# Transflective Liquid Crystal Displays

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*Invited Paper*

***Abstract*—In this review paper, a detailed overview of the transflective liquid crystal display (LCD) technology is presented. We first introduce the transflector classifications based on their composition and properties. Then, in reviewing the development history, we investigate the mainstream transflective LCDs, including their operating principles, advantages, and disadvantages. Finally, the image quality issues of transflective LCDs, such as color balance, image brightness, and viewing angle, are discussed.**

***Index Terms*—Reflectance, reflection region, reflective mode, transflective liquid crystal display (LCD), transmission region, transmissive mode, transmittance.**

## I. Introduction

TRANSMISSIVE liquid crystal displays (LCDs) have been widely used in laptop computers, desktop monitors, high-definition televisions (HDTVs) and so on. The most commonly used transmissive 90° twisted-nematic (TN) LCD [1] exhibits a high contrast ratio due to the self phase compensation effect of the orthogonal boundary layers in the voltage-on state. However, its viewing angle is relatively narrow since the liquid crystal (LC) directors are switched out of the plane and the oblique incident light experiences different phase retardations at different angles. For TV applications, wide viewing angle is highly desirable. Currently, in-plane switching (IPS) [2] and multi-domain vertical alignment (MVA) [3] are the mainstream approaches for wide-view LCDs. A major drawback of the transmissive LCD is that its backlight source needs to be kept on all the time as long as the display is in use; therefore, the power consumption is relatively high. Moreover, the image of a transmissive LCD is easily washed out by the strong ambient light such as direct sunlight.

Reflective LCD, on the other hand, has no built-in backlight source. Instead, it utilizes the ambient light for displaying images. The detailed introduction of available operating modes for reflective LCDs can be found in [4]. In comparison to transmissive LCDs, reflective LCDs have advantages in lower power consumption, lighter weight, and better outdoor readability. However, a reflective LCD relies on the ambient light and thus is inapplicable under low or dark ambient conditions.

In an attempt to overcome the above drawbacks and take advantages of both reflective and transmissive LCDs, transflective LCDs have been developed to use the ambient light when available and the backlight only when necessary. A transflective LCD can display images in both transmissive mode (T-mode) and reflective mode (R-mode) simultaneously or independently. Since LC material itself does not emit light, the transflective LCD must rely on either ambient light or backlight to display images. Under bright ambient circumstances, the backlight can be turned off to save power and, therefore, the transflective LCD operates in the R-mode only. Under dark ambient conditions, the backlight is turned on for illumination and the transflective LCD works in the T-mode. In the low-to-medium ambient surroundings, the backlight is still necessary. In this case, the transflective LCD runs in both T- and R-modes simultaneously. Therefore, the transflective LCD can accommodate a large dynamic range. Currently, the applications of transflective LCD are mainly targeted to mobile display devices, such as cell phones, digital cameras, camcorders, personal digital assistants (PDAs), pocket personal computers (PC), and global position systems (GPS), etc.

In this review paper, we first explain the transflector classifications, which will help us to understand the transflective mechanism. Then, based on the development history of transflective LCDs, we will address their underlying operating principles and analyze their pros and cons. Finally, we will discuss those factors that affect the image qualities of transflective LCDs.

## II. Classification of Transflector

Since a transflective LCD should possess dual functions (transmission and reflection) simultaneously, a transflector is usually required between the LC layer and the backlight source. The main role of the transflector is to partially reflect the incident ambient light back and to partially transmit the backlight to the viewer. From the device structure viewpoint, the transflector can be classified into 4 major categories: 1) openings-on-metal transflector; 2) half-mirror metal transflector; 3) multilayer dielectric film transflector, and 4) orthogonal polarization transflectors, as shown in Figs. 1(a)–(c) and 2(a)–(c), respectively.

### A. Openings-On-Metal Transflector

The concept of openings-on-metal transflector was first disclosed by Ketchpel who was with Rockwell International Corporation [5]. Fig. 1(a) shows the schematic structure. The typical

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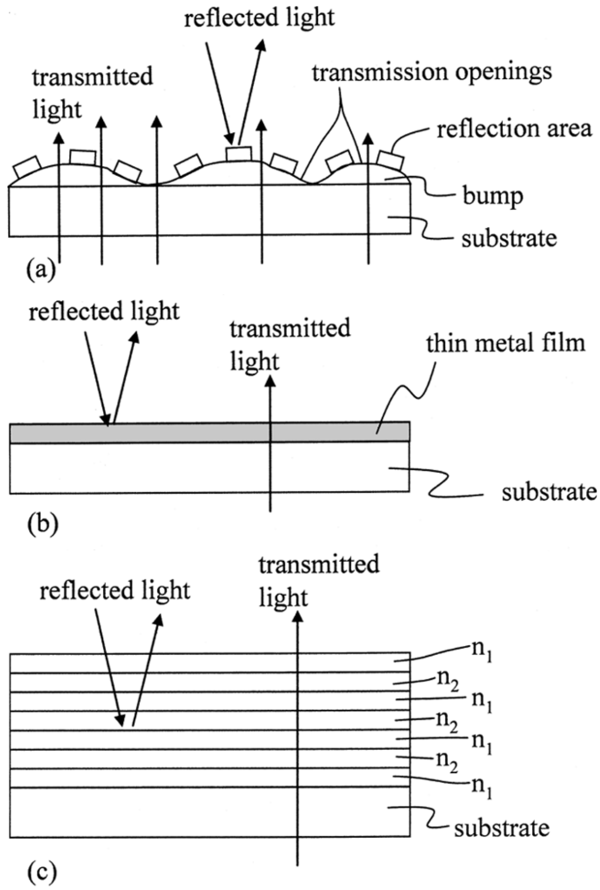



Fig. 1. Schematic illustration of the first three major types of transflectors. (a) Openings-on-metal transflector. (b) Half-mirror metal transflector. (c) Multilayer dielectric film transflector.

manufacturing steps include first forming wavy bumps on the substrate, then coating a metal layer, such as silver or aluminum, on the bumps, and finally etching the metal layer according to the predetermined patterns. After etching, those etched areas become transparent so that the incident light can transmit through. While those unaffected areas are still covered by the metal layer and serve as reflectors. The wavy bumps function as diffusive reflectors to steer the incident ambient light away from surface specular reflection. Thus, the image contrast ratio is enhanced and the viewing angle is widened in the R-mode. Due to the simple manufacturing process, low cost, and stable performance, this type of transflector is by far the most popularly implemented in the commercial transflective LCD products.

### B. Half-Mirror Metal Transflector

The half-mirror has been widely used in optical systems as beam splitter. It was implemented into transflective LCD by Borden [6] and Bigelow [7] with basic structure shown in Fig. 1(b). When depositing a very thin metallic film on a transparent substrate, one can control the reflectance and transmittance by adjusting the metal film thickness. The film thickness could vary, depending on the metallic material employed. Typically, the film thickness is around a few hundred angstroms. Since the transmittance/reflectance ratio of such a half-mirror transflector is very sensitive to the metal film thickness, the manufacturing tolerance is very narrow and the volume production is difficult. Consequently, this kind of transflector is not too popular in the commercial products.

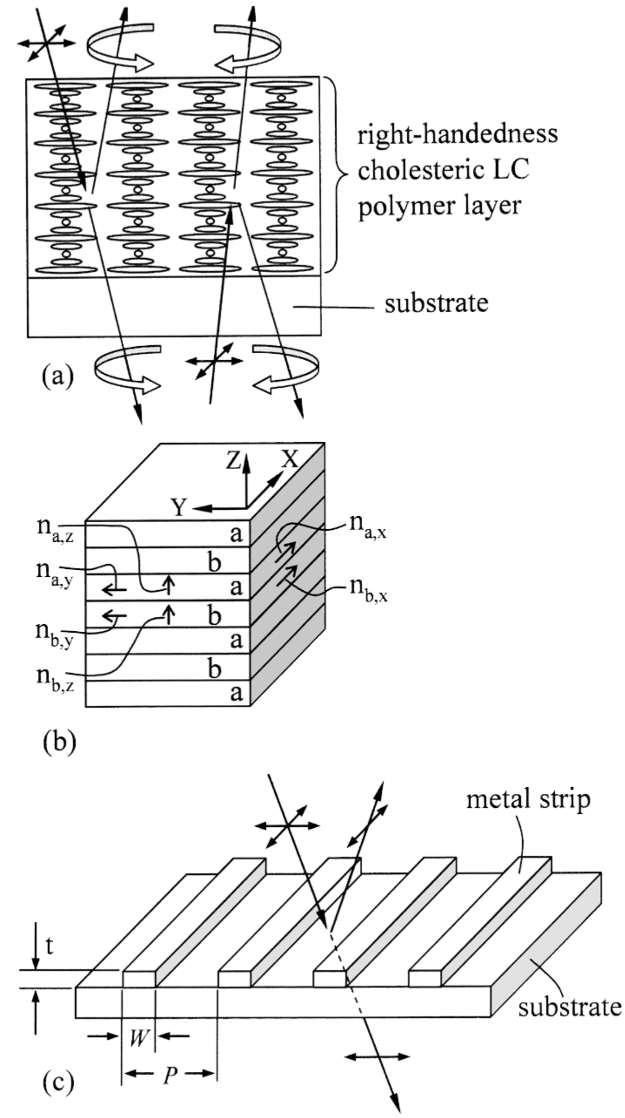



Fig. 2. Schematic illustration of the three eexamples of orthogonal polarization transflectors. (a) Cholesteric reflector. (b) Birefringent interference polarizer. (c) Wire grid polarizer (WGP).

### C. Multilayer Dielectric Film Transflector

Multilayer dielectric film is a well-developed technique in thin-film optics. But only until most recently, it was incorporated into the transflective LCDs [8]. As illustrated in Fig. 1(c), two dielectric inorganic materials with refractive indices $n_1$ and $n_2$ are periodically deposited as thin films on the substrate. By controlling the refractive index and thickness of each thin layer as well as the total number of layers, one can obtain the desired reflectivity and transmissivity. Similar to the half-mirror transflector, the transmittance/reflectance ratio of the multilayer dielectric film is sensitive to each layers thickness. In addition, to produce several layers successively increases the manufacturing cost. Therefore, the multilayer dielectric film transflector is rarely used in the current commercial transflective LCDs.

### *D. Orthogonal Polarization Transflectors*

The orthogonal polarization transflector has a special characteristic that the reflected and the transmitted polarized lights from the transflector have mutually orthogonal polarization states. For instance, if a transflector reflects a horizontal linearly (or right-handed circularly) polarized light, then it would transmit the complementary linearly (or left-handed circularly) polarized light. Fig. 2(a)–(c) show three such examples: 1) cholesteric reflector [9]; 2) birefringent interference polarizer [10]; and 3) wire grid polarizer (WGP) [11].

Cholesteric liquid crystal (LC) layer manifests as a planar texture with its helix perpendicular to the cell substrates when the boundary conditions on both substrates are tangential. If the incident wavelength is comparable to the product of the average refractive index and the cholesteric pitch, then the cholesteric LC layer exhibits a strong Bragg reflection [12]. Fig. 2(a) shows the schematic configuration of a right-handed cholesteric reflector, where the cholesteric LC polymer layer is formed on a substrate. For an incident unpolarized light, the right-handed circularly polarized light which has the same sense as the cholesteric helix is reflected, but the left-handed circularly polarized light can transmit such a right-handed cholesteric reflector.

The birefringent-interference-polarizer transflector consists of a multilayer birefringence stack with alternating low and high refractive indices, as shown in Fig. 2(b). One way to produce such a transflector is to stretch a multilayer stack in one or two dimensions. The multilayer stack consists of birefringent materials with low/high index pairs [13]. The resultant transflective polarizer exhibits a high reflectance for the light polarized along the stretching direction and, meanwhile, a high transmittance for the light polarized perpendicular to the stretching direction. By controlling the three refractive indices of each layer, $n_x$, $n_y$, and $n_z$, the desired polarizer behaviors can be obtained. For practical applications, an ideal reflective polarizer should have $\sim$100% reflectance along one axis (the so-called extinction axis) and 0% reflectance along the other (the so-called transmission axis) axis, at all the incident angles.

Wire grid polarizer is widely used in infrared [14]. It is constructed by depositing a series of parallel and elongated metal strips on a dielectric substrate, as shown in Fig. 2(c). To operate in the visible spectral region, the pitch of metal strip $\boldsymbol{P}$ should be in the range of around 200 nm, which is approximately half of a blue wavelength [15]. In general, a WGP reflects (transmits) light with its electric field vector parallel (perpendicular) to the wires of the grid. In practice, the wire thickness $\boldsymbol{t}$, wire width $\boldsymbol{W}$, and grid pitch $\boldsymbol{P}$ play important roles in determining the extinction ratio and acceptance angle of the polarizer.

Unlike the first three transflectors discussed above, the entire area of the orthogonal polarization transflector can be utilized for reflection and transmission simultaneously. Nevertheless, the transmitted light and reflected light possess mutually orthogonal polarization states so that the reflective and transmissive images exhibit a reversed contrast. Although an inversion driving scheme may correct such a reversed contrast problem [11], the displayed images are still unreadable under moderate brightness surroundings when both ambient light and backlight are in use. Thus, the orthogonal polarization transflectors have not yet been widely adopted in the current high-end commercial transflective LCD products.

## III. Classification of Transflective LCDs

LCDs rely on an ambient light or backlight to display images. Based on the light modulation mechanisms, transflective LCDs can be classified into four categories: 1) absorption type; 2) scattering type; 3) reflection type; and 4) phase-retardation type. The first three categories do not modulate the phase of the incident light; rather, they absorb, scatter, or reflect light. In some cases, it is possible to use one polarizer or none at all to achieve high brightness. As for the phase-retardation type, two polarizers are usually indispensable in order to make both transmissive and reflective modes work simultaneously.

### *A. Absorption Type Transflective LCDs*

Guest-host LCDs utilize the absorption mechanism to modulate light. In a guest-host LCD, a few percent ($\sim$2%) of dichroic dye is doped into a liquid crystal host. As the LC directors are reoriented by the electric field, the dye molecules follow. Because of the dyes dichroism, the absorption of the LC cell is modulated. This mechanism was first introduced in nematic phase by Heilmeier [16] and later on in cholesteric phase by White and Taylor [17]. In the twisted or helical LC structure, the guest-host display does not require a polarizer. A major technical challenge of guest-host displays is the tradeoff between reflectance/transmittance and contrast ratio. A typical contrast ratio for the guest-host LCD is $\sim$5:1 with $\sim$40%–50% reflectance. The low contrast ratio is limited by the dichroic ratio (DR) of the dye.

*1) Nematic Phase:* Bigelow [7] devised a transflective LCD structure using a half-mirror metallic transflector, two quarter-wave films, and nematic phase LC/dye mixtures, as illustrated in Fig. 3(a). In the figure, the upper half and lower half show the voltage-off and voltage-on states, respectively.

When no voltage is applied, the LC/dye mixtures are homogeneously aligned within the cell. In the R-mode, the unpolarized incident ambient light becomes linearly polarized after passing through the LC/dye layer. Then, its polarization state turns into right-handed circularly polarized after the inner quarter-wave film. Upon reflection from the transflector, its polarization state becomes left-handed circularly polarized due to a $\pi$-phase change. When the left-handed circularly polarized light passes through the inner quarter-wave film again, it becomes linearly polarized, whose polarization direction is parallel to the LC alignment direction. As a result, the light is totally absorbed by the dye dopant and a dark state is achieved. In the T-mode, the unpolarized light from the backlight source becomes linearly polarized after the polarizer. Then it changes to a left-handed circularly polarized light after emerging from the outer quarter-wave film. After penetrating the transflector, it still keeps the same left-handed circular polarization state. Thereafter, its travel path is identical to that of R-mode. Finally, the light is totally absorbed by the dye mixture, resulting in a dark state.

In the voltage-on state, the LC directors and dye molecules are reoriented nearly perpendicular to the substrates, as illustrated in the lower half of Fig. 3(a). Therefore, the light passing through it experiences little absorption and no change in the polarization state. In the R-mode, the unpolarized ambient light

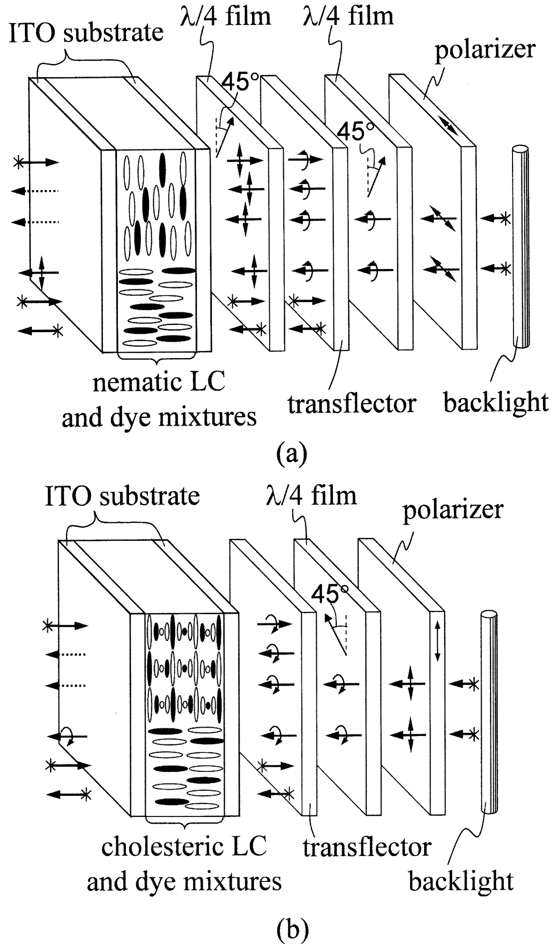



Fig. 3. Schematic configurations and operating principles of two absorption type transflective LCDs with: (a) nematic phase LC (host) and dye (guest) mixtures and (b) cholesteric phase LC (host) and dye (guest) mixtures.

passes through the LC/dye layer and the inner quarter-wave film successively without polarization state change. Upon reflection from the transflector, it is still an unpolarized light and then goes all the way out of the transflective LCD. Consequently, a bright state with very little attenuation is achieved. In the T-mode, the unpolarized backlight becomes linearly polarized after passing through the linear polarizer, the outer quarter-wave film, the transflector, and the inner quarter-wave film, successively. Since the vertically aligned LC/dye layer causes very little absorption to it, the linearly polarized light finally emerges from the transflective LCD, resulting in a bright state.

In the above-mentioned transflective guest-host LCD, the inner quarter-wave film is put between the transflector and the guest-host layer. There are two optional positions for the transflector means. If the transflector is located inside the LC cell, then the quarter-wave film should also be sandwiched inside the cell. Nevertheless, it is difficult to fabricate such a quarter-wave film and assemble it inside the cell. On the other hand, if the transflector is located outside the cell, then both quarter-wave film and transflector can be laminated on the outer surface of the LC cell. In this case, however, a serious parallax problem occurs, as will be explained in Section III-D-1.

*2) Cholesteric Phase:* To eliminate the quarter-wave film between the transflector and the LC layer, Cole proposed a transflective LCD design using a half-mirror metallic transflector and cholesteric LC/dye mixture [18], as illustrated in Fig. 3(b). As we can see, only one quarter-wave film is employed, which is located between the transflector and the linear polarizer. Consequently, the quarter-wave film can be put outside of the cell, while the transflector can be sandwiched inside the cell. As a result, no parallax occurs. The upper and lower portions of this figure demonstrate the voltage-off and voltage-on states, respectively. In the voltage-off state, the LC/dye layer renders a right-handed planar texture with its helix perpendicular to the substrates. In the R-mode, the unpolarized light is largely attenuated by the LC/dye layer and only a weak light passes through it. Upon reflection from the transflector, it is further absorbed by the guest dye molecules, resulting in a dark state. In the T-mode, the unpolarized backlight first becomes linearly polarized and then right-handed circularly polarized after it passes through the polarizer and, in turn, the quarter-wave film. The circularly polarized light is further attenuated after it penetrates the transflector. Such a weak right-handed circularly polarized light is absorbed by the same twist sense cholesteric LC/dye mixture, resulting in a dark state.

In the voltage-on state, both LC directors and dye molecules are reoriented perpendicular to the substrates. As a result, little absorption occurs to the incident light. In the R-mode, the unpolarized light is unaffected throughout the whole path, resulting in a very high reflectance. In the T-mode, the unpolarized backlight becomes right-handed circularly polarized after passing through the polarizer, the quarter-wave film, and the transflector. It finally penetrates the LC/dye layer with little attenuation. Again, a bright state is obtained.

In the above-mentioned two absorption type transflective LCDs, only one polarizer is employed instead of two. Therefore, the overall image in both T- and R-modes is relatively bright. However, due to the limited dichroic ratio of dye materials (DR$\sim$15:1), a typical contrast ratio of the guest-host LCD is around 5:1 [19], which is inadequate for high-end full color LCD applications. Thus, the absorption type transflective LCDs only occupy a small share of the hand-held LCD market.

### *B. Scattering Type Transflective LCD*

Polymer-dispersed LC (PDLC) [20], polymer-stabilized cholesteric texture (PSCT) [21] and LC gels [22] all exhibit optical scattering characteristics and have wide applications in displays and optical devices. The LC gel based reflective LCD, which is proposed by Ren *et al.*, can also be extended to transflective LCDs [23]. Fig. 4 shows the schematic structure and operating principles of the LC gel based transflective LCD. The device is comprised of a LC gel cell, two quarter-wave films, a transflector, a polarizer, and a backlight. The cell was filled with homogeneously aligned nematic LC and monomer mixture. After UV-induced polymerization, polymer networks are formed and the LC materials are confined within the polymer networks.

When no voltage is applied, the LC directors exhibit a homogeneous alignment. Consequently, the LC gels are highly transparent for the light traveling through, as illustrated in the upper portion of Fig. 4. In the R-mode, the unpolarized ambient light remains unpolarized all the way from entering to exiting the LC cell. As a result, a fairly bright state is obtained. In the T-mode, the unpolarized backlight turns into a linearly polarized p-wave

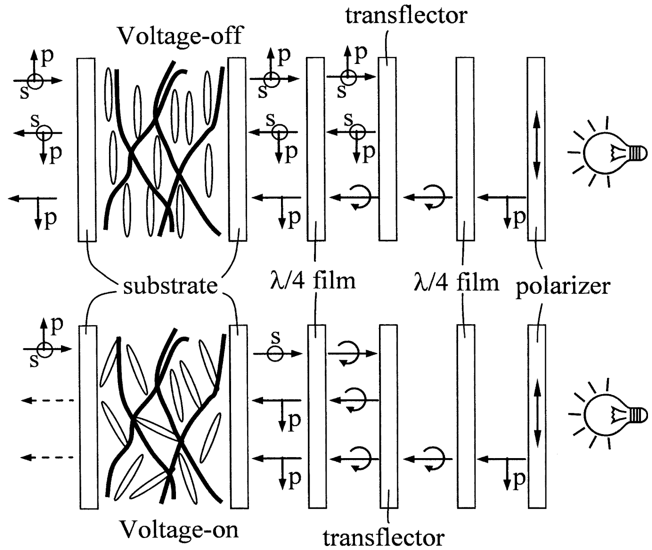



Fig. 4. Schematic configuration and operating principles of scattering type transflective LCD with homogeneously aligned LC gel.

after the polarizer. After passing the first quarter-wave film, penetrating the transflector and the second quarter-wave film whose optical axis is orthogonal to that of the first one, the p-wave remains linearly polarized. Since the LC gel is highly transparent in the voltage-off state, the linearly polarized p-wave finally comes out of the display panel, resulting in a bright output.

On the other hand, when the external applied voltage is high enough, the LC directors deviate from the original homogeneous alignment by the exerted torque of electric field. Therefore, microdomains are formed along the polymer chains such that the extraordinary ray, i.e., the linear polarization along the cell rubbing direction, is scattered, provided that the domain size is comparable to the incident light wavelength. In the mean time, the ordinary ray would pass through the LC gels without being scattered. In the R-mode, the unpolarized ambient light becomes a linearly polarized s-wave after passing the activated LC cell since the p-wave is scattered. After a round trip of passing the quarter-wave film, being reflected by the transflector, and passing the quarter-wave film again, the s-wave is converted into a p-wave. Due to the scattering of LC gels, this p-wave is scattered again. Consequently, a scattering translucent state is achieved. In the T-mode, the unpolarized backlight turns into a linearly polarized p-wave after passing the polarizer, the second quarter-wave film, the transflector, and the first quarter-wave film, successively. Thereafter, similar to the case of R-mode, the p-wave is scattered by the activated LC gels, resulting in a scattering translucent output.

This scattering type transflective LCD only needs one polarizer; therefore, it can achieve a very bright image. However, there are three major drawbacks in the above LC gels based transflective LCD. First, light scattering mechanism usually leads to a translucent state rather than a dark state. Therefore, the image contrast ratio is low and highly dependent on the viewing distance to the display panel. Although doping a small concentration black dye into the LC gels can help to achieve a better dark state, the contrast ratio is still quite limited due to the limited dichroic ratio of dye dopant. Second, the insertion of the first quarter-wave film will cause a similar parallax problem as the absorption type transflective LCD using cholesteric LCs. Third, the required driving voltage is usually over 20 V due to the polymer network constraint, which is beyond the capability of current thin-film-transistors developed for LCD applications. Therefore, these drawbacks hinder the scattering type transflective LCD from commercialization.

### C. Reflection Type Transflective LCDs

As mentioned in Section II-D, the cholesteric LC layer exhibits a strong Bragg reflection at a central reflection wavelength $\lambda_o = nP_o$, where $n$ and $P_o$ are the average refractive index and the cholesteric helix pitch, respectively. The reflection bandwidth $\Delta\lambda_o = \Delta n P_o$ is proportional to the birefringence $\Delta n$ of the cholesteric LC employed. Apparently, to cover the whole visible spectral range, a high birefringence ($\Delta n > 0.5$) cholesteric LC material is needed, assuming the pitch length is uniform. Because the transmitted and reflected circular polarization states are orthogonal to each other, the cholesteric LC layer must rely on some additional elements to display a normal image without the reversed contrast ratio. By adopting an image-enhanced reflector (IER) on the top substrate as well as a patterned ITO and a patterned absorption layer on the bottom substrate, the transflective cholesteric LCD can display an image without reversed contrast ratio [24], [25], as shown in Fig. 5(a) and (b). The opening areas of the patterned absorption layer on the bottom substrate match the IER on the top substrate. In addition, right above the openings area of the patterned absorption layer and below the IER is the openings area of the patterned ITO layer. Therefore, the cholesteric LC directors below the IER are not reoriented by the external electric filed.

In operation, when no voltage is applied, the cholesteric LC layer exhibits a right-handed planar helix texture throughout the cell, as shown in Fig. 5(a). In the R-mode, when an unpolarized ambient light enters the cholesteric LC cell, the left-handed circularly polarized light passes through the right-handed cholesteric LC layer and is absorbed by the patterned absorption layer. At the same time, the right-handed circularly polarized light is reflected by the same sense cholesteric LC layer and the bright state results. In the T-mode, when the unpolarized backlight enters the cholesteric LC layer, similarly, the right-handed circularly polarized light is reflected and it is either absorbed by the patterned absorption layer or recycled by the backlight system. In the meantime, the left-handed circularly polarized passes through the cholesteric LC layer and impinges onto the IER. Due to a $\pi$-phase change upon reflection, it is converted to a right-handed circularly polarized light, which is further reflected by the cholesteric LC layer to the reviewer. Consequently, a bright state occurs.

In the voltage-on state, the planar helix texture above the bottom-patterned ITO layer becomes a focal conic texture, while the LC directors between the IER and the opening area of the bottom-patterned ITO layer are still unaffected, as shown in Fig. 5(b). The focal conic texture, if the domain size is well controlled, exhibits a forward scattering for the incident light [4]. In the R-mode, the unpolarized incident ambient light is forward scattered by the focal conic textures. It is then absorbed by the patterned absorption layer, resulting in a dark state. In the T-mode, the unpolarized light still experiences a right-handed planar helix texture before it reaches the IER on the top substrate. Thus, the right-handed polarized light

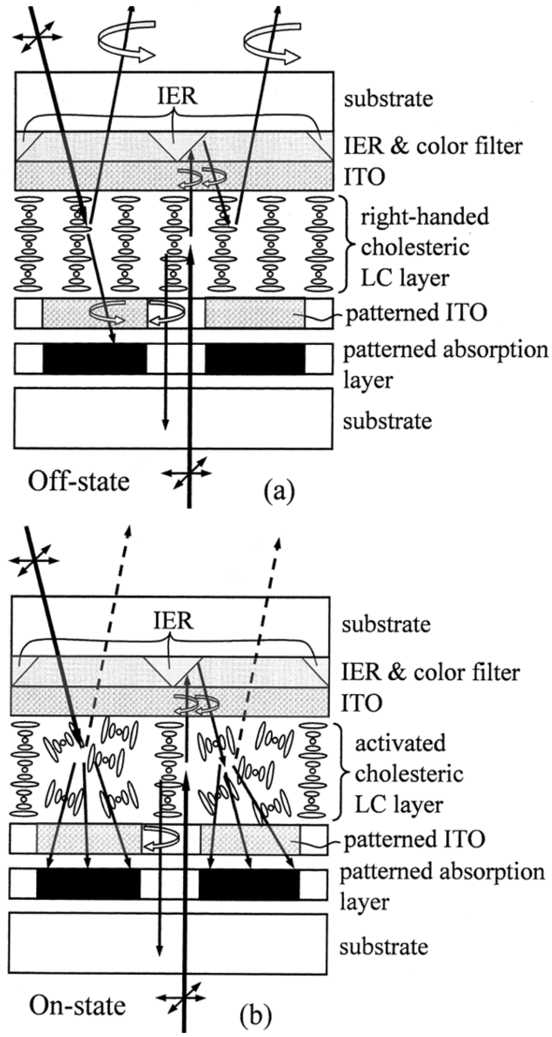



Fig. 5. Schematic configuration of reflection type transflective cholesteric LCD and its operating principles at (a) off-state and (b) on-state.

is reflected back and it is either absorbed by the patterned absorption layer or recycled by the backlight system. At the same time, the left-handed circularly polarized light passes through the planar texture and impinges onto the IER. Upon reflection, it turns into a right-handed circularly polarized light. Then it is forward scattered by the focal conic texture and finally absorbed by the patterned absorption layer. As a result, the dark state is obtained.

In the above-mentioned reflection type transflective cholesteric LCD, no polarizer is employed. Therefore, its light efficiency is high. However, to produce the IER array on the top substrate increases the manufacturing complexity. In addition, the IER should be well aligned with the patterned absorption layer; otherwise, light leakage will occur. More importantly, the forward scattering of the focal conic texture is incomplete. Some backward scattered light causes a translucent dark state, which deteriorates the image contrast ratio. Therefore, the reflection type transflective cholesteric LCD is not yet popular for the high-end transflective LCD applications.

### *D. Phase-Retardation Type Transflective LCDs*

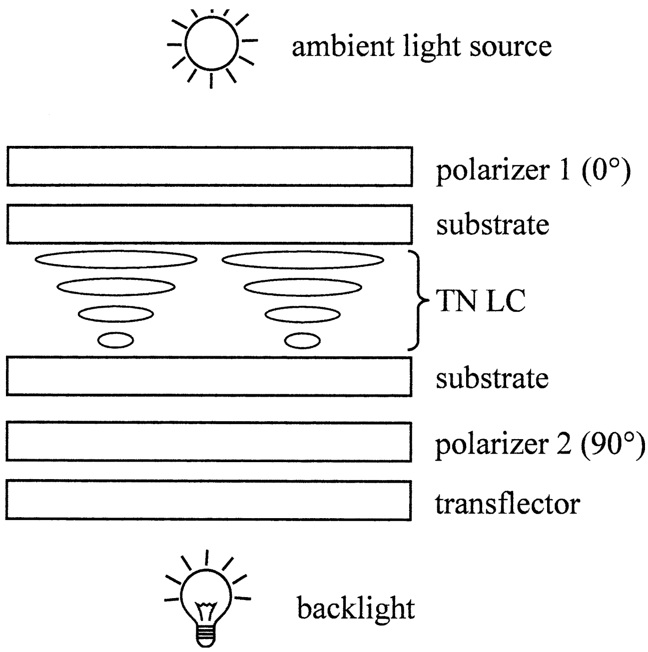
The operation principle of the phase-retardation type transflective LCDs is based on the voltage-induced LC phase retardation modulation. Since a transflective LCD consists of both T- and R-modes, two polarizers are usually required. Compared to the absorption, scattering, and reflection types, the phase-retardation type transflective LCDs have the advantages of higher contrast ratio, lower driving voltage, and better compatibilities with the current volume manufacturing techniques. Therefore, the phase-retardation type transflective LCDs dominate the current commercial products, e.g., cellular phones and digital cameras. In this section, we will describe the major transflective LCD approaches based on the phase-retardation mechanism.

To have a better understanding of the underlying operation principle and electro-optical (EO) performances of each transflective LCD approach, we carried out numerical simulations based on extended Jones matrix method [26]. Hereafter in this paper, unless otherwise specified, we assume that 1) LC material is MLC-6694-000 (from E. Merck), 2) the polarizer is a 190-micrometer-thick dichroic linear polarizer with complex refractive indices $n_e = 1.5 + i \times 0.0022$ and $n_o = 1.5 + i \times 0.000\,032$, 3) the transflector does not depolarize the polarization state of the impinging light upon reflection and transmission, 4) the transflector does not cause any light loss upon reflection and transmission, 5) the ambient and backlight enters and exits from the panel in the normal direction, and 6) the light wavelength is $\lambda = 550$ nm.

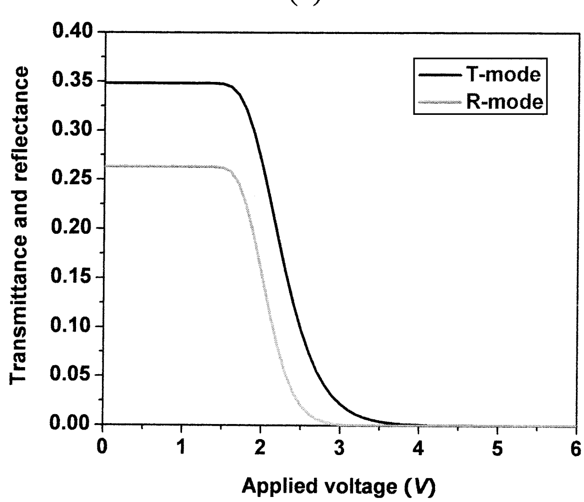
It should be pointed out that the brightness of a transflective LCD depends on two major factors: 1) the area ratio between the transmission and reflection regions and 2) the reflectance of R-mode and the transmittance of T-mode. The first factor mainly depends on the application of the transflective LCD. For indoor applications, the area of transmission region is usually larger than that of reflection region. On the contrary, if the transflective display is intended for outdoor applications, the reflection region should be comparable to or even larger than the transmission region. The second factor, however, mainly relies on the operating mode employed. Throughout this paper, we focus our discussion on optimizing the reflectance for the R-mode and transmittance for the T-mode.

*1) Transflective TN and STN (Super-Twisted Nematic) LCDs:* The 90° TN cell can be used not only in transmissive [1] and reflective LCDs [27], but also in transflective LCDs [28]. The device configuration of a transflective TN LCD is shown in Fig. 6(a). A 90° TN LC cell, which satisfies the Gooch–Tarry minima conditions [29], is sandwiched between two crossed polarizers. In addition, a transflector is laminated at the outer side of the bottom polarizer and a backlight is intended for dark ambient.

In the null voltage state, the LC directors exhibit a uniform twist throughout the cell from the lower substrate to the upper substrate. In the T-mode, the incoming linearly polarized light which is generated by the bottom polarizer, closely follows the twist profile of the LC directors and continuously rotates 90° with respect to its original polarization state. This is known as the polarization rotation effect of the TN cell. Thus the linearly polarized light can pass through the top polarizer, resulting in a bright output known as a normally white (NW) mode. While in the R-mode, the incoming linearly polarized light which is generated by the top polarizer, rotates 90° as it passes through the TN LC layer. It then penetrates the bottom polarizer and reaches the transflector. A portion of the linearly polarized light is reflected back by the transflector and passes the bottom polarizer




(a)




(b)

Fig. 6. Transflective TN LCDs. (a) Schematic device configuration. (b) Voltage dependent transmittance and reflectance curves.

again. This linearly polarized light then follows the twist LC directors and its polarization axis is rotated by 90°, i. e, parallel to the transmission direction of the top polarizer. Accordingly, a bright state is achieved.

In the voltage-on state, the bulk LC directors are reoriented substantially perpendicular to the substrate, leaving two orthogonal boundary layers. The perpendicularly aligned bulk LC directors do not modulate the polarization state of the incoming light. At the same time, those two orthogonal boundary layers compensate with each other. Consequently, the incoming linearly polarized light still keeps the same polarization state after it passes through the activated TN LC layer. In the T-mode, the linearly polarized light which is generated by the bottom polarizer propagates all the way to the top polarizer without changing its polarization state. Therefore, it is blocked by the top polarizer, resulting in a dark state. In the R-mode, the linearly polarized light produced by the top polarizer passes through the activated LC layer without changing its polarization state. Consequently, it is absorbed by the bottom polarizer and no light returns to the viewers side. This is the dark state of the display.

Fig. 6(b) plots the calculated voltage dependent transmittance and reflectance curves of a typical transflective TN LCD. Here twist angle $\phi = 90°$ and the first Gooch-Tarry minimum condition $d\Delta n = 476$ nm is employed, where $d$ is the cell gap and $\Delta n$ is the LC birefringence. We can see the grayscales of both T- and R-modes overlap well with each other. This is because the reflection beam in the R-mode experiences the bottom polarizer, LC layer, and the top polarizer successively in turn, as the transmission beam does in the T-mode.

Compared to the conventional transmissive TN LCD, the above transflective TN LCD only requires one additional transflector between the bottom polarizer and the TN LC layer. Naturally, this transflective LCD device configuration can also be extended to an STN-based transflective LCD [30]. Different from the so-called polarization rotation effect in TN LCD, the STN LCD utilizes the birefringence effect of the super-twisted nematic LC layer [31]. Therefore, a larger twist angle $(180° \sim 270°)$, a different LC cell gap, and a different polarizer/analyzer configuration are required.

The above-mentioned TN and STN type transflective LCDs have advantages in simple device structure and matched grayscales; however, their major drawbacks are in parallax and low reflectance.

Parallax is a deteriorated shadow image phenomenon in the oblique view of a reflective LCD [32]. Similarly, it also occurs in some transflective LCDs, such as the above described transflective TN and STN LCDs. Fig. 7 demonstrates the cause of parallax in the R-mode of a transflective TN LCD when the polarizer and transflector are laminated at the outer side of the bottom substrate. The switched-on pixel does not change the polarization state of the incident light because the LC directors are reoriented perpendicular to the substrate. From the observer side, when a pixel is switched on, it appears dark, as designated by $\mathbf{a}'\mathbf{b}'$ in the figure. The dark image $\mathbf{a}'\mathbf{b}'$, generated by the top polarizer, actually comes from the incident beam $\mathbf{ab}$. Meanwhile, another incident beam $\mathbf{cd}$ passes through the switched-on pixel and does not change its linear polarization state as well. Therefore, it is absorbed by the bottom polarizer, resulting in no light reflection. Accordingly, a shadow image $\mathbf{c}'\mathbf{d}'$ occurs from the observer viewpoint. Different from the dark image $\mathbf{a}'\mathbf{b}'$, which is generated by the top polarizer, the shadow image $\mathbf{c}'\mathbf{d}'$ is actually caused by the bottom polarizer. This is why the shadow image $\mathbf{c}'\mathbf{d}'$ appears to subside under the dark image $\mathbf{a}'\mathbf{b}'$. Because the bottom polarizer and transflector are laminated outside the bottom substrate, the incident ambient light beams $\mathbf{ab}$ and $\mathbf{cd}$ must traverse the bottom substrate before they are reflected back. Due to the thick bottom substrate, the reflection image beams $\mathbf{a}'\mathbf{b}'$ and $\mathbf{c}'\mathbf{d}'$ are shifted away from the pixel area that the incoming beams $\mathbf{ab}$ and $\mathbf{cd}$ propagate in, resulting in a shadow image phenomenon called parallax. Such a parallax problem becomes more serious with the decreased pixel size as well as increased bottom substrate thickness. Therefore, the transflective TN and STN LCDs with above-mentioned structures are not suitable for the high resolution full color transflective LCD devices.

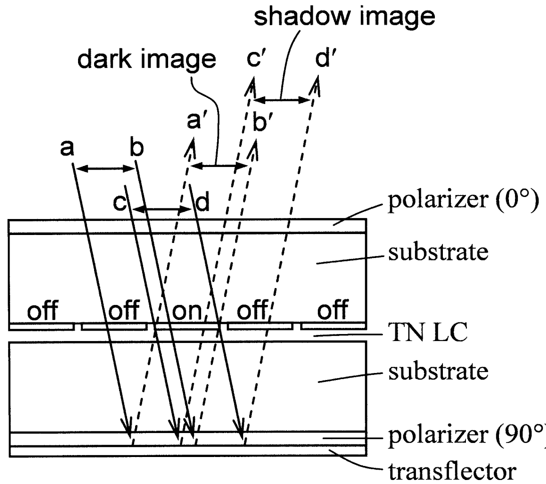



Fig. 7. Schematic view of the cause of parallax phenomenon in the R-mode of transflective LCD with polarizer and transflector laminated outside of the bottom substrate.

To overcome the parallax problem in transflective TN and STN LCDs, the bottom polarizer and transflector must be located inside the LC cell. Recently, a burgeoning in-cell polarizer technology, based on thin crystal film (TCF) growth from aqueous lyotropic LC of supramolecules, attracts some transflective LCD manufactures' interests [33]. By depositing both transflector and polarizer inside the cell, the above-mentioned annoying parallax problem can be eliminated.

Nevertheless, the transflective TN and STN LCDs still have another shortcoming, which is low reflectance in the R-mode. As shown in Fig. 6(b), although the grayscales of both modes can overlap with each other, one can still clearly see that the reflectance in the R-mode is much lower than the transmittance in the T-mode. This is because the light accumulatively passes through polarizers four times in the R-mode while only twice in the T-mode. Due to the absorption of polarizers, the light in the R-mode suffers much more loss than that in the T-mode. Accordingly, the reflectance of the R-mode is reduced substantially.

*2) Transflective MTN (Mixed-Mode Twisted Nematic) LCD:* To overcome the parallax and low reflectance problems of the transflective TN and STN LCDs, the bottom polarizer for the R-mode should be removed to the outer surface of the bottom substrate. Thus, the transflector can be implemented on the inner side of the LC cell, acting as an internal transflector. Under such a device configuration, the R-mode operates as a single polarizer reflective LCD. More importantly, both ambient light and backlight pass through the polarizer twice; therefore, both T- and R-modes experience the same light absorption from the polarizer. Nevertheless, the conventional TN LC cell does not work well in the single polarizer reflective LCD [4]. This is because, after the light travels a round-trip in the LC layer, the light polarization state in the voltage-on state is identical to that in the voltage-off state.

By reducing the $d\Delta n$ value of the TN LC layer to around half of that required in a conventional transmissive TN LCD, the MTN mode overcomes the problem mentioned above [4], [34]. Unlike the TN LCD, the twist angle of MTN mode can vary from 0° to 90° and its operating mechanism is based on the proper mixing between the polarization rotation and birefringence effects. Molsen and Tillin of Sharp Corp. incorporated the MTN mode into their transflective LCD design [35], as shown in Fig. 8(a). Compared to the transflective TN LCD shown in Fig. 6(a), this transflective MTN LCD exhibits two different features. First, the transflector is located inside the LC cell, thus no parallax problem occurs any more. Second, a half-wave film and a quarter-wave film are inserted in each side of the MTN LC cell. These two films together with the adjacent linear polarizer function as a broadband circular polarizer over the whole visible spectral range [36]. Thereby, a good dark state can be guaranteed over the whole visible range for the R-mode.

In the voltage-off state, the MTN LC layer is equivalent to a quarter-wave film. In the R-mode, the incident unpolarized ambient light is converted into a linearly polarized light after passing through the top polarizer. After penetrating the top two films and the MTN LC layer, the linearly polarized light still keeps its linear polarization except it has been rotated 90° from the original polarization direction. Upon reflection from the transflector, it experiences the MTN LC layer and the top two films once again. Hence its polarization state is restored back to the original one, resulting in a bright output from the top polarizer. In the T-mode, the unpolarized backlight turns into linearly polarized after passing through the bottom polarizer. After it passes through the bottom two films, penetrates the transflector, and continues to traverse the MTN LC layer and the top two films, it becomes a circularly polarized light. Finally, a partial transmittance is achieved from the top polarizer.

In the voltage-on state, the bulk LC directors are almost fully tilted up and those two unaffected boundary layers compensate with each other in phase. Therefore, the LC layer does not affect the polarization state of the incident light. In the R-mode, the linearly polarized light generated by the top polarizer turns into an orthogonal linearly polarized light after a round-trip in the top two films and the activated LC layer. Accordingly, this orthogonal linearly polarized light is blocked by the top polarizer, leading to a dark state. In the T-mode, the linearly polarized light, caused by the bottom polarizer, passes through the bottom two films, penetrates the transflector, then continues to pass through the activated LC layer and the top two films. Before it reaches the top polarizer, its linear polarization state is rotated by 90°, which is perpendicular to the transmission axis of the top polarizer, and the dark state results.

As an example, Fig. 8(b) depicts the voltage dependent transmittance and reflectance curves of a transflective MTN LCD with $\phi = 90°$ and $d\Delta n = 240$ nm. Here both T- and R-modes operate in a NW mode. Generally speaking, for the TN- or MTN-based LCDs, the NW display mode is preferable to the normally black (NB) because the dark state of the NW mode is controlled by the on-state applied voltage. Thus, the dark state of the NW mode is insensitive to the cell gap variation. Such a large cell gap tolerance is highly desirable for improving manufacturing yield.

When comparing Fig. 8(b) with Fig. 6(b), one can see two distinctions between the transflective MTN LCD and the transflective TN LCD. First, without bottom polarizer absorption, the reflectance of the transflective MTN LCD is higher than that of the transflective TN LCD. Second, the transmittance of the transflective MTN LCD is much lower than that of the transflective TN LCD. This is because the maximum obtainable normalized transmittance is always less than 100% for a transmis-

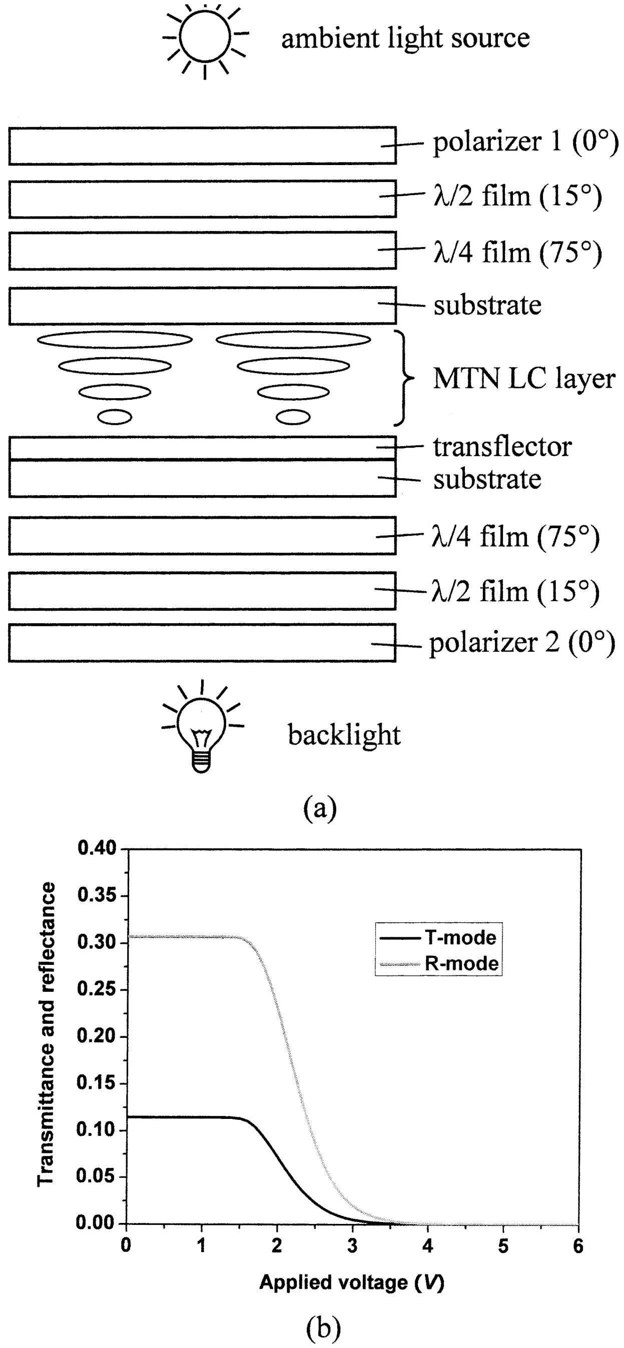



Fig. 8. Transflective MTN LCDs. (a) Schematic device configuration. (b) Voltage dependent transmittance and reflectance curves.

sive TN cell sandwiched between two circular polarizers [37]. Fig. 9 shows the maximum obtainable normalized reflectance and transmittance in optimized transflective MTN and TN LCDs as a function of twist angle. Here the normalized reflectance and transmittance represent only the polarization state modulation efficiency is taken into consideration and the light loss caused by the polarizers and reflector are all neglected. Due to the effect of circular polarizer on both sides of the MTN cell, as long as the twist angle is larger than 0°, the maximum obtainable normalized transmittance gradually decreases in spite of the $d\Delta n$ value of the MTN LC layer, as represented by the solid gray line in Fig. 9. For instance, in the 90° MTN cell with circular polarizer on both sides, the maximum obtainable normalized transmittance is $\sim$33%. On the other hand, the dark dashed line shows that the maximum obtainable normalized reflectance steadily keeps 100% until the twist angle reaches beyond 73°. In short, although the transflective MTN LCD overcomes the parallax problem, its maximum obtainable normalized transmittance in the T-mode is too low. Such a low normalized transmittance demands a brighter backlight which, in turn, would consume more battery power and reduces its lifetime.

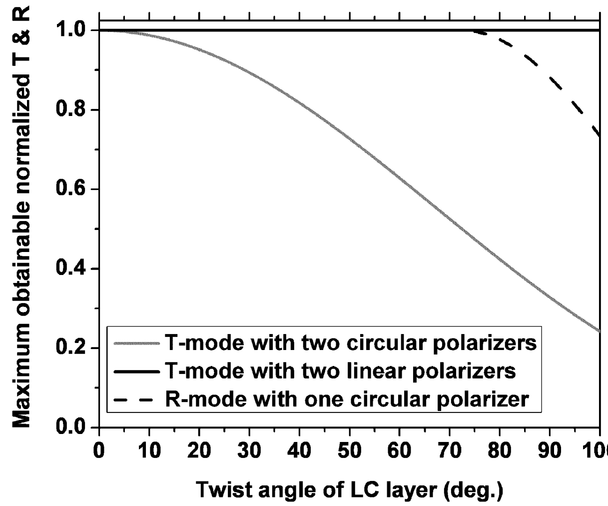



Fig. 9. Maximum obtainable normalized reflectance and transmittance in the transflective MTN LCD and the transflective TN LCD as a function of twist angle.

*3) Patterned-Retarder Transflective MTN/TN LCD:* If we can replace the circular polarizers with linear polarizers on both sides of the MTN/TN cell, the maximum normalized transmittance can be boosted to 100% for any twist angle from 0° to 100°, as designated by the solid dark line shown in Fig. 9. With a linear polarizer on each side of the cell, the T-mode operates at the same way as a conventional transmissive TN LCD. Philips research group proposed a dual-cell-gap transflective MTN/TN LCD using patterned phase retarders [37]. Fig. 10(a) shows the schematic device structure. Each pixel is divided into a transmission region and a reflective region by a derivative openings-on-metal type transflector. A patterned broadband phase retarder is deposited on the inner side of the top substrate. More specifically, the patterned phase retarder is located at right above the reflection region, while no phase retarder exists above the transmission region. In addition, the cell gap in the transmission region is around twice that of the reflection region and the LC layer twists 90° in both regions. The patterned phase retarder actually comprises a half-wave film and a quarter-wave film fabricated by wet coating techniques [38]. In the transmissive region, the cell is identical to the traditional transmissive TN LCD; while in the reflective region, it is a MTN mode. Fig. 10(b) shows the voltage dependent transmittance and reflectance curves with $d\Delta n = 476$ nm in the transmission region and $d\Delta n = 240$ nm in the reflective region. As we can see from the figure, both T- and R-modes have a very good grayscale overlapping. Since the maximum normalized reflectance of the 90° MTN mode is around 88% (see the dark dashed line in Fig. 9), the reflectance is slightly lower than the transmittance.

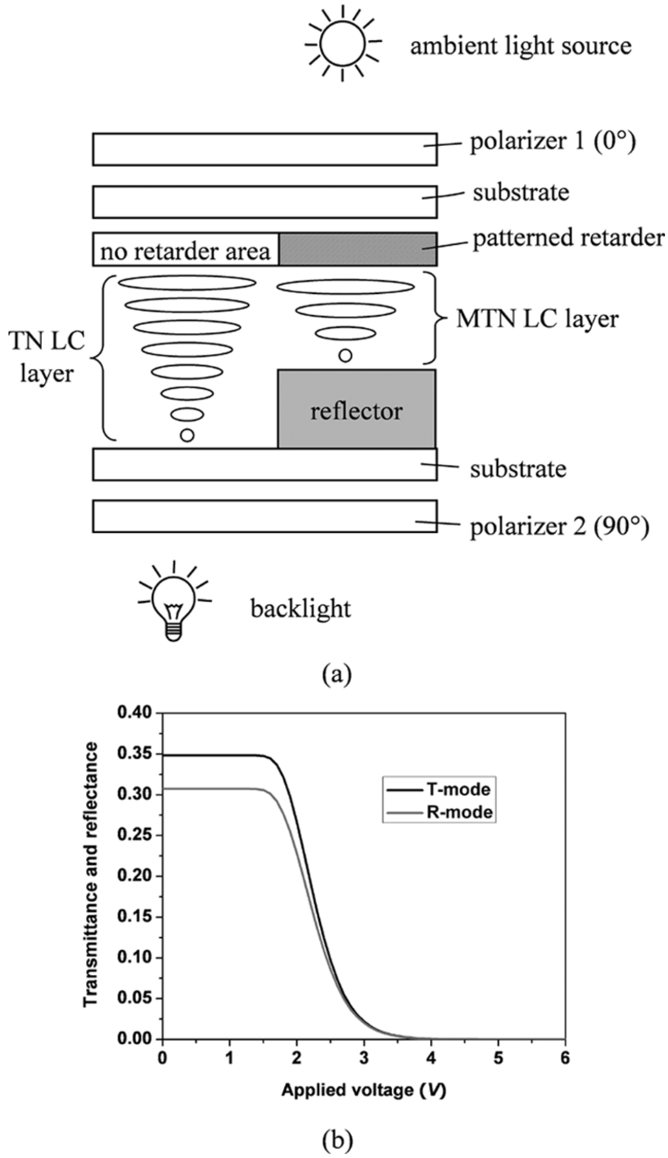



Fig. 10. Patterned retarder transflective MTN/TN LCDs. (a) Schematic device configuration. (b) Voltage dependent transmittance and reflectance curves.

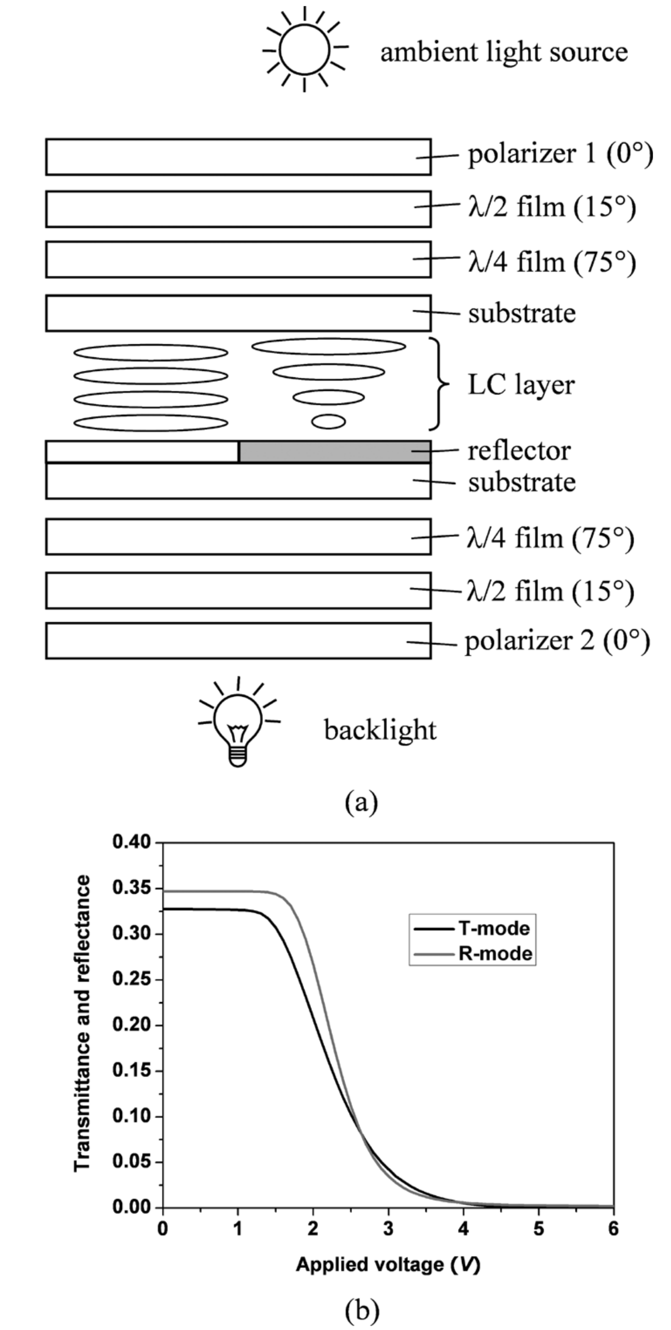



Fig. 11. Dual-rubbing transflective MTN/ECB LCDs. (a) Schematic device configuration. (b) Voltage dependent transmittance and reflectance curves.

This patterned retarder transflective MTN/TN LCD has advantages in the matched grayscale, high contrast ratio, and low color dispersion. However, it still requires a dual-cell gap configuration, which might cause a distorted twisted LC director profile on the border of the transmission and reflection regions.

*4) Transflective Mixed-Mode LCDs:* To compensate the intrinsic optical path differences between the transmission and reflection regions, Sharp Corporation proposed an approach to generate different director configurations simultaneously in both regions [39]. The different director configurations can be realized by such as applying different alignment treatments, exerting different driving voltages, generating different electric fields, producing different cell gaps in both regions and so on. Thus, the transmission region may, in principle, operate in a different LC mode from the reflection region, which leads to the name of transflective mixed-mode LCDs.

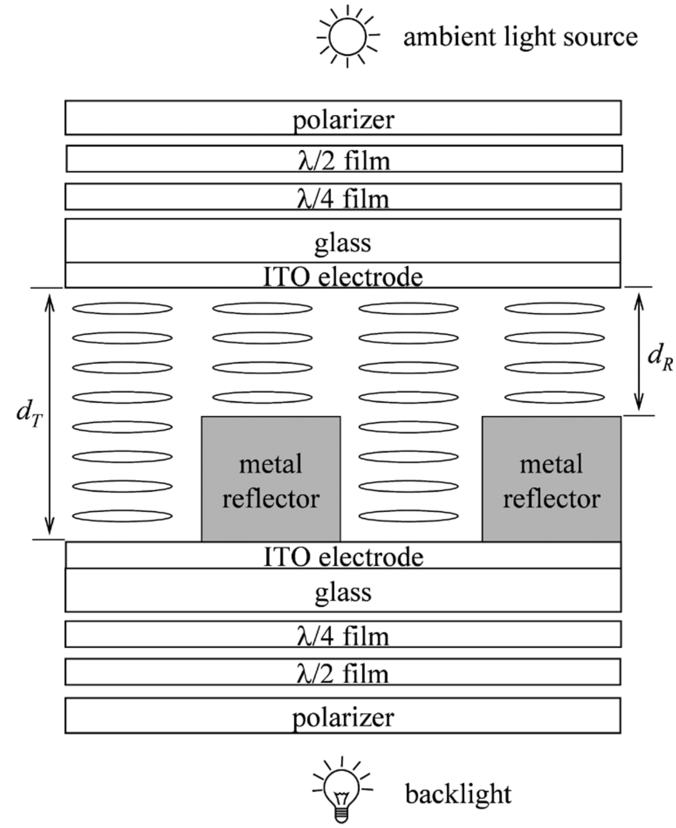
If two circular polarizers are indispensable in both sides of the cell, one solution to maximize the normalized transmittance is to decrease the LC twist angle to 0° in the transmission region while still maintain a twist profile in the reflection region. Thus the transmission region can operate in electrically controlled birefringence (ECB) mode while the reflection region still runs in MTN mode. Fig. 11(a) shows the device configuration of a transflective MTN/ECB LCD using the opening-on-metal transflector [40]. The top substrate is uniformly rubbed while the bottom substrate has two rubbing directions: in the reflective region the LC layer twists 75°, while in the transmission region the LC layer has zero twist, i.e., homogenous alignment. Therefore, the reflective region works in the 75° MTN mode while the transmission region operates in the ECB mode. Coincidently, their $d\Delta n$ requirements are very close to each other; therefore, a single cell gap device configuration is adopted in both regions. Fig. 11(b) plots the voltage dependent transmittance and reflectance curves with $d\Delta n = 278$ nm in both regions. Both T- and R-modes in the transflective MTN/ECB LCD almost simultaneously reach their maximum light efficiency through such a dual-rubbing process. Still, one might notice that the T-mode has slightly lower light efficiency than the R-mode. This is because the $d\Delta n$ requirement for both T- and R-modes is slightly different and a compromise is taken to optimize the R-mode.

Besides the above-demonstrated dual-rubbing transflective MTN/ECB LCD, other similar dual-rubbing transflective mixed-mode LCDs are also reported by different research groups, such as dual-rubbing transflective VA/HAN (vertical alignment/hybrid aligned nematic) LCD [41] and dual-rubbing transflective ECB/HAN LCD [42]. The common characteristic of these dual rubbing transflective LCDs is that different rubbing directions or different alignment layers are required on at least one of the substrates. This leads to two obstacles for its commercial applications. First of all, the dual rubbing requirement induces a complicated manufacturing process and hence an increased cost. More seriously, the dual rubbing usually introduces a disclination line on the border of different rubbing regions, which lowers the image brightness and deteriorates the contrast ratio as well.

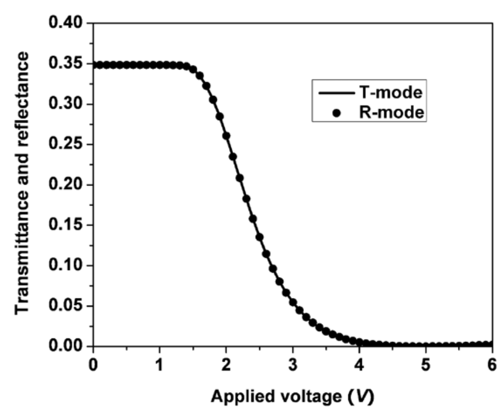
To avoid the dual rubbing process while still maintain a single cell gap device configuration, an alternative way to achieve different director configurations in both regions is to introduce different electric field intensities in both regions. For example, the transflective VA LCD utilizes periodically patterned electrodes to generate different LC tilt angle profiles in both regions [43]. Nevertheless, therein the metal reflector is insulated from its surrounding ITO electrodes, which increases the manufacturing complexity. On the other hand, the patterned reflector is either connected with the common electrode or electrically floated, which results in either a dead zone in reflection region or charge stability uncertainties. Another example is transflective IPS LCD, which uses the different twist-angle profiles along the horizontal direction of interdigitated electrodes for both transmission and reflection regions [44]. In this design, the in-cell-retarder is used between the transflector and LC layer. When no voltage is applied, the LC layer is homogeneously aligned. The LC cell together with the in-cell-retarder plays the roll of broadband quarter-wave film [36]. Such a design has two shortcomings. First, unlike the conventional transmissive IPS LCD, here the dark state is very sensitive to the LC layer thickness. Second, the in-cell-retarder is still difficult to be assembled inside the cell even using the state-of-the-art fabrication techniques.

*5) Dual-Cell-Gap Transflective LCDs:* Unless identical display modes are adopted in both T- and R-modes, otherwise there are always some discrepancies between their voltage dependent transmittance and reflectance curves. This is the reason that none of the above-mentioned transflective mixed-mode LCDs has perfectly matched voltage dependent transmittance and reflectance curves. Different from the mixed display modes employed between transmission and reflection regions as described above, Sharp Corporation also introduced the dual-cell-gap concept for transflective LCDs [39], [45].

Fig. 12(a) shows the schematic device configuration of a dual-cell-gap transflective ECB LCD. Similar to the case of dual-rubbing transflective MTN/ECB LCD, this dual-cell-gap transflective ECB LCD also has a circular polarizer on both sides of the cell. The role of the circular polarizer is to make the display operate in a NW mode so that its dark state is not too sensitive to the cell gap variation, as explained in Section III-D-2. Each pixel is divided into a transmission region with cell gap $d_T$ and a reflection region with cell gap $d_R$. The LC directors are homogeneously aligned within the cell; therefore, no dual rubbing process is necessary and both regions operate identically in the ECB mode. Since the homogeneously aligned LC layer only imposes pure phase retardation on the incident polarized light, $d_R$ is set to be around half of $d_T$ to compensate the optical path difference between ambient light and backlight. Fig. 12(b) depicts the voltage dependent transmittance and reflectance curves with $d_R\Delta n = 168$ nm and $d_T\Delta n = 336$ nm. As one can see, both



(a)



(b)

Fig. 12. Dual-cell-gap transflective ECB LCDs (a) schematic device configuration and (b) voltage dependent transmittance and reflectance curves.

curves perfectly match with each other and both modes reach the highest transmittance and reflectance simultaneously. Here $d_R\Delta n$ and $d_T\Delta n$ are designed to be slightly larger than $\lambda/4$ and $\lambda/2$, respectively, in order to reduce the on-state voltage.

The downside of the dual-cell-gap approach is twofold. First, the thicker cell gap in the transmission region results in a slower response time than the reflective region. However, the dynamic response requirement in mobile applications is not as strict as those for video applications. This response time difference, although not perfect, is still tolerable. Second, the view angle of the T-mode is very narrow because the LC directors are tilted up along one direction by the external electric field. By substituting the quarter-wave film with a biaxial film on each side of the cell, the viewing angle can be greatly improved [46]. Because the manufacturing process is completely compatible with the state-of-the-art techniques, this dual-cell-gap transflective ECB LCD is so far the mainstream approach for the commercial transflective LCD products.

Besides the above dual-cell-gap transflective ECB LCD, others dual-cell-gap transflective LCDs are also proposed, such as dual-cell-gap transflective VA LCD [47], dual-cell-gap transflective HAN LCD [48], and dual-cell-gap transflective FFS (fringe-field switching) LCD [49], [50]. Similar to the dual-cell-gap transflective ECB LCD, both dual-cell-gap transflective VA LCD and dual-cell-gap transflective HAN LCD also operate in ECB mode although their initial LC alignments are different. On the other hand, in the dual-cell-gap transflective FFS LCD, LC directors are switched in the plane parallel to the supporting substrates. Its dark state is achieved by a half-wave film and the initially homogeneously aligned LC layer. Consequently, the dark state is very sensitive to the LC cell gap, which causes difficulties to maintain a good dark state in both transmission and reflection regions due to the dual-cell-gap device configuration.

*6) Single-Cell-Gap Transflective LCDs:* Different from the dual-cell-gap transflective LCD, single-cell-gap transflective LCD renders a uniform cell gap profile throughout the cell. Therefore, the dynamic response of both T- and R-modes are close to each other. For instance, Huang proposed a single-cell-gap transflective LCD using an IER [51], which is similar to the structure described in Section III-C. In his design, the backlight is reflected by the IER to the reflection area; as a result, the transmitted beam from the backlight traverses a similar optical path to that of the ambient beam, which leads to the same color saturation in both T- and R-modes. However, similar to the transflective cholesteric LCD described in Section III-C, to produce an IER on the top substrate increases the manufacturing complexity. Besides, the mismatch between the IER and bottom pixel layout may cause light leakage.

As a matter of fact, several transflective LCDs described in the above sections also belong to this single-cell-gap category, such as transflective TN and STN LCDs, transflective MTN LCD, dual-rubbing transflective MTN/ECB LCD, dual-rubbing transflective VA/HAN LCD, dual-rubbing transflective ECB/HAN LCD, transflective VA LCD utilizing periodically patterned electrodes, and transflective IPS LCD. Due to the fact that the ambient light travels twice while the backlight propagates only once in the LC layer, the light efficiency of both T- and R-modes cannot reach the maxima simultaneously unless mixed display modes are employed. This leads to the transflective mixed-mode LCDs as described in Section III-D-4. As discussed therein, the transflective mixed-mode LCDs require either dual-rubbing process or complicated electrode designs. Consequently such single-cell-gap transflective mixed-mode LCDs have not been commercialized yet.

*7) Other Transflective LCDs:* In addition to the above described transflective LCDs, some other miscellaneous transflective LCDs were proposed as well. For instance, Philips Research group reported a transflective LCD using cholesteric reflector [52]. However, it displays reversed images among the reflected ambient light and transmitted backlight due to the intrinsic orthogonal polarization features of the cholesteric reflector. By using a circular polarizer on each side of the cell, the cholesteric half reflection mode (CHARM) LCD overcomes the reversed image problem [53]. Nevertheless, it must use a half cholesteric transflector, which only partially reflects and transmits the desired circularly polarized light. As a result, its light efficiency is close to that of the transflective LCDs using noncholesteric reflectors. Consequently, this CHARM LCD design loses the high light efficiency property of the cholesteric reflectors. Besides, a transflective LCD using ferroelectric and antiferroelectric LC materials was also reported [54]. Nevertheless, due to the intrinsic ferroelectric LC technology limitations, these efforts are still in the lab demo stage.

## IV. Discussion

We have just described the basic operating principles of some main transflective LCDs. The simulation results are based on some ideal assumptions. It is understandable that many other factors can affect the display image qualities, such as color balance, image brightness, and viewing angle.

### A. Color Balance

Because the reflection beam passes through the color filter (CF) twice while the transmission beam only passes once, generally speaking, the transflective LCD has a problem of different color balance between the T- and R-modes. To solve the color imbalance problem, different CF approaches have been developed. Sharp Corp. proposed a multi-thickness CF (MT-CF) design for the transflective LCDs [55]. In that design, the CF thickness in the reflection region is around half of that in the transmission region. Because the ambient beam passes through the thinner CF twice, while the transmission beam passes through the thicker CF once. As a result, these two beams experience almost the same spectral absorption. Therefore, such a CF thickness difference ensures almost identical color saturation between the transmission and reflection regions, resulting in a good color balance between T- and R-modes.

In addition to the MT-CF design, a pinhole type CF design was also proposed [55]. Therein, the thicknesses of the CF in both regions are equal, but the CF in the reflection region is punched with some pinholes. Therefore, a portion of the ambient light does not "see" the CF; instead, it passes through the pinholes directly. The problem of such a pinhole type CF is its narrow color reproduction area because the ambient light spectrum is mixed with the RGB primary colors, respectively, which causes the color impurity.

TABLE I
COMPARISON BETWEEN DIFFERENT TYPES OF TRANSFLECTIVE LCDs

| Transflective LCD type | Dual-rubbing requirement | Dual-cell-gap requirement | Grayscales overlap capability | Merits and drawbacks |
|---|---|---|---|---|
| 1 | No | No | Good | High brightness but low contrast ratio |
| 2 | No | No | Good | High brightness, but no dark state, parallax problem, and high driving voltage |
| 3 | No | No | Good | Good color balance, but complicated structure and low contrast ratio |
| 4 | No | No | Good | Simple device structure, but low reflectance and parallax problem |
| 5 | No | No | Good | Simple device structure, but low transmittance |
| 6 | No | Yes | Good | High brightness, but poor oblique viewing performance |
| 7 | Yes | No | Good | High brightness, but complicated manufacturing process and disclination line |
| 8 | No | No | Good | High brightness, but complicated device structure |
| 9 | No | Yes | Perfect | High contrast and high brightness, but different response speed in T- and R- modes |
| 10 | No | Yes | Good | High brightness but low cell gap tolerance |
| 11 | Yes | No | Good | Same response speed, but different rubbings or complicated structure/electrodes required |
| 12 | No | No | Good | Limitation in commercialization |

Note: 1: Absorption type transflective LCDs [7], [18]; 2: Scattering type transflective LCD [23]; 3: Reflection type transflective cholesteric LCD [24], [25]; 4: Transflective TN and STN LCDs [28], [30]; 5: Transflective MTN LCD [35]; 6: Patterned-retarder transflective MTN/TN LCD [37]; 7: Dual-rubbing transflective MTN/ECB LCD [39], [40], dual-rubbing transflective VA/HAN LCD [41], and dual-rubbing transflective ECB/HAN LCD [42]; 8: Transflective VA LCD using periodically patterned electrode [43], and transflective IPS LCD [44]; 9: Dual-cell-gap transflective ECB LCD [39], [45], dual-cell-gap transflective VA LCD [47], and dual-cell-gap transflective HAN LCD [48]; 10: Dual-cell-gap transflective FFS LCD [49], [50]; 11: Single-cell-gap transflective LCDs [28], [30], [35], [39]-[44], [51]; 12: transflective LCD using cholesteric reflector [52], CHARM LCD [53], and transflective LCD using FLC and AFLC [54].

An alternative approach to obtain the same color balance between the T- and R-modes is to fill some scattering materials into the CF in the reflection region [56]. The filled scattering materials have two functions. First, the equivalent CF thickness in the reflection region decreases to around a half of that in the transmission region. Second, the scattering materials can steer the reflection beam from the specular reflection direction; therefore, a pure flat metal reflector can be used in the reflection region, which simplifies the manufacturing process.

### B. Image Brightness

Image brightness is a very important feature for transflective LCDs. However, many factors decrease the overall image brightness. For instance, the red, green, and blue color filters have different light attenuation, which affects the overall brightness of the display panel. Besides, the reflection region of the openings-on-metal transflector, usually made from aluminum, has $\sim$92% reflectivity over the visible spectral region [57], which leads to a slightly lower light efficiency in the R-mode.

In the case of openings-on-metal transflector, the transflector area is intended for either reflection region or transmission region. To increase the backlight utilization efficiency while still keeping the ambient light efficiency unchanged, Yang proposed a transflective LCD design using a microtube array below the transmission pixels region [58]. The microtube structure, which is similar to a funnel in shape, allows most of the backlight to enter from a larger lower aperture and to exit from a smaller upper aperture. Consequently, the backlight utilization efficiency can be greatly enhanced, provided that the transmission/reflection area ratio still remains unchanged. After optimization, the average backlight utilization efficiency is improved by a factor of 1.81.

Except for the transflective LCDs using cholesteric transflectors [52], [53] as discussed in Section III-D-7, all of the other transflective LCDs discussed in this paper have the issue of "exclusive transflector". This means the transflector is exclusively used for either T- or R-mode. As a result, the light loss from the transflector itself is fairly considerable. To further improve the light efficiency of both T- and R-modes simultaneously, using the orthogonal polarization transflectors might be a potential solution. However, it should be conducted before the reverse image problem is resolved.

### *C. Viewing Angle*

Viewing angle is another important concern for transflective LCDs. As mentioned in Section III-D-5, the dual-cell-gap transflective ECB LCD has a narrow viewing angle in the T-mode. But by substituting the quarter-wave film with a biaxial film on each side of the cell, the viewing angle of the T-mode can be greatly widened [46].

In the R-mode, surface reflection is the main factor deteriorating the image contrast ratio and viewing angle. To solve this problem, bumpy reflector in the reflection region is commonly employed. The bumpy reflectors serve two purposes: 1) to diffuse the reflected light which is critical for widening viewing angle and 2) to steer the reflected light away from the specular reflection so that the images are not overlapped with the surface reflections. To design bumpy reflectors, one needs to consider the fact that the incident beam and reflected beam might form different angles with respect to the panel normal. In the optical modeling for the R-mode, the asymmetric incident and exit angles feature should be taken into consideration [59].

## V. Conclusion

In this review paper, we first introduce the transflector classifications. Then based on the development history, we investigate some mainstream transflective LCDs, including their operating principles, advantages and disadvantages. As a summary, Table I compares all of the transflective LCDs discussed in this review paper. Among them, the dual-cell-gap transflective ECB LCD has the best overall performances. This explains why it dominates the commercial transflective LCD market. In addition, the image quality issues of transflective LCDs, such as color balance, image brightness, and viewing angle, are discussed as well.

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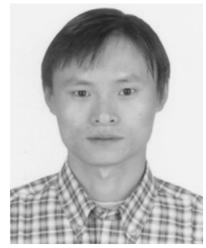

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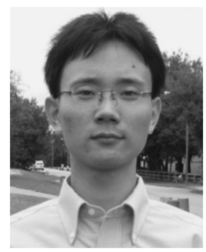

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