Transflective Liquid Crystal Displays

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Transflective Liquid Crystal Displays
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The requirements for flat panel displays are ever evolving towards lower power, more saturated colours, higher reflectivity, greater luminance, faster response, wider viewing angle etc. Yet there is one area of display technology, the subject of the present volume in the Wiley-SID Series in Display Technology, where any such improvements become the more difficult to achieve because of the need for displays to operate under any ambient illuminant condition from darkness to bright sunlight. Clearly, the image on a reflective display will be invisible in darkness; that on a backlit or self-luminous display will wash out in full sunlight.

Thus we enter the world of the transflective display – one which is partially backlit and partially reflective. This architecture offers many challenges to the display engineer; a transflective display can never achieve the luminance of a backlit display nor the reflectivity of a reflective display, so compromise will always be involved. Such compromise can be minimised by innovative design of liquid crystal electro-optic effects so that the threshold voltage, the gamma curve, the chromatic properties, the off-axis viewing characteristics and the cell thickness requirements of the transmissive part of the display match as closely as possible those of the reflective part.

In their preface, the authors have described in detail the contents of the individual chapters of this book, so I shall not dwell on that in more detail here. However, I would emphasise that transflective displays require some of the most elegant and exacting applications of liquid crystal science. That fact is demonstrated abundantly in this book, which covers the basic concepts, the device physics and provides detail of every known liquid crystal effect applicable to transflective displays at a level suitable for both postgraduate
students and practising engineers. I thank the authors for their efforts in writing this timely addition to the series.

Anthony Lowe
Series Editor
Braishfield, UK, 2010
About the Authors

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Zhibing Ge received his BS degree in electrical engineering from Zhejiang University, Hangzhou, China in 2002, and MS and PhD degrees in electrical engineering from the University of Central Florida (UCF), Orlando in 2004 and 2007, respectively. Currently, Dr Ge is a senior display engineer in the Flat Panel Displays department at Apple Inc., California. Between January 2008 and August 2009 he was with the College of Optics and Photonics, University of Central Florida, as a research scientist. His research interests include novel liquid crystal displays and laser beam steering technologies. He has published a chapter in a book, over 30 journal papers, and 12 issued or pending patents in related areas. Dr Ge is the recipient of the 2008 Otto Lehmann award. Since May 2008, he has been serving as an associate editor for the Journal of the Society for Information Display (JSID) in the LCD division.

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The explosive growth in personal mobile electronics has not only driven continuous improvement in image quality and power efficiency of existing displays, but also has nourished rapid development of novel ones that could have multiple functions. A stylish display has become a key factor for consumers when choosing an electronic device. Among various display technologies such as organic light-emitting displays (OLEDs), super-twisted nematic (STN), liquid crystal displays (LCDs), and electronic ink (e-ink), active matrix LCDs dominate the mobile display market owing to their capacity to provide high resolution and full color with high contrast and a wide viewing angle, and good legibility under different ambient conditions. A characteristic of LCDs in terms of maintaining vitality in the market is our ability to make advances in most of their components, from the backplane backlight unit to the front polarizer and anti-reflection film.

With the rising demand for outdoor image readability in portable displays, two parallel research and development directions in novel LCDs are: (i) developing high brightness transmissive LCDs that adaptively adjust the backlight output according to different ambient light conditions, and (ii) developing transflective LCDs that incorporate both transmissive and reflective functions into one display. The first approach maintains the superior image quality and simple device architecture of the transmissive mode, but its power consumption will be too high even for a short time use to enable it to compete with reflected sunlight, resulting in a short battery life. Transflective LCDs, on the other hand, utilize sunlight as an external light source for outdoor applications, thus their power consumption is relatively low. In addition, their outdoor ambient contrast ratio can be almost independent of the lighting conditions to maintain good image legibility. But the image
quality of the transmissive sub-pixel might be compromised by, for example, a reduced transmissive aperture and lower contrast ratio. Both approaches have their own merits and demerits. However, the performance of a transflective LCD can still be improved, to ultimately have comparable image quality to a transmissive LCD in a dim environment as well as high reflectivity, high contrast, and good color reproduction in the reflective sub-pixel for outdoor use. This requires engineers and scientists to first have an in-depth understanding of the device architecture, operating principles, and device performance. This is the major purpose of this book.

Chapter 1 gives a general review of LCD systems and key display elements covering the backlight unit, various LC modes, reflectors, linear polarizers, and compensation films. This chapter serves as a basis for readers to become familiar with transmissive and transflective LCDs.

Chapter 2 describes the device physics and modeling methods associated with the design and characterization of, but not limited to, typical transflective LCDs. In the modeling methods, we delve into LC molecular reorientation under the influence of an electric field and the corresponding electro-optical properties. Several exemplary transflective LCD device configurations are used to illustrate the design principles and underlying physics.

Chapters 3 and 4 further describe the wide-view technologies which are crucial to both transmissive LCD TVs and transflective LCDs. In Chapter 3, the detailed optical principles associated with phase compensation are illustrated using a Poincaré sphere. The analysis of linear polarizer and circular polarizer compensation provides readers with a clear pattern of the status and challenge in achieving wide-view transflective LCDs, especially in multi-domain vertical alignment (MVA) mode-based devices. In Chapter 4, detailed device configuration and design considerations of MVA, in-plane switching (IPS), and fringe field switching (FFS) transflective LCDs are discussed. Up-to-the-minute progress in these technologies is introduced, such as polymer-sustained surface alignment technology for MVA LCDs and in-cell-retarder-free FFS transflective LCDs. These two technologies possess great potential for next generation mobile displays.

Chapter 5 discusses the fast-response technology intended for color sequential displays and video-rate transflective LCDs. The fundamental physics and electro-optics including flow, response time, and compensation of optically compensated bend (OCB) modes using a pi-cell to achieve a fast response time are analyzed in detail.

Chapter 6 is designed to give readers some future technological perspectives. The comparison of a backlit transmissive display with a transflective
LCD is investigated in the real environment from which readers can see the irreplaceable role of transflective technologies in mobile displays. Emerging functionalities such as touch panel technology, including both external and in-cell touch designs, are also briefly introduced.

By the nature of their inherent advantages and great improvement potential, transflective LCDs will continue to attract significant research and application attention. This book aims to provide readers with a comprehensive introduction to the device configuration, underlying device physics, technical design considerations, and technological perspectives of transflective LCDs for next generation, sunlight-readable mobile display applications.

We would like to thank those who provided technical and financial support during the preparation of this book. In particular, we are deeply grateful to Dr Xinyu Zhu (Dow Chemical), Professor Thomas X. Wu (University of Central Florida), Dr Chung-Kuang Wei and Dr Wang-Yang Li (Chi-Mei Optoelectronics, Taiwan), Professor Seung Hee Lee (National Chonbuk University, Korea), and Dr Hyang-Yul Kim (Samsung, Korea), and our LCD group members. We are also grateful to Series Editor Anthony Lowe for his valuable suggestions and proofreading of the book. Special thanks go to our family members. With their understanding and spiritual support, we were able to finish this book on time.

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Device Concept of Transflective Liquid Crystal Displays

1.1 Overview

The ability to electrically tune optical birefringence makes liquid crystal (LC) a useful material for electro-optical applications. Because of its compact size and light weight, liquid crystal displays (LCDs) have been used extensively in electronic devices and appliances, from microdisplays and small handheld mobile phones to medium-sized notebook and desktop computers and large-panel LCD TVs. After decades of development, LCD technology is capable of giving excellent image performance at a relatively low cost. Compared with other display technologies, a unique characteristic of LCDs in terms of maintaining long-term competitiveness is the vigorous technical progress being made in almost every key element, including the LC material, TFT, LC cell structure, color filters, compensation films (including polarizers), backlight source, backlight films, driving electronics and algorithms, etc. In the foreseeable future, LCDs will continue to maintain their dominance in the display market.

Presently, three types of LCD have been developed to suit different applications: (i) transmissive, (ii) reflective, and (iii) transflective LCDs. In a transmissive LCD, a backlight is usually embedded as the light source to illuminate the LCD panel. A transmissive LCD typically exhibits high
brightness (300–500 cd/m²), high contrast ratio (>1000 : 1), and good color saturation. With its high image quality, transmissive LCD is the most adopted display technology and its performance is being improved steadily. For example, with film compensation and a multi-domain structure, a contrast ratio over 50 : 1 can now be easily obtained omnidirectionally in a wide-view LCD TV. Utilizing new backlight sources, like RGB light emitting diodes (LEDs), the color gamut can reach over 110% of NTSC to show pretty rich and vivid colors. With advanced low-viscosity LC materials and fast LC modes, a refresh rate of over 120 Hz (i.e., 240 Hz or even 480 Hz) has been achieved. Together with backlight local dimming, the dynamic image qualities, including dynamic contrast ratio and motion picture response time, have also been continuously enhanced which, in turn, leads to a significant energy saving. Therefore, for mobile displays, the high image quality of a transmissive LCD is advantageous, but some of its features mean it is still imperfect for mobile applications. First, transmissive LCDs rely on backlight white LEDs to illuminate the image. The associated power consumption is relatively high, resulting in a short battery life. Second, for some outdoor situations such as under strong sunlight, the surface luminance provided by a backlight cannot compete with the sunlight, leading to a washed out image and poor outdoor readability. Although increasing backlight intensity to elevate surface brightness above the ambient light intensity could improve the readability, the power consumption would also be dramatically increased. A solution for reaching good sunlight readability of a transmissive LCD is to embed an ambient light intensity sensor into a pure transmissive LCD that can dynamically or smartly adjust the brightness of the backlight to meet different ambient conditions. But this approach can only really target short usage times given the power consumption needed. For example, most transmissive mobile displays have a surface luminance at about 200 to 300 cd/m². To compete with regular outdoor sunlight (direct sunlight > 100 000 lux), huge backlight power is required to increase surface luminance to over 500 cd/m², even with anti-reflection coatings on the display front surface.

Another type of display is the reflective LCD, which embeds a metal reflector behind the LC cell, such as a mixed twisted nematic cell [1, 2] or cholesteric cell [2, 3], and uses external light to illuminate the displayed image. A reflective LCD has low power consumption and good sunlight readability. On the other hand, since a reflective LCD relies on external light to display the image, it exhibits poor readability in a low ambient light environment. Besides, the imperfect removal of surface reflection degrades its contrast ratio and color performance. Its low reflectivity (in most cases using circular polarizers), low contrast ratio (a typical value is ~5 : 1, while a
diffusive white paper has a contrast ratio of \( \sim 15:1 \) and low color saturation give viewers a different image experience from what would be seen on a transmissive LCD. Therefore, reflective LCDs are usually employed for low-end applications, such as devices that only require outdoor daytime viewing. Nevertheless, their low power consumption and sunlight readability are superior to transmissive displays, making reflective LCDs useful in portable devices where battery life is critical.

As a direct consequence, transflective LCDs have been designed to combine both transmissive and reflective functions into one display \([4, 5]\). In dark or low ambient light conditions, the backlight is turned on and the image is mainly displayed in the transmissive mode, exhibiting excellent image quality with high contrast ratio and good color saturation. In a bright ambient light situation such as under strong sunlight, the reflective mode mainly functions to display images and the backlight may either be turned on to assist the image display or turned off to save power. According to different application requirements, the ratio of transmissive to reflective regions can be varied. For instance, for a portable audio player that requires longer battery life, a larger reflective region can be adopted. But for a video cell phone where a vivid image is very important, the transmissive region can be made larger. Driven by the increasing demands of the mobile electronics market, high brightness, wide viewing angles, vivid color, fast response, outdoor readability, and low cost are all now required for small mobile displays. Research into transflective LCDs is being undertaken to meet such requirements.

In this book we will focus on the mainstream TFT-addressed wide-view transflective LCDs for mobile applications. First, the fundamental device elements including polarizers, liquid crystal alignment, relevant compensation films, reflectors, and backlight films that comprise a portable LCD device and their associated principles are briefly introduced. This is followed by the introduction of related modeling methods of LCD directors and optics which serve as the basis for transflective LCD characterization and optimization. More details on developing good light efficiency and wide viewing angle transflective LCDs are then discussed in terms of both TFT LC cell design and compensation films. Advanced topics related to applications like touch panels and fast response time for video mobile displays will also be addressed. Finally, Chapter 6 re-addresses the unique and irreplaceable role of transflective LCDs in the mobile display market and discusses the possible directions in which they could be developed to enhance competitiveness.

Figure 1.1 depicts the device structure of an active matrix-driven transmissive LCD based on amorphous silicon (a-Si) thin-film-transistor (TFT) technology. An LCD is a non-emissive display, i.e., it does not emit light by
itself; instead, it utilizes a backlight and the LC cell sandwiched between two sheets of stretched dichroic polarizers functions as a light valve. A diffuser close to the backlight is used to homogenize the backlight intensity in order to avoid hot spots. Prism films, such as 3M’s brightness-enhancement-film (BEF) [6] are stacked to confine the incident Lambertian backlight into a central cone to ±40° for enhancing axial display brightness. On the rear substrate (the TFT-array substrate), a TFT-array is formed to provide an independent switch for each pixel. Color filters are fabricated on the front substrate (namely the color-filter-array substrate) and aligned with the rear TFT pixels. In each time frame, signals (short high-voltage pulses) from the gate lines turn on the TFTs in a scanning sequence, and the voltages from the data lines are applied thereafter to drive each individual LC pixel to the targeted gray level. Under such a spatial RGB-sub-pixel configuration, different colors are achieved by combining the separate colors from RGB sub-pixels at assigned gray levels, and the eyes average the overall optical response from them. For large-panel TV applications, the typical sub-pixel size is about 80 µm × 240 µm. The sub-pixel size is reduced to about 50 µm 150 µm in small cell phone panels. In practice, the effective aperture for light

**Figure 1.1** Device structure of one pixel (with RGB sub-pixels) of a transmissive TFT LCD
transmission is much smaller than the sub-pixel area. The aperture ratio, defined as the effective region for transmission over the total region of each pixel, is usually less than 80%. Several factors cause a low aperture ratio. For TFTs, the active channel is sensitive to visible light, requiring a light shielding layer to cover that region. To avoid light leakage and color mixing from adjacent sub-pixels, black matrix (BM) is also formed at the boundaries between sub-pixels. The metal or alloy gate and data lines and the storage capacitor, made of opaque material, lead to a further reduction in the aperture ratio. Even for the area that is transparent to light, the light transmission cannot always reach 100% owing to the LC alignment there. In some LC modes such as the multi-domain vertical alignment (MVA) LCD [7–9], non-desired LC reorientations such as disclination lines also lower the effective light output.

For the LC cell, both inner surfaces are coated with a thin (~80 nm) polyimide layer to provide initial alignment of LC molecules that will adjust the ordered LC reorientation when a voltage is applied. Presently, major LCD technologies like twisted nematic (TN) [10], in-plane switching (IPS) [11, 12], fringe field switching (FFS) [13], and pi-cell or optically-compensated-bend (OCB) cells [14, 15] require a surface rubbing alignment, and technologies based on the VA mode, such as MVA [7–9], and patterned vertical alignment (PVA) [16] can yield initial vertical alignment without rubbing for high contrast. The LC cell gap is usually controlled at about 4.0 μm for a transmissive LCD, and the phase change of the LC layer between a fully bright state and a dark state is about half a wavelength. The electro-optical performance of the display in terms of light efficiency, response time, and viewing angle is related to the LC material, alignment, and cell structure.

For a direct-view reflective LCD, the cross-sectional view is depicted in Figure 1.2. This device utilizes external ambient light to display images, where incident light is reflected by the rear reflector and traverses the LC cell twice. The front linear polarizer and the retardation film (such as a quarter-wave plate) form a crossed-polarizer configuration for incident light. The aperture ratio of a reflective LCD is much higher than that of a transmissive one, since the TFT, and storage capacitor can be buried under the metal reflector. The cell gap of the LC layer is typically about 2 μm and the phase change between the bright state and the dark state is about quarter of a wavelength. Here, the color filter layer is formed on the front substrate in the figure, but alternatively it could be formed on the rear glass substrate. To avoid specular reflection and widen the viewing angle, a bumpy reflector surface is usually required and asymmetrical reflection is preferred, i.e., the incident angle and exit angle of the rays are designed to be different. Thus, strong surface specular reflection, which is considered noise, will not
overlap with the useful signal coming out of the LC cell. Compared with a transmissive LCD, the contrast ratio, viewing angle, and color saturation of a reflective LCD are inferior, resulting from many factors such as non-negligible surface reflection, complex optical films for circular polarizer configuration, and uncolored openings on the color filters for high reflectivity. Research efforts are being made to improve the image quality of reflective LCDs, e.g., by designing new anti-reflection films and high-reflectivity reflectors.

1.2 Polarizers

1.2.1 Linear Polarizers

As discussed above, optical performance of an LCD relies on each optical element, such as the LC cell, compensation film, and polarizer. For transmissive LCDs, linear polarizers partially determine the contrast ratio and hue balance (the spectral distribution of light output from the polarizers) of the display. For reflective LCDs, circular polarizers, comprising both a linear polarizer and a quarter-wave plate, are usually employed where viewing angle and dark-state spectral light leakage are important. Below, we will briefly introduce different polarizers employed in LCDs and their associated mechanisms. Typically, linear polarizers for LCDs are made from
polyvinyl-alcohol (PVA) films with iodine compounds using the wet-dyeing method [17]. After the PVA is stretched, dichroic species, such as $I_3^-$ and $I_5^-$ complexes, are aligned along the stretching direction, thus light polarized along this stretch direction will be strongly absorbed, while light polarized perpendicular to this direction will be transmitted. The degree of polarization and transmittance of PVA-stretched polarizers is highly dependent on the dichroism and the amount of dichroic species. In other words, one can control these parameters to adjust the transmittance and hue balance of the polarizers, which is very important for displays, especially for LCD TVs.

Figure 1.3 shows the optical transmittance from two identical linear polarizers set parallel or perpendicular to each other. For the parallel setup, the output transmittance in the blue region is much weaker than that at longer wavelengths. Here, the absorption of light is proportional to $\exp\left(-\frac{2\pi d n'}{\lambda}\right)$, where $\lambda$ is the wavelength, $d$ is the thickness of the medium, and $n'$ is the imaginary part of the refractive index of the polarizer along the transmission or absorption axis. In a typical polarizer, the transmission axis $n'$ (of the order of $10^{-5}$) decreases as wavelength increases. Blue light (with a smaller $\lambda$ value) experiences a larger $\exp\left(-\frac{2\pi d n'}{\lambda}\right)$ value and in turn a stronger absorption than red light through two parallel polarizers. As a result, a weaker output of blue light in the bright state causes the so-called blue decoloration phenomenon, making the display at full bright state appear a little yellowish. On the other hand, light leakage from these two crossed linear polarizers is inherently well suppressed over most of the visible range, although there is still evident light

![Figure 1.3](image)

**Figure 1.3** Wavelength-dependent transmittance of two linear polarizers at parallel (open) and perpendicular (closed) positions