# Chapter 8
# Next-Generation Liquid Crystal Displays

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## 8.1 Flexible Displays

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### *8.1.1 Role of Liquid Crystal Displays in Information Society*

#### 8.1.1.1 Possibilities for Liquid Crystal Displays

The development of information industry in recent years is largely attributable to the eminent development of flat-panel display technology as an interface between people and information. The innovation of flat-panel displays will pioneer the possibility of new information services in the future. Even though there are many different display types including plasma display panels and organic light-emitting

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diodes, the liquid crystal display evolved from small to large area and used many different optical operation modes, such as projection, reflective, and semi-transmissive displays.

The evolution and adaptation of a liquid crystal display for various applications is due to the basic principle of being a non-emissive display type. Because the two basic functions of light source and light modulation are separated, the individual performance can be optimized depending on the requirements and applications. In addition, elements of both technologies are rich in diversity, and by integration and combination, the degree of freedom in display design is large and extremely flexible systems can be achieved.

For example, large screen liquid crystal display currently have been developed that use glass substrate panels with a diagonal of more than 100 in. Such ultra-large screen displays become part of the wall and evolve into highly realistic video systems to even influence the lighting and atmosphere of the room. High resolution is also progressing with large screen liquid crystal panels, beyond the current high-definition (1,920 × 1,080 pixels), towards ultra-high-definition panels (4 K system; 3,840 × 2,160 pixels and 8 K systems; 7,680 × 4,320 pixels) for next television broadcast services.

Liquid crystal displays are evolving in terms of image quality. Contrast characteristics have been improved by the innovation of the panel components and sophistication of the liquid crystal alignment control. A drastic improvement of contrast ratio is possible by dimming control of the backlight. In addition, dynamic and local control of the backlight has become an effective method to save power and its importance has increased recently. Also in terms of color reproduction, the use of light-emitting diodes in backlights in recent years and the introduction of laser diodes in the near future will further enhance color gamut of liquid crystal displays. The quality of the video images has been greatly improved by increasing driving frequency and frame rates of the liquid crystal panels.

On the other hand, the current panel manufacturing technology has reached a mature stage and a paradigm shift is required in order to promote industrial development and new applications. In that sense, flexible displays are the most promising next-generation technology of a new concept. Displays turned from box-type cathode-ray tubes to thin flat-panel displays. The next step is to evolve into flexible structure at last. It can be said that the display is a human interface for communicating information and its appearance is going to be less and less felt.

#### 8.1.1.2 Impact of Flexible Liquid Crystal Displays

In science fiction novels and movies that deal with the near future, alongside with three-dimensional holographic displays, displays that can be folded have appeared frequently as future technology items. However, the specific path for the realization of such a flexible display has become clear as recent flat-panel display technology is maturing. At present, the term “flexible display” is becoming more widely used, and it becomes essential as a next-generation display technology.

**Fig. 8.1** Possible applications for various flexible displays

By making displays flexible, the freedom of display design becomes spread borderless, based on their excellent portability, storability, and installability. As a result, a flexible display can create a variety of new human interfaces (Fig. 8.1). Therefore, it can be said that flexible displays form the ultimate evolution of flat-panel displays.

For example, by carrying a display panel, in conjunction with a wireless network technology, it is possible to easily enjoy various information contents and to promote a ubiquitous information society. In the recent past, even medium-sized displays have required a bag to carry, but flexible displays can be stored in a pocket. The effect of flexible displays is particularly prominent on the video service field, using portable tablet devices to enjoy realistic images. The advantages of flexible displays are enhanced for large displays. Superlarge screen displays used for the next-generation Super Hi-Vision with a diagonal of 100 in. or more can be easily installed in the home by carrying a roll through the door. In addition, space-saving curved screens can be effectively used in room corners.

Such large and flexible displays will influence our daily necessities in a variety of living conditions. Therefore, we expect that the technology infrastructure provides a vast amount of real-time information services in the future to present necessary and appropriate information.

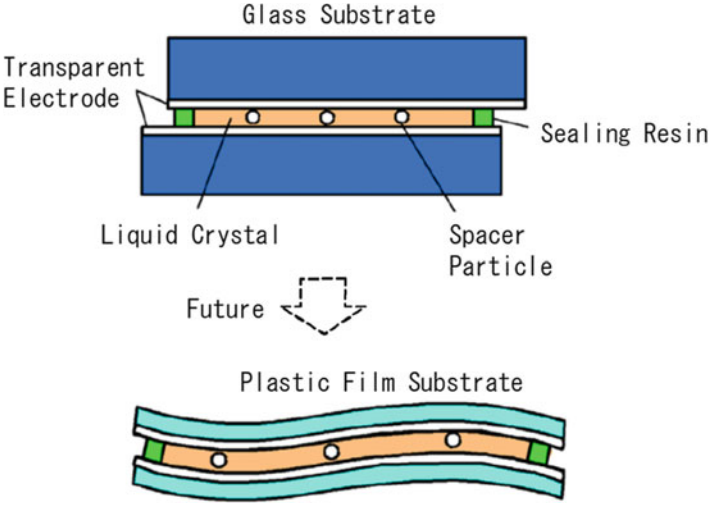


**Fig. 8.2** From hard to soft substrates in liquid crystal display panel structure evolution

Below, we will explain the basic structure and operating principle of flexible liquid crystal displays, their panel production method, design of the flexible backlight, demonstration of full-color display panels, and introduction of active matrix drive technology.

## *8.1.2 Towards the Development of Flexible Liquid Crystal Displays*

### 8.1.2.1 Advantages of Liquid Crystal Method

The large degree of freedom in system design is a big driving force for the evolution of flexible displays. One important tool to adapt flexibility for liquid crystal displays is a plastic substrate.

Currently, the thickness and weight of the liquid crystal displays have been reduced by polishing the two glass substrates. The introduction of a plastic substrate is its logic extension. Thereby, it is possible to realize a display panel that does not crack even though it is very thin and has light weight. By using a filmlike thin plastic substrate, it becomes possible to freely bend a liquid crystal panel (Fig. 8.2). Efforts towards flexible displays have been made not only in the field of the liquid crystal displays but also in the field of organic light-emitting diode. Various flexible display types have been proposed, and the liquid crystal method shows important advantages especially in the following three points:

1. Panel manufacturing and drive technology that have been accumulated for glass-substrate liquid crystal displays can also be used for plastic substrate, which will accelerate the development of large-area and high-resolution panels.

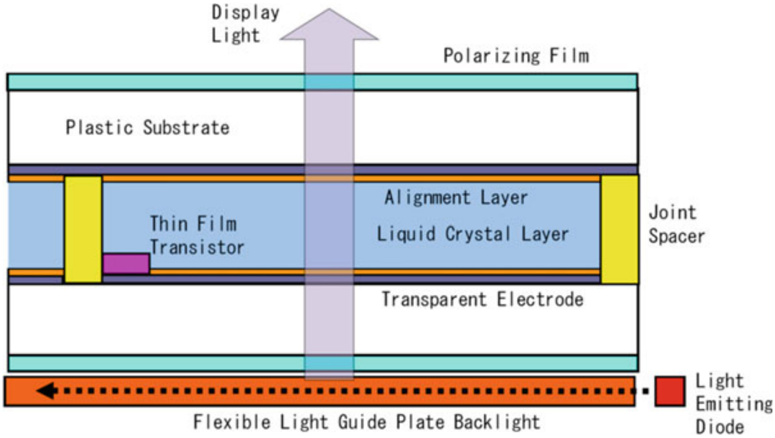


**Fig. 8.3** Fundamental device structure for flexible display

2. The time degradation of liquid crystal materials without electronically excited molecular states is not recognized in contrast to materials for organic light-emitting diodes. Therefore, stable display operation is guaranteed.
3. The backlight control can adapt to the illumination situation in various environments. Furthermore, power-saving displays are also possible.

On the other hand, the drawback is the complex panel structure that consists of several components, such as the two plastic substrates, two polarizers, and a backlight system, which is disadvantageous for ultrathin and ultrasoft panels.

#### 8.1.2.2 Technology Issues to Be Overcome

During researching device structure and fabrication (Fig. 8.3), concrete technical problems have been encountered. Main breakthrough technologies that are required include thin-film transistors to be formed at low temperature, spacer technology for stabilizing the gap between the substrates sandwiching the liquid crystal, flexible backlight, and the plastic substrate. Among them, the most pressing issue is the construction of a new spacer to improve the panel structure that holds the flexible plastic film substrates.

If you configure the flexible display by replacing the glass substrates with plastic substrates, fatigue fracture of the liquid crystal layer will not occur during bending, but the liquid crystal layer needs to be kept in a uniform thickness between the two substrates [1]. In flexible liquid crystal displays using plastic substrates, the thickness of the liquid crystal layer changes in response to a variety of external forces, and the light modulation characteristic is changed, which leads to distorted display images. In conventional rigid panels, particle spacers and post spacers have been used (Fig. 8.4) to tolerate compression force on the panel, but a new spacer concept is needed to tolerate both compression and expansion forces upon bending.

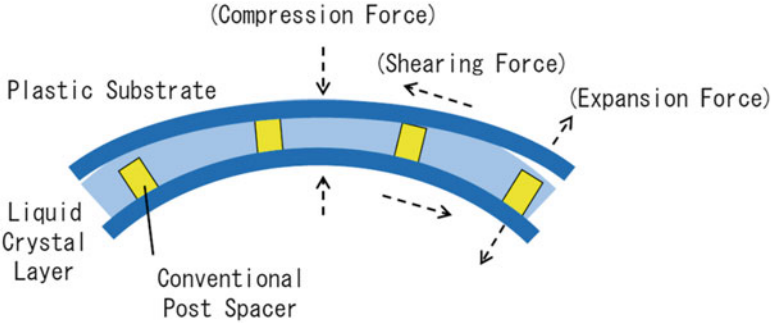


**Fig. 8.4** Deformation of plastic-substrate-based liquid crystal panel using conventional post spacers

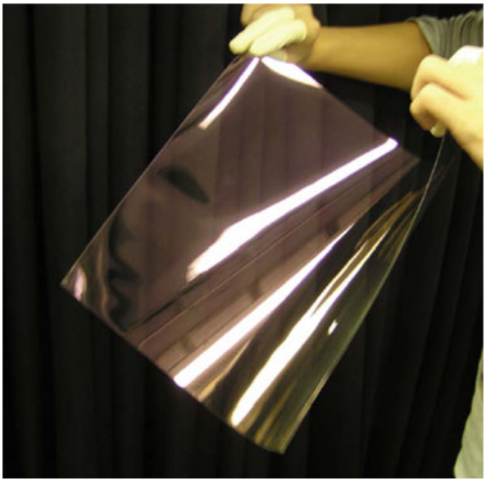


**Fig. 8.5** Photograph of flexible plastic film substrate

## *8.1.3 Spacer Technology Using Polymer Dispersion*

### 8.1.3.1 Liquid Crystal Polymer Composite Film

Therefore, a flexible liquid crystal panel consisting of two thin plastic substrates needs joint spacers to keep the plastic substrates in a constant and determined gap.

In order to realize a flexible video display with a large screen, we have investigated a flexible liquid crystal display using a microstructured polymer. The plastic film substrates (Fig. 8.5) of display panel are supported by a liquid crystal/polymer composite film that is a self-holding elastic sheet. This composite film is used as an adhesive and spacer and is also responsible for light modulation. Since the entire surface bonds the two substrates, it can withstand shearing as well as expansion force, and seal resin breakage of the panel outer periphery by stress concentration can be prevented.

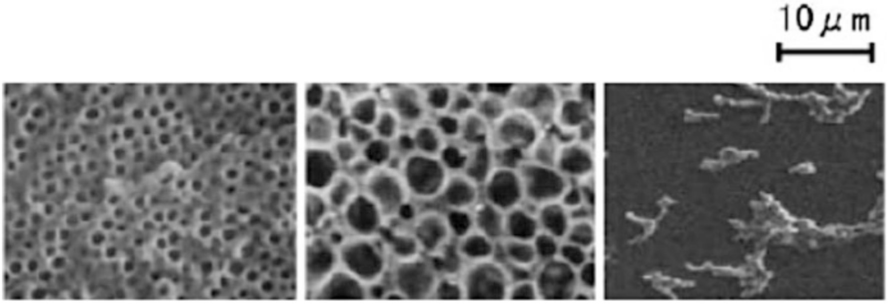


**Fig. 8.6** Morphological control of segregated polymers

In this composite film, the polymer structure must not disturb the liquid crystal alignment. That is, it needs to maintain the highly ordered liquid crystal alignment (that is indispensable for the high-contrast light modulation) in the dispersion structure of the polymer. Therefore, the composite film preparation uses the phase separation of polymer and liquid crystal materials with molecular alignment, as described below.

Recently, a method of forming a liquid crystal/polymer composite film has been invented in which a homogeneous mixture of the monomers and liquid crystal is polymerized. During polymerization, a phase separation occurs, because the polymer components become insoluble in the low molecular weight liquid crystal solution and aggregate.

Photopolymerization by irradiation with ultraviolet light irradiation [2] in particular is known as a method having excellent controllability of polymer dispersion structure. With decreasing monomer concentration, the aggregating morphology from phase separation changes from liquid crystal droplets to bubble-shaped cellular polymer structure and to polymer fiber networks, as shown in Fig. 8.6.

Thus we used a nematic phase mixture solution consisting of low molecular weight liquid crystals and liquid crystalline monomers (photo-curable monomer in which the acrylate group was directly and rigidly attached to the mesogen of liquid crystal molecular skeleton) that could easily be oriented between the alignment layers on substrates. Photopolymerization resulted in a phase-separated structure with a high purity liquid crystal and submicron polymer networks (Fig. 8.7). Thus, it is possible to construct the hard polymer fiber networks along the liquid crystal alignment direction, and the polymer networks also have a stable substrate spacing function [3]. Because the polymer networks are grown so as not to inhibit the molecular flow in the nematic phase solution with one-directional molecular alignment during the ultraviolet irradiation, fibers extending in the direction of the liquid crystal alignment are formed. In addition, after the polymer has cured completely, the networks play the role to stabilize the liquid crystal molecular alignment. Thus, a flexible liquid crystal device having good contrast characteristics becomes possible.

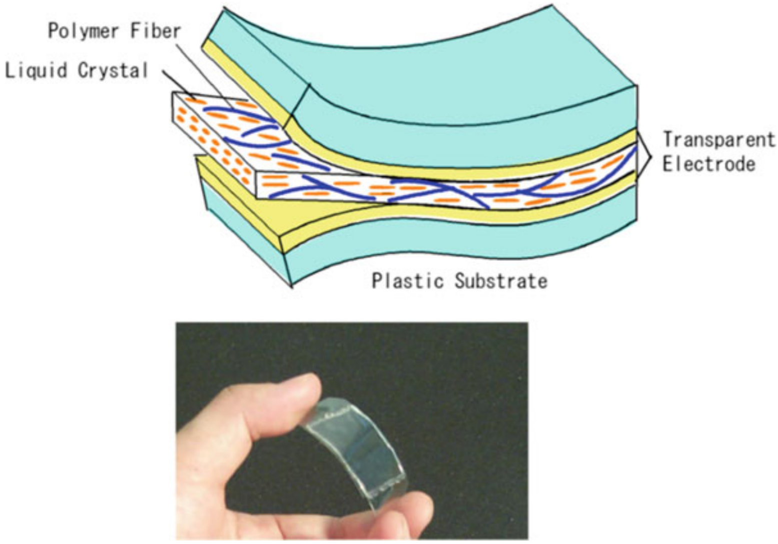


**Fig. 8.7** Flexible liquid crystal device containing polymer fiber networks (*top*, structure; *bottom*, photograph)

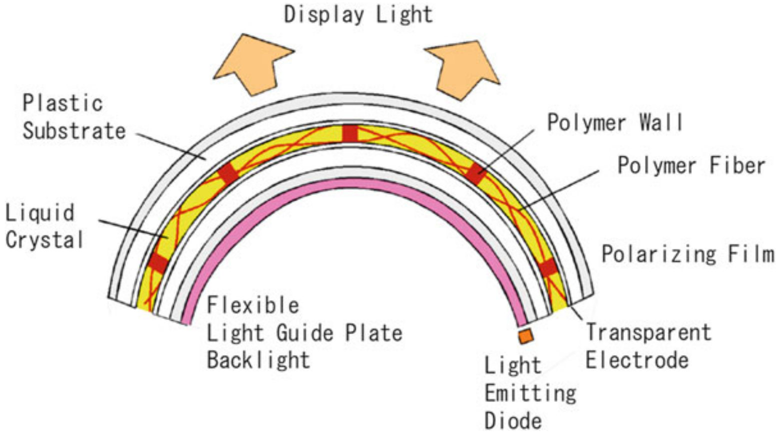


**Fig. 8.8** Total flexible display system using liquid crystal with polymer walls and fibers

### 8.1.3.2 Introduction of Polymer Walls

In order to enhance the bending resistance of the display panel as shown in Fig. 8.8, we decided that, in addition to a network of polymer fibers, lattice-shaped polymer “walls” [4] should be introduced. Furthermore, we developed an easy method in which two fine polymer elements of wall and fiber are separately formed from a

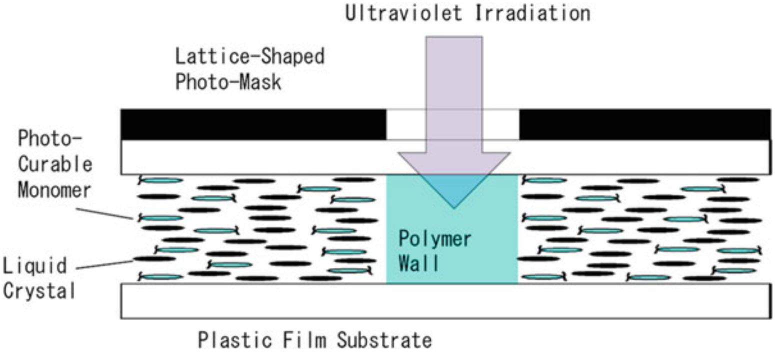


**Fig. 8.9** Forming principle of polymer walls in liquid crystal layer

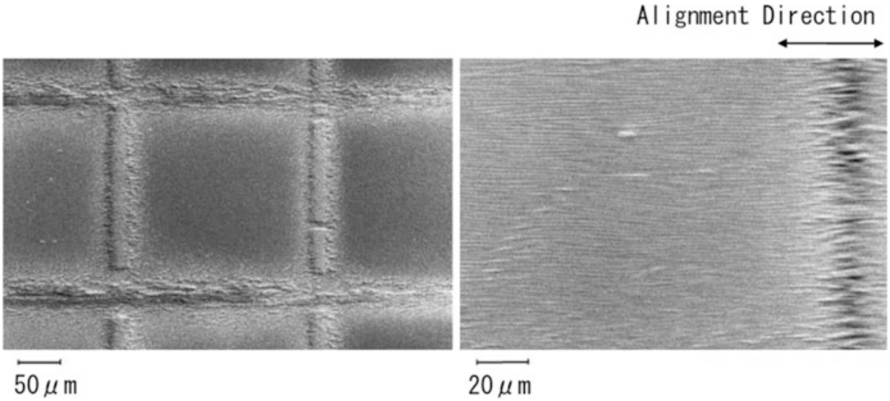


**Fig. 8.10** Scanning electron micrographs of polymer walls (*left*) and polymer fibers (*right*)

single monomer material. The polymer formation method utilizes two-stage exposure using ultraviolet light as follows.

The same monomer in the solution is used for both the wall and the fiber structures. Therefore, the concentration of monomer has to be increased. First, the wall-patterned exposure of ultraviolet light is made through an orthogonal lattice-like photomask (Fig. 8.9). The suspended monomer diffuses in the illuminated solution region and continues to aggregate. As the result, both substrates are connected by the segregated dense polymer wall.

Then the second ultraviolet exposure is performed after removing the optical mask. The concentration of remaining monomers which was left in the unexposed area leads to the formation of low-density polymer fiber networks in the display area of the device. Figure 8.10 shows the formation of the polymer networks and walls (the width of the wall is approximately 20 μm). From the figure, it becomes clear that the polymer surface morphology of the fibers and walls shows a significant anisotropy and an alignment in the rubbing direction of the polyimide alignment layers coated on the substrate.

This is because the polymer fibers and walls are formed in the molecular-aligned solution by oriented polymerization in the rubbing direction. Therefore, no birefringence of the formed polymer occurs under crossed Nicol polarizers, and a good contrast characteristic is easily obtained with suppressed black level in the off-state.

Incidentally, the use of polymer fibers and walls as spacer is not limited to future flexible display application; the spacer technique for bonding and fixing substrates is also useful in the practical usage field of superlarge glass-substrate liquid crystal displays. Those display screens are prone to a gap variation between the substrates due to the large weight of the glass substrates, which leads to image display distortions. If those screens could be made with the above adhesive spacers, this problem would be solved.

## *8.1.4 Introduction of Various Liquid Crystal Materials*

### 8.1.4.1 Ferroelectric Liquid Crystal

It is possible to use a liquid crystal material in various ways depending on the application in flexible display. In order to stabilize the substrate spacing, polymer walls and fibers allow also the application of ferroelectric liquid crystal, whose molecular alignment structure is conventionally known to be fragile and called as smectic layers.

For realizing a fast response display with excellent moving image quality, the ferroelectric liquid crystal [5] is thought to be an ideal liquid crystal material, but it is difficult to form stable and uniform liquid crystal alignment. We have found that the smectic layered structure is stabilized against thermal shock and mechanical shock and shows a self-recovering ability, when ferroelectric liquid crystal is dispersed in dense rigid polymer fibers with a surface anchoring force. Thereto, the molecular switching in the low molecular weight ferroelectric liquid crystal is not bound or restricted by the molecular structure of the polymers by a clear phase separation. The fast response time for rise and decay operation is ensured to be 1 ms or less for obtaining high moving image quality.

The surface-stabilized ferroelectric liquid crystal in a conventional contrast was limited to binary display operation. In order to display a natural color image including gradation, it is necessary to obtain grayscale capability. Therefore, we realized the grayscale-capable display by two methods with polymer dispersion. First, we formed a polymer composite film by dispersing nonliquid crystalline monomers of low concentration (3 % by weight). The fine dispersion structure to reach the molecular order exerts a subtle alignment control effect to the liquid crystal; the polymer thereby changes spatially threshold voltage for switching the liquid crystal molecules. Therefore, the spatial distribution of switching domains is induced, in order to vary continuously according to the applied voltage intensity, and the area ratio of the microscaled binary domains exhibits a spatial grayscale function.

Because it is based on the bistable liquid crystal switching, the device in this device also has the memory function of the halftone levels.

Subsequently, in order to keep the grayscale display reproducibility and to obtain mechanical stability for holding the substrate, by adding the liquid crystalline monomers of high concentration (20 wt%), the molecular-oriented polymer fibers (sub-μm diameter) were finely dispersed in ferroelectric liquid crystal. The formed polymer fibers with molecular alignment were segregated through phase separation of liquid crystal and polymers, in order to exert a strong anchoring force from short range for ferroelectric liquid crystal. The cone angle of liquid crystal switching reaches full angle of 90°, and the rotation of the liquid crystal molecules is monostable into fiber alignment direction. As a result, the electro-optical properties obtain the V-shaped curve symmetrical to 0 V. The V characteristic is useful in the same manner as the conventional nematic liquid crystal displays, for bipolar voltage driving scheme using thin-film transistors, to prevent unstable display operation such as image sticking or afterimage.

Further, by achieving hardening of the polymers by high strength ultraviolet irradiation as well as reducing the polymer concentration to 15 wt%, it was possible to lower the drive voltage until normal operating voltage of prevailed thin-film transistors. For the composite structure mingled at the molecular level, where the high-concentration polymers of such do not phase-separate the liquid crystal in macroscopic scale, the tangled fixed polymer chain inhibits movement of the liquid crystal molecules, and low-voltage operation cannot be expected.

#### 8.1.4.2 Nematic Liquid Crystal and Cholesteric Liquid Crystal

For wide range applications of flexible display, selecting a liquid crystal material according to each application is desirable. Therefore, besides the ferroelectric liquid crystal above with the aim of moving image display with high quality, flexible low-cost displays using nematic liquid crystal are also useful.

For example, with the aim of inexpensive simple display, a twisted nematic liquid crystal device [6] is resistant for variation of substrate spacing. Formation of twisted-alignment polymer walls is useful to hold two substrates and can have good contrast ratio. This is because the light leakage from the walls is suppressed to be small.

Further, two thick rigid polarizing films spoil device flexibility to be unnecessary. Therefore, guest–host twisted liquid crystal devices with dichroic dyes [7] were fabricated to absorb the all-polarization-angle incident light. In this device, a nematic liquid crystal with low birefringence is introduced, and optical rotation effect is suppressed in the twisted liquid crystal layer. The contrast ratio of the display is inferior, but the guest–host nematic liquid crystal of twist orientation is suitable for simple text display.

In addition, we have proposed and fabricated a device dispersing polymer walls in cholesteric liquid crystal [8] having the wavelength selective reflection for electronic paper applications. In this case, the control of the changing twist pitch (deciding the wavelength of the reflected light) will be the developing technical point when the polymer walls are segregated and formed.

## *8.1.5 Development of Peripheral Technology*

### 8.1.5.1 Printing Process and Transfer Process

We also introduced flexographic printing method for the coating process of a liquid crystal monomer solution during the forming of the composite film. In this printing method, the mixed solution thickness is controlled with high accuracy, and we can accurately select the coating area by relief structure on a printing drum. Furthermore, the coated solution film is sandwiched by the substrate of another one by using a conventional film laminator with a pressing roller. The printing and laminating processes such as above are extremely useful in large-area fabrication of the flexible liquid crystal panel.

Also, to configure the display, a fine pixel structure including metal wiring, transparent electrodes, and black matrix must be accurately formed on a flexible plastic substrate. The dimensional stability of plastic substrates to solvent exposure and heating process is generally inferior to that of glass substrates, in the conventional photolithography for forming a high-precision fine pixel structure in large area. So we applied the transfer method from the glass substrate. That is, after the pixel pattern is precisely formed in reverse order on the glass substrate by photolithography, the pattern is peeled off from the glass substrate by bonding a plastic substrate, resulting in being transferred to the plastic substrate.

By the printing process and the transfer method, display panel fabrication up to A4 size has become possible. In Fig. 8.11, the display panel actually fabricated is demonstrated. Since the thin plastic substrates are rigidly bonded with a polymer composite structure, the displayed images are not disturbed even when the panel is bent.

### 8.1.5.2 Color Display Scheme

In order to colorize a flexible display, we have developed two panel-driving methods of micro color filter [9] and field sequential color. The former is based on mixing three-primary-color fine pixels that cannot be identified with the human eye. In most of the liquid crystal display existing, this method is used. Using the transfer method of the above, high-precision fine microfilter of three primary colors is fabricated on a plastic substrate.

Color scheme in another way is to switch the three-primary-color images in speed high enough where people cannot discriminate flicker, based on color-mixing visual effects by afterimage. In this method, in synchronization with the backlight of light-emitting diodes that emits three-primary-color lights sequentially, the liquid crystal panel is fast rewritten at 180 Hz rate. In this scheme, high-speed response is required for the liquid crystal panel. We have realized a full-color display panel using fast response ferroelectric liquid crystal so far. We obtained an advantage of high light efficiency because there is no light loss caused by the color filters with light absorption.

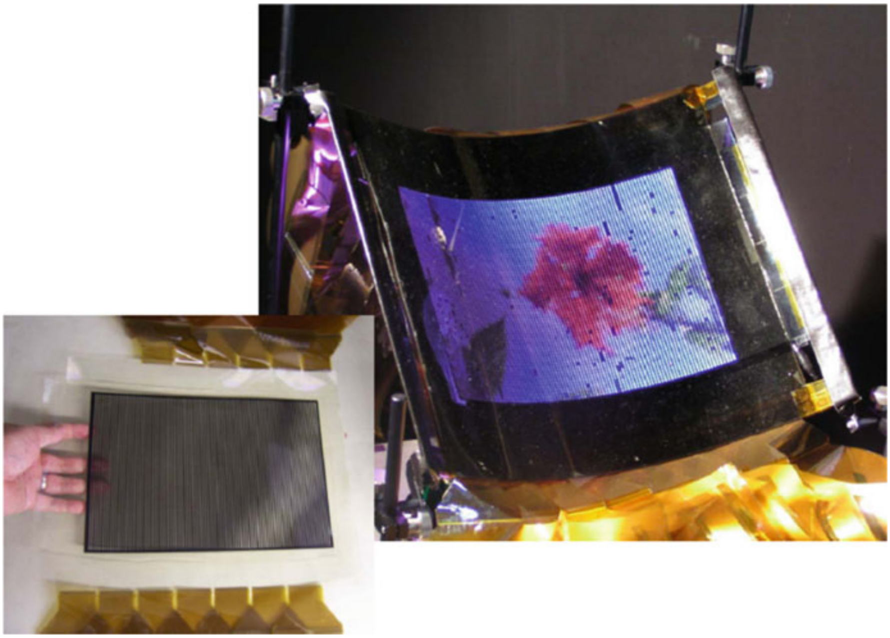


**Fig. 8.11** Demonstration of A4-sized flexible liquid crystal panel made by printing and transfer techniques

#### 8.1.5.3 Flexible Backlight

In reflective displays of cholesteric liquid crystal for electronic paper with power saving by using external ambient light, a backlight system is not needed. On the other hand, similar to the liquid crystal displays existing, in order to obtain a color image with excellent visibility with a high contrast ratio, the backlight system is indispensable. Currently, for a backlight for a liquid crystal display, the light-emitting diodes with high color purity have progressed, so we also developed two flexible backlight systems.

Our first backlight system is a direct illumination method, and a two-dimensional array of fine light-emitting diode chips with three primary colors is surface-mounted on a thin polyimide film used for flexible printed circuit board. In this case, via a light diffusion plastic film and a transparent optical spacer thick vinyl sheet, the light-emitting diode backlight and the flexible liquid crystal panel are stacked and laminated to obtain a uniform illumination light. This method has the advantage of good heat dissipation, and a dynamic local dimming control of the backlight is also possible to obtain high contrast and power saving.

In order to obtain a flexible backlight with high light usage efficiency, the light-guide plate [10] using a thin transparent silicone rubber is fabricated as shown in Fig. 8.12. As edge light source, we mounted thin light-emitting diode chips of three

Fig. 8.12 Flexible light-guide plate backlight using small light-emitting diodes

primary colors on the side surface of the light-guide plate. The backlight in this method is flexible and thin and has features such as high light efficiency and low cost with fewer light-emitting diode chips.

### 8.1.5.4 Thin-Film Transistor

In order to obtain a high-contrast display, a flexible liquid crystal display using plastic substrates requires an active matrix driving. The driving method is effective for simplifying driving circuit and reducing the panel electric connection and wiring. In scanning drive by the voltage pulse, an active electronic device like field-effect transistor having switch/memory functions is required in each pixel, which maintains the display state after the selected period finishes.

For realizing an image display with high contrast and high resolution, we have developed the thin-film transistor array for driving the liquid crystal polymer composite film. In the active matrix driving scheme, we introduced the polycrystal Si thin-film transistor technology of low-temperature formation (maximum process temperature, 150 °C or less) suitable for high-resolution high-speed driving with high mobility. As the result of the development of the flexible liquid crystal panel [11] using a heat-resistant substrate, color display operation has been successfully obtained (Fig. 8.13, 5.1 in. diagonal, 128 × 72 pixels).

To obtain the thin-film transistor array suitable to softening the panel, flexible 5 inch diagonal liquid crystal displays were also fabricated by lower-temperature vacuum deposition of the organic semiconductor (pentacene). The fabricated panel (QQVGA, 160 × 120 pixels) has confirmed the video display function [12].

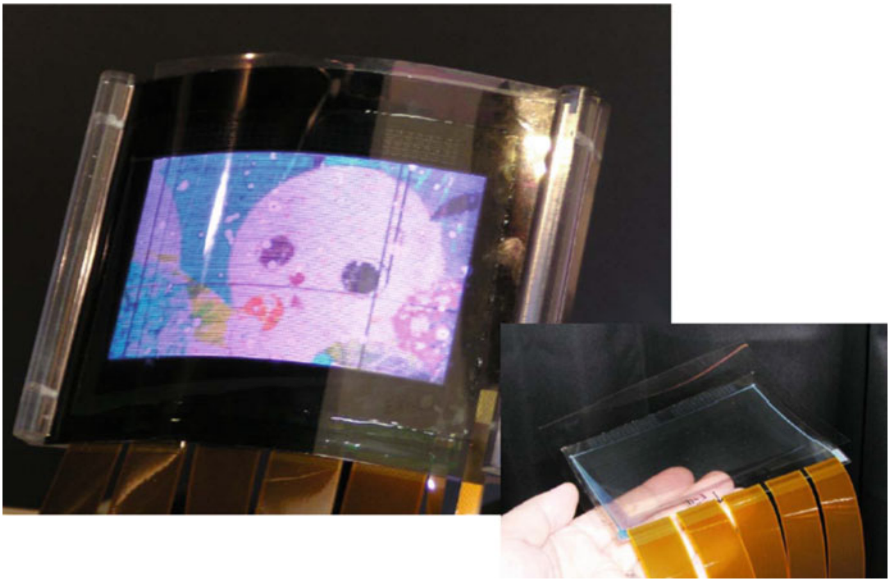


**Fig. 8.13** Fabricated flexible display driven by active matrix method with polycrystal Si thin-film transistors

In both the active matrix display panel using the fast response liquid crystal and the three-primary-color light-emitting diode backlight, full-color display operation is achieved by a field sequential color driving method.

As for the formation of fine thin-film transistor array, photolithography is often used now, but significant effort to continuously produce the panel by a roll-to-roll process with printing technique has also been made for the future. The steady progress in roll-to-roll manufacturing technology is expected for highly productive large-area screen flexible liquid crystal displays.

### *8.1.6 Development of the Future*

Through the development of a plastic-substrate-based liquid crystal device stabilized by liquid crystal polymer composite film, a foundation of various techniques is established towards flexible displays. The features of small-sized displays are light weight and robustness not to crack. On the other hand, in a wide range of applications from medium-sized portable devices to stationary-usage large screen panels, flexible electronic device technology using plastic substrates has a huge impact.

To make rapid progress towards the practical use and commercialization of a small- and medium-sized flexible liquid crystal displays, the flexibility, tolerance, and screen size must be determined according to the specific applications.

Furthermore, in order to obtain large screen high-resolution flexible liquid crystal panel, novel fabrication technique for forming a fine pixel structure on a plastic substrate is essential.

To support it, these days, peripheral technology has also prepared. For example, organic electronics using organic semiconductors and conductors and printable electronics associated with high precision attract a great deal of attention for next-generation flexible displays.

We believe that it is important to continue to evolve a flexible display fabrication technology for the near-future information-oriented society.

**Acknowledgment** Upon research works of flexible liquid crystal displays by the authors, with respect to the transfer process using plastic substrates, fabrication of light-guide plate backlights, and formation of low-temperature polycrystal Si thin-film transistors, we greatly thank the collaborators in Kyodo Printing Co., Minebea Co., and Dai Nippon Printing Co., respectively.

## 8.2 Blue Phase Displays

**Hirotsugu Kikuchi**

### *8.2.1 Characteristic Properties of Blue Phases*

Blue phases appear in a small temperature range between the chiral nematic phase with a sufficiently short helical pitch length and the isotropic phase. The blue phase has very peculiar characteristics [13–15]:

1. It exists in a narrow temperature range (typically a few kelvin).
2. It is optically isotropic.
3. It is optically active.
4. There are three types, named blue phase I (body-centered cubic), blue phase II (simple cubic), and blue phase III (isotropic symmetry) with increasing temperature.
5. The lattice constants of the unit cells of blue phases I and II are typically a few hundred nm, and the phases show Bragg diffraction in the ultraviolet–visible range. The name “blue phase” originates from the color of the diffracted light; many actually appear bluish, but some do not.

There is a record of the observation of a blue phase in 1888 when a liquid crystal compound was discovered. However, serious research started in the 1970s and blue phases were recognized in the academic world as specific liquid crystal phases in the 1980s. Two major reasons for why these phases failed to catch the attention of

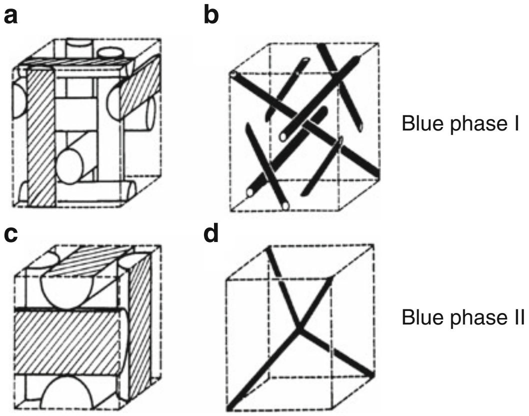


**Fig. 8.14** Structure of blue phase I (**a**, **b**) and blue phase II (**c**, **d**). Blue phase I has body-centered cubic symmetry, and blue phase II has simple cubic symmetry. (**a**) and (**c**) show the chiral cylinder and (**b**) and (**d**) the disclination lines

researchers are that they did not exhibit birefringence and the stable temperature range was extremely narrow. It was unavoidable that the blue phase was misunderstood to be a transient phenomenon during a phase transition because the identification of the blue phase as an intrinsic liquid crystal phase was difficult only by polarizing microscopal observation. After the concept of frustration was introduced in blue phase studies in the 1980s, the understanding of the blue phase was further deepened. One of the characteristic properties of blue phases is the complicated and three-dimensional hierarchical structure that will be introduced in the next chapter.

### *8.2.2 Structure of Blue Phases*

Blue phases I and II show cubic 3D lattice structures. Figure 8.14a–d shows the unit cell structures of blue phases 1 and II, respectively. Blue phases I and II have a body-centered cubic lattice structure and a simple cubic lattice structure, respectively, with lattice constants of several 100 nm.

Figure 8.14a, c shows double twist cylinders, and the bold black lines in Fig. 8.14b, d show disclinations (defect lines). In each double twist cylinder, the molecules are radially twisted towards each other through 90°. The molecules are parallel to the cylinder axis at the cylinder center and are tilted by 45° at the outer radial periphery. In other words, the molecules twist from −45° to +45° through the cylinder, which corresponds to a quarter pitch. The diameter of a double twist cylinder is typically about 100 nm, and a simple calculation shows that approximately 200 molecules with a diameter of 0.5 nm mildly twist against each other. The lattice constant for blue phase I corresponds to a one helical pitch, and the lattice constant for blue phase II corresponds to one half helical pitch. We generally see a very small mismatch in pitch length with that of the lower-temperature chiral nematic phase. Peculiar to soft matter, a complex hierarchical structure is formed in a self-organized manner as a result of repetitively twisted molecular alignment. It is interesting to see that behind this structure is a frustration between space topologies that smoothly connect the doubly twisted geometry and space. I refer to review articles in textbooks [13, 15] about frustration. A disclination (a type of defect line), which stems from frustration, is formed as if to run through the corner where the three double twist cylinders orthogonally come close to one another. The symmetry of the disclination geometry is body-centered cubic in blue phase I and simple cubic in blue phase II. It is estimated that the diameter of a disclination core is about 10 nm and the inner molecular alignment is thought to be disordered. Although details are not yet certain, blue phase III has also been identified; it is presumed that its structure is amorphous and that there is only doubly twisted, short-range order.

Due to the giant periodic structure discussed above, the blue phase exhibits Bragg diffraction in the ultraviolet-to-visible range. Blue phase I mainly exhibits diffraction from the (110), (200), to (211) planes, and blue phase 2 shows diffraction from the (100) to (110) planes. Hence, there are several reflection peaks, which is not the case with the chiral nematic phase. Typically, the diffractions from the (110) and (200) planes in blue phase I and from the (100) plane in blue phase II are in the blue region, which is the origin of the name “blue phase.”

### 8.2.3 Polymer-Stabilized Blue Phase

It has long been believed that the temperature range of the blue phase is small and cannot be extended. Recently, however, many attempts have been made to address this issue.

In 1993, Kitzrow et al. formed a blue phase with polymerizable crystal monomers: the monomers were polymerized in the blue phase, which immobilized the molecules, thus preserving the blue phase structure in the solid resin [16]. In this type of material, although the characteristics of the blue phase structure had been preserved, the dynamics of the liquid crystal had been lost because all molecules had been polymerized and thus immobilized to a certain extent.

Then in 2002, the author and coworkers reported that the temperature range of a blue phase could be increased to over 60 K by forming a small amount (7–8 wt%) of polymers in the blue phase; the material was named the “polymer-stabilized blue phase” (Fig. 8.15) [17]. The molecular dynamics are not lost in the polymer-stabilized blue phase, and moreover, the electro-optical response is very fast. It is believed that the polymers in the blue phase condense around disclinations and the blue phase is stabilized when the disclinations are thermally stabilized.

In 2005, Yoshizawa et al. synthesized T-shaped liquid crystal molecules and achieved a temperature range of 13 K for the blue phase [18]. They suggested that the biaxial nature played an important role.

In 2005, Coles et al. reported a temperature range as large as 44 K in the cooling process for a dimeric liquid crystal with strong flexoelectricity [19]. They suggested that flexoelectricity stabilizes disclinations. It is interesting, from an application

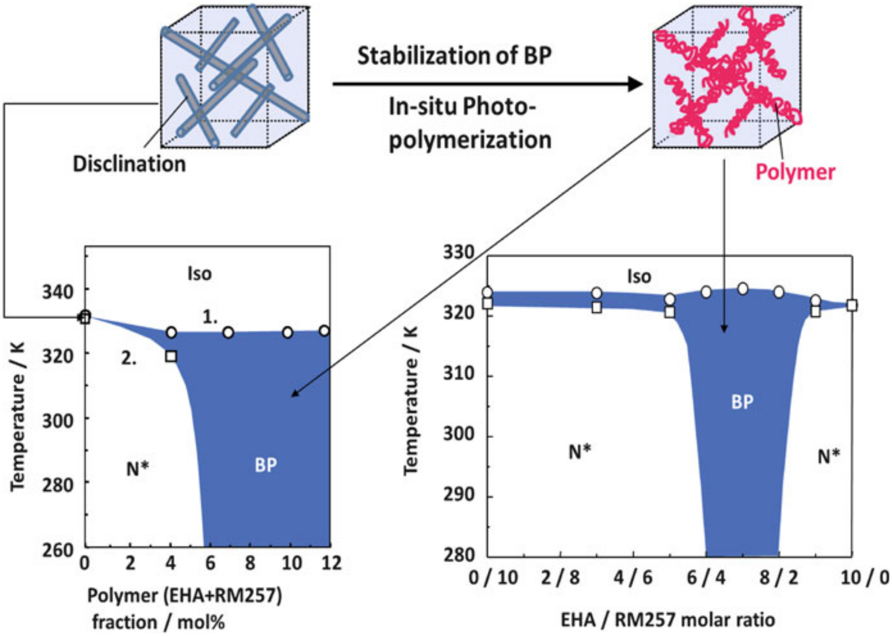


**Fig. 8.15** Polymer-stabilized blue phases. The monomers were 2-ethyl hexyl acrylate and 2-methyl-1,4-phenylene-bis(4(3(acryloyloxy)propyloxy)benzoate) (RM257, Merck)

standpoint, that the diffraction wavelength of the blue phase lattice varies reversibly with the electric field.

As discussed above, technologies have recently been advanced in important ways to solve the problem of the narrow temperature range of the blue phase, and we now believe strongly in the prospective future for the blue phase.

Let us consider the role of the polymer in the polymer-stabilized blue phase (PSBP) from the viewpoint of the thermodynamic interaction between the liquid crystal and the polymer. A feature of the blue phase is that it must coexist with disclination lines, and the very existence of the disclinations is the reason why the temperature range of the blue phase is small. Looking at it from the opposite direction, the blue phase could be stabilized by the disclinations.

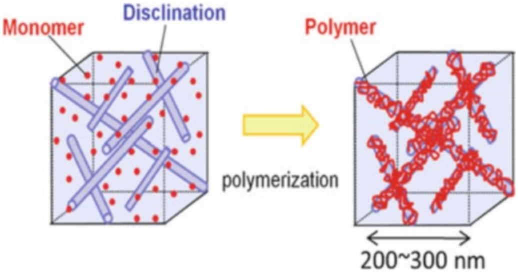
In general, the thermodynamic stability of a phase and the temperature range of a stable phase result from a competition with other phases on the higher- and lower-temperature sides. In the case of a PSBP, the thermodynamic balance between the blue phase and the chiral nematic phase can be changed by the polymer, because the temperature range of the PSBP is extended towards the lower-temperature side, that is, into the chiral nematic phase. In the blue phase and chiral nematic phase, double and simple twist alignments compete with each other. If the double twist alignment dominates, the blue phase occurs, and vice versa. Because the double twist alignment cannot continuously fill three-dimensional space, the blue phase must coexist with disclinations that form a regular network with cubic symmetry. Basically, the phase transition temperature of the lower side of the blue phase is determined by the relative stability of the single and double twist alignments. When the phase is heated up and the temperature comes close to the isotropic phase, the blue phase readily appears, because the coexistence of the disclinations becomes more allowable. As a result, blue phases appear in the temperature region just below the isotropic phase.

There is a contrast between liquid crystals and polymers with respect to entropy. In general, the entropy of soft matter can be separated into two parts corresponding to the translational and rotational motion of the molecules or chain segments. The orientational ordering of liquid crystals is based on an increase in the entropy of the translational freedom of the molecules, i.e., the packing entropy, while that of the random coils of the polymer is due to the maximized entropy of the rotational freedom of the chain segments. Therefore, the mixing of a liquid crystal with orientational order and a polymer forming random coil reduces the mutual entropy; as a result, the miscibility of both is generally very poor and phase separation readily occurs. Therefore, compositions comprised of liquid crystals and polymers induce varying competitive and/or cooperative interactions between them, resulting in unique behavior.

It has been suggested in a recent study that when polymers are generated and propagated in a blue phase, the resulting polymers are possibly concentrated in the areas of the disclinations [20]. The disclinations in the blue phase should be fixed by the polymer and should not disappear even when the phase transition into the chiral nematic phase takes place. Therefore, the disclination-free state, which is the only advantage of the chiral nematic phase over the blue phase, is lost. The balance between both the phases is changed, and the blue phase is stabile at a lower temperature. In other words, the blue phase is stabilized over the chiral nematic phase, because the disclination, which is a negative characteristic, becomes a common feature for both phases. Because the polymer has little influence on the phase transition between the blue phase and the isotropic phase, which is on the high-temperature side of the blue phase, it does not play a role in stabilizing the molecular orientational order as in other polymer-stabilized liquid crystals, such as in polymer-stabilized cholesteric textures.

It is also meaningful to discuss the phenomenon of polymer assembly in the disclination from the viewpoint of entropy. As mentioned above, the orientational order of liquid crystals is induced by the entropy of translation, while the random coils of polymers are due to the entropy of rotation. The coexistence of a liquid crystal and a polymer causes a conflict between the different entropies. The polymers in the liquid crystal phase thus assemble in the disclination region, where the orientational order is lowered and the polymers can maximize their conformational entropy. A satisfactory coexistence is then self-sufficiently achieved by cooperation between the blue phase (which must have disclinations) and the polymer (which tends to be excluded from the ordered region). The elastic energy of the liquid crystal orientational field that accumulates around the disclination also plays an important role in the diffusion of the polymer. The curvature of the director increases closer to the disclination core. The elastic energy, which is proportional

**Fig. 8.16** The monomer is randomly distributed, but after polymerization, the polymer aggregates in the disclinations

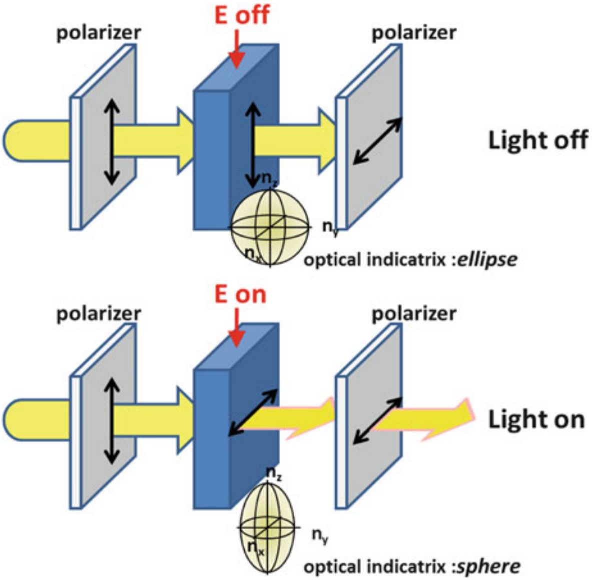


to the square of the director curvature, increases divergently near the disclination core. The orientational order should be small or zero at the areas being very close to the disclination core because the elastic energy exceeds the thermal energy to disorder, which is approximately the latent heat of the nematic–isotropic phase transition. If a random coil polymer or small particle with a certain volume comes closer to the distorted director field, it should be increasingly attracted towards the disclination core, because the elastic energy corresponding to its volume is reduced. Therefore, the polymers synthesized by in situ polymerization within a blue phase are drawn more to the disclination as the molecular weight increases, resulting in the fixation of the disclinations and stabilization of the blue phase (Fig. 8.16).

### 8.2.4 Electro-optical Effect and Driving Method

Because blue phases are optically isotropic without an electric field, a dark field can be obtained under crossed polarizers if the Bragg diffractions due to the lattice structure are shifted out of the visible wavelength range. The index ellipsoid is then a sphere. Therefore, initially there is no viewing angle dependence originating from the phase structure. However, when an electric field is applied, anisotropy or birefringence appears in the direction of the electric field as the optical axis. If the dielectric anisotropy of the host liquid crystal is positive, the index ellipsoid becomes stretched in the direction of the electric field. Conversely, a flattened ellipsoid contracted in the direction of the electric field is obtained if the dielectric anisotropy of the host liquid crystal is negative. Therefore, the blue phase exhibits electric field-induced birefringence of the type that can be switched between optical isotropy and anisotropy, i.e., from zero to finite birefringence, as shown in Fig. 8.17. The induced birefringence is proportional to the square of the electric field at small fields, which is known as the Kerr effect. This type of electro-optical effect is significantly different from that in conventional liquid crystals, where the initial state is anisotropic, and the optical axis changes with the electric field. Electric field-induced birefringence also exists and the Kerr effect has been confirmed in PSBPs, their related materials, and polymer-stabilized isotropic liquid crystals, which is referred to as the pseudo-isotropic phase. In the pure blue phase, i.e., free from polymers, a local reorientation of the molecules, a lattice distortion, and a

**Fig. 8.17** The display mode of blue phases. *Upper figure*: dark state under crossed Nicols in the absence of an applied electric field, because the blue phase is optically isotropic. *Lower figure*: bright state, because the blue phase becomes optically anisotropic upon application of an electric field and an appropriate retardation is induced in the electric field direction



phase transition occur as the electric field increases. In the PSBP, the latter two effects are suppressed, and only the high-speed local reorientation of the molecules remains after polymer stabilization. Therefore, PSBPs show a fast electro-optical response of less than 1 ms.

To exploit the electric field-induced birefringence in display applications, the polarization of the incident light through the optical retardation produced by the induced birefringence is simply controlled in a manner similar to the mode of retardation control used for in-plane switching (IPS). If a simple comb-shaped IPS electrode is used for the device, the optical axis of the induced birefringence is parallel to the electric field, and the optical axes lie mainly in a plane perpendicular to the comb [21, 22]. A typical voltage–transmittance curve is shown in Fig. 8.18.

### *8.2.5 Current State of the Art and Challenges That Remain*

The most significant possible problem with the polymer-stabilized blue and isotropic phases is the need for large driving voltages. The short correlation length in orientational order is the source of both the fast switching speed and the large driving voltage. In fact, several tens of volts are required across an electrode distance of 10 μm. Although the driving voltage could be reduced by decreasing the electrode distance, it would be difficult to fabricate such small electrodes. The driving voltage of the polymer-stabilized blue phase depends on the dielectric anisotropy, the birefringence and elastic modulus of the host liquid crystal [22], the fraction and structure of polymers, and the helix pitch, i.e., the chiral dopant

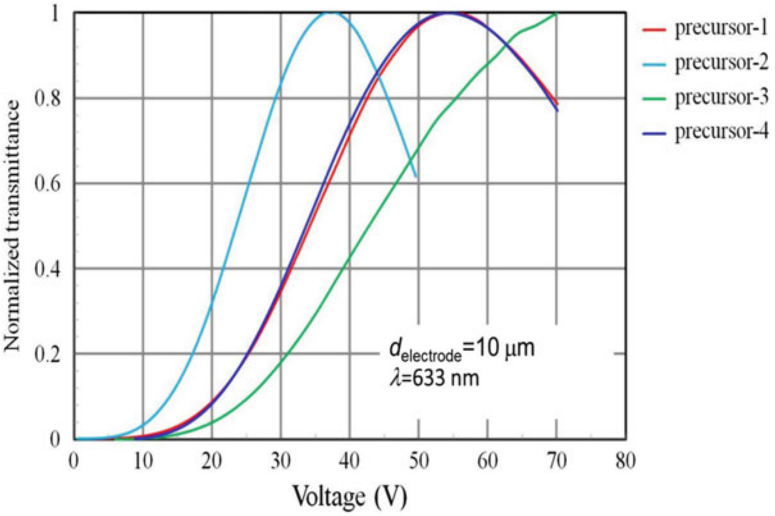


**Fig. 8.18** Electro-optical response of polymer-stabilized blue phases. Precursor 1 is an acrylate monomer (11 %), precursor 2 is an acrylate monomer (8 %), precursor 3 is a methacrylate monomer (11 %), and precursor 4 is a methacrylate monomer (8 %). The liquid crystal was provided by JNC. The electrodes were simple interdigitated electrodes with a spacing of 10 mm

concentration. Although there could be some other parameters, it would be difficult to reduce the driving voltage to levels used by nematic liquid crystals merely through improvements to the material. It is very likely that improved electrode structures will be required for application requiring large electric fields.

Residual birefringence will become a serious problem if the dielectric anisotropy and the birefringence of the parent liquid crystal become greater. When the dielectric anisotropy is zero (initial state without zero electric field), the so-called printing phenomenon occurs: birefringence does not disappear after the electric field is removed. By improving the uniformity of the polymer network in the cell, the problem is partly, but not wholly, solved.

The light shield is an important factor in controlling display contrast. In the polymer-stabilized blue and isotropic phases, short wavelength light can easily leak through because while diffraction and scattering occur mainly in the ultraviolet range, the longest wavelength tail is still in the visible range. This problem would not occur if the lattice constant and the correlation length of short-distance ordering are sufficiently small, but there is a trade-off with the driving voltage.

In the manufacture of the polymer-stabilized blue and isotropic phases, a polymerization reaction occurs in the entire panel. Conventional liquid crystal display technology does not use this type of process, and hence a change will be required in the manufacturing process. Furthermore, we expect several other unknown adverse factors, especially long-term stability, from the use of liquid crystals containing polymers as impurities. The challenge will then be to remove unreacted monomer or eliminate the adverse effects of the residual monomer.

### *8.2.6 Summary*

Although both polymer-stabilized blue and isotropic phases have truly excellent characteristics, they have innate problems stemming from their structures and driving mechanisms, not to mention many as yet unidentified factors. In the flat-panel display industry, with excellent products and heated competition, the barrier for introducing an entirely new mode could be considerably high. In order to put the technology to practical use, an essential requirement will be cooperation among the various organizations bearing responsibility for materials, fabrication processes, device design, drive circuits, and so on.

## 8.3 Polymer-Stabilized V-Shaped Ferroelectric Liquid Crystal Display PSV-FLCD

**Toru Fujisawa and Shunsuke Kobayashi**

### *8.3.1 Introduction*

The development of the LCD has been actively carried out to improve a display performance in terms of high contrast and wide viewing angle. In recent years, there are strong demands for an LCD that is well capable of displaying full-color moving video image without blurring and with a high resolution and a high contrast ratio. The improvement of these subjects has been achieved from two sides: one is progress of liquid crystal material properties by reduction of rotational viscosity. The other is acceleration of switching speed by specific driving method such as an overdrive and a frame rate controlling. In such a background in view of a fast switching, the polymer-stabilized blue phase [17] and ferroelectric liquid crystal attract our attention, because those liquid crystal materials exhibit a high response speed.

Professor Clark and Lagerwall discovered surface-stabilized liquid crystal displays (SS-FLCDs) that show a fast switching with bistability in the 1980s [5]. However, there are several issues towards a full-color display application, which include the existing of zigzag defects causing the reduction of contrast ratio on the screen of display, the producing of grayscale capability for color reproduction, and the productivity of LCDs with a narrow gap less than 2 μm. Hence, FLCs were only practical uses for watches and ultrasmall viewfinders. In these applications of FLCDs, biaxial alignments in which exhibits two states to be switched between a dark state and a light state by applied electric filed are utilized.

The solution for these issues that we have adapted is the polymer stabilization of FLCs exhibiting a continuous grayscale V-shaped switching free from zigzag defects producing a high contrast ratio and a high-speed response below 400 μs

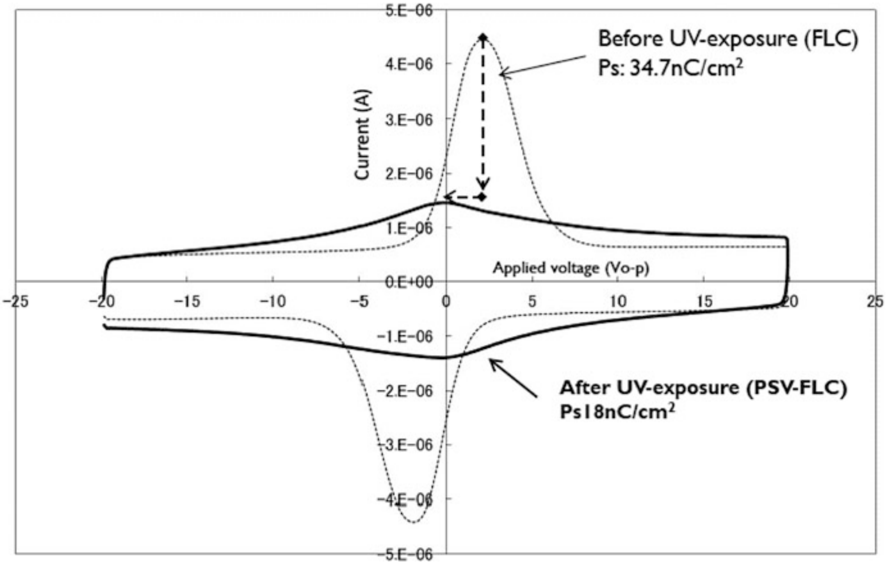


**Fig. 8.19** Comparison of polarization reversal current before/after UV exposure

[23]. Polymer-stabilized liquid crystals are obtained by a formation of the polymer network made of the small amount of photo-curable liquid crystalline monomer added into a liquid crystalline host under the UV light exposure. In the case of using ferroelectric liquid crystals, the effect of polymer stabilization appeared remarkably by a UV light exposure for a formation of polymer networks stabilizing FLC alignment with an applying AC voltage. By the application of this process, a bistable switching in a biaxial alignment based on surface-stabilized ferroelectric liquid crystal display (SS-FLCDs) changes into uniaxial alignment to be possible to exhibit V-shaped switching to lead an analog gray scale, called polymer-stabilized V-shaped ferroelectric liquid crystal displays (PSV-FLCDs) discovered by Kobayashi [23–25]. In this chapter, the influence of the physical properties of the ferroelectric liquid crystal by polymer stabilization is discussed.

### 8.3.2 Switching Properties

Liquid crystalline monomers that are contained in the liquid crystals form three-dimensional polymer networks by UV curing. The alignment control force derived from the polymer network affects the electro-optical switching connected closely with the motion of liquid crystal molecules. The effect of the anchoring force coming from the polymer network leads to the change in the polarization reversal current and switching properties. The differences of polarization reversal current before and after UV exposure can clearly be seen in Fig. 8.19.

When the change of current was measured with applying a triangular wave, a polarity of polarization reversal current peak depended on a polarity of electric fields observed at the coercive electric field of voltage in the first and third quadrant on the graph of the current as a function of applied voltage before UV exposure as shown in Fig. 8.19. The polymer network has not yet been formed and liquid crystal molecules behave as a conventional ferroelectric liquid crystal having a spontaneous polarization of 34.7 nC/cm$^2$. UV curing was carried out while applying an alternating electric field of 1 kHz. After that, the area of the spontaneous polarization peak drops to 18 nC/cm$^2$, which is due to the anchoring force by the polymer network. The decrease of the polarization reversal current of the spontaneous polarization of the liquid crystal molecules reflects the movement of the liquid crystal molecules. The decreased spontaneous polarization by UV exposure polymerization means that the movement of liquid crystal molecules is suppressed by the anchoring force of the polymer network. In addition, another key feature is that the position of the peak shifted to the vicinity of zero voltage less than the coercive electric field. It is suggested that switching mechanism in FLCs is changed by the polymer stabilization. This can be described as the force of interaction between liquid crystal molecules and the polymer network. When there is no electric field, the molecules are in the ground state orientation exhibiting optical uniaxial alignments.

When an electric field is applied, a force to orient the molecules towards the electric field direction conflicts with the intermolecular interaction. The higher the electric field, the more the dipole of the liquid crystal molecules aligns towards the direction of the electric field. If the electric field is weakened, the effect to attempt the return of the molecules to the ground state becomes stronger and as a result, the polarization reversal current is maximum at the central position near zero voltage.

The force of the liquid crystal molecules to return to the ground state affect also obviously the switching characteristics. The optical switching characteristics of the device before and after UV exposure are shown in Fig. 8.20, which show the change in current flowing through the liquid crystal during switching. We can compare the optical response waveform and current waveform when a rectangular waveform is applied to the liquid crystal cell. The polarization reversal current appeared after the end of charging current of capacitor due to the polarity inversion of applied waveform. The optical response for this duration, which is the delay of optical response caused by the charging current and the polarization reversal current, is approximately 500 μs.

On the other hand, after the UV exposure, the response improved significantly to 25 μs. It can be seen that after UV exposure the polarization reversal current peak overlaps with the capacitor charging current peak. This is because the polarization reversal occurs at the same time as the polarity of the rectangular waveform is inverted, which has contributed greatly to faster relaxation times of the optical response. To describe this in terms of alignment force, the liquid crystal molecules begin to move and return to the ground state when the potential of the rectangular wave passes through zero volts. The switching by such a mechanism is a major feature of the PSV-FLCD.

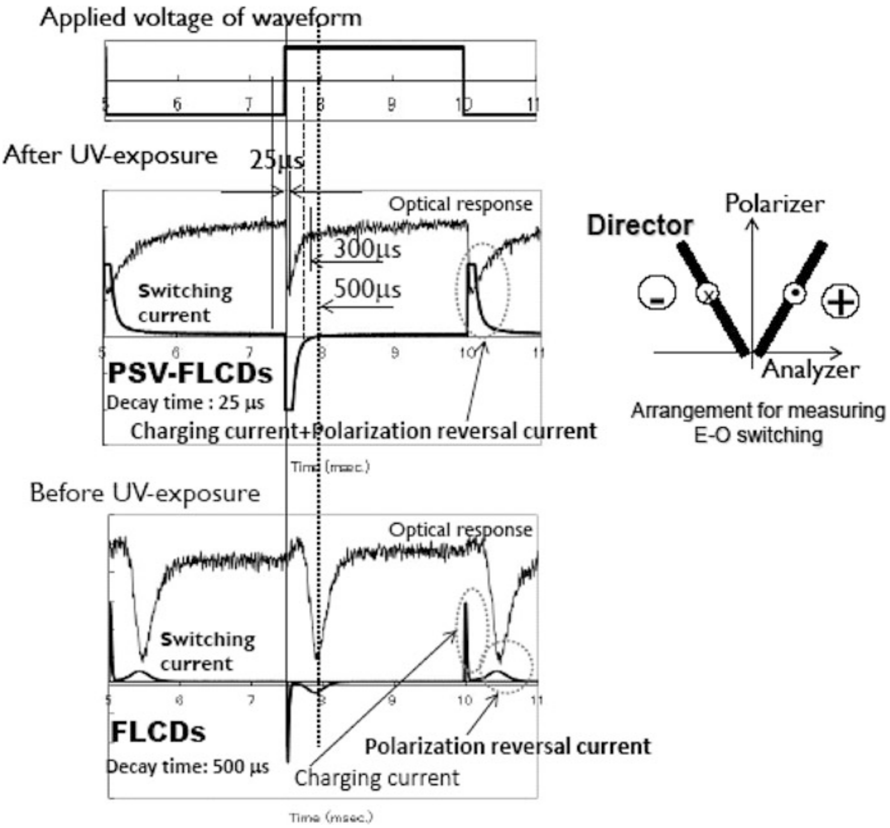


**Fig. 8.20** Comparison of optical response and switching current before/after UV exposure

### *8.3.3 Uniaxial Orientation*

Figure 8.21 shows the micrograph of PSV-FLCD under crossed polarizer. The device was obtained by UV exposure while applying a rectangular waveform to the oriented state of the SS-FLCD with a cell thickness of 1.4 μm. In the portion where the rectangular waveform is applied to the liquid crystal during UV exposure, the uniaxial orientation generated by the effect of polymer stabilization can be observed as a dark state. The biaxially oriented state around the electrodes is exhibited as a bright fleck dark spots. Uniaxial polarization properties along with a direction perpendicular to the layer structure of SmC* phase appear only in the portion of the cell where the electric field is switched by applying an AC voltage of about 1 kHz (see Fig. 8.21).

Figure 8.22 shows the relationship between the frequency of the rectangular waveform applied during the UV exposure and minimum transmittance ($T_o$). The lowest transmission ($T_o$) is determined by setting the transmission of crossed

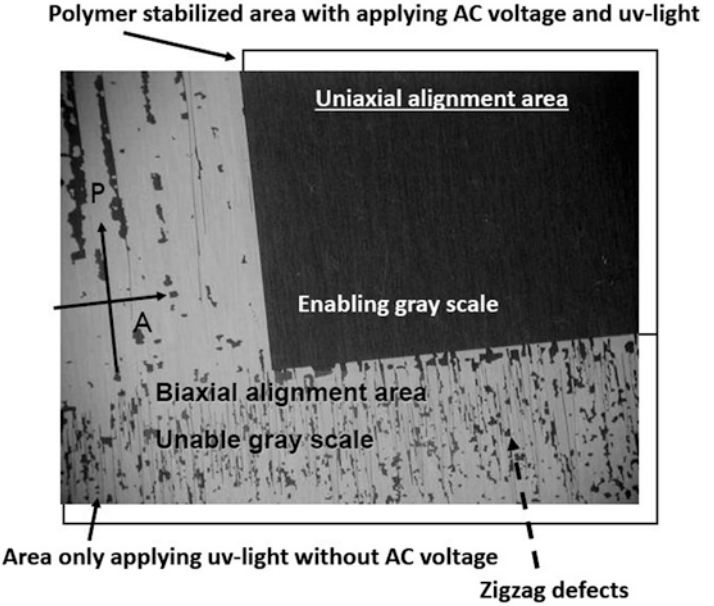


**Fig. 8.21** Polarization microscopic photograph of PSV-FLCDs at 1.8 μm of cell gap

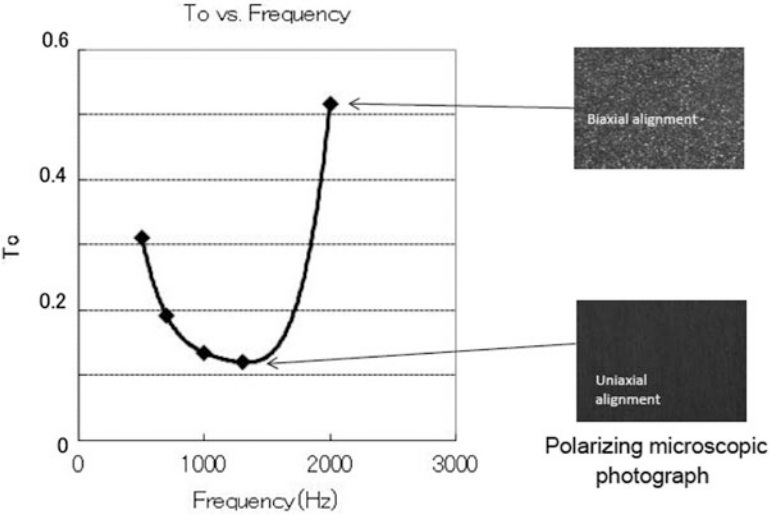


**Fig. 8.22** $T_0$ of minimum transmittance versus frequency of rectangular waveform

polarizers at 0 % and the transmission of parallel polarizers at 100 %. The minimum transmittance is measured with polarizing microscope equipped with a photomatter when the direction of uniaxial orientation is adjusted to the polarization axis of crossed polarizer. The uniaxial orientation obtained by the polymer-stabilized LC phase is greatly influenced by the frequency of the rectangular waveform applied during the UV exposure as shown in Fig. 8.22. If the frequency is below 1 kHz, a multi-domain fine grain of biaxial orientation is observed with a polarizing microscope. Between 1 and 1.5 kHz, the polarization properties of the uniaxial orientation improved and minimum transmittance decreases. A fine multi-domain structure appears again at a frequency of 2 kHz so as to increase the minimum transmittance. One of the reason for this phenomenon is that the liquid crystal molecules are no longer able to follow the square wave completely which may be the causes of $T_o$ increase. Thus, the uniaxial orientation by polymer stabilization significantly affects the dynamic behavior of liquid crystal molecules during switching.

### 8.3.4 Effect of Cell Thickness

In order to establish a method to extend a cell thickness from a cell gap for a conventional FLCDs less than 2 μm to a cell gap to be suitable for mass production over a 3 $\mu$m, we should consider with the change of LC director configuration in smectic C* phase in which the configuration of liquid crystalline directors is depended on a relation between the length of helical pitch in smectic C* and the cell gap. The stripped pattern appeared at the cell gap more than the helical pitch. In this case, electro-optical properties are not suitable for a display application owing to a generating light scattering based on the helix. To avoid an influence of the helix, it is necessary to unwind the helical structure in smectic C* with a condition that the cell gap is a smaller than the helical pitch. For the solution of the helix, we examined a capability of polymer stabilization to retain the unwinding configuration of LC directors aligned by the electric field during UV exposure.

We have examined the method to stabilize unwinding helical structures in smectic C* phase. Experimental results are shown in Fig. 8.23. A cell gap in the photo shown in Fig. 8.23 is 5 μm with parallel alignment layers in which a liquid crystal with a 1.9 μm pitch of a chiral smectic C phase has been injected.

The stripped pattern derived from helical structures exists throughout LC cell with such cell gap before UV exposure, and then AC voltage is applied across the layer of FLCs containing UV curable monomers through ITO electrodes coated on glass substrates so that the helix is unwound at the area of electrode. After that, a 5 mW/cm$^2$ of UV light at 365 nm by using UV-LED array is exposed for 10 min with the applying AC voltage at the same time to attain uniaxial alignments at a portion of the electrode shown in Fig. 8.23. The area of the uniaxially oriented LC on the electrode portion becomes a dark state under crossed polarizers, as shown in Fig. 8.23. This result indicates that uniaxial alignment is formed by fixation of

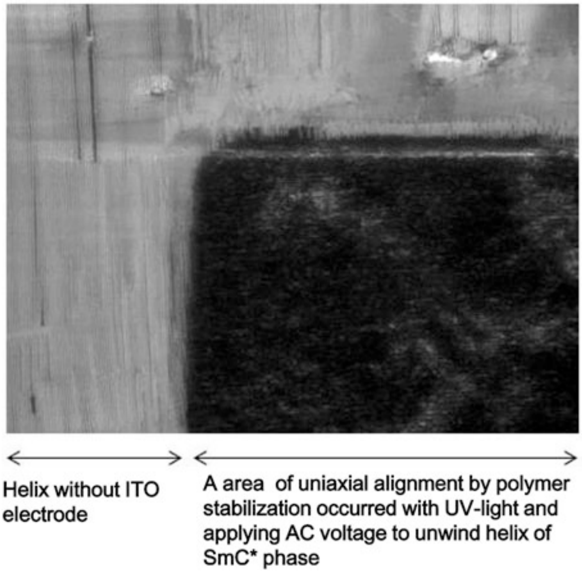


**Fig. 8.23** Polarizing microphotograph of PSV-FLCDs in case of a 5 μm of cell gap with a 1.9 μm of helical pitch in SmC* phase

unwinding the helical structures with the applied AC electric field and polymer-stabilized alignment of liquid crystals. It is revealed that retaining of an unwound helix is not the effect of conventional surface stabilization but the effect of polymer stabilization with applying AC voltage.

We succeeded in fabricating polymer-stabilized ferroelectric liquid crystals exhibiting a transmittance as a function of applied voltage with a V-shaped switching with a 3 μm of cell gap as shown Fig. 8.24. The cell thickness was 1.8 and 3 μm. As shown in Fig. 8.24, the 3 μm cell does not show any inferior uniaxial alignment compared with the 1.8 μm cell. This means that production of PSV-FLCDs becomes possible for 3 μm cells. However, the maximum transmittance is lower for the 3 μm cell, because the retardation of the liquid crystal ($\pi d\Delta n/\lambda$) depends on $\Delta n$ (refractive index anisotropy) and $d$ (cell thickness). An improvement of the maximum transmittance in thicker cells is expected in the future because the development of ferroelectric liquid crystal with a low $\Delta n$ is in progress.

### 8.3.5 Prototype of a TFT Drive Panel

We fabricated a field sequential full-color (FS-FC) LCD with 4 in. diagonal and SVGA (800 × 600, 254 ppi, 1.8 μm of cell gap) specification that makes it possible to display high-quality moving video images without blurring and without significant color break due to the fast response of our PSV-FLCDs as shown in Fig. 8.25 [26]. Materials used in the TFT-driven LCD are a ferroelectric liquid crystal composition containing a UV polymerizable liquid crystalline monomer with

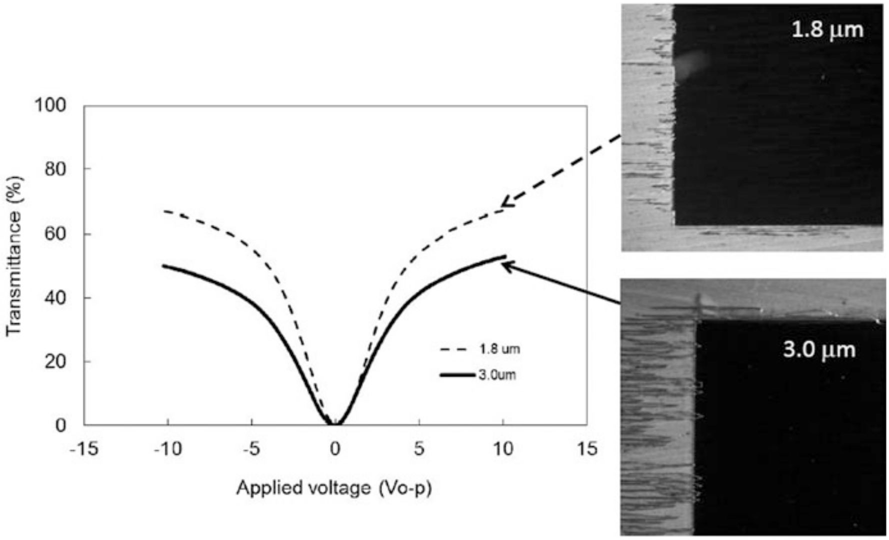


**Fig. 8.24** Transmittance as a function of applied voltage in PSV-FLCDs with different cell gap

**Fig. 8.25** A photograph of displayed image of the prototype field sequential full-color TFT-LCDs using PSV-FLCD 4 in. diagonal SVGA (800 × 600 pixels) 254 ppi

spontaneous polarization 33 nC/cm$^2$, tilt angle 27°, and phase sequence Iso 76.3 °C N* 70.6 °C SmA 66.2 °C · SmC* −12 °C Crystal.

The prepared mixture was injected into an empty cell at a temperature showing a nematic phase via vacuum filling, because the viscosity of the smectic liquid crystal is too high for vacuum filling. After the injection, the cell was cooled gradually at a cooling rate of 2 °C/min to room temperature at which the SmC* phase is observed. And then, the FLC mixture was photocured with a 5 mW/cm$^2$ of UV light source at 365 nm for 10 min to form uniaxial alignments at electrode in the SmC* phase. A square wave voltage of ±9 $V_{o\text{–}p}$ at a frequency of 1 kHz was applied simultaneously to the data line of TFT array during the UV exposure in order to obtain V-shaped switching.

The panel is driven by voltage modulation to display a gray scale at a voltage of ±9 $V_{o\text{–}p}$ or less. Images were displayed with the frame frequency of 60 Hz as a default frequency, and a flashing LED array backlight system was used to emit three monochrome lights in the sequence of a red, green, and blue light at intervals of 1/180 s, where the frame period of 1/60 is divided into three sub frames: R, G, and B of monochrome images.

These emissions of monochrome lights were synchronized with the addressing period and erase period of images for PSV-FLCDs. The black frame was inserted as erase period to prevent a generating overlap of colors between the subframes. Thus we could demonstrate the potential of polymer-stabilized ferroelectric liquid crystal displays for application as full-color displays and analog grayscale displays. If it is possible to further improve the uniaxial orientation and the transmittance in the future, such displays could be used for excellent video display performance with high contrast.

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