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*Review*

# Development and Prospect of Viewing Angle Switchable Liquid Crystal Devices

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**Abstract:** As we move from the industrial age to the information age, nowadays, the opportunity to access personal information in public increases as personal computers (PCs), cell phones, automated teller machines (ATM) and other portable display devices have come into wider use, so it is well suited for these liquid crystal displays (LCDs) to switch between wide viewing angle (WVA) (share mode) and narrow viewing angle (NVA) (privacy mode). In this review, we have summarized structures, principles and characteristics of several devices that show great potential application in controllable anti-peeping displays in the eyesight of materials consist of pure liquid crystals (LCs), polymer dispersed LCs (PDLCs), polymer stabilized LCs (PSLCs) or polymer network LCs (PNLCs) and non-LCs, which provides systematic information for next-generation viewing angle-controllable LCDs with lower operating voltage, higher transmittance and good viewing angle controllable characteristics. Because LCs/polymer composite films have the advantages of long life, low power consumption and energy saving, they are regarded as the mainstream technology of next-generation viewing angle controllable displays.

**Keywords:** wide viewing angle; narrow viewing angle; liquid crystals; PDLC; PSLC; PNLC



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## 1. Introduction

In this new digital information age, recently, with the rapid development of LCD technologies such as a wide view-twisted nematic (TN), in-plane switching (IPS), fringe-field switching (FFS), multidomain vertical alignment (MVA) and patterned vertical alignment (PVA), an increasing number of electronic products such as computer screens, mobile phones, electronic books, personal digital assistants (PDAs), tablet devices and LC televisions have been extensively applied [1–3]. Viewing angles are defined by a range of angles where the image displayed on an LCD remains suitable to the users, which refers to contour of isocontrast ratio that is dominated by the dark state dependent on the observation angle [1]. Ambient contrast ratio (ACR) is vital for evaluating an LCD performance, Figure 1a describes the schematic diagram of an LCD, the main reflection happens at front surface of LCD is defined as $R_1$, the ambient light passing into LCD is mostly absorbed by polarizers and optical components, by assuming no reflected light, $ACR_{LCD}(\theta,\phi) = \frac{L_{on}(\theta,\ \phi)+R_1}{L_{off}(\theta,\ \phi)+R_1}$, $L_{on}$ and $L_{off}$ represent the on-state and off-state luminance values of an LCD, $\theta$ and $\phi$ represent the polar angle and azimuthal angle, respectively [4]. In the past decades, WVA has been one of the most important characteristics in attaining the image quality in all viewing angle directions, which can be extended to 170° (polar angle) [5]. Currently, in applications of information devices in privacy contexts, such as using a notebook in public or an ATM machine, devices for adjusting viewing angle have drawn a lot of interest. Two different modes are demanded in the controllable viewing angle devices: share mode and privacy mode, generally, 3M light control films (also named anti-peeping films) including two films with a plurality of light absorbing regions are often used and taped on the front of screens (Figure 1b), the images on the LCD are visible only within a viewing angle range of −30° to 30° (Figure 1c), if a share mode is needed, the film must be removed from the LCD, which is unpractical and inconvenient [6]. Light control film containing closely spaced micro-louvers can also be LC or non-LC based, for LC-based materials, a lot of works focus on dual-mode switching of pure LC panel with alignment for viewing angle control [7]. To achieve both WVA and NVA properties in LCDs, various methods have been proposed for viewing angle control, such as multiple LC layers, one is utilized for gray level control, the other one is used for viewing angle control, which increases panel thickness and fabrication cost [1–7]. Dual backlight is introduced into viewing angle controllable devices, a normal backlight is for WVA mode and collimated backlight is for viewing angle control [1–7]. Dual cell method is proposed by using an additional LC cell to control the viewing angle, sub-pixel method in which the pixel is used to two parts, the main pixel is utilized for presenting images, sub-pixel is for controlling the viewing angle, which decreases aperture ratio of the main pixel [1–6]. Three-terminal electrode structure based on the FFS mode LCDs is introduced, different dark states are induced by various bias voltages, thus viewing angle controllable ability is presented [1–6]. However, these devices can achieve the viewing angle controllable characteristic, but have increase in thickness, cost and power consumption [1–7].

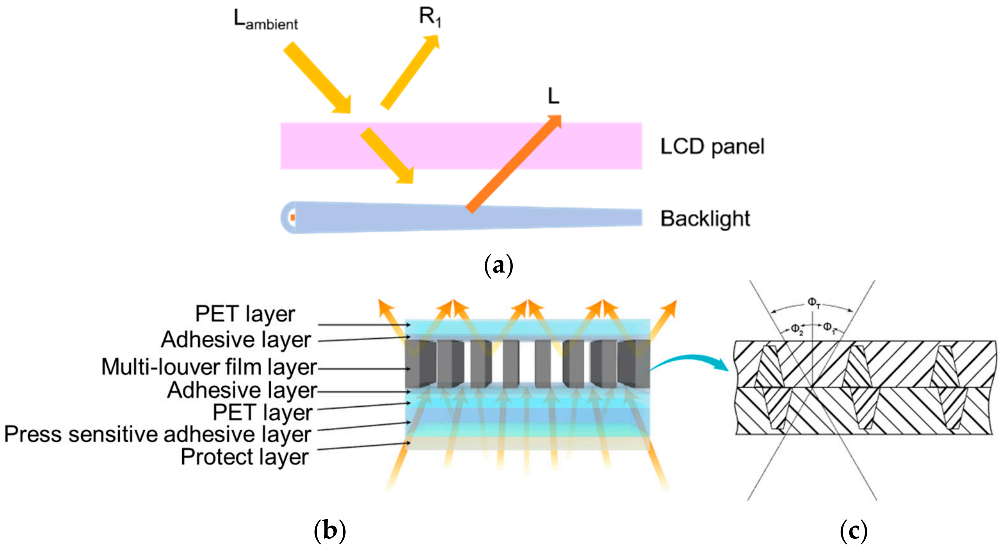


**Figure 1.** (**a**) Schematic diagram of an LCD; (**b**) Structure of 3M light control film; (**c**) The microlouver structure of 3M light control film.

Some researchers pay attention to light scattering ability of LC and polymer composite films, when the PDLC, PNLC or PSLC is at transparent state, the light remains narrow resulting in a NVA of the LCD. As the incident light transmits through PDLC, PNLC or PSLC, light is scattered because of the difference of refractive index between LCs and polymer, the LCD acts as a diffusing backlight source leading to a WVA. For non-LC devices, a multi-axial viewing control film for smart devices utilizing an array of optical micro-rods is proposed, it is convenient for users without removing the film from the information devices, additionally, a viewing angle switchable backlight module consists of a hybrid light guide plate and dual-light sources or two stacked backlight units is introduced [8,9]. However, switchable viewing angle displays based on non-LC devices require additional components or materials, thus cost, weight and thickness enhance.

In this review, we have summarized various designs to control the viewing angle and compared their characteristics in contrast ratios and viewing angles in WVA and NVA modes, taking thickness, brightness, power consumption, operating voltage and viewing angle switchable properties into consideration, LCs/polymer composite films show great potential for applications in viewing angle controllable LCDs.

## 2. Pure LC Devices

For pure LC system, methods for switchable viewing angle devices are divided into hybrid aligned nematic (HAN) LC cells, double cells, pixel division and three-electrode structure [10–15]. The controllable viewing angle device is located on the top of the LC panel, the device can be in transmissive mode (Figure 2a) or reflective mode (Figure 2b) [14]. To functionalize the device, the LC cell controls the transmission of light at predetermined azimuth angles and polar angles by applying the electric field on the LC layer, meanwhile, the light transmission in the normal direction is unchanged, thus the LC cell has no phase difference in the normal direction when changing the voltages [14]. For solving that, two types of LC cells including of homogenous aligned LC cell (Figure 2c) and HAN LC cell (Figure 2d) are utilized in this device [14]. The absorption axis of the polarizing films is parallel to the alignment of LC in both cells, in the homogeneous cell, the light-shielding effect exists in small range at an azimuth angle of 0°, while a negative C-plate is added between the LC layer and the polarizing film in the HAN LC cell for obtaining the desired light polarization state shift, a wider range of light-shielding angles can be achieved [14].

In the MVA or PVA devices, in the dark state, to improve the brightness uniformity in the gray levels, the addition of a compensation film is for suppressing light leakage. In the film compensation method, to compensate for the dark state, a negative C plate and positive A plate are introduced for compensating for the dark state, a WVA with the contrast ratio over 10 is extended from 30° to 80° of polar angle is achieved [16]. The double-cell display is mainly composed of a vertically aligned LC layer for displaying information, a homogeneous aligned LC layer replacing the positive A plate for viewing angle switching, and a negative C plate for compensation under crossed polarizer [16]. Without electric field, the vertically aligned LCs with negative dielectric anisotropy tilt down to make an angle of 45°, the optic axis of the homogeneous aligned LC layer with positive dielectric anisotropy is parallel to the analyzer's transmission axis, thus light transmitting through negative C plate and double LC cells is blocked by the analyzer, additionally, light leakage can be suppressed by homogeneous aligned LC cell and negative C plate [16]. For viewing angle switching, the mid-director of the homogeneous aligned LC layer is controlled by a vertical electric field (Figure 2e) [16], the high image quality in share mode has a polar viewing angle of 30° in the horizontal direction. However, this approach for tuning viewing angle requires additional components, leading to higher thickness and higher production cost.

When there is no electric field applied, blue phase typically appears in a very narrow temperature range, with polymer or nanomaterials stabilization, the temperature range can be extended, cubic structure in a BPLC appears to be optically isotropic, if there is a strong electric field, the anisotropy is induced along the electric field direction, which is defined as Kerr effect. By dividing pixel of the LCD device filled with a BPLC into two parts: a main pixel and a sub-pixel (Figure 2f–g), while the main pixel displays the image contents that are insensitive to viewing angle, as the birefringence is induced by transversal electric field and the LC reorientation is in the same plane, the sub-pixel controls the viewing angle. The LC cell is sandwiched between crossed polarizers, when applying a voltage between two electrodes, in-plane and vertical electric fields are produced in the main pixels and sub-pixels, respectively [16,17]. Without a bias voltage, BPLC is alike optically isotropic sphere, which is presented in Figure 2f, by the application of a bias voltage, the birefringence is induced due to Kerr effect, optic axes of BPLCs are parallel and perpendicular to the substrate in the main and sub-pixels, respectively (Figure 2g) [16,17]. A WVA is realized as the main pixels are only operated, the LCDs present a good dark in all directions, while a NVA is achieved as a bias voltage is applied to the sub-pixels, light leakage controlled by the applied voltage happens in the oblique viewing direction (Figure 2g) [16,17]. For WVA mode, the viewing angle at contrast ratio of over 10 exists up to ~ 50° in all azimuthal directions, while for NVA mode, the viewing angle at contrast ratio of 10 exist along 20° in the horizontal and the vertical directions [10]. This approach exhibits some disadvantages such as lower contrast ratio or higher driving voltage and reduces transmittance more as the dark state is kept at the area of sub-pixel [18].

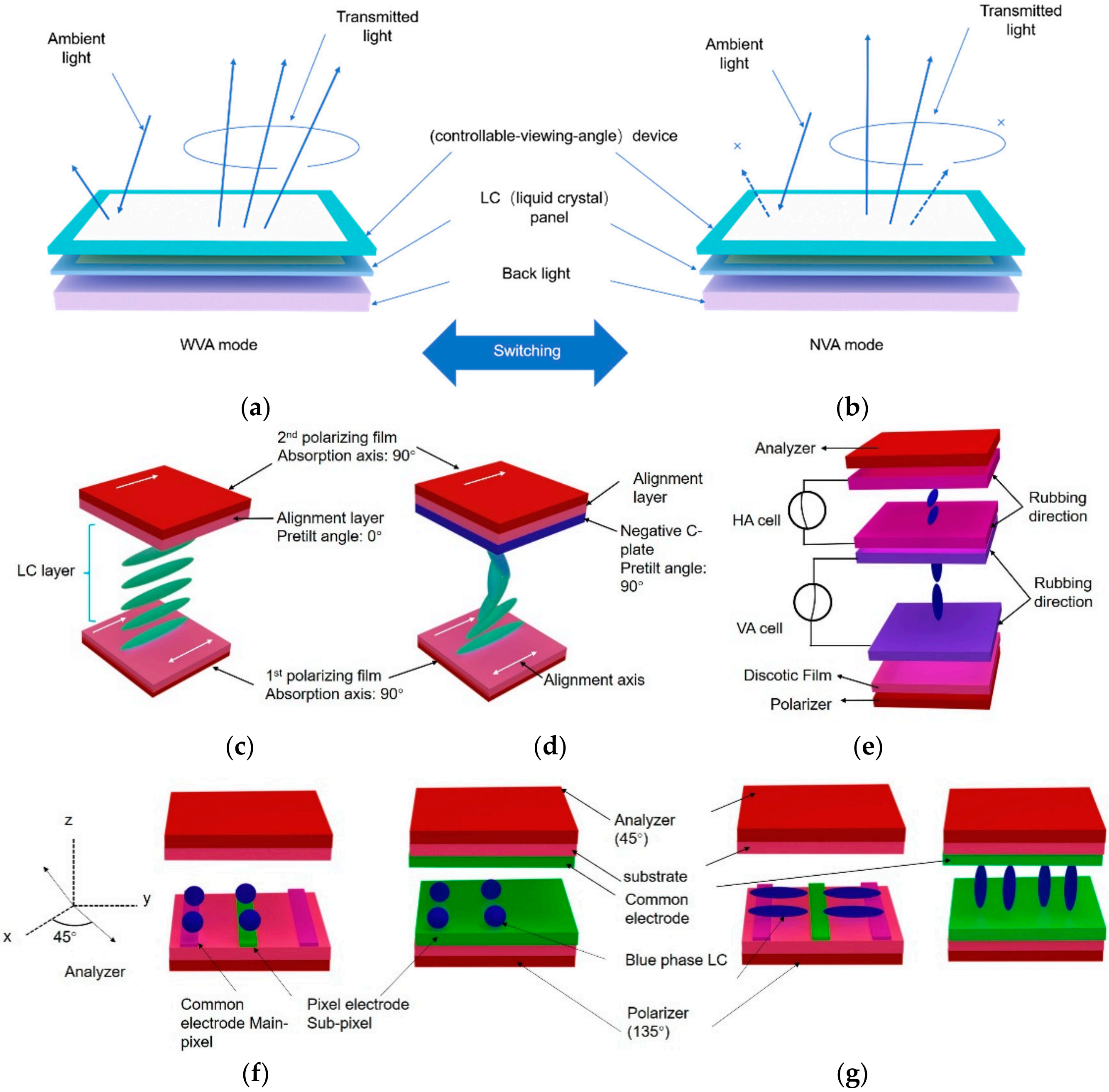


**Figure 2.** Schematic diagram of controllable viewing angle LCD: (**a**) WVA mode; (**b**) NVA mode. Schematic diagram of simulation models of controllable viewing angle device: (**c**) homogeneous aligned LC cell and (**d**) HAN LC cell; (**e**) optical cell configurations of the viewing angle device; (**f**) switchable LCD with an optically isotropic LC: voltage-off state and (**g**) voltage on state.

To decrease the volume, weight and fabrication cost of LCD, a viewing angle switchable LCD owning an interlayer support with surface microstructures that is placed between the top and bottom substrates, the original LC layer is for presenting images and the complementary LC layer is for viewing angle tunning, thus WVA and NVA can be switched between $\pm$ 70° and $\pm$ 40° [19]. A viewing angle controllable LCD using two stable states of bistable nematic LC such as splay and 180°-twist at $\pi$ cell with three-terminal electrodes, WVA is shown at splay state with interdigitated electrodes at the IPS or FFS modes, NVA is presented at the twisted state with vertical electrode [20].

For a controllable viewing angle LCD inserting by BPLC cell, BPLC plays as a tunable positive C-film or a negative C-film, the LCD has no alignment layer and sub-millisecond response time [21]. By designing electrode structure that is same as the one used for dual-mode switching in FFS LCD, an additional electrode is introduced to the top substrate, viewing angle with a contrast ratio of over 10 is tuned between $\pm$ 70° and $\pm$ 10° along the azimuthal direction by applying a small vertical bias voltage [22]. By using in-plane electrodes and etched substrate, double in-plane electric field is for reducing the driving voltage, operating voltage decreases to 8.2 V [18,23]. A fringe and in-plane switching BPLCD with a top common electrode has been proposed [24], of which three-terminal electrode structure gives it good dark state for NVA display and similar voltage-dependent transmission curves for NVA and WVA displays. If there is no bias voltage on the top common electrode, it shows the similar viewing angle, contrast ratio and transmission compared to that of conventional BPLCD. If different various bias voltages are applied on the top common electrode, viewing angle can continuously and uniformly change from WVA to NVA at a high contrast ratio of over 500 [25,26]. However, electrode structure designing method leads to a gray inversion in NVA mode utilizing vertical and horizontal fields at the same time.

By adopting a thermally variable retardation layer (TVRL) composed of a homeotropically aligned nematic LC with transparent electric-heating lines to control temperature, the LCD shows continuous and symmetric viewing angle characteristics, by thermally changing the birefringence of the film, the WVA mode is obtained by Joule heating in the TVRL where the LCs are isotropic phase, while the NVA mode is achieved at the nematic phase in the TVRL, the polar angle with the contrast ratio of 10 decreases up to 20° along the diagonal axis [27–29]. Except for these approaches, by using a guest-host (GH) LC cell doped with 5.0 wt.% of a dichroic dye (DD), as the polarization direction is orthogonal to the long molecular axis of DD, light transmits the cell, if the polarization is parallel to the long molecular axis of DD, light is absorbed by DD in the cell, the NVA and WVA modes can be realized by applying the voltage of 10.0 V across the GH cell [30].

## 3. PDLC Devices

Utilizing 3M light-control film and PDLC film together to create switchable anti-peeping film, PDLC is a voltage-controlled LC film that can switch between transparent and scattering (Figure 3a), light scattering intensity of PDLC film is dependent on electric field, switchable voltage between light scattering (share mode) and transparent state (privacy mode) is approximately 5.0 V [31]. As 3M light control film and PDLC film are not integrated, a control method for light distribution patterns of PDLCs is established by controlling an internal polymer structure formed by irradiating unidirectional diffused UV light in isotropic phase (Figure 3b) [32]. To investigate the effect of micro-louver size on the viewing angle controllable ability, four micro-louver structures with the same thickness are fabricated by utilizing thiol-ene photopolymerization (40-40 μm, 40-60 μm, 60-40 μm and 60-60 μm) (Figure 3c–f), four controllable anti-peeping devices can realize WVA and NVA modes at 0 and 8 V [33]. However, external switchable anti-peeping films need to be installed on the screen, to solve this problem, the LCD containing the switchable anti-peeping film is fabricated based on PDLC, the propagation direction of the light passing the 3M light control film can be tuned by the PDLC film, the NVA mode is presented without electric field and WVA mode is shown in the application of electric field (24 V) [34].

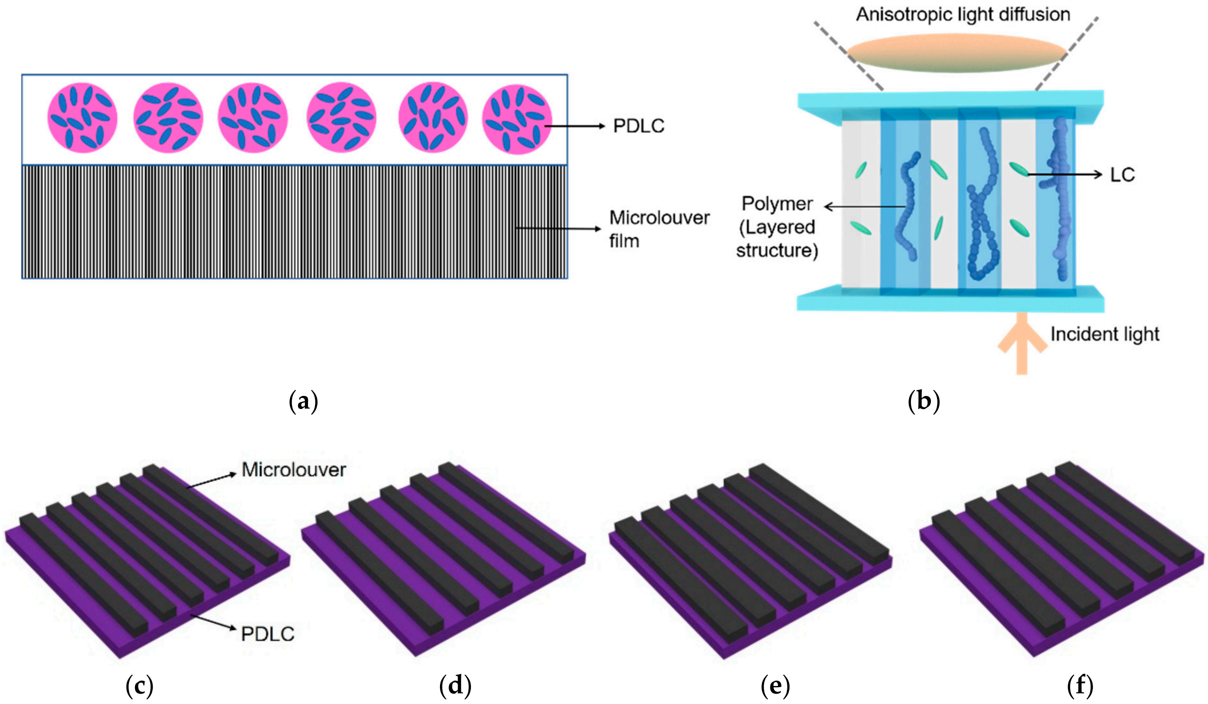


**Figure 3.** (**a**) Configuration structure and schematic mechanism of switchable anti-peeping film consists of 3M light control film and PDLC film; (**b**) schematic representation of PDLC having layered distribution of polymer network structure; (**c**–**f**) four microlouver structures with the same thickness, (**c**), 40–40 µm, (**d**), 40–60 µm, (**e**), 60–40 µm, (**f**), 60–60 µm, the first number represents the width of micro-stripe and the second number represents the space between two microstripes.

## 4. PSLC/PNLC Devices

The structure of the viewing angle-tunable LCD is depicted in Figure 4a, it consists of two cells: an ultra-super twisted (UST) cell, which is situated between the upper polarizer and the TN-TFT cell, and a PNLC cell, which is situated between the lower polarizer and the backlight. When the electric field is absent, the PNLC cell acts as a negative retarder, causing viewing angle to be wider than a conventional TN-cell [35]. Polymer stabilized BP (PSBP) LCD becomes more and more attractive due to no alignment, the simple fabrication process and fast response time, a PSBP LCD with double-size IPS electrode structure is proposed, which shows transflective characteristics because the bottom electrodes are made by aluminum material. With the application of a bias voltage on the top electrodes, a good viewing angle controllable display is exhibited [36]. A viewing angle-controllable LCD utilizing PSBPLC and a single-panel method, without electric field, a BPLC appears to be optically isotropic, if there is a strong electric field, due to Kerr effect, the birefringence is induced along the electric field direction in the BPLC and increases with the electric field, viewing angle of the device can be controlled from 100° to 30° (Figure 4b) [37]. We have developed an electrically switchable viewing angle device that fabricated by DDs doped polymer stabilized cholesteric LCs (DD-PSCLCs) [38], with the additional photo-mask in the UV irradiation process, polymer has formed in the irradiated part, as shown in Figure 4c, when applying a relative lower electric field, CLCs in the irradiated part turn to be in focal conic state, while CLCs in the non-LC-irradiated part still keep planar state, as is described in Figure 4d, if the electric field is higher, CLCs in the irradiated part change to be homeotropic state, while CLCs in the irradiated part still be in the planar state (Figure 4e).

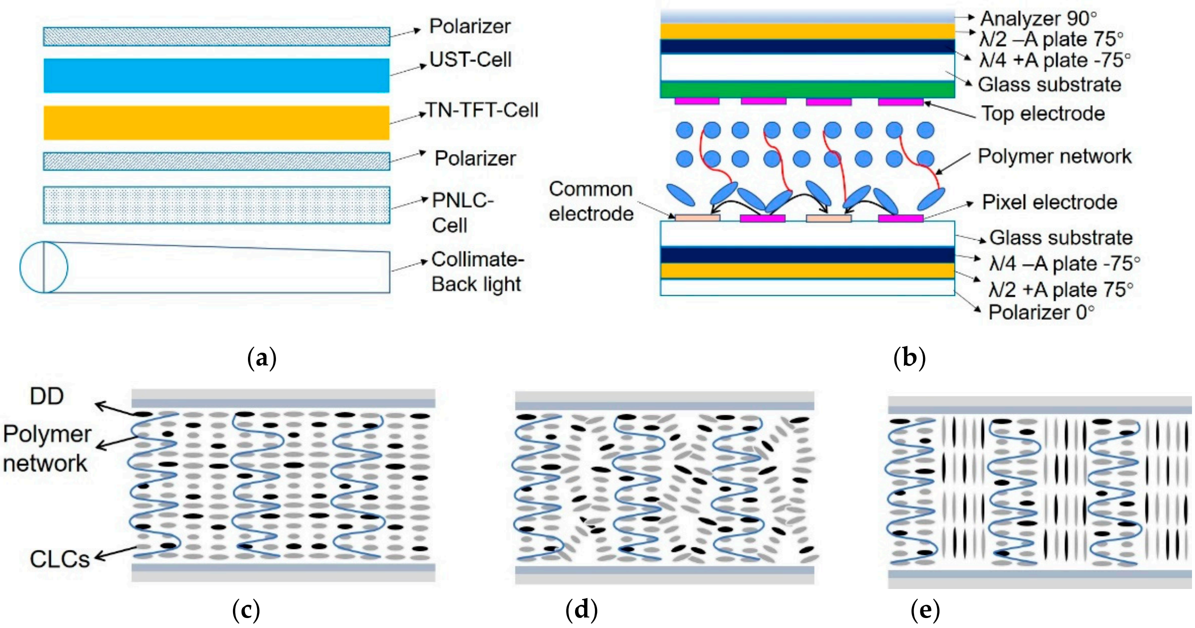


**Figure 4.** (**a**) Structure of a viewing angle controllable device; (**b**) Cell structure of the proposed viewing angle-controllable PSBP-LCD; (**c**–**e**) Various states of CLCs in the DD-PSCLC device under the application of electric field: (**c**) planar state; (**b**) focal conic state; (**e**) homeotropic state.

## 5. Non-LC Devices

Setting an array of optical micro-rods, consisting of electrophoretic material that composed of black particles dispersed in a transparent medium, with a rectangular parallelepiped shape, whose size is 40 μm wide, 40 μm deep and 120 μm high, while the space between each optical micro-rod is 10 μm [8,39]. As the black particles are gathered electronically to one side in the transparent resin, the cross-stripe part filled by transparent substrate transmit incident light the same as the light-transmitting portions. A viewing angle switching device based on array of optical micro-rod is demonstrated (Figure 5a), as the black particles which enables switching two states between a WVA and a NVA in one second at 20 V of applied voltage (Figure 5b). Two modes are electrically switched, (a) NVA mode and (b) WVA mode. The limited viewing angle mode is +/− 30° of the visible angle and 50% of the transmittance, and the one for the non-limited viewing mode is 58% of the transmittance by the applied voltage of 20 V. A compact light guide plate (LGP) with special designed microstructures and dual light sources is proposed (Figure 5c), of which the micro-prisms are utilized to guide the emitting rays toward normal viewing cones while a set of strip-patterned diffuser toward wide viewing cones [40,41]. By simply switching the separate light sources, quick switching between the two modes is possible. If light source 1 is on, the backlight operates in the NVA mode, and if light source 2 is on, the backlight operates in the WVA mode [9]. Figure 5d represents the viewing angle switchable backlight module that is divided into three parts, the hybrid light guide plate (HLGP) is called the light incidence surface, the first light sources provide NVA mode and the second light sources provide WVA mode, Figure 5e depicts side view of the viewing angle controllable backlight module, the HLGP is composed of main layer and sub-layer with various refractive indices, the top micro-prisms are spaced with a graded interval for controlling the uniformity degree and the bottom micro-prisms reflect the rays to the main layer [9]. Consequently, in the NVA mode, the half-luminance angle decreases 11 degrees in the horizontal direction, while in the WVA mode, the half-luminance angle increases 56 degrees in the horizontal direction [9].

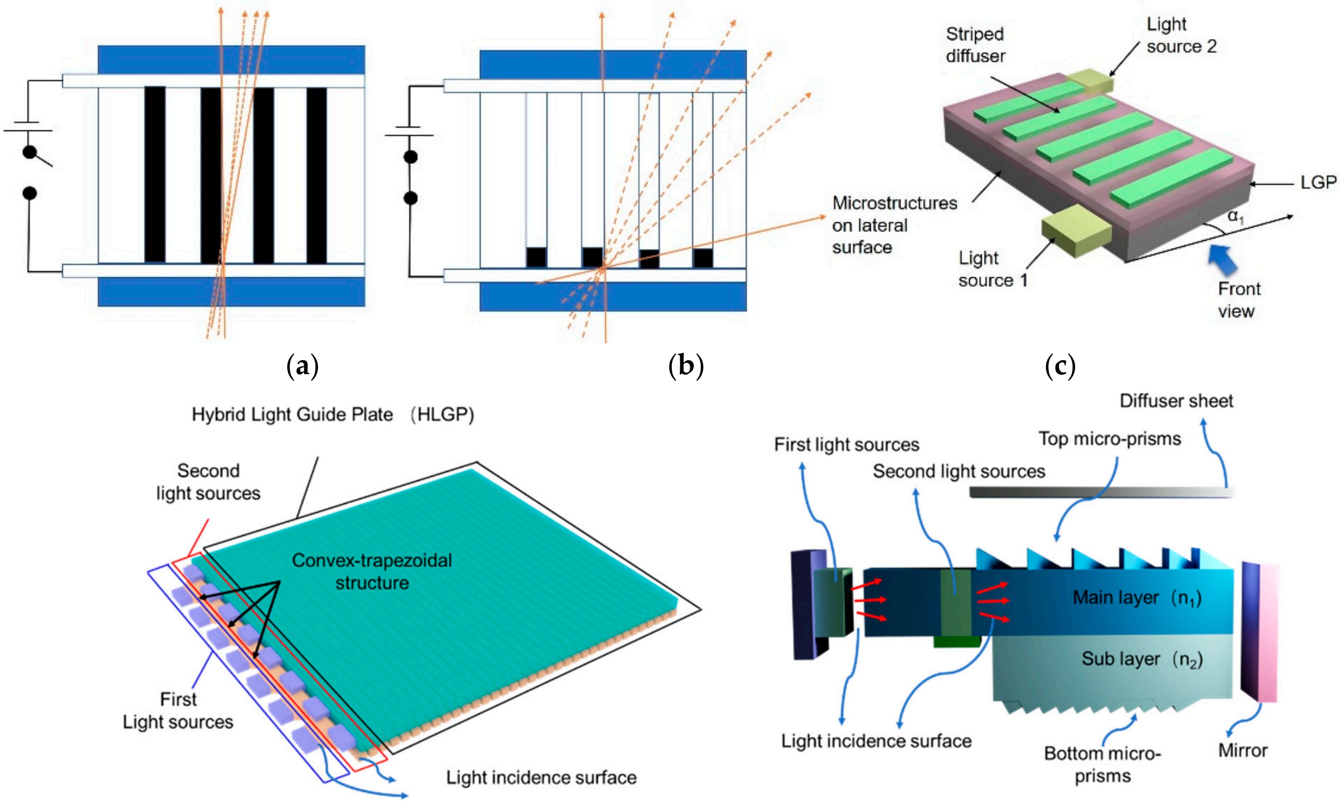


**Figure 5.** Illustration of concept for (**a**) narrow mode and (**b**) wide mode can be selected electronically. The narrow mode (**a**) is achieved as black particles are fully dispersed, and the wide mode (**b**) is achieved as black particles are completely gathered one side in the optically transparent medium. (**c**) Sketch of the backlight configuration, (**d**,**e**) optical structure of the dual backlight viewing angle switchable device: (**d**) tilt view; (**e**) side view.

## 6. Discussion

Over the past few decades, viewing angle controllable devices for LCDs have been introduced, comparative analysis of performances of various LC and non-LC devices is presented in Table 1, dual cell method increases the production cost for needing two LC cells, two-pixel method reduces transmittance more as the dark state is held at the area of sub-pixel, but viewing angle in the narrow mode is only 20°, three-terminal electrode structure based on the FFS mode LCDs has simple structure, but the contrast ratio for NVA is not good because of light leakage induced by the bias voltage. The existing switchable privacy protection displays based on LC and non-LC devices (Table 2) on the market have been applied in ATMs, monitors and high-end notebooks, but the function of switchable anti-peeping function leads to higher power consumption or lower image quality, moreover, the switchable viewing angle effect is mainly in horizontal view.

To consider next-generation commercial switchable anti-peeping products, LC devices especially for LC/polymer composite films may be applied to almost any situations due to their tunable optical properties and easier fabrication, for example, by achieving various controllable microlouver structures under the mask-assisted UV curing of LC monomers, DD-doped PSCLC device can be developed to meet thinness, low power consumption, high image quality, it is believed that this new viewing angle switching mode will have strong potential for future display applications.

**Table 1.** Comparison of the performances of various LC and non-LC devices.

| Types | Principles | WVA/ Contrast Ratio | WVA/ Viewing Angle | NVA/ Contrast Ratio | NVA/ Viewing Angle | References |
|---|---|---|---|---|---|---|
| LC devices | Pixel division | >10:1 | 50° | 10:1 | 20° | 10 |
| | Optically isotropic LC | / | 120° polar angle | / | 35° | 11 |
| | Homogeneous aligned LC layer | 10:1 | 170° | 2:1 | 60° | 16 |
| | Electrical tilting of LC | 10:1 | ±70° | 10:1 | ±10° | 21 |
| | TVRL | 10:1 | 80° polar angle | 10:1 | 20° | 28 |
| | 3M/PDLC | / | ±60° | / | ±30° | 30 |
| | Microlouver/PDLC | / | ±62° | / | ±39° | 32 |
| | PSBPLC | / | 100° | / | 30° | 37 |
| Non-LC devices | Dual light source | / | 140° | / | 60° | 9 |
| | Optical micro-rods | / | / | / | ±30° | 38 |
| | Striped diffuser | / | ±55° | / | ±10° | 41 |

**Table 2.** Comparison of various LC and non-LC devices.

| Types | Privacy Effect | Privacy Viewing Angle | Thickness | Power | Application |
|---|---|---|---|---|---|
| LC devices | Excellent | Horizontal perspective | Thin | High | Monitors |
| Non-LC devices | Moderate | Horizontal perspective | Thick | Moderate | ATMs |

## 7. Conclusions and Perspective

In conclusion, it is impractical to preserve privacy in display devices by adding more panels and backlight units due to the increasing panel thickness and high production costs. Utilizing a dual lighting system is also not recommended for achieving NVA due to its greater cost and insufficient brightness, a more expensive LCD is required for developing electrode structures. The electronically switchable scattering and transparent modes of polymer and LCs composite films allow the incident light to be either weakly (strongly) scattered or transmitted. Due to their simple manufacturing process, it is possible to produce perfect viewing angle controllable commercial LCDs by inserting the polymer/LCs composite films into the backlight, adding some special patterns or gratings to the films during the photopolymerization process of UV cured LC or non-LC monomers under masks, controlling their thickness and microstructures, contrast ratio between scattering mode and transparent mode and driving voltage can be both further tuned, moreover, multi-directional switchable viewing angle devices are also developed by utilizing the system of polymer/LCs composites.

Recently, viewing angle controllable devices have been the mainstream of high-end displays, while the width of microlouvers in the devices is still difficultly to be refined. Additionally, the brightness of backlight is relatively low in the WVA mode compared to that in the NVA mode. Moreover, the current anti-peeping effect originated from the NVA mode in the devices is mainly demonstrated in horizontal view, to meet the needs of all-angle anti-peeping effect in the future displays, the horizontal and vertical viewing angle controllable devices are the development trend. Adjustable viewing angle devices are currently popular in shielding sensitive or private information, except for that, they can also avoid the light of PCs from interfering with others or reduce the light on the car display screens that disturbs the drivers at night.

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