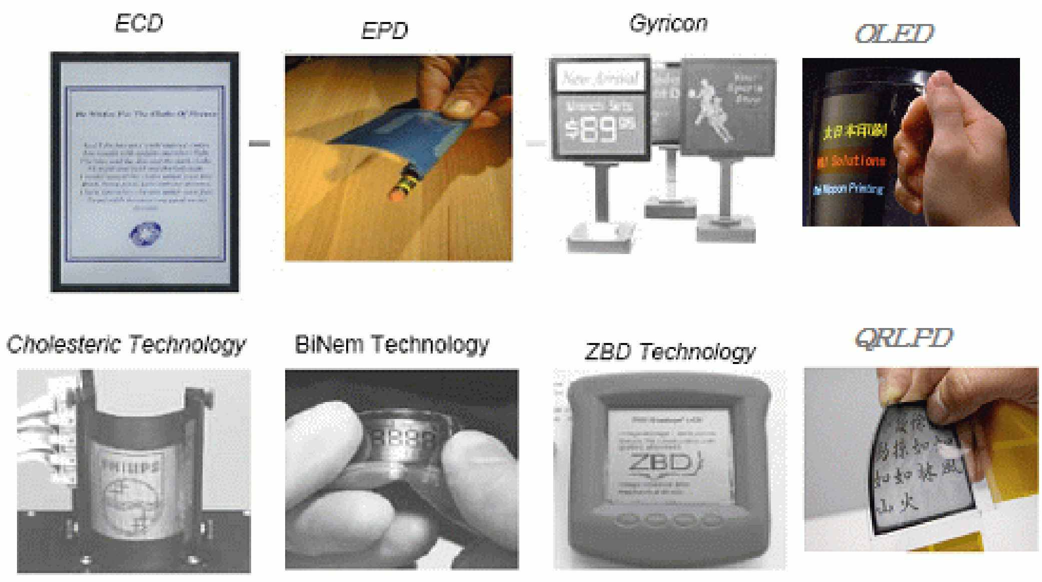

Fig 2 **Flexible Display Modes**

colors move upward and downward inside microcapsulated fluid [2]. Therefore EPD can exhibit black and white information and without external field the colors of each pixel is maintained. E ink developed color EPD with two different method. One is to use microcapsules containing colored reflecting balls. The other is using colored reflecting layer (color filter) where capsule layer act as shutter.

Reiji Hattori at Kyushu University have developed also electrophoretic panel, termed the Quick-Response Liquid Powder Display (QRLPD) which can be operated using passive matrix addressing and commercialized by Bridgestone corporation (Fig. 4). Specially treated pigment particles are used in QRLPD and operated in air gap rather than in a fluid. The charged pigments moved toward electrodes according to polarity of external field through air. Same as for EPD, the charged pigment show colors black and white and without external field the information is maintained.

Gyricon displays use rotating balls with two or more colored inks. Gyricon media, a company spun out from Xerox, the balls are held in oil-filled cavities within plastic sheets and can be rotated by the application of electric fields but due to the friction with the cavity surface, it can shows the memory effects when the field is removed. Operating voltage is about 50V and memory time is longer than 6 months.

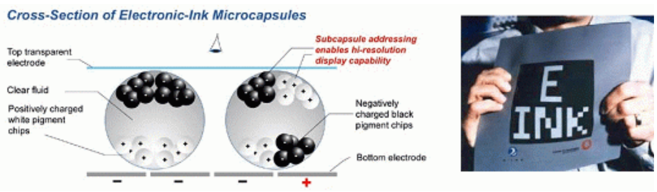

Fig 3 **Electrophoretic display mode**

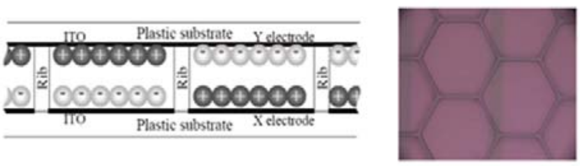

Fig 4 **Schematic illustration of pixel operation and hexagonal Rib structure of QRLPD**

Electrochromic display (ECD) is rather different operation mechanism unlike the display mode mentioned before with a view point of mode structure. Electrochromism is a reversible color change in a material caused by an external field or current. The molecules, such as viologens, change their color through the addition or loss of an electron, which result in color information. Researchers in Sweden, the University of Uppsalaand the IVF Industrial R&D corporation developed ECD panel with response time of 200ms with switching times below 2 ms.

In the approach of liquid crystal based display, the well-known display mode is using cholesteric liquid crystal. In cholesteric liquid crystals, the molecules form a helical structure and intensity of Bragg reflection is used as information display. The pitch of helical structure affects the reflected wavelength band. Cholesteric liquid crystal have two bistable stable structures, called planar and focal conic states, respectively, as shown in Fig. 5. Bragg reflections is high in the planar state and weak scattering in the focal conic states. For the case focal conic state, the light is absorbed by absorption layer coated on one substrate. The two bistable states are transformed by applying electric field. At the beginning of cholesteric displays, the operating voltage is about 100 V and nowadays by implementation of driving scheme and liquid crystal materials, it is reduced about 35V which can be used STN drivers.

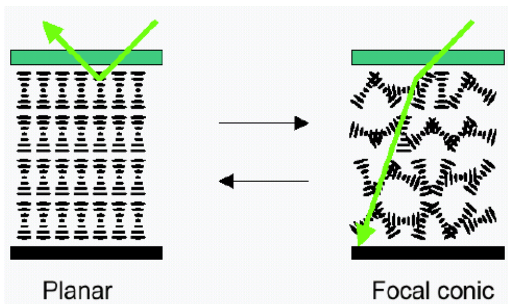

Fig 5 **Bistable modes of cholesteric liquid crystals**

Since the Bragg reflection depends on viewing angle, by addition of small amount of polymer which is polymerized by UV exposure, wide viewing angle and mono display can be achieved [3]. Recent researches on cholesteric displays are focused on color representation. There are two approaches, one is multilayer method which use stacking of each Red,Green, and Blue layer. The other is realization by single layer through several methods of color separation (Fig 6). But in multilayer, due to the complexity of electrodes and fabrication process, currently many approaches are conducted using single layer such as LC injection by pixel by pixel, color freezing using polymerization or control of helical pitch by electric field.

The other bistable liquid crystal modes are surface stabilized ferroelectric liquid crystal (SSFLC) mode and bistable nematic modes such as binem LCD and zenithal bistable display(ZBD). SSFLC uses the ferroelectric phase of liquid crystal stabilized by surface with very thin cell gap of 1um. It shows very fast response time of few microseconds but due to the layerd structure of ferroelectric phase, it is difficult to obtain uniform alignment which makes it difficult to applications. Nemopic has developed bistability using standard polyimide rubbing layers, through strong anchoring on one surface and weak anchoring on the other. This binem display mode shows two stable states, one is uniform alignment and the other is 180 degree twisted. The two states can be transformed into each other by applying electric field. Although this display uses two polaizers, reflectance of 30% has been achieved over a sufficiently large viewing angle. Another bistable nematic mode is ZBD which is being commercialized by ZBD displays. This mode also uses strong and weak anchoring but in this case, the strong anchoring is obtained by creating a grating on one surface. Two stable states can be formed, one with high tilt close to the grating and one with a low tilt states The two states show extremely stable against external shock. Since the Binem LCD and ZBD modulate the polarization of light, unlike cholesteric LCD, they are sensitive to cell gap which restricts the flexibility of display. Fig 7 shows the comparison of performances of various reflective display modes including paper. Commonly, the operating voltages are relatively high with compared that twisted nematic display.

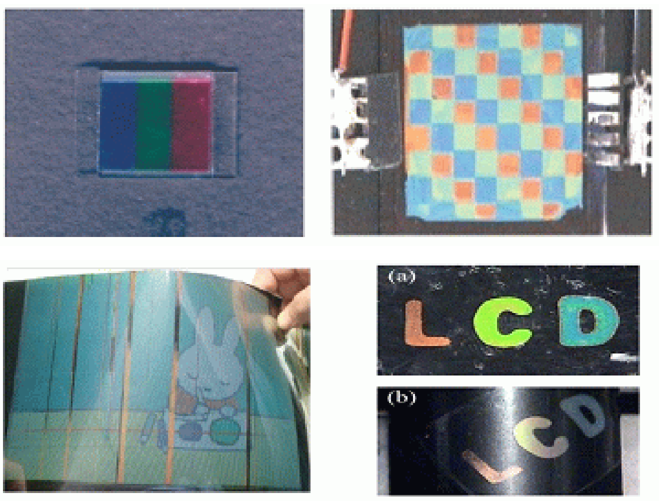

Fig 6 Samples of realization of full color cholesteric display with single layer

Display type / Parameter	Paper	Cholesteric LCD	Gyricon	Electro-phoretic	Reflective TN-LCD
Contrast	20:1 laser print 7-10:1 newspaper	20-30:1	10:1	10-30:1	< 5:1
Reflectivity	80% laser print 50% newspaper	40%	20%	40%	< 5%
Viewing angle	All angles	All angles	All angles	All angles	Narrow
Flexibility	Yes	Moderately	Yes	Yes	No
Full color	Yes	Yes	No[a]	No[b]	No
Reflection type	Lambertian	Near Lambertian	Lambertian	Lambertian	Highly specular
Response time	-	30-100 ms	80 ms	100 ms	20 ms
Max. voltage	-	40 V	90 V	90 V	5 V
Substrate	-	Plastic or glass	Plastic or glass	Plastic or glass	Glass
High-resolution drive scheme	-	Passive	Active	Active	Active

[a] Development is under way of colorful cell stacks for subtractive color techniques
[b] Color filter arrays may be possible * TNLCD: Twisted nematic liquid crystal display

Fig 7 **Comparison of performances of reflective displays**

- Flexible display with Dynamic mode

We briefly introduced the display modes for flexible displays as paper. The realization of moving picture using flexible display is also widely studied in many institute and companies. OLED may be one of the good candidate for this application since it can be made from very thin film. But there are several problems in application such as sensitivity to oxygen and water of OLED material, high driving current and TFT arrays for high resolution OLED. Moreover OLED is still challenging to flat panel display market which means OLED technology is not matured sufficiently. On the contrary the LCD has advantages in their full growth of fabrication technology in FPD and efficient light-control capabilities with low power consumption [4-7]. We here focused on the LCD mode for flexible display applications. When we apply the conventional LCD mode to flexible display, due to use the flexible substrates, there exist basic obstacles in fabricating plastic LCD. One is mechanical instability of LC modes, and the other is adhesion of two substrates because flexible displays always experience pressing and bending stresses [8].

In order to overcome the above underlying problems, polymer walls [9] and/or networks as supporting structures have been proposed and demonstrated. However there are some drawbacks in using these methods, such as high electric field in fabrication process, residual polymers in active region which can reduce display quality significantly and increase the operating voltages. To solve the above problems, we have proposed pixel-isolated liquid crystal (PILC) mode [10]. In PILC mode, the LC and polymers are fully separated in horizontal and vertical direction therefore we can minimize the residual polymers in active LC regime as shown in Fig 8. Fig 9 shows

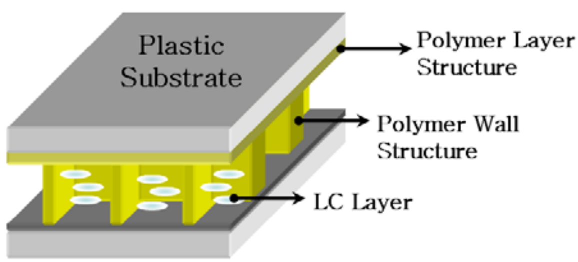

Fig 8 Schematic diagram of PILC mode

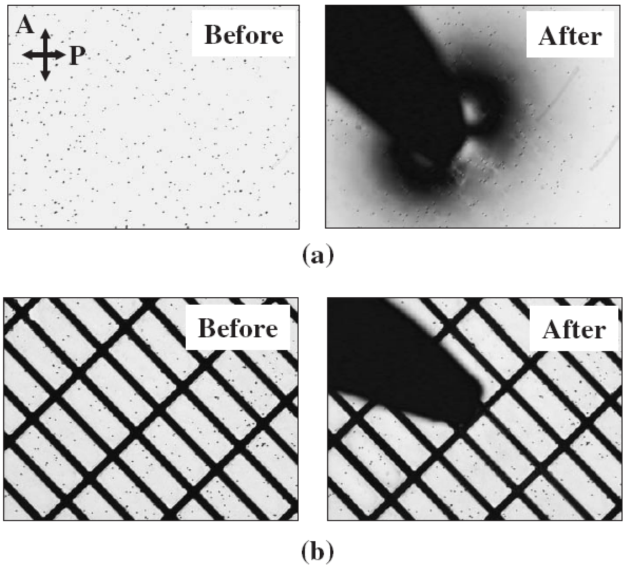

Fig 9 Microscopic textures of normal plastic cell and PILC structure before and after point pressure on (a) normal cell and (b) PILC cell.

the mechanical stability of PILC structure under external point pressure [11]. We compared the results with normal plastic samples without PILC structure. We prepared a normal LC cell under the same fabrication condition except mixing with prepolymer. The cell gap was controlled by spacers. Fig 9(a) and 9(b) show polarizing microscopic textures of the normal and PILC cells in the presence of an external point pressure with a sharp tip, respectively. Under the same amount of pressure, the alignment texture of normal sample was severely distorted due to the cell gap variation. This means that spacers between tow substrates in the normal cell do not resist LC molecular reorientation induced by the pressure. The distortion of LC molecular propagates over a sufficiently large area as shown in figure and degrades the display quality. However, the PILC cell showed no appreciable changes since the LC molecular reorientation is restricted in pixels by the vertical polymer wall structure and can not propagate to other pixels. These polymer walls act as supporting structures to maintain the cell gap from external pressure and bending. The dispersed small dots in the figure are glass spacers. Figure 10 is prototype of 3 inch size of LC sample with PILC structure. The resolution is 124 × 76 with a pixel size of 500 × 500 μm^2 and polymer walls are well formed throughout the sample.

Fig 10 3-inch size LC sample using plastic substrates with pixel-isolated liquid crystal structure

Fig 11 Prototypes of applications using flexible liquid crystal displays

Fig 11 shows the prototypes of applications using liquid crystal mode such as TN or STN. One of the aim of developing the flexible liquid crystal mode is replacing the glass substrates by plastic substrates because of cost reduction, ruggedness and robustness. Therefore curved displays which allow a little bending will be appear in the market at the early stage of flexible display.

III MARKET PERSPECTIVES

Since flexible display is at the stage of developing, there are various market perspectives. At the beginning stage, replacing glass by plastic substrate in small size display and application to e-paper will be appear. As the flexible technologies are growing, as shown in Fig 12, replacing large size FPD and new market of LCD and OLED is expected to be appear. But the main moments of market growth are small and medium size of flexible display in mobile display and e-paper. According to report of Displaybank at 2007, the market will be about $280 million in 2010 and the market could grow as much as $12 billion by the year 2017.

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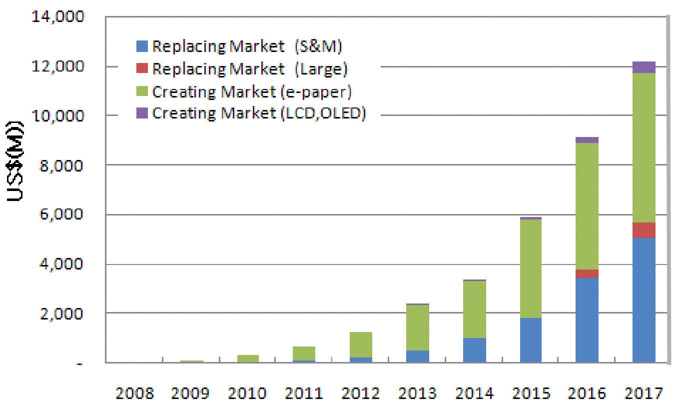

Fig 12 Market perspective of flexible displays (Displaybank 2007)

IV SUMMARY

We introduced the various display mode for flexible display applications. We also introduced the some basic obstacles when we apply conventional LCD mode to flexible displays. Surely, there are many flexible display modes besides LCD. Each display mode has pros and cons. But as we mentioned in market perspectives, flexible display market will be new moment of growth of display industry. Moreover, by using flexible substrates such as plastic, it is possible to fabricate by roll-to-roll process which is more cost-efficient and providing more simple fabrication processes. Fig. 13 shows the schematic diagram of roll process for flexible liquid crystal display. We believe flexible display is the promising technologies as the next generation display.

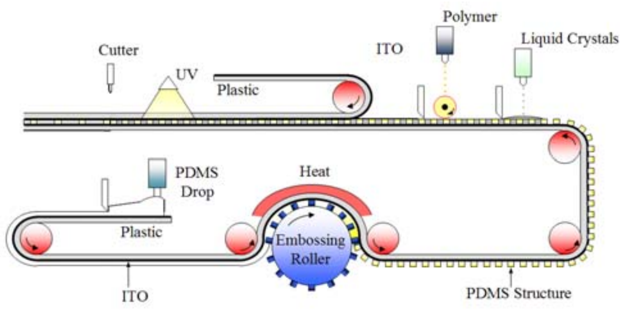

Fig 13 Schematic diagram of the continuous roll processing for fabrication of flexible LCDs

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