Chapter 7

Conclusions and Future Works

As the demands of information in image, text and video rapidly grow, various display applications have already become requisites in people's daily life. Among a variety of display technologies, liquid crystal displays (LCDs) are predominant in the market due to the appealing features of thin format, compact size, light weight, low power consumption. In order to pursue brighter, thinner and lighter LCDs, many aggressive efforts have been contributed to the improvement on LC panels. Nevertheless, as LC technologies become mature in both designs and fabrication, relatively limited enhancement in optical performances of the display was obtained due to the constraints of LC characteristics. As a result, a high performance illumination system for LCDs naturally becomes another key component to be explored aiming for further enhancement in optical performances. However, conventional illumination systems for LCDs are poor in light utilization efficiency, uniformity and lack of compactness.

In this thesis work, we successfully developed several novel illumination systems aiming for various LCD applications that bring more flexibility in system design. Simultaneously, the ray-tracing approach was used to design and simulate the proposed optical systems. The diffraction and geometry optics were utilized for optimizing the optical performance, such as uniformity, efficiency and suppression of moiré pattern, etc. Additionally, the illumination system fabrication process, such as embossing/extrusion technology, diamond knife micromachining process with injection molding and e-beam lithography, were demonstrated for achieving better optical properties and higher fabrication accuracy. Most of all, these illumination systems greatly improve the optical performance of various LCD applications, thus, offering more appealing and competitive LCD performance.

7.1.1 Sub-wavelength Grating for Polarization Conversion

Various issues of LCD technologies, such as narrow viewing angles and low contrast ratio, have been greatly improved in recent years. Nevertheless, a key issue of LCDs, inadequate light efficiency, needs to be further enhanced. The optical efficiency of conventional backlight modules is low due to the lack of p-polarized to s-polarized light conversion (P-S conversion). Therefore, brightness of LCD and the lifetime of battery are restricted. In addition, the complex assembling of optical films, such as Brightness Enhancement Film (BEF), Dual Brightness Enhancement Film (DBEF) and diffuser, usually hinders compact packaging.

For alleviating these drawbacks, we developed a polarized backlight using sub-wavelength grating to achieve polarization conversion and compactness for LCD illumination. This novel element combined micro slot structures and a sub-wavelength grating on both sides of the lightguide. When unpolarized light was coupled to the lightguide, slot structures on the back side of the lightguide make light extracted. Light was then reflected by the reflective sheet. Upon the impingement on the sub-wavelength grating on the front side of the lightguide, only p-polarized light was transmitted while s-polarized light was reflected. S-polarized light was then converted into p-polarized light by passing through the quarter wave plate twice.

An integrated polarized lighguide was fabricated and evaluated for its functionality. 80% brightness uniformity and 69% polarization efficiency were achieved. Thus, a gain factor of 1.7 in polarization efficiency was achieved. Consequently, an integrated lightguide of high polarization conversion efficiency shall provide a high efficiency backlight module in a compact form for LCD illumination.

7.1.2 Selective T.I.R at Micro grooves for Polarization Conversion

Sub-wavelength grating was utilized to separate p-polarized and s-polarized light, then, using quarter-wave plate to achieve polarization conversion. However, sub-wavelength grating was fabricated by e-beam lithography. High cost and small writing area of e-beam writer usually constrain its applications. Consequently, we proposed a novel polarized backlights using selective T.I.R.

An anisotropic layer with micro-grooves was filled with an isotropic index-matching layer, adhered to the lightguide substrate. The approach to separate the polarized light was aimed to extract one polarization state of light by selective T.I.R at the micro structure interface. The extraordinary refractive index n_e of the anisotropic layer should be significantly larger than the refractive index n_c of index-matching layer to achieve a sufficiently small critical angle at the interface. In contrast, the critical angle at the interface is not present for the orthogonally polarized light. Light therefore remains its propagating direction at the interface of micro-structures.

In the experiment, stretched PET and PEN foils were used as the anisotropic layer. PEN foil exhibits better polarization separation ratio because of higher birefringence. By using PEN foil, outcoupling of s-polarized light is in a cone of $\pm 30^{\circ}$ around the surface normal, while p-polarized stray light is in large inclination angles. Contrast ratio in normal viewing direction can be as high as 64. Additionally, polarized backlights with end and back reflectors provide luminous uniformity of higher than 80%. Furthermore, 1.6 gain in efficiency is obtained aiming for high efficiency LCD illumination.

7.1.3 Directional Backlights for Time-multiplexed 3D Displays

As the advancement of image display from monochromic to color, each development is driven by pursuing ever more natural visions. Therefore, autostereoscopic display is seen to be the major advancement to provide human perception closer to reality. Autostereoscopic display can be generally classified into “spatial-multiplexed type” and “time-multiplexed type”. For spatial-multiplexed type, odd and even pixels of panel control projected images to left and right eyes, respectively, yet, resulting in resolution of half or less. In addition, the parallax barrier plate usually blocks parts of light from the backlight module and hence degrades the light utilization efficiency. Furthermore, critical alignment between the parallax barrier plate and LCD pixels is a serious concern.

For solving the concerned issues, a compact time-multiplexed 3D display was developed by using a switching, directional backlight combined with a fast switching LCD. Two restricted viewing cones were sequentially emitted from switching backlight, which consists of a grooved-lightguide in combination with asymmetric focusing foil. Two sates of image were therefore obtained in our left eyes and right eyes, respectively. The fast switching LC panel was then utilized with the directionally switching backlight to achieve binocular disparity.

The measured crosstalk of the backlight module with LC panel is of less than 6%. In addition, the blinking backlight was applied on the module to reduce the crosstalk while refreshing the image. The response time of LC can reach 7.1 ms, so that the frame rate of LC panel can be faster than 60 Hz. Furthermore, the proposed autostereoscopic display module provides 2D/3D compatibility without degrading display resolution and efficiency in switching mode.

In summary, an integrated polarized backlight using sub-wavelength grating exhibits very high potential to enhance the light utilization efficiency. Higher gain in the light utilization efficiency can be obtained in case of line width of sub-wavelength grating less than 0.1 μm. Nevertheless, reproducibility of narrow line-width and large sized writing area of sub-wavelength grating are the main concerns in fabrication. Nano-imprint accompanying with tiling approach might be a feasible solution to the concerned issues. However, continuous trials of fabrication recipes are unavoidable.

Another approach that can simplify the fabrication and remain the functionality of polarization recycling was therefore proposed by using a polarized backlight based on selective T.I.R at micro-grooves. However, this design still suffers from inadequate contrast ratio due to the occurrence of dust and bubble in the micro-machining process, thus, scattering the polarized light. These issues can be greatly improved by applying the embossing/extrusion technology to fabricate anisotropic foils with micro-grooves.

For directional backlights on time-multiplexed 3D applications, inadequate light efficiency and complex structures are the key issues to be solved. As a result, a novel directional backlight consist of dual, identical lightguides was proposed to improve the concerned issues.[1]

7.2 Future Works

We have successfully developed and demonstrated several illumination systems for various LCD applications. Nevertheless, some work will be continuously done to further improve the optical performance of the LCD illumination systems, even explore the new application fields for LCD illumination.

7.2.1 High Efficiency Color Sequential LCD Illumination Systems

In section **1.3**, we have discussed and concluded that the major energy consuming devices in LCD embodiment are polarizers and color filters. In the research work of this thesis, several feasible approaches were provided to leave out polarizers. Nevertheless, the system optical efficiency, which is greatly decreased due to the absorption of color filters, and the color saturation that limited by the spectra of color filter are the other serious issues for LCD applications.

A color sequential backlight, which utilizes sequentially switching color LEDs and fast response ferroelectric liquid crystal (FLC) panel, as illustrated in Fig. 7-1, can overcome the mentioned issues. Both of LEDs and FLC have micro-second response time, so that the flicker can not be resolved by human eyes while displaying the image. Additionally, since the backlight emits R, G and B light in time sequence by using color LEDs, the optical efficiency and color saturation can be increased due to absence of color filters.[2][3]

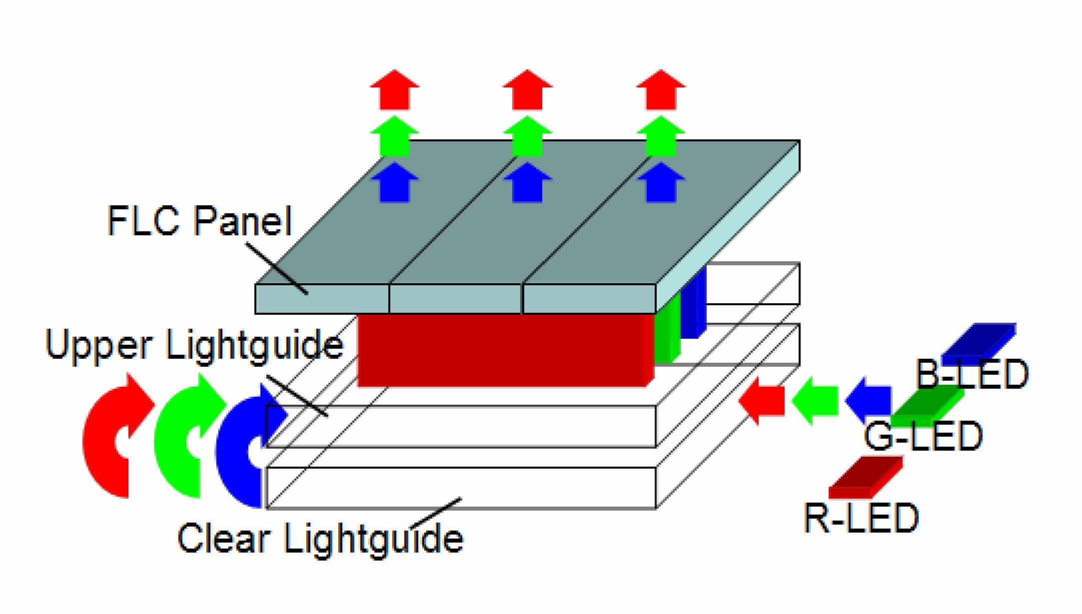

Fig. 7-1. Schematics of color sequential backlight with FLC panel.

Nevertheless, non-uniformity might be an important issue for color sequential backlights, especially in small sized applications. Unlike the Lambertian angular distribution of CCFL, confined emitted cones of LEDs usually cause non-uniformity at the edge of the backlight. One feasible solution to improve uniformity is to use a clear lightguide as a light mixing element. A uniform light distribution is obtained at the end surface of a clear lightguide due to T.I.R of light. Light propagates by several bounces of T.I.R and remains trapped in the lightguide until it is extracted at the end surface of lightguide. As a result, light is uniformly mixed. Then, a uniform light source is coupled into an upper lightguide which is placed above a clear lightguide. According to our design and fabrication abilities of LCD backlights, this high efficiency color sequential backlight shall be an appealing topic to explore in the future.

7.2.2 High Efficiency Tandem Illumination Systems for LCD-TVs

For LCD-TVs, the ability to be hanged on a wall or integrated with the furniture is very appealing. As a result, demand for large-sized LCD-TV is increasing at a rapid rate and grow significantly faster than expected. The present backlight solutions for large size LCD TV's are relying on direct lights using multiple CCFLs in reflective cavities. Nevertheless, the direct-lit configuration constrains the compactness, light efficiency and power consumption of backlight modules.[4][5] The reflective cavities that reflect the backward emitted light from CCFLs are utilized to obtain a uniform light distribution, yet, greatly increase the thickness of the backlight modules. Additionally, light from CCFLs is emitted in all directions. The lack of directionality of backlights usually degrades light efficiency and power consumption. Therefore, tandem lightguides shown in Fig. 7-2 shall be a feasible approach to solve these issues for LCD-TVs. By using edge-lit lightguides with multiple CCFLs in a tandem configuration, the thickness of backlight modules can be greatly reduced. Simultaneously, excellent uniformity and directionality of backlights are achieved. As a result, light efficiency can be much enhanced for less demanding on power consumption. Besides, the tandem configuration shall be applicable for LED backlights. Using side-emitted LEDs as the light source, color saturation of the display can be greatly increased.

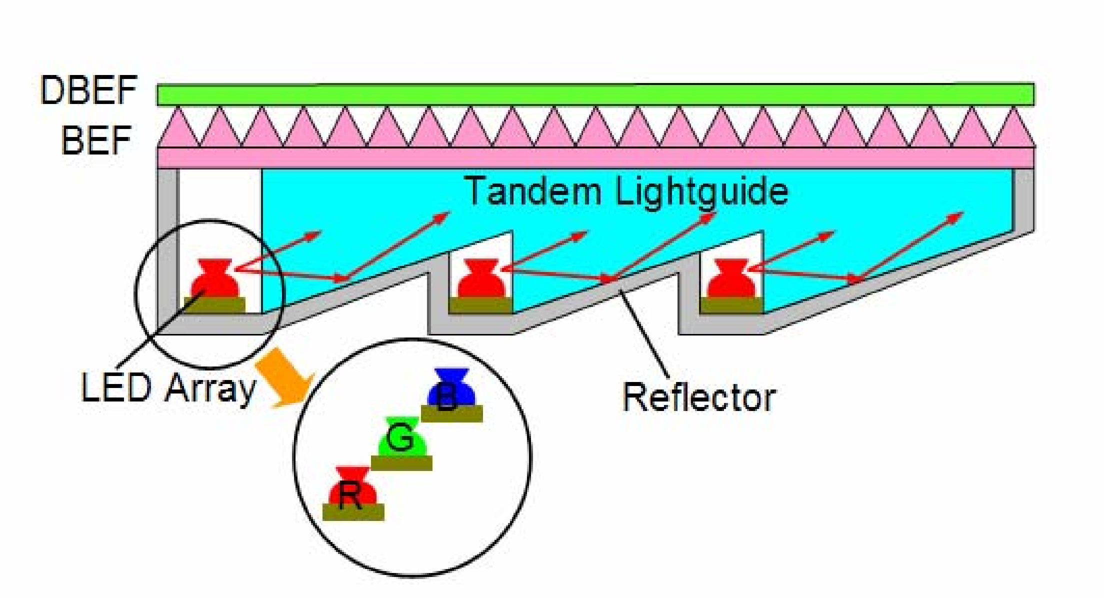

Fig. 7-2. Schematics of tandem lightguides for LCD-TVs.

7.3 References

[1] Y. M. Chiu, K. W. Chien and H. P. D. Shieh, Proc.of the International Display Manufacturing Conference (IDMC), p. 799 (2004).

[2] T. Yoshihara, T. Makino, S. Tadaki, H. Shiroto, Y. Kiyota, S. Kasahara, and K. Betsu, Society Information Display (SID) Digest, p. 1276 (2003).

[3] S. Kawamoto, M. Oh-kouch, S. Kundu, S. Kobayashi, H. Hasebe, and H. Takatsu, Society Information Display (SID) Digest, p.1160 (2004).

[4] L. Hitzschke, F. Vollkommer, and K. D. Bauer, Society Information Display (SID) Digest, p. 1322 (2004)

[5] G. Harbers, W. Timmers, and W. S. Smitt, Proc.of the International Display Manufacturing Conference (IDMC), p. 313 (2002).