Chapter 1

Introduction

1.1 Information Display Technology

As the trend of multimedia, internet and communication applications, various display technologies to present mass information in image, text and video, are rapidly developed to fulfill the demands of vast amount of information exchange. To pursue more natural visions, image displays span in complexity from monochrome to the more advanced high resolution, high brightness, and true color displays. For this purpose, a wide variety of flat panel displays were therefore developed: Liquid Crystal Displays (LCDs), Plasma Display Panels (PDPs), Field Emission Displays (FEDs), Light Emitting Diodes displays (LEDs) and Electroluminescent displays (ELs). Due to high performance, light weight, compact size, and low power consumption, LCDs become the most widespread technologies, especially in portable applications such as mobile phones, Personal Digital Assistants (PDAs) and notebook. However, issues such as low light efficiency, narrow viewing angles and slow response time of current LCDs need to be resolved.

1.2 Liquid Crystal Displays

Liquid crystal is an electro-optical light shutter that does not emit light but modulates transmission of incident light source in the Liquid Crystal Display embodiment. The configuration of Liquid Crystal Displays comprises of two glasses, i.e, the bottom and top glasses, and a sandwiched layer of liquid crystal (LC) between two glasses[1], as shown in Fig. 1-1. The thickness of the liquid crystal layer is defined by spacer beads in between the substrate plates and in the seal line at the display's periphery.

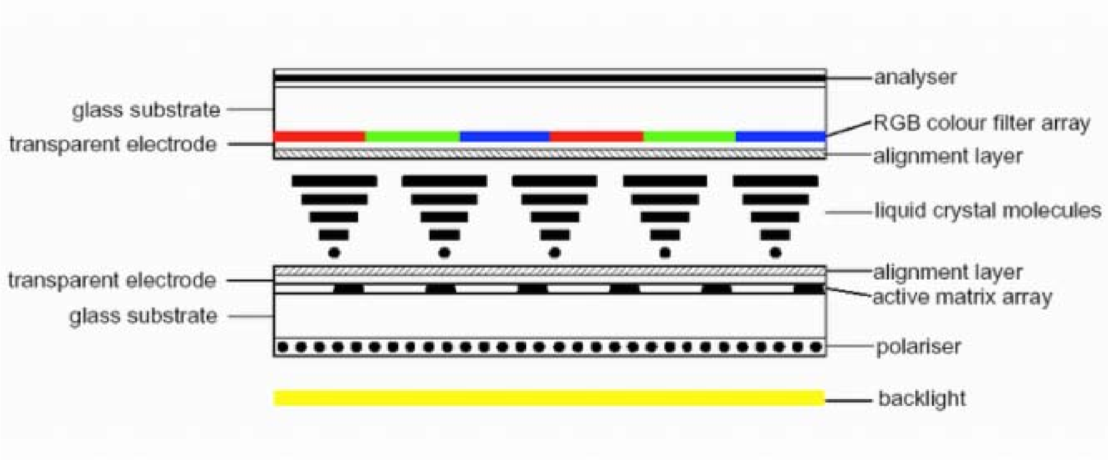

Fig. 1-1. Liquid crystal cell and module layout.

Thin Film Transistor (TFT) array is patterned on the bottom glasses to drive LC cells. Color filter array is fabricated on the top glass to select colors. The outside of each glass plate is covered with a polarizing sheet. The LC layer is placed between transparent electrodes (e.g. Indium Tin Oxide, ITO) to electrically modulate the transmission of each pixel in the liquid crystal display.

The most conventional LC layer is a nematic type in a twisted configuration, which is schematically shown in Fig. 1-2. As the alignment layers, which impose a uniform orientation of the nematic liquid crystal molecules parallel to the rubbing direction, are crossed at the bottom and top glasses, the nematic liquid crystal twists over 90° across the cell. Two absorbing polarizers are conventionally parallel to the direction of the alignment layers and hence are crossed with respect to each other. When no voltage is applied to the cell, the incident light is linearly by the first polarizer, twisted over 90° across the cell and transmitted through the second polarizer (analyser).[2] This is a bright state of the LCD cell. When a sufficient voltage is applied to the cell, the LC molecules will be aligned in the direction parallel to the electric field. The liquid crystal molecules no more twist, thus, resulting in a block of incident light by two crossed polarizers. This is a dark state of the LCD cell. By applying an intermediate voltage, intermediate brightness levels (gray-scales) can be achieved. Additionally, after passing through red, green, blue color filters, a color image can be generated by selectively addressing the electric field of the pixel cells of the display.

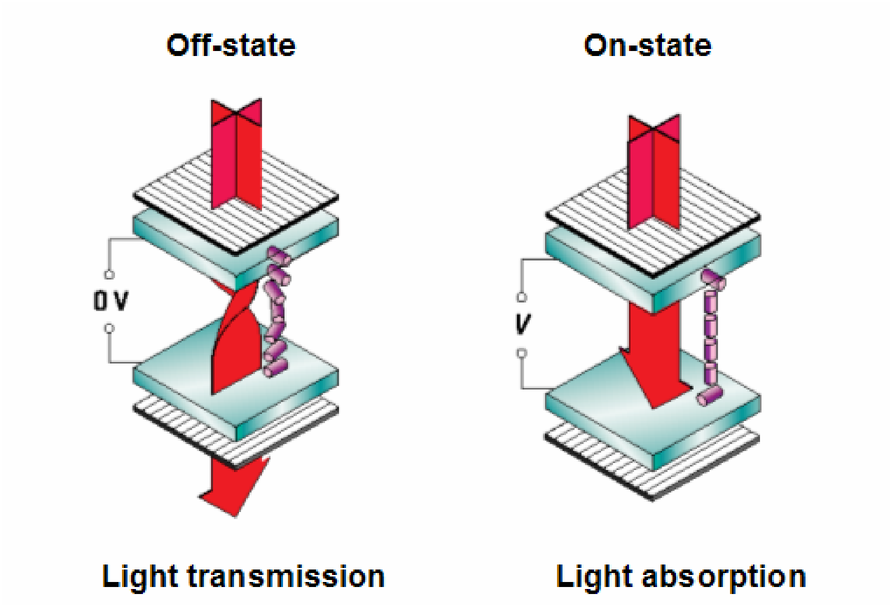

Fig. 1-2. Schematics of a Twisted Nematic (TN) liquid crystal display cell. Incident light is transmissive and absorbed, respectively, by switching off and on the LC cells.

As LC is a non-emissive device; an adequate light source becomes essential in order to illuminate LC panel. Due to the differences of applied light sources, i.e. ambient light, frontlight or backlight, LCDs can be generally classified into three types: reflective, transflective, and transmissive LCDs, which are schematically shown in Fig. 1-3.

Reflective LCDs, which use ambient light to illuminate the display, was proposed by T. Uchida in 1995.[3] The reflective type LCDs (Fig. 1-3(a)) are provided with a reflector behind the rear polarizer, so that the ambient light is reflected to show the images. In general, reflective LCDs work better in outdoor or bright indoor environments, thus, widely using in portable applications, such as cellular phones, e-book, and watch displays. Reflective LCDs are advantageous of light weight and low power consumption due to the elimination of the backlight. However, most of reflective LCDs still suffer from inadequate brightness and contrast ratio. Additionally, when the ambient light is dim, reflective LCDs are not readable if no built-in light source is available. Transflective LCDs are therefore developed, which both ambient light and backlight are used separately or simultaneously.

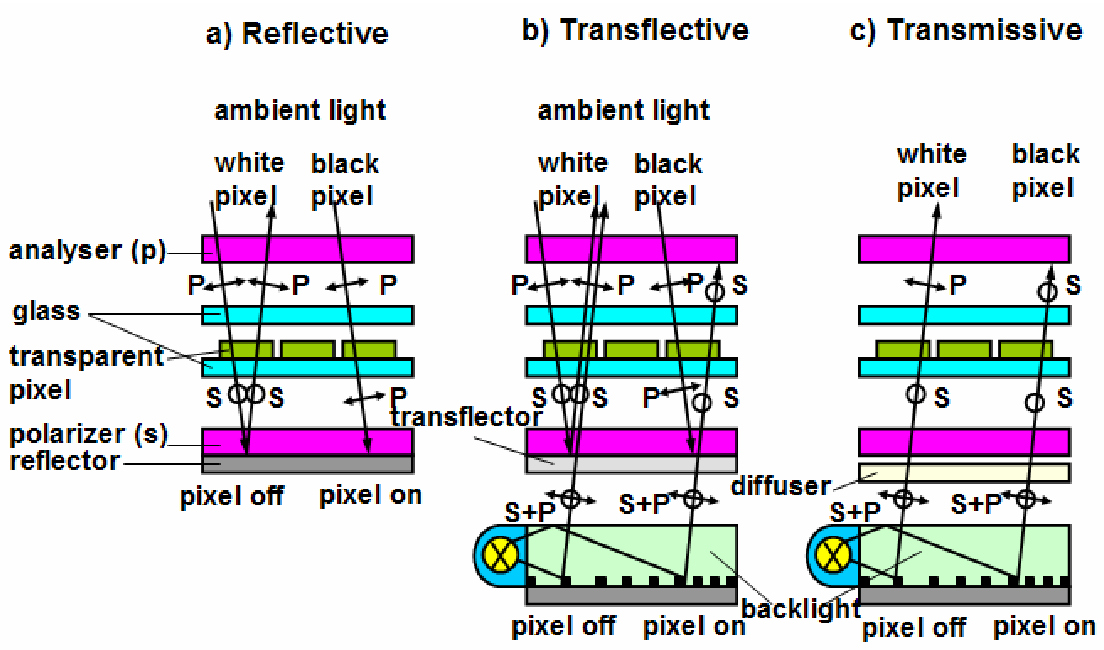

Fig. 1-3. Schematics comparison of LCD types with respective to illuminating light source. (a) reflective (b) transflective and (c) transmissive LCDs.

Transflective LCDs (Fig. 1-3(b)) utilize a transflector, which split each sub-pixel into transmissive and reflective portions, to display the image in any ambience.[4] In a bright ambience, incident light on the transmissive region is absorbed by the rear polarizer, so that the device works as a reflective display. In a dark ambience, the backlight transmits the transmissive region, and hence the device works as a transmissive display.

In the conventional transmissive LCDs, a backlight system, which can be placed directly behind the display, is necessary as the main built-in light source. Transmissive LCDs modulate the amount of light from the backlight and produce images.[5] Transmissive LCDs are advantageous in thinness, brightness, high contrast ratio and good color saturation. However, transmissive LCDs require high power consumption and are difficult to read under too bright environment, thus, mostly used in desktop monitor or TV applications.

1.3 Backlight Systems in Transmissive and Transflective LCDs

The backlight consists of a transparent lightguide, optical films and an adequate light source that can be placed either directly behind or at the edge of the display, which are so-called direct and edge-backlighting, respectively. Edge-backlighting is the most widely used because of its thinner thickness and lower power consumption. For small size LCDs, such as cellular phone, Light Emitting Diodes (LEDs) are used as light sources while Cold Cathode Fluorescent Lamps (CCFLs) widely applied for large size applications. Incident light from LEDs or CCFLs is then coupled into the side-faces of a transparent plastic substrate, as shown in Fig. 1-4.Because the refractive index of plastic substrate is significantly larger than the refractive index of air, light is therefore trapped in the plastic lightguide plate due to Total Internal Reflection (T.I.R). Light can be extracted from the lightguide while scattering at the printed pigment or micro-structures which are fabricated on the bottom surface of the lightguide.[6] Then, a diffuser sheet is conventionally applied to obtain a more uniform light distribution. Additionally, prism sheets, which are so-called Brightness Enhancement Films (BEFs)[7], are used to redirect the light of large inclined angles toward the normal direction, so that brightness can be much enhanced in the normal viewing direction.

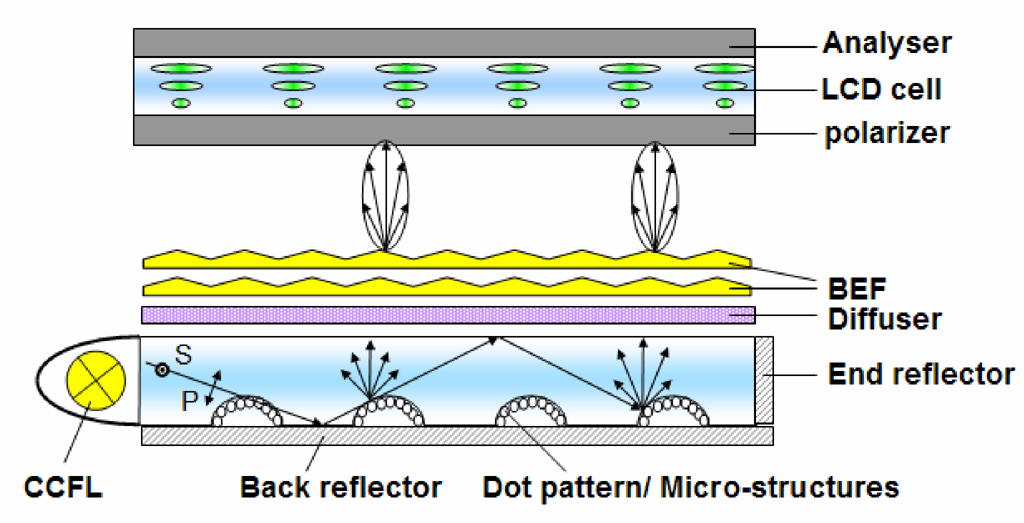

Fig. 1-4. Schematics of conventional LCD backlight systems.

Nevertheless, the backlight of transmissive/ transflective LCDs still exists a major concerned issue in its low light efficiency, thus, reducing brightness of LCD and the lifetime of battery.[8] As shown in Fig. 1-5, the devices in the transmissive LCD embodiment including polarizer, pixel electrode, LC cell, color filter, and analyzer will absorb or block the backlight.

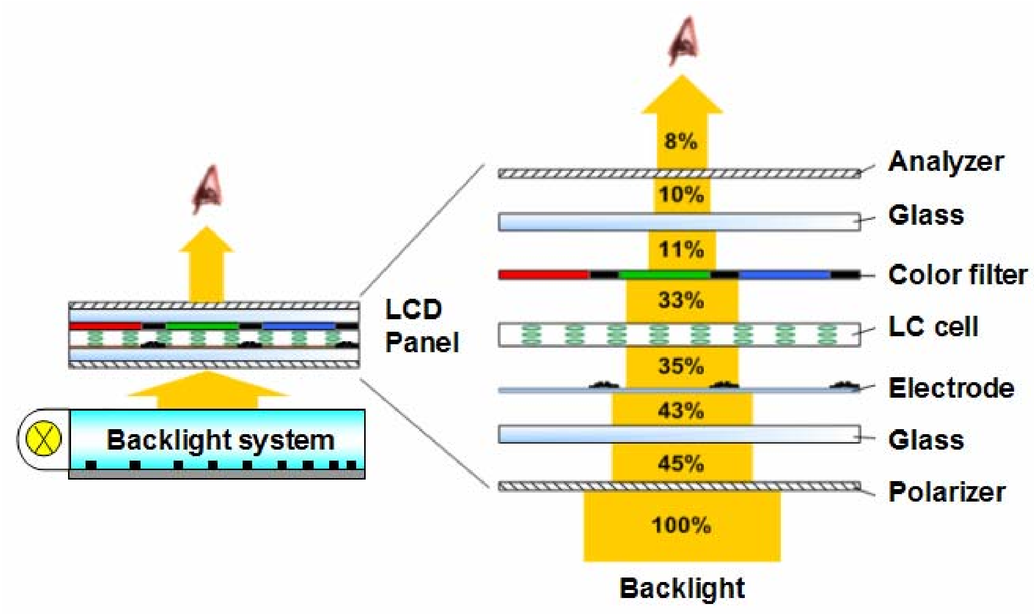

Fig. 1-5. Transmissive LCDs with backlight system and the light efficiency after light passes through each component of the LCDs.

The major energy consuming devices are polarizers and color filters. Typically, polarizers and color filters absorb 55% and 70% of the incident light, which only yields 45% and 30% of efficiency, respectively. Therefore, a typical transmissive LCD device has a transmittance of about only 8%.

1.4 Non-absorbing Devices in Transmissive and Transflective LCDs

As polarizers and color filters are the major energy consuming devices in LCDs, they consequently become the key components needed to be further developed. Many extensive research and work have been exploring the non-absorbing devices to produce linear polarized light and do without color filters to improve light efficiency in LCDs. For example, reflective polarizer was proposed to produce linear polarized light based on Bragg reflection of circularly polarized light in the cholesteric LC material.[9][10]

Generally, circularly polarized light is reflected with the same handed direction of the helical structure in the cholesteric LC material while the opposite circular polarized light is transmitted, then, combines with a quarter-wave plate to convert the circular polarized light into linearly polarized light. In order to obtain reflection in the whole visible spectrum, a gradient helical pitch is utilized. However, reflective polarizers use relatively costly materials and are not compatible in conventional fabrication. In addition, polarizers can be left out by producing polarized light source. The polarizing devices converted the unpolarized light extracted from the LCD backlight systems into linear polarized light while recycling the orthogonal polarized light into the backlight system until it has an appropriate polarization to be transmitted through the devices. Therefore, light efficiency can be much enhanced by achieving polarization conversion.

Tanase et al. have proposed to couple out linearly polarized light by using micro-structures that are inclined at the Brewster angle.[11] Only s-polarized (TE electric field) is extracted while p-polarized light (TM electric field) is trapped. However, this is a strongly angular dependent polarization phenomenon. Polarization efficiency is rapidly degraded while the incident angle differs from the Brewster angle. Furthermore, Pang and Li used frustrated total interference in a stack of thin films to extract one specific polarization state of light.[12] However, this approach is very limited in incident angles and wavelength as well.

1.5 Motivation of this Thesis

As LCD becomes the most important display applications, novel LCD technologies were therefore developed aiming for enhancing the image quality. Many efforts have been devoted to elevating the performance of LC panels. Nevertheless, a key component, an illumination system, i.e. LCD backlight, is lack of intensive analyses and study. Systematic analyses and optical design are thus proposed for resolving the concerning issues of LCD backlights, such as inadequate light efficiency, brightness and uniformity.

In this thesis research, three novel LCD illumination systems, polarized backlights with sub-wavelength grating[13], polarized backlights based on selective total internal reflection[14][15], and directional backlights[16] for three-dimensional displays, were designed to further improve the main issues of conventional portable LCDs for yielding high efficiency and great image quality. The design and fabrication of micro-optical patterns in LCD illumination systems were studied and developed for optimizing their optical performance.

The first and second illumination systems are focused on enhancing light efficiency and brightness of the display by using non-absorbing optical mechanism in

LCD illumination. For this purpose, the polarizing function is integrated into the lightguide for extracting the linearly polarized light straightforward, so that the polarizer can be left out.

The first approach uses sub-wavelength grating to separate orthogonally polarized light. The sub-wavelength grating provides high transmission for p-polarized light and high reflection for s-polarized light, respectively. The polarization separation and recycling are achieved by the reflection of s-polarized light while p-polarized light transmitting through the sub-wavelength grating simultaneously. Then, a quarter-wave plate with a reflective sheet is used to achieve polarization conversion by double-paths of s-polarized light, hence, a linearly uni-polarized light is obtained.

The second approach is using a selective Total Internal Reflection (T.I.R) at a interface of micro-grooves to extract linearly polarized light from the lightguide. One polarized light is extracted at the micro-structured anisotropic-isotropic interface while the orthogonally polarized light remains trapped in the lightguide and is to be recycled. Compared with reported polarizing devices, the integration of the polarizing and recycling function of polarized backlights potentially reduces complexity, weight and cost.

Furthermore, a three-dimensional display is seen to be the major trend of the display technologies to achieve ever more natural visions. The third LCD illumination system, which provides good directionality, is hence designed aiming for realizing three-dimensional display. In combination with fast switching LC panel and light sources, two alternate images, which are observed by left eye and right eye, respectively, can be sequentially obtained. Therefore, stereoscopic perception of image is sensed by our brain due to binocular parallax. Compared with conventional approaches, such as using lenticular lens and parallax barrier, critical alignment is no longer needed. Additionally, light efficiency and resolution of the display can be further improved.

1.6 Organization of this Thesis

The thesis is organized as following: The theories and optical design of LCD illumination systems are presented in **Chapter 2.** Basic diffractive optical component designs, such as micro-lens, micro-grooves and grating, are introduced in this chapter. Additionally, this chapter also describes the working principle of key components in LCD illumination systems, such as lightguide plates, Brightness Enhancement Film (BEF), and polarizer. In **Chapter 3**, the fabrication technologies of LCD backlights are summarized, and the major instruments used to measure the performance of LCD backlights are represented. In **Chapter 4**, polarized backlights using sub-wavelength grating were demonstrated. Furthermore, polarized backlights using selective internal reflection mechanism to achieve polarization separation and recycling for LCD illumination was described in **Chapter 5**. Polarized backlights greatly suppress the energy absorption in polarizers, thus, yielding large gain in light efficiency. Additionally, polarized backlights, which exhibit collimated and wide angular distributions, respectively, were demonstrated aiming for various transmissive and transflective LCD applications. Moreover, in **Chapter 6**, with switching, directional backlights and LC panel, a three-dimensional display, which further improves image perception, was presented. Finally, discussions and summary of this dissertation, and recommendations for the future works are given in **Chapter 7**.

1.7 References

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