Chapter 12
Liquid Crystal Display—Present Status and Emerging Technology

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Nowadays, in your daily lives, the applications of LCs, such as LCD TVs, computer/laptop monitors, mobile phones, navigators, digital cameras, and so on, are widely used worldwide. Even, wherever you are whatever you do, you can take your electronics out of your pocket to check your e-mails, listen to music, watch movies, find your way, and so many others. LCDs provide high performance in regard to the weight, volume, contrast ratio, viewing angle, low power consumption, etc. That's why the high-quality applications of LCDs are indispensable and paid much attention by scientists and electronics industries in the recent decade. Undoubtedly, LCDs have acted as a leader in the field of flat panel displays, in not only small-sized displays, but also large-sized ones. Refer to cathode ray tube (CRT) monitors; LCDs have almost completely replaced CRT monitors in the display market because of their bulky and high power consumption, despite their good response time, viewing angle, image quality. However, in addition to the present status of LCD applications, some emerging technologies, such as wide viewing angle displays, fast response displays, blue phase LCDs, flexible displays, 3D displays, high resolution displays, in-cell touch panel, electronic papers, tablets, etc., have also attracted much attention. In this chapter, the introductions of the present status of LCD industry, as well as the emerging technology for improving the performances of LCDs will be given.

12.1 Liquid Crystal Display Modes

Regarding the commercial products of LCDs [1–3], their operating principles for modulating light intensity and/or light polarization include polarization rotation, phase retardation, scattering, absorbance, etc. LCs possess, as described in

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Chap. 10, several anisotropic properties, such as refractive index (birefringence, Δn), dielectricity (dielectric anisotropy, $\Delta\varepsilon$), elastic constants, susceptibility, and others. Briefly, without applying any external field, LCs are aligned along the direction corresponding to the alignment layers. Because of the properties of dielectric anisotropy and flow of LCs, LCs can be oriented by applying an external field, resulting in light modulation based on phase retardation, polarization rotation, light reflection and transmission, etc. Additionally, if the applied external field is removed, LCs can recover to its initial orientation state due to the elasticity and viscosity. Notably, LCs in LCDs do not emit light, they only control whether light gets through LCs or not, so that back-light/front-light units are needed for LCDs according to transmissive or reflective modes. In terms of the operating mechanisms, the commercially adopted LCDs are divided into the following modes [1–3], including twisted nematic (TN), super twisted nematic (STN), mixed-mode twisted nematic (MTN), vertical alignment (VA), optically compensated bend (OCB, π-cell), in-plane-switching (IPS), ferroelectric LC (FLC), guest-host (G-H), polymer dispersed LC (PDLC), cholesteric reflection, LC on silicon (LCoS), reflective, transflective modes, and so on. Typically, for a LCD, each pixel is divided into three (red, green and blue) or four (red, green, blue and yellow/white) sub-pixels with the color based on additive color principle. For another kind of LCDs, called field sequential color (FSC), or color sequential displays, all of the pixels display the image for only one color of RGB at the one third frame time, indicating that its mechanism is based on separating color temporally not spatially. In this section, we will focus on several modes those attach importance to LCD industry recently.

(a) polarization rotation mode

The physical mechanism for LCDs using polarization rotation mode is based on waveguiding effect [4, 5], showing that the polarization direction of the incident light beam follows the twist of LC director in a LC cell. Hence, the polarizations of incident and output light are two points to be discussed. Briefly, if the polarization direction of the incident light is selected to be parallel to the LC director near the incident layer, the polarization state will be rotated to the direction of the LC director close to the output layer. However, strictly speaking, the polarization rotation effect is valid with the limitation, called Mauguin condition,

$$\phi \ll \frac{2\pi d \Delta n}{\lambda}, \tag{12.1}$$

where ϕ, d, Δn and λ are, respectively, the twisted angle, thickness of LC cell, birefringence, and wavelength of light [4]. In LC industry, the representative is twisted nematic (TN) LCD, extensive commercially used in the recent decade. It was first proposed by Schadt and Helfrich in 1971 [5]. For example, in a typical 90° TN cell, the polarization direction of the incident linearly polarized light is rotated by 90°. In other word, the polarization direction of the output light remains linearly polarized if the condition of Mauguin limitation is satisfied. Otherwise, the polarization of the output beam will be changed to elliptic polarization, indicating that the transmission will be reduced under cross- or parallel- polarizers. For a special case of 90° TN cell ($\phi = 90^{o}$), the Mauguin condition can be reduced to

$$\frac{\lambda}{4} \ll d\Delta n, \tag{12.2}$$

Here, we do not talk about its details of electromagnetic wave, but operating principle of 90° TN-LC cell will be shown. First of all, a LC cell having a pair of orthogonal rubbing directions, resulting in a total twisted angle of 90°, is considered. In brief, the polarization of linearly polarized light can be rotated by 90°, indicating that the polarization will follow the twist of the local director. It should be noted that in order to ensure the unidirectional rotation of the LCs, a little fraction of chiral dopant will be doped into the TN-LC cells. A typical 90° TN-LC cell can be divided into two kinds of operating mode; they are normally white (NW) and normally black (NB) modes. The word "normally" means that the state without applying any voltage. Hence, the transmissions of NW and NB modes at voltage-off state are, respectively, bright and dark. According to the layout, the only difference between NW and NB modes is the transmission axes of polarizer and analyzer. As shown in Fig. 12.1a, b (Fig. 12.1c, d), it is the NW (NB) mode that the transmission axes of polarizer and analyzer are set perpendicular (parallel) to each other. Considering the NW mode TN-LC cell, it is bright state if no voltage is applied (Fig. 12.1a). However, when a voltage is applied onto the TN-LC cell, the LCs ($\Delta\varepsilon > 0$) will be aligned along the direction of electric field if the voltage is high enough. At this moment, the TN-LC cell changes to homeotropic LC cell so that zero transmission can be obtained under cross-polarizers (Fig. 12.1b).

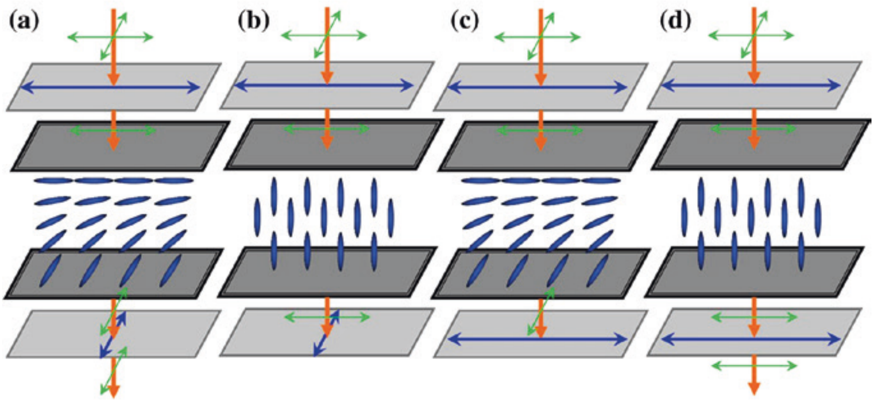


Fig. 12.1 Schematic diagrams of twisted nematics, **a** *bright* (field-off) and **b** *dark* states (field-on) of normally *white* TN LCDs; **c** *dark* (field-off) and **d** *bright* (field-on) states of normally *black* TN LCDs

Moreover, if the amplitude of the applied voltage is between zero and that to align LCs homeotropically, gray scales can be obtained. Here, we give the formula describing the transmittance of a NW 90° TN-LC cell.

$$T = \cos^2 X + \left(\frac{\Gamma}{2X}\cos 2\beta\right)^2 \sin^2 X, \tag{12.3}$$

where β is the angle between the polarization axis and the front LC director, ϕ the twisted angle, $X = \sqrt{\phi^2 + (\Gamma/2)^2}$, $\Gamma = 2\pi d\Delta n/\lambda$, d, Δn and λ are, respectively, cell gap, birefringence, and wavelength. For a special case, cosX = ±1, i.e. X = mπ, m is an integer; T is independent of β and the Gooch-Tarry condition can be obtained [4].

$$\frac{d\Delta n}{\lambda} = \sqrt{\left(m^2 - \frac{1}{4}\right)}, \tag{12.4}$$

For m = 1, it's the Gooch-Tarry first minimum. Notably, 90° TN-LC cell has been widely used for many kinds of displays, such as transmissive, projective and reflective LCDs, using two polarizers. However, the narrow viewing angle and gray scale inversion, caused by optical anisotropy of LCs, off-axis light leakage from cross-polarizers, and others, are the major drawback of TN-LC cells even the performances are acceptable for notebook computer applications. Therefore, compensated films are employed to enhance their performance.

The mixed twisted nematic (MTN) mode is developed based on TN mode. The main difference between TN mode and MTN mode LCDs are the setting of polarizers and the total twisted angles. For MTN mode LCD, the angle of intersection of polarizer axis and rubbing is set to be non-zero angle, and the total twisted angle of 90° is unnecessary. The mixed mode means the combination of polarization rotation and phase retardation. Usually, it should be noted that MTN mode can be adopted to fabricate a reflective LCD, and will be introduced in next section [1–4].

(b) phase retardation mode

First of all, phase retardation should be introduced and defined. Supposing one uniaxial crystal or LC, whose ordinary and extraordinary refractive indexes are n_o and n_e, respectively, is prepared. When a light beam is normally incident into the material through a linear polarizer, the output light beam will experience corresponding phase retardation, Γ, according to the intersection angle of the polarization direction and the optical axis of the uniaxial material. The formation of the phase retardation is caused by the difference of refractive indexes between n_o and n_e, resulting in the different propagating velocities of ordinary and extraordinary beams inside the uniaxial material. The phase retardation, Γ, can be given as [1–4]

$$\Gamma = \frac{2\pi d(n_e - n_o)}{\lambda} = \frac{2\pi d\Delta n}{\lambda}, \tag{12.5}$$

where d is LC cell gap, Δn is birefringence and λ is the wavelength of incident light. For two special cases, polarization direction of the incident light parallel or perpendicular to optical axis of the uniaxial material, the phase retardation equals zero. Otherwise, the effective phase retardation causes the transformation of polarization of the output beam. For example, just like half-waveplates, if the effective phase retardation is $\pi/2$, the incident linearly polarized light will be transferred to elliptically polarized light (be rotated by 2θ, θ: intersection angle). Accordingly, if a uniaxial LC layer is sandwiched between two cross polarizers, the transmission can be electrically tuned because of the variation of Δn by applying voltage, or the so-called electrically controlled birefringence (ECB) effect. Many types of LCDs, including vertical alignment, homogeneous alignment, hybrid alignment, in-plane-switching (IPS) modes, and others, are operated using this ECB effect.

In principle, the relationship between transmittance and phase retardation under crossed ($T_{\perp}$) and parallel ($T_{//}$) polarizers can be given as,

$$T_{\perp} = \sin^2 2\theta \ \sin^2\left(\frac{\Gamma}{2}\right), \quad T_{//} = 1 - \sin^2 2\theta \ \sin^2\left(\frac{\Gamma}{2}\right), \qquad (12.6)$$

where θ is the angle between the polarizer direction and the LC director.

(c) scattering mode

In scattering mode for modulating light intensity, LCs and polymers are two candidates for use in such kind of LC devices, including displays, light shutters, diffusers, etc. Initially, they will be homogeneously mixed with each other, and then, will be phase separated. Two famous catalogs—polymer-dispersed LCs (PDLCs) and polymer-stabilized LCs (PSLCs) are developed according to their morphologies.

Regarding PDLCs, the micron- or sub-micron-size LC droplets, isolated from one another, will be formed and dispersed in polymer matrix. The incident light will be scattered because of the mismatch of refractive indexes of LCs and polymers at zero applied voltage. Notably, the concentration of polymer and LCs are comparable with each other. In PSLCs, divided into scattering and non-scattering devices, the concentration of LCs is much higher than that of the polymer. Here, the scattering devices, where exist multi-domain LC structures, are discussed only. The size of LC domain is comparable to the scattered light. Notably, the size of LC domains in both of PDLCs and PSLCs can be controlled during phase separation processes. Here, a brief introduction of the operation mechanism for scattering mode LC devices will be shown following. As depicted in Fig. 12.2a, the material of polymer matrix is optically isotropic with its refractive index, n_p, and the LC droplets are randomly oriented in polymer matrix in the absence of an applied voltage. Regarding the boundary of two materials with discontinued refractive indexes, the refractive indexes mismatch between the LC droplets and polymer matrix leads to strong scattering in the voltage-off state (scattering state). On the other hand, the director of LCs with $\Delta\varepsilon > 0$ are aligned along the applied electric filed in the voltage-on state (transparent). A very important key is that the ordinary refractive index (n_o) of the used LCs should be as close as n_p for the application of light shutters. Accordingly, the unidirectional director provides almost insignificant differences ($n_o = n_p$) in the refractive indexes of neighboring polymers such that the PDLC appears perfectly transparent, as shown in Fig. 12.2b. However, the polymer matrix walls produce a strong surface

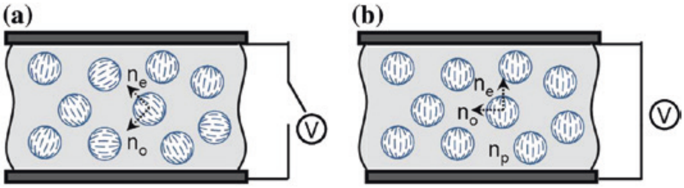


Fig. 12.2 Schematic diagrams of polymer-dispersed LCs; **a** scattering (field-off) state and **b** transparent (field-on) state

anchoring effect that increases driving voltages, indicating that the operated voltage of a traditional PDLC scattering mode light shutter is high [6, 7]. Accordingly, many scientists have recently paid much attention to such approaches as surface rubbing effect [8], dichoric dyes [9], and others, to reduce the operated voltage of PDLCs. Next, a newly proposed approach, particular thermally-induced phase separation (TIPS), is introduced [6]. Fuh et al. reported particular TIPS method that involves a combination of dissolution process of LCs and poly(N-vinylcarbazole) (PVK), and TIPS. Briefly, a nematic LC cell fabricated by two substrates coated with uniform PVK films is heated and then cooled, generating the rough PVK layers onto the surfaces of the substrates. The LC cell having rough PVK layers produces micron-sized, multiple domains of disordered LCs that can scatter incident light. The fabricated LC light shutter possessed the advantages of low driving voltage, fast response in the order of milliseconds, independent of polarization, high contrast ratio, and being polarizer free.

Moreover, scattering mode light shutters can also be used to fabricate many LC devices, such as holography [10], smart windows [11], etc.

(d) absorbance mode

So far, we have introduced several physical mechanisms, such as polarization rotation, phase retardation and scattering, for modulating the transmissive light through a LC cell. In the following section, we'd like to discuss another mode for modulating light intensity, absorbance mode. The famous LCD type using absorbance mode is guest-host (G-H) display that does not need any polarizer. To introduce G-H LCD, dichroic dyes should be paid attention to firstly. The LC and dyes play the roles of host and guest, respectively, because of the properties of electrical switching of LCs and anisotropic absorbance of dichroic dyes. Usually, the LC host is highly transparent in visible wavelength, and the selected dyes should strongly absorb one polarization direction of incident light, and unabsorb the other one. Importantly, the rod-like dichroic dyes are aligned along the long axis of LCs. Thus, the mechanism of G-H LCDs is electrically controllable light absorption. About the dichroic dyes, dichroic ratio, DR, the most important parameter in determining the performance of a G-H LCD, is defined as

$$DR \equiv \frac{A_{\parallel}}{A_{\perp}} = \frac{1 + 2S}{1 - S}, \tag{12.7}$$

where $A_{//}$ and $A_{\perp}$ are the absorbances when the polarization direction of the incident light is, respectively, parallel and perpendicular to the optical axis of the dyes. S is the order parameter [12]. According to the absorbance performance, the contrast ratio, defined as the transmittance ratio at voltage on and off states, of G-H LCDs increases with increasing DR. Additionally, the contrast ratio is also dependent on the cell thickness and concentration of dyes, but the prices are the increases of operating voltage, response time, etc. Notably, powder dyes exhibit extremely low solubility into LCs. Several LC dyes are developed to enhance the concentration of dyes [13, 14].

Next, we'd like to introduce the most commonly used G-H LCDs—White-Taylor cell, which does not need any polarizer [15]. The materials used in the cell are nematic LC ($\Delta\varepsilon > 0$), about 2 wt% absorbing dyes and about 1 wt% chiral dopant. Due to the doping chiral dopant, the dye-doped chiral nematic LCs present twisted structures, in which the twisted aligned dyes can absorb incident unpolarized light at voltage-off state (dark state, Fig. 12.3a). Moreover, at voltage-on state (bright state, Fig. 12.3b), LCs and dyes are aligned along the direction of electric field, resulting in the low absorbance. Since no polarizer is required, the brightness is excellent, which is very suitable for fabricating reflective mode LCDs. Additionally, other kinds of G-H LCDs, which need polarizers or quarter waveplates, using dye-doped nematic LCs have also been developed [16]. Also, Toshiba group demonstrated a prototype of reflective color LCDs using 3-layer guest-host mode [17].

(e) cholesteric reflection mode

In recent decade, cholesteric LCs (CLCs), also known as chiral nematic LCs, have been studied by many scientists [18–23]. CLCs usually consist of nematics and a chiral dopant, as well as have two stable textures, planar (P) and focal conic (FC) textures. The P textures (Fig. 12.4a) present reflective state due to the Bragg reflection. Briefly, circularly polarized light with the same handedness as that of the P textures of CLCs is selectively reflected. The central reflection wavelength (λ_c) of the selective reflection band by P textures can be described by p and $\bar{n}$, and can be expressed as $\lambda_c = \bar{n}\, p\cos\theta$ ($\theta = 0$ for normally incident light, $\bar{n} = (n_{\parallel} + n_{\perp})/2$). Pitch length ($p$) is determined by the concentration (c) of the chiral dopant and the relative helical twisting power (HTP) according to their relationship $HTP = 1/pc$. Positive (negative) values of HTP

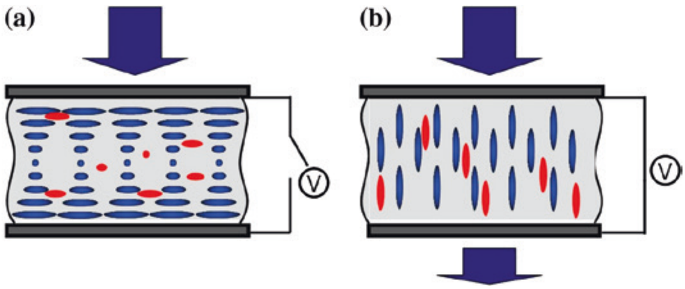


Fig. 12.3 White-Taylor guest-host cell; **a** *dark* (field-off) state and **b** *bright* (field-on) state

represent right- (left-) handed helix. Moreover, the FC textures (Fig. 12.4b) show strong light scattering because of the randomly arranged helical axes. Such various potential bistable (reflective planar and scattering focal conic states) LCD technologies have been developed because they present low power consumption [22, 23].

Moreover, P textures can be switched to FC ones by applying a voltage with relatively low amplitude. In this state, the Bragg reflection can be eliminated mostly, and the incoming light is scattered. The FC textures are transformed into homeotropic texture, which is a transparent state, if a relative high voltage is applied. When the applied high voltage is switched off rapidly, CLCs in homeotropic textures can be relaxed back into P textures. Notably, the homeotropic textures can also be switched back to FC textures by reducing the high applied voltage to a low bias voltage, or removing the high voltage gradually. Figure 12.5 presents the possible texture transitions of CLCs. Importantly, both of P and FC textures are stable states, and can be used to achieve bistability with applying any external voltage to maintain them. Accordingly, cholesteric reflection modes LCDs are widely used because of their low power consumption, bistability, readable under sun, good viewing angle, etc. Also, polymer-stabilized cholesteric textures, full-color reflective LCDs, and others, are developed to improvement their performance.

(f) LC on silicon (LCOS) mode

LC on silicon mode, which is a reflective LCD, has been widely adopted for developing projection systems and virtual display (micro-display). Such a kind of reflective LCDs is fabricated by only one glass substrate (front substrate) and a silicon wafer (back substrate), containing the corresponding circuits for addressing each pixel. Briefly, the pixel electrodes of LCOS displays are coated with a flat and highly reflective aluminum mirror and an alignment layer, as shown in Fig. 12.6. LCOS can be adopted to achieve high-resolution LCDs because of the

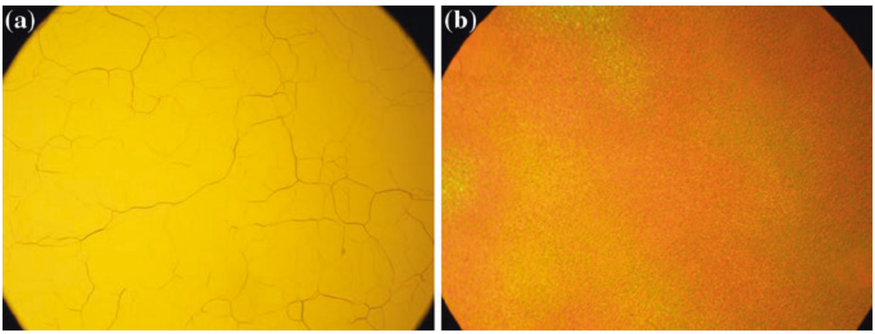


Fig. 12.4 Observations of cholesterics under cross-polarized optical microscope; **a** planar and **b** focal conic textures

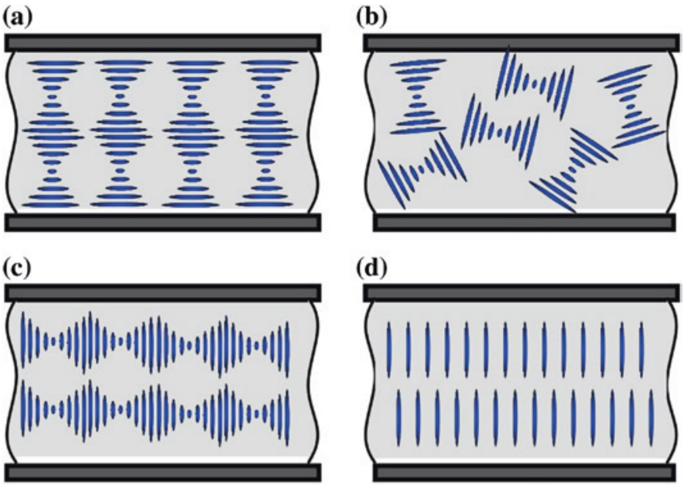
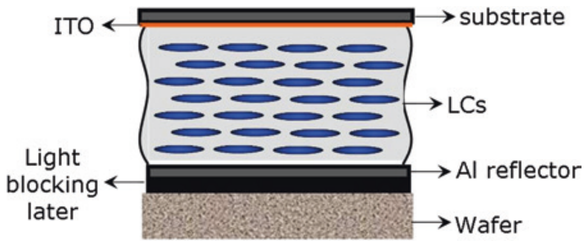


Fig. 12.5 Schematic diagrams of cholesterics; **a** planar texture, **b** focal conic texture, **c** fingerprint texture and **d** homeotropic textures

Fig. 12.6 Basic configurations of LC on silicon cell



existing silicon technology. Moreover, considering the color display using LCOS technology, three methods, including color pixellization, multiple LCOS panels, and field sequential color, can be used to achieve color. However, because of a small size of LCOS display, the second and third approaches are commonly used in projectors and virtual displays, respectively. It should be noted that the mechanism of field sequential color (FSC), or the so-called color sequential display, is based on separating color temporally rather than spatially (sub-pixels), so that the switching time of LC cell is extremely important.

However, LCOS mode still has some drawbacks, resulting from the temperature. The stability of surface alignment layer will be reduced due to the high temperature inside the LCOS system so that the LC director alignment will be disturbed. Accordingly, usually, the used materials to form the alignment layers are inorganic materials, such as SiOx. Additionally, color breakup is another issue should be solved in color sequential display.

12.2 Emerging Technology

LC technology has been widely paid much attention to over the past decade. LCs are not only applied for fabricating flat displays, but also for developing many non-display applications, such as gratings, spatial filters, polarization convertors, lenses, and so on. They will be introduced in Chap. 14. Moreover, in LC fields, some emerging technologies, such as flexible LCDs, high resolution LCDs, green technologies, reflective LCDs, transflective LCDs, three-dimension (3D) LCDs, fast response LCDs, touch panels, and others, have attracted considerable interest recently. Among them, flexible displays have been developed in recent years for applying in many products, such as smart cards, e-books, e-papers, mobile phones, and others. The challenges include the uniformity, reliability, etc. Commercially, customers can buy a flexible LCD based on bistable cholesteric reflective displays. The detailed mechanism can be read in the previous Sect. 12.1. About high resolution, the famous 4K2K and 8K LCDs (ultra high definition, UHD) are believed to dominate the mainstream market. To achieve such high resolution, the technical processes, including high aperture ratio TFT pixel design, high accurate process equipments, optimization of the processes, and so on, are the main keys. Moreover, green technology in LC fields can be extended to multi-stability, low power consumption, simple fabrication processes, and so on. The techniques of polymer stabilizations, LED backlight units, frontier LC materials are developed to achieve the issue. 3D LCD technologies will be described in detail in Chap. 13. Touch panel, combined with high definition flat display, is another challenge in LC fields. In this section, in-plane-switching (IPS)/fringing field switching (FFS), blue phase, and reflective/transflective LCDs will be introduced.

(a) in-plane-switching (IPS)/fringing field switching (FFS) LCD

Conventionally, as shown above, the direction of the applied voltage to drive LCs is perpendicular to the substrates (parallel to the normal direction of the substrates). With the applied voltage, the electrically controllable birefringence results in proper phase retardation, and can be adopted to control gray scales with polarizers. However, the phase retardations obtained from right and left sides are different due to the directional asymmetry of tilted LC. Such a shortage causes narrow viewing angle and asymmetric transmittance, especially along the vertical directions. To overcome the problems, it is in-plane-switching (IPS) technique that was proposed in 1970s by Soref et al. [24, 25]. IPS mode is, in brief, a driving scheme by a fringing electric field, which keeps the directors of LCs lying parallel to the surface of substrates during the treatment of electrical driving. Restated, the directors of LCs are rotated in the plane parallel to the direction of the applied transverse electric field, so that the viewing angle and asymmetric transmittance can be improved. In IPS mode, to provide a transverse electric field, the periodically interdigital electrodes are fabricated onto one of the substrates to generate the fringing field in the transverse plane. It should be noted that the distance (l) between the electrodes should be larger than the cell gap (d) ($l > d$) and the width of the electrode. Refer to the previous Sect. 12.1(b), the phase retardation mode can be achieved in both of homogeneous (planar) and homeotropic (vertical) alignments using longitudinal fields. In the IPS mode, both of them can also be switched by transverse fields [26]. Especially, in homeotropic alignment, LCs having either positive or negative dielectric anisotropy can be adopted. The famous electronics, including iphone, ipad, LG smart phone, etc., are employed IPS mode as their displays.

The first design of the IPS cell, using positive dielectric anisotropy LCs in homogeneous alignment cell, was proposed by Hitachi [27, 28]. Such a LC cell, as shown in Fig. 12.7, shows normally black mode under cross-polarizers, indicating that in the field-off state, the LCs are aligned by the homogeneous alignment layer in parallel to the direction of the polarizer, so that no phase retardation can be experienced. Finally, the incident light is thus blocked by the analyzer. Moreover, in the field-on state, the LCs are electrically rotated so that the phase retardation modulates the polarization of the incident light. Hence, the transmittance can be electrically switched. Additionally, IPS modes using positive dielectric anisotropy LCs in homeotropic alignment layers were also developed by Hyundai [29] and Samsung [30]. To overcome the dark lines, existing between the electrodes, Hyundai and Samsung groups proposed different approaches to achieve four-domain configurations. The viewing angle can be improved further.

Furthermore, to improve the performance of LCDs, such as aperture ratio, viewing angle, small-size high-resolution, large-size ultra-hugh-resolution, etc., Hydis group developed fringing field switching (FFS), which also utilizes the transverse field to switch LC directors [31]. The configuration of the FFS mode is very similar to that of the IPS mode. The main difference between these two modes is the electrode gap. In the FFS mode, the electrode gap (l) is smaller than the cell gap (d) (l < d), so that the fringing field can reorient the LCs just above the electrodes. Hence, the high transmittance can be achieved because of the absence of the dead zones. Also, LCs with both positive and negative dielectric anisotropy

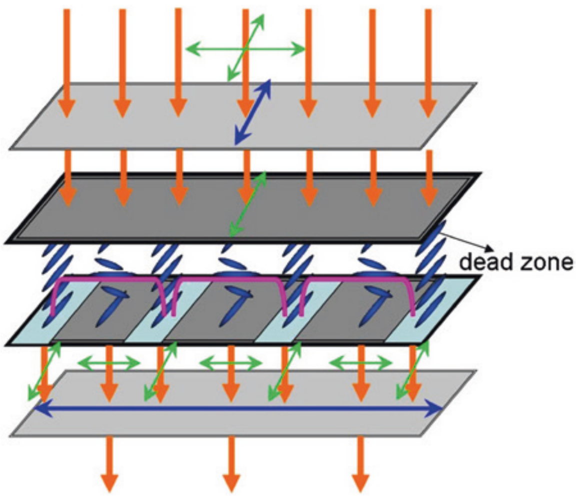


Fig. 12.7 Basic configuration of the IPS mode LCD in voltage-on state with a homogeneous alignment LCs ($\Delta\varepsilon > 0$) parallel to the stripes of electrodes

can be used in the FFS mode. Figure 12.8 shows the basic configuration of the FFS mode LCD with a homogeneous alignment parallel to the stripes of electrodes. The used LCs are with positive dielectric anisotropy. Clearly, the fringing field distributes over the electrodes and their gaps, resulting in high transmittance. The LCDs, produced by the FFS mode, are called Super-LCDs. Recently, the Hydis group also developed Advanced FFS (AFFS) technique, providing superior performance, low power consumption, wide viewing angle, high transmittance, fast response, and color gamut with high luminosity, as well as the improvement of outdoor readability [32]. Additionally, high aperture FFS has also been developed for small size LC panels [33]. AUO also proposed several techniques, including VA-IPS with positive dielectrically anisotropic LCs, VA-FFS using inverse electric fields, etc., to improve the performances of LCDs.

In summary, IPS and FFS modes provide some advantages, such as wide viewing angle, high contrast, and others, resulting from the principle of in-plane reorientation of LCs. The incoming light from any directions experiences the short axis of LCs so that the viewing angle can be widened and symmetric. Additionally, IPS and FFS modes LCDs are hard screen mode LCD, suitable for the applications of touch panel displays. However, the yields and the cost are the main keys for IPS and FFS modes to compete with the general LCD panels with wide viewing angle.

(b) blue phase LCD

BP-LCs, including PBI (body-centered cubic symmetry), BPII (simple cubic symmetry) and BPIII (amorphous structures), are LC phases that appear in a narrow

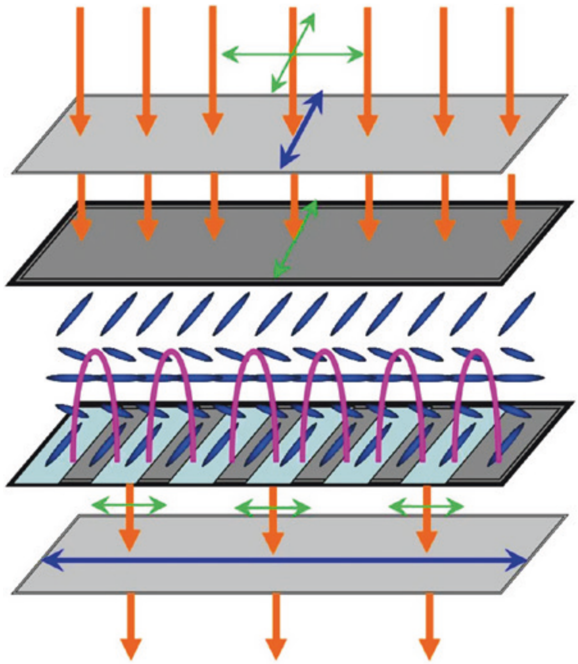


Fig. 12.8 Basic configuration of the FFS mode LCD in voltage-on state with a homogeneous alignment parallel to the stripes of electrodes

temperature range, usually less than a few K, between chiral nematic and isotropic phases. Unlike the cholesteric LCs with single twisted structures, BP-LCs are assembled by double twisted structures. Such two twisted structures are crossed with each other and generate double twisted cylinders (DTCs), as shown in Fig. 12.9. BP-LCs exhibit selective Bragg reflections due to their three-dimensional cubic structures with lattice periods in the order of 100 nm. Moreover, observing BP-LCs under polarized optical microscope, BPI and BPII present colorful platelet textures, while BPIII fog-like textures. [34]

For application in LCDs, because BP-LCs present extremely fast response (μs), wide viewing angle, alignment layer free process, cell gap insensitivity, etc., they are much benefit for the next generation of display and electro-optical devices if the temperature range can be broadened. Briefly, the isotropic sphere will be elongated or flattened to be ellipsoid, depending on whether the LCs are positive or negative dielectric anisotropic materials, when electric field is applied. In 2008, Samsung announced its prototype TFT-LCD panel with 240 Hz image frame rate based on blue phase LCs (BP-LCs) at 2008 SID (Society for Information Display) [35]. Moreover, not only the direct-view, but also the projection displays based on Kerr effect using BP-LCs high have potential for LCDs. Regarding projection displays, field-sequential, or the so-called color-sequential, projection LCDs with several advantages of high optical efficiency, low cost, and others, are newly and famous displays in the recent decades. However, color breakup, resulting from

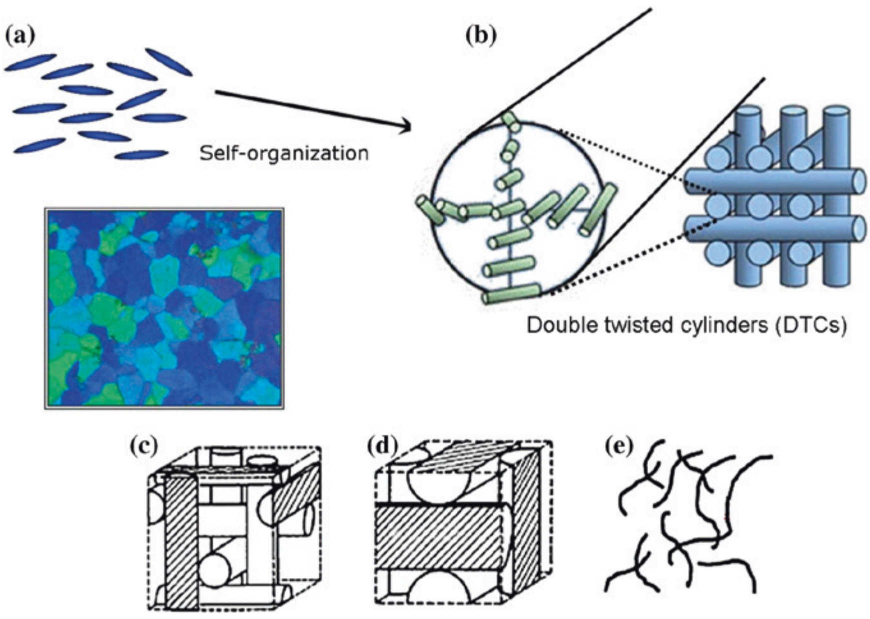


Fig. 12.9 Blue phase LCs, **a** observation under cross-polarized optical microscopy; **b** double twisted cylinders (DTCs); **c** PBI (body-centered cubic symmetry); **d** BPII (simple cubic symmetry) and **e** BPIII (amorphous structures)

slow response time, should be paid much attention. Hence, BP-LCs are the promising candidates for such display applications due to their fast response [36–41].

Regarding to the temperature range, recently, it is demonstrated that the polymer can be used to stabilize BP-LCs to extend the temperature range more than 60 K, including room temperature [42]. Also, other approaches were developed to broaden the temperature range of BP-LCs [43]. Accordingly, the stabilized BP-LCs at room temperature possess the electro-optical switching with extremely fast response (μs).

Under the application of electric field, the optically isotropic LCs can be changed to anisotropic LCs with the optical anisotropy parallel to the applied field. It indicates that the described IPS or FFS modes are adopted to produce birefringence for BP-LCDs. Notably, the optically anisotropy follows the Kerr Effect [37]. In order to increase the phase retardation, the birefringence can be increased with the increase of the applied field until the saturated birefringence appears. However, the extremely high operating voltage of BP-LCDs based on IPS mode is not suitable for practical application. To reduce such high operating voltage, several modified structures of IPS electrodes, such as protrusion electrodes [44], wall-shaped electrodes [45], double-penetrating fringe fields [38], and corrugated electrodes [36], are developed. Also, Kim et al. and Wu et al. also proposed vertical field switching (VFS), whose electric field is in longitudinal direction and uniform, in BP-LCs [40, 46, 47]. However, although BP-LCs were discovered a 100 years ago and were also improved technically, they were almost failed to be really applied for fabricating practical devices due to the described instinct shortages.

(c) transflective mode LCD

Nowadays, transmissive LCDs have been widely developed in most of the display electronics. As described above [1–4], the mechanisms for operating principle of light modulations include polarization rotation, phase retardation, scattering, absorbance, and so on. The performances, including wide viewing angle, fast response, low power consumption, high contrast ratio, etc., are also improved. However, an inevitable issue for transmissive LCDs is the continued "on" backlight source as long as the display is turned on. Restated, the relatively high power consumption cannot be reduced according to this point. Of course, light emitting diodes are great for reducing the power consumption of backlight unit. However, it is worth to be noticed. Additionally, if you bring your electronics out of doors under sunlight, the contrast of the displayed image onto your electronics can be reduced by the sunlight. So, it is reflective LCDs that have been developed [1]. It is clear to understand that the reflective LCDs do not include built-in backlights so that the undesired ambient light for transmissive LCDs can be used to be the "front light" to reflective LCDs for displaying information. Accordingly, comparing reflective LCDs with transmissive ones, not only the outdoor readability can be improved, but also the power consumption can be reduced. But, how about bring your electronics with reflective LCDs into a dark room? Reflective LCDs do not work there. Combing transmissive and reflective LCDs can keep their advantages in one LCD, which is named transflective LCDs.

As described above, transflective LCDs, whose light sources are the ambient light or backlight units, are developed to be used under both bright and dark ambient, and can simultaneously or independently display images based on the transmissive and reflective modes. Hence, the transflective LCDs can be applied onto the electronics, which can be used indoors and outdoors, such as mobile phones, watches, digital cameras, navigators, and so on. Briefly, transflective LCDs can be divided into several categories according to the operating mechanisms [48]; they are absorption, scattering, reflection and phase retardation modes. Among them, the phase retardation mode, requiring two polarizers usually, has higher potential for commercial applications than the others, due to their higher contrast ratio, lower driving voltage, and so forth. Here, we will introduce two main types of transflective LCDs based on phase retardation mode, one is dual-cell-gap transflective LCDs, and the other one is single-cell-gap transflective LCDs. The key point is the identical phase retardation from the transmissive region (T-region) and reflective region (R-region) after the light leave the LCs regions when any amplitude of the electric field is applied.

(1) dual-cell-gap transflective LCDs

Figure 12.10 shows the schematic configuration of a simple dual-cell-gap transflective LCD with the homogeneous aligned LCs in both the T- and R-regions. The cell gaps of these two region, d_T and d_R are different, and the relationship between d_T and d_R is $d_T = 2d_R$. Notably, the LC alignments in T- and R-regions are the same so that the complicated alignment process is unnecessary. Regarding the waveplates in the configuration, a half- and a quarter-wave plate are setup on both sides of T- and R-regions. It should be noted that the combination of these tow waveplates with a linear polarizer equals a broadband circular polarizer [49], and can be employed to achieve a normally white mode transflective LCD. Restated, good dark state can be obtained, and is not too sensitive to the variation of cell gap in T- and R-regions. Although the mechanism for such a dual-cell-gap transflective

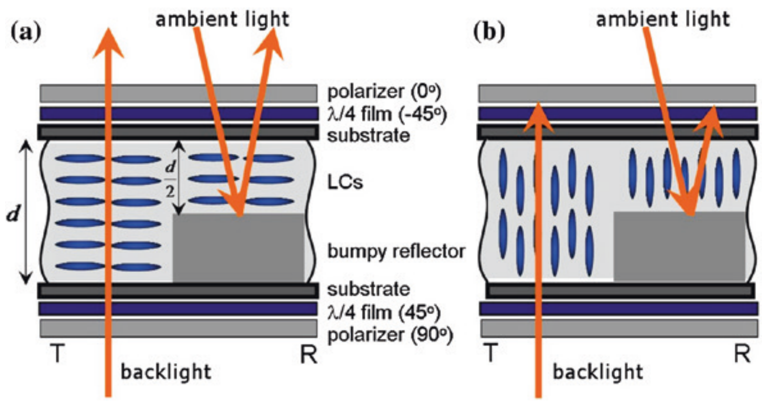


Fig. 12.10 Schematic configuration of a simple dual-cell-gap transflective LCD with the homogeneous aligned LCs in both the T- and R-regions. **a** *bright* and **b** *dark* states

LCD is very simple, several problems, including the different response time in T- and R-regions, narrow viewing angle, complicated fabrication process, etc., should be considered [50]. Fortunately, so far, the manufacturing processes are completely compatible with the existing technique, so the dual-cell-gap transflective LCDs are the first candidate for the commercial transflective LCD products.

Furthermore, many scientists worldwide have also proposed several kinds of dual-cell-gap transflective LCDs, such as dual-cell-gap transflective vertical alignment LCD [51], dual-cell-gap transflective hybrid alignment LCD [52], dual-cell-gap transflective FFS LCD [53, 54], and so on. The detailed operating principles of these kinds of transflective LCDs follow the electrically controllable birefringence LCDs, as describe above.

(2) single-cell-gap transflective LCDs

It is clear to understand that the difference between dual-cell-gap and single-cell-gap transflective LCDs. An identical cell gap in T- and R-regions of single-cell-gap transflective LCDs is made. Ideally, similar to the dual-cell-gap transflective LCDs, the electro-optical properties, including the dynamic responses, viewing angles, gray-scale controls, and others, in T- and R-regions, are identical to each other. The backlight travels the LC film once in the T-regions, while the ambient light twice in the R-regions. General speaking, single-cell-gap transflective LCDs are more favorable because they are easier to fabricate, but the matching phase retardation between T- and R-regions is difficult to achieve. In recent decade, many single-cell-gap transflective LCDs has been developed, for example, transflective TN, transflective STN, transflective MTN, transflective HA/hybrid, transflective BP, transflective IPS LCDs, and so on.

For instance, Fig. 12.11 depicts that the dual LC alignments, comprising the homogeneous (HA) and hybrid (HB) alignments, sandwiched between two crossed

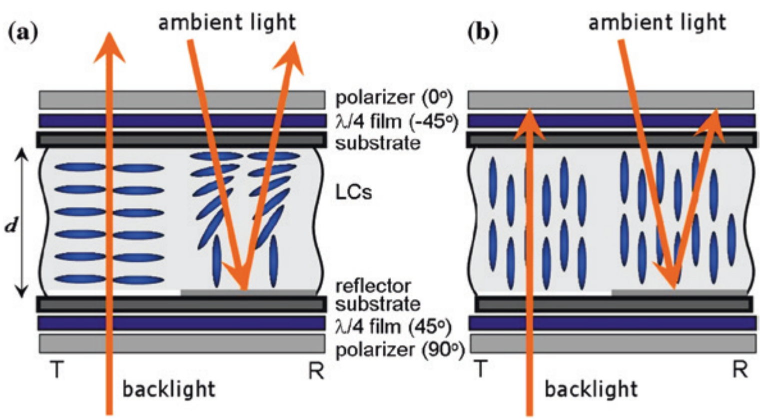


Fig. 12.11 Schematic configuration of a single-cell-gap transflective LCD with the dual LC alignment of homogeneous and hybrid alignments both the T- and R-regions, respectively. **a** *bright* and **b** *dark* states

polarizers. Such a binary configuration can be used to examine the electro-optical characteristics of the transmissive and reflective pixels in one kind of single-cell-gap transflective LCDs. [55]. Theoretically, the optical path of the reflective pixel (hybrid alignment) is twice as long as that of the transmissive pixel (homogeneous alignment) by a reflector, and the phase retardation for the bright state in the T-region should be set as $\lambda/2$ ($=\pi$), while that in the R region $\lambda/4$ ($=\pi/2$). Therefore, the quarter-wave plate is set between the substrate and polarizer to optimize the bright and dark states. Moreover, the angles between the transmission axes of the polarizers and the rubbing direction (along the ***y***-axis) were +45° and −45°. The same phase retardation ($2\pi d\Delta n/\lambda$) in the T- and R- (with a reflector) regions can be essential in achieving high optical performance of the transflective LCDs. Hence, it schematically depicts the designed single-cell-gap transflective LCD. In this design, according to the electrically controlled birefringence (ECB) mode LCD, the transmittance observed under the cross-polarizers can be given by $\sin^2 2\beta \ \sin^2(\delta/2)$, where β and δ denote the angle between the polarization direction of the incident light and the rubbing direction, and the phase retardation [$2\pi d(n\text{-}n)/\lambda$], respectively [2–4]. In this case, the transmittance observed under the cross-polarizers equals $\sin^2(\delta/2)$ when β is set to 45°. Therefore, the maximum (minimum) transmittance implies that the phase retardation equals $(2n + 1)\pi$ [$(n\pi)$], where n represents an integer. Additionally, the phase retardation in T- and R-regions decreases when the applied voltage increases, ultimately reaches nearly zero. The ratio of phase retardation in the R-region to that in T-region at an applied voltage should be optimized to be around 0.5. The bright, dark, and grayscale states that originated from the phase retardation between 0 and π, therefore, can be obtained by applying an AC voltage in the LCDs.

In summary, as discussed herein, the single-cell-gap transflective LCDs based on dual LC configuration require either dual-rubbing process or complicated electrode designs, so such kind of transflective LCDs have not been commercialized yet.

References

1. S.T. Wu, D.K. Yang, *Reflective Liquid Crystal Displays* (John Wiley, Chichester, 2001)
2. E. Lueder, *Liquid Crystal Displays* (John Wiley, Chichester, 2001)
3. D.K. Yang, S.T. Wu, *Fundamentals of Liquid Crystal Devices* (John Wiley, Chichester, 2006)
4. P. Yeh, C. Gu, *Optics of Liquid Crystal Displays* (John Wiley, Chichester, 1999)
5. M. Schadt, W. Helfrich, Voltage-dependent optical activity of a twisted nematic liquid crystal. Appl. Phys. Lett. **18**, 127–128 (1971)
6. Y.D. Chen, Andy Y.-G. Fuh, K.T. Cheng, Particular thermally induced phase separation of liquid crystal and poly(N-vinyl carbazole) films and its application. Opt. Express **20**, 16777–16784 (2012)
7. Andy Y.-G. Fuh, C.C. Chen, C.K. Liu et al., Polarizer-free, electrically switchable and optically rewritable displays based on dye-doped polymer-dispersed liquid crystals. Opt. Express **17**, 7088–7094 (2009)
8. G.Z. Liu, D.L. Xia, W.J. Yang et al., The surface rubbing effect on morphologies of LC droplets and electro-optic properties of flexible PDLC films. Sci. China Ser. Biol. Chem. **52**, 2329–2335 (2009)

9. K.J. Yang, D.Y. Yoon, Electro-optical characteristics of dye-doped polymer dispersed liquid crystals. J. Ind. Eng. Chem. **17**, 543–548 (2011)
10. R.L. Sutherland, V.P. Tondiglia, V.L. Natarajan, Electrically switchable volume gratings in polymer-dispersed liquid crystals. Appl. Phys. Lett. **64**, 1074 (1994)
11. http://www.polytronix.com/index.html
12. A.C. Lowe, R.J. Cox, Order Parameter and the performance of nematic guest-host displays. Mol. Cryst. Liq. Cryst. **66**, 309–318 (1981)
13. S.T. Wu, J.D. Margerum, M.S. Ho et al., Liquid crystal dyes with high solubility and large dielectric anisotropy. Appl. Phys. Lett. **64**, 2191 (1994)
14. N. Tabiryan, U. Hrozhyk, S. Serak, Nonlinear refraction in photoinduced isotropic state of liquid crystalline azobenzenes. Phys. Rev. Lett. **93**, 113901 (2004)
15. D.L. White, G.N. Taylor, New absorptive mode reflective liquid crystal display device. J. Appl. Phys. **45**, 4718 (1974)
16. T. Uchida, H. Seki, C. Shishido et al., Bright dichroic guest–host LCDs without a polarizer. Proc. Soc. Inf. Disp. **22**, 41–46 (1981)
17. K. Taira, H. Iwanaga, A. Hotta et al, Optical and color design of the reflective three-layer guest-host color LCD. in SID Tech Digest 1996 international workshop on active-matrix liquid-crystal displays in conjunction with IDW'96, pp. 333–336 (1996)
18. D.K. Yang, L.C. Chien, J.W. Doane, Cholesteric liquid crystal/polymer dispersion for haze-free light shutters. Appl. Phys. Lett. **60**, 3102–3104 (1992)
19. M. Xu, D.K. Yang, Dual frequency cholesteric light shutters. Appl. Phys. Lett. **70**, 720–722 (1997)
20. K.T. Cheng, C.K. Liu, C.L. Ting et al., Electrically switchable and optically rewritable reflective Fresnel zone plate in dye-doped cholesteric liquid crystals. Opt. Express **15**, 14078–14085 (2007)
21. D.K. Yang, J.L. West, L.C. Chien et al., Control of reflectivity and bistability in displays using cholesteric liquid crystals. J. Appl. Phys. **76**, 1331–1333 (1994)
22. Andy Y.-G. Fuh, Z.H. Wu, K.T. Cheng et al., Direct optical switching of bistable cholesteric textures in chiral azobenzene-doped liquid crystals. Opt. Express **21**, 21840–21846 (2013)
23. Y. Wang, Q. Li, Light-driven chiral molecular switches or motors in liquid crystals. Adv. Mater. **24**, 1926–1945 (2012)
24. R.A. Soref, Transverse field effect in nematic liquid crystals. Appl. Phys. Lett. **22**, 165 (1973)
25. R.A. Soref, Field effect in nematic liquid crystals obtained with interdigital electrodes. J. Appl. Phys. Lett. **45**, 5466 (1974)
26. M. Ohe, M. Yoneya, K. Kondo, Switching of negative and positive dielectro-anisotropic liquid crystals by in-plane electric fields. J. Appl. Phys. Lett. **82**, 528 (1997)
27. M. Ohe, M. Ohta, S. Arantani et al., Principle and characteristics of lelctro-optical behavior with in-plane switching mode. Asia Disp. **95**, 577 (1995)
28. M. Ohta, M. Ohe, K. Kondo, Development of super-TFT-LCDs with in-plane switching mode. Asia Disp. **95**, 707 (1995)
29. S.H. Lee, H.Y. Kim, I.C. Park et al., Rubbing-free, vertically aligned nematic liquid crystal display controlled by in-plane field. Appl. Phys. Lett. **71**, 2851 (1997)
30. K.H. Kim, S.B. Park, J.U. Shim et al., New LCD modes for wide-viewing-angle applications. SID Tech. Digest. **29**, 1085 (1998)
31. S.H. Lee, S.L. Lee, H.Y. Kim, Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching. Appl. Phys. Lett. **73**, 2881 (1998)
32. K.H. Lee, H.Y. Kim, K.H. Park et al., A novel outdoor readability of portable TFT-LCD with AFFS technology. SID Symposium Digest. Tech. Pap. **37**, 1079–1082 (2006)
33. S. Choi, S. Sun, K. Kim et al., Novel gray-toneless technology for mask reduction in high aperture rate FFS mode. SID Symposium Digest. Tech. Pap. **44**, 1126–1129 (2013)
34. S. Meiboom, J.P. Sethna, P.W. Anderson et al., Theory of the blue phase of cholesteric liquid crystals. Phys. Rev. Lett. **46**, 1216–1219 (1981)

35. http://www.samsung.com/us/aboutsamsung/news/newsIrRead.do?news_ctgry=irnewsrelease&news_seq=8351
36. M. Jiao, Y. Li, S.T. Wu, Low voltage and high transmittance blue-phase liquid crystal displays with corrugated electrodes. Appl. Phys. Lett. **96**, 011102 (2010)
37. J. Yan, H.C. Cheng, S. Gauza et al., Extended Kerr effect in polymer-stabilized blue-phase liquid crystals. Appl. Phys. Lett. **96**, 071105 (2010)
38. L. Rao, H.C. Cheng, S.T. Wu, Low voltage blue-phase LCDs with double-penetrating fringe fields. J. Disp. Technol. **6**, 287–289 (2010)
39. J. Yan, S.T. Wu, Polymer-stabilized blue phase liquid crystals: a tutorial. Opt. Mater. Express **1**, 1527–1535 (2011)
40. H.C. Cheng, J. Yan, T. Ishinabe et al., Wide-view vertical field switching blue-phase LCD. J. Disp. Technol. **8**, 627–633 (2012)
41. H.C. Cheng, J. Yan, T. Ishinabe et al., Blue-phase liquid crystal displays with vertical field switching. J. Disp. Technol. **8**, 98–103 (2012)
42. H. Kikuchi, M. Yokota, Y. Hisakado et al., Polymer-stabilized liquid crystal blue phases. Nat. Mater. **1**, 64–68 (2002)
43. F. Castles, F.V. Day, S.M. Morris et al., Blue-phase templated fabrication of three dimensional nanostructures for photonic applications. Nat. Mater. **11**, 599–603 (2012)
44. L. Rao, Z. Ge, S.T. Wu et al., Low voltage blue-phase liquid crystal displays. Appl. Phys. Lett. **95**, 231101 (2009)
45. M. Kim, M.S. Kim, B.G. Kang et al., Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays. J. Phys. D Appl. Phys. **42**, 235502 (2009)
46. Y.H. Kim, S.T. Hur, K.W. Park et al, A vertical-field-driven polymer-stabilized blue phase liquid crystal displays. in SID Symposium Digest **42**, pp. 298–301 (2011)
47. H.C. Cheng, J. Yan, T. Ishinabe et al., Vertical field switching for blue-phase liquid crystal devices. Appl. Phys. Lett. **98**, 261102 (2011)
48. X. Zhu, Z. Ge, T.X. Wu et al., Transflective liquid crystal displays. J. Disp. Technol. **1**, 15–29 (2005)
49. S. Pancharatnam, Achromatic combinations of birefringent plates: part I. An achromatic circular polarizer. Proc. Indian Acad. Sci. **41**, 130–136 (1995)
50. M. Shibazaki, Y. Ukawa, S. Takahashi et al., Transflective LCD with low driving voltage and wide viewing angle. SID Dig. Tech. Pap. **34**(1), 90–93 (2003)
51. H.D. Liu, S.C. Lin, A novel design wide view angle partially reflective super multi-domain homeotropically aligned LCD. in SID Digest of Technical Papers, pp. 558–561 (2002)
52. C.L. Yang, Electro-optics of a transflective liquid crystal display with hybrid-aligned liquid crystal texture. Jpn. J. Appl. Phys. **43**, 4273–4275 (2004)
53. T.B. Jung, J.C. Kim, S.H. Lee, Wide-viewing-angle transflective display associated with a fringe-field driven homogeneously aligned nematic liquid crystal display. Jpn. J. Appl. Phys. **42**, L464–L467 (2003)
54. T.B. Jung, J.H. Song, D.S. Seo et al., Viewing angle characteristics of transflective display in a homogeneously aligned liquid crystal cell driven by fringe-field. Jpn. J. Appl. Phys. **43**, L1211–L1213 (2004)
55. Andy Y.-G. Fuh, C.Y. Huang, C.K. Liu et al., Dual liquid crystal alignment configuration based on nanoparticle-doped polymer films. Opt. Express **19**, 18525–18531 (2011)