Chapter 7

Conclusions and Future Works

7.1 Conclusions

Microoptics has emerged as a new branch of science during the past 10-20 years and is gradually making its way towards commercialization in a number of fields. Because of its capabilities of miniaturization and design flexibility, microoptics has become the key technology for building compact optoelectronic system.

Portable liquid crystal displays (LCDs), a kind of optoelectronic system, has the desired features of thin format, compact size, light weight, low power consumption, and sunlight readability. All these properties of portable LCDs can fulfill the requirements of the applications including the wireless internet, cellular phones, digital cameras, and vehicle displays, which are revolutionizing our society. With the developments of these various applications, portable LCDs have become one of the most important information displays technology nowadays.

In this thesis work, we successfully developed several key microoptical components for different portable LCD systems that bring more flexibility in system design. Simultaneously, the ray-tracing method was used to design and simulate the proposed optical system. The diffraction and geometric optics were utilized for optimizing the image performance, such as avoiding surface scattering, moiré pattern and color dispersion, etc. Additionally, from this thesis research, the microoptics fabrication process, such as VLSI process with plastic stamp molding, half-tone mask and thermal reflow technologies, were demonstrated for achieving better optical properties, higher fabrication accuracy and lower fabrication cost. Most of all, these microoptical components greatly improve the image performance of various portable LCD systems, thus, offering more appealing and competitive portable LCDs.

7.1.1 Light control films for improving reflective images

Reflective / transflective LCDs are being widely used in portable personal digital assistants and mobile communications. However, the reflective images of these portable LCDs still suffer from inadequate brightness and contrast ratio, thus the applications of portable LCDs are limited.

In order to improve these drawbacks, we developed multidirectional asymmetrical microlens array light control film (MAMA-LCF) and random grating light control film (RG-LCF) which are externally laminated on the front surface of reflective LCDs to change the reflected light distribution. The multidirectional asymmetrical microlens array LCF can focus the reflective light into a lower viewing angle yielding an ultra-high brightness image without affecting by glare. The use of MAMA-LCF effectively enhances the display brightness and contrast of reflective color-STN (1.5x MgO, CR~15), PDLC (2.8 x MgO, CR~23) and Ch-LCD (2.8 x MgO, CR~13) under ambient light condition. Random grating LCF can redirect the reflective light distribution in the effective viewing region, thus a wide viewing angle (0^{o}~25^{o}) with uniform brightness (0.8 x MgO), and paper white image can be achieved.

By using optimized design, the dispersion, moiré patterns, and surface scattering, that may be caused by the micro-components, are all invisible. Furthermore, the LCFs can be easily fabricated by semiconductor processes and injection/stamping molding. By using these well-developed fabrication processes, the designed microlens and grating structures on thin transparent plastic substrate (<100μm) can be produced economically and reproducibly in large volume.

7.1.2 Image-enhanced reflector for enhancing transmissive images

Transflective LCDs realized both the transmissive and reflective mode in one liquid crystal device become the most popular portable display technology. However, low optical efficiency, slow response time, and different color saturation are the main issues of conventional transflective LCDs.

Therefore, a single cell gap transflective LCD with biprism structure named "image-enhanced reflector (IER)" was proposed to make the backlight and ambient light follow the similar paths, yielding high transmissive light efficiency (close to double cell gap structure), high area utilization (~100%), matched color saturation (Both R and T has 19.1% NTSC ratio), and same response time (single cell gap structure) in both transmissive and reflective sub-pixels.

Moreover, IER structure can be further applied on cholesteric LCDs (Ch-LCDs), which has advantages in high brightness, memory effect, and low power consumption. Due to the IER structure allowing the paths of backlight similar to that of the ambient light, Ch-LCD displays same color images in both reflective and transmissive modes, and maintains good readability in any ambience. Additionally, by using high birefringence LC material ($\Delta n > 0.6$) with conventional color filter process, a full color transflective cholesteric LCD can be demonstrated.

In the fabrication, we utilized the half-tone mask technology to carry out the continuous profile IER structure with only one mask exposure. The designed IER structure with 14μm width and 1.8μm height, were precisely be generated with uniform surface after excimer laser micromachining. Therefore, the microoptical components with half-tone mask technology, which is a very reliable, convenient and cost-effective technology, were developed.

7.1.3 Micro-tube array for increasing backlight efficiency

The transflective LCD utilizes a transflective layer, which split each sub-pixel into T (transmissive) and R (reflective) portions, to display the image in any ambience. However, when the backlight system is utilized as the light source, the reflective region blocks most of the backlight for illuminating LCD's, thus much reducing the backlight utilization efficiency.

Micro-tube array (MTA) was then proposed for collecting the blocked backlight into the transmissive area to increase backlight utilization efficiency in a transflective LCD. The micro-tube structure is formed as a reversed funnel, which has larger aperture at the bottom but smaller aperture at the top. With high reflectance metal film coated on the side of micro-tube, the funnel shaped micro-tube array allows most the backlight enter from larger bottom aperture and exit from smaller top aperture so that backlight utilization efficiency can be increased substantially.

The measured backlight efficiency enhancement in different viewing angle was a factor of 1.65 to 2.3, and the averaged enhancement was a factor of 1.81. Moreover, the enhancement allows area ratio of the reflective region to the transmissive region to be re-defined for enhancing the image qualities, appealing for the mobile display market.

Furthermore, a typical TFT-LCD process with thermal reflow technique was utilized to fabricate the micro-tube array structure due to its convenient and cost-effective process. Consequently, this backlight efficiency enhanced micro-component, micro-tube array, can be easily integrated in the conventional display manufacturing procedure to effectively improve the image quality of portable LCDs.

In conclusion, this dissertation explores the applications of microoptical components and improves the performance of various portable liquid crystal display systems. The economical and compatible fabrication processes of microoptics are successfully developed. In this thesis research, we have demonstrated that the microoptical components have great potential to improve the performance of portable LCD systems resulting in more attractive displays for different applications.

7.2 Future works

The proposed microoptical components, light control film, image-enhanced reflector, and micro-tube array, successfully improve the image quality of portable LCDs. However, their applications may not only be limited on portable type LCDs. For example, light control film which can redirect the light distribution shall be applicable for backlight system to collect and uniformize the backlight. The biprism structure of image-enhanced reflector can be used as MVA technology[103] to wider the viewing angle of LCDs. Moreover, for increasing the backlight efficiency of conventional transmissive displays, micro-tube array is one of the suitable approaches to direct the blocked light, which are absorbed by the black matrix and TFT, into the useful transmissive region.

In this dissertation, although the high quality images are demonstrated, the color filter in the portable LCDs still absorbs about 60% incident light, thus much lower the output light efficiency. Therefore, a non-absorption color filter, which combined with color separation grating and deflection microlens or micro-prism, can be used to replace the conventional color filters, as shown in Fig. 7-1. By using developed half-tone mask technology and semiconductor process, the proposed hybrid microoptical component can be easily fabricated. In this novel color filter, grating separates three primary colors to three diffraction angles, and then the microlens or micro-prism collect the three primary colors to their respective sub-pixel. This novel microoptical component for portable LCDs can almost use the energy of entire visible spectrum to increase the light efficiency around a factor of 3 to further enhance the reflective brightness.

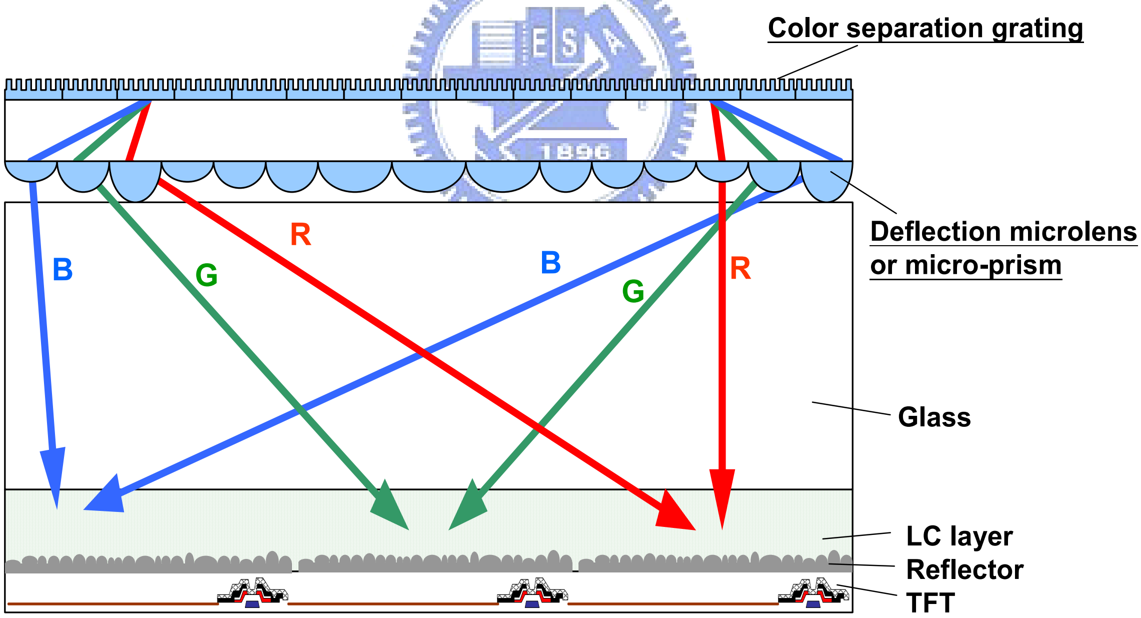


Fig. 7-1. Configuration of novel high efficiency color filter with hybrid microoptical components, color separation grating and deflection microlens.

Except the mentioned approaches, more advanced applications of microoptics, such as high efficiency microoptical layer for LCD-TVs and active microoptics for portable displays are described in the following sections.

7.2.1 High efficiency microoptical layer for LCD-TVs

Accounting for all the planned production of LCD-TV panels in 2004 gives an available supply of about 10 million or more TV panels for the year[104]. Demand for large-sized LCD-TV is increasing at a rapid rate and grow significantly faster than expected. One of the biggest challenges for LCD-TV manufacturers has been speeding up the response time to ensure that fast-moving objects don't exhibit "motion lag" or ghosting. Additionally, the system optical efficiency, which is greatly decreased due to the absorption of polarizer and color filter, and the color saturation that limited by the spectra of color filter are the other serious issues for LCD-TVs.

A color sequential LCD-TV[105], [106], which utilizes side-emitting color LEDs and fast response FLC panel, as illustrated in Fig. 7-2, can overcome the mentioned issues. Both of LEDs and FLC have micro-second response time thus can display moving pictures at high quality. 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. However, for applying to a large size panel, the LED emissive profile has to be "side-emitted". Consequently, a high efficiency microoptical layer that can effectively direct the side-emitted light into normal viewing direction with high uniform appearance will be one of the key components in this novel LCD-TV system. Additionally, polarization converted structure, such as sub-wavelength gratings[107], [108], shall also be developed on the microoptical layer to further enhance its optical efficiency. According to our design and fabrication abilities of microoptics, this high efficiency microoptical layer for large size LCD-TVs shall be among the interests to explore in the future.

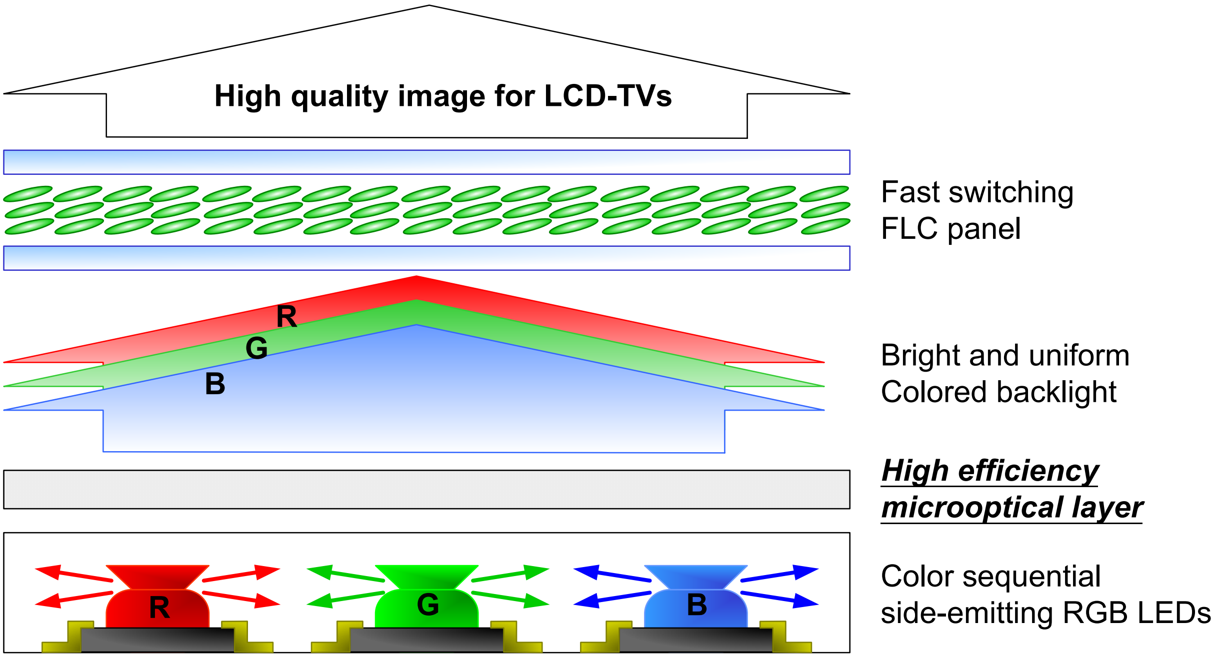


Fig. 7-2. Schematic plot of high quality color sequential LCD-TV structure.

7.2.2 Active microoptics for novel portable displays

Due to the improvements of microoptics fabrication technology, a passive microoptical component can be easily produced. Therefore, active microoptics for portable displays, which can eliminate the use of liquid crystal to yield much higher image performance, shall be developed.

Display is basically an ON/OFF switching device. We utilize passive microoptics on active ON/OFF LCDs for demonstrating high performance portable displays. However, the limitations of the image performance are still mainly depended on the properties of LCD itself, such as the requirement of polarizer reduces much brightness, and the orientation of LC director limits the viewing angles. Optical micro-electromechanical systems (MEMs) can easily provide ON/OFF device by using active microoptical components without operating any LC material. Interferometric modulator, or iMoDs™[109], is one of the most successful optical

MEMs display. The iMoD element is a simple active optical device that is composed of two conductive plates. One is a thin film stack on a glass substrate, the other is a metallic membrane suspended over it. There is a gap between the two that is filled with air, as illustrated in Fig. 7-3. iMoDs^{TM} uses interference to create color as the microscopic structures on butterfly wings that cause light to interfere with itself, creating the shimmering iridescent colors, as shown in Fig. 7-4

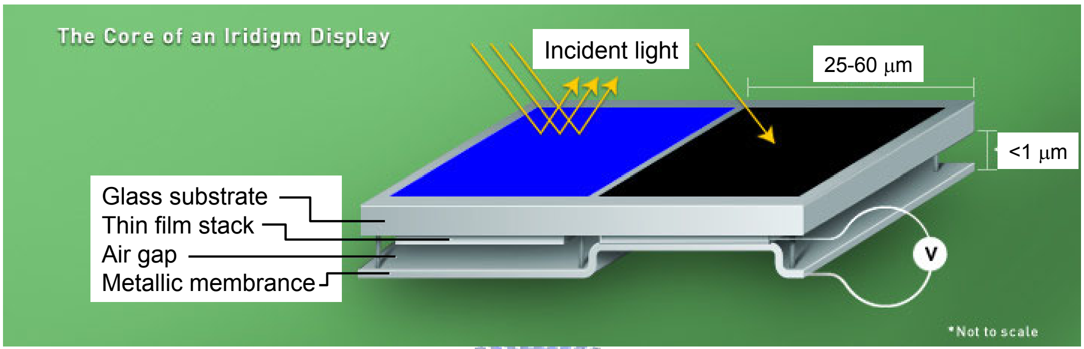


Fig. 7-3. The basic optical configuration of an active microoptical display, iMoD^{TM}.

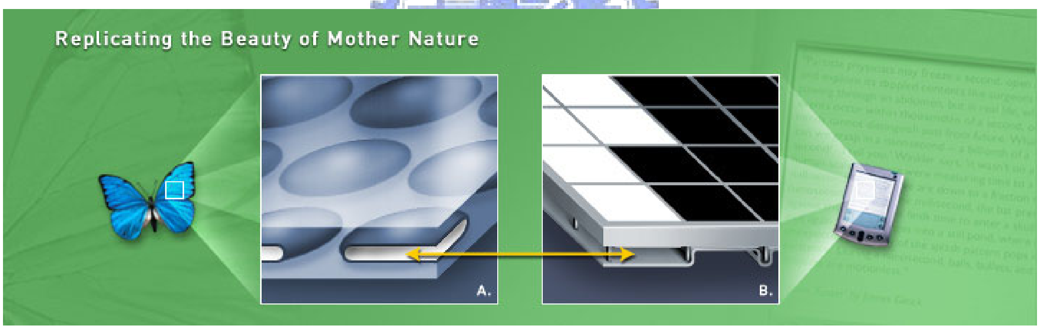
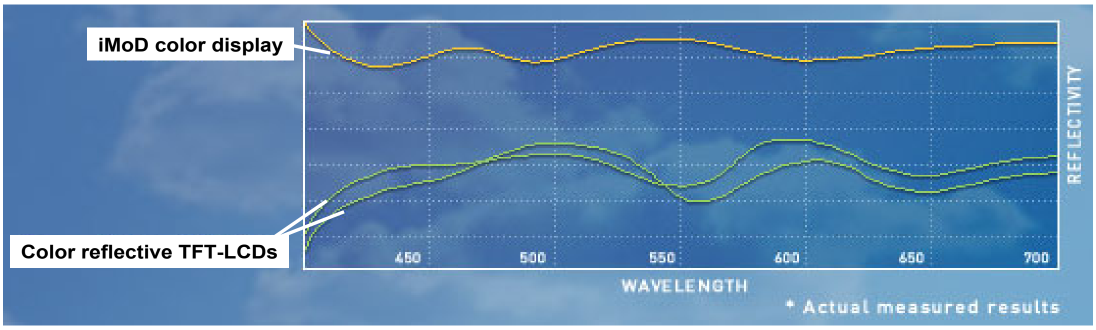
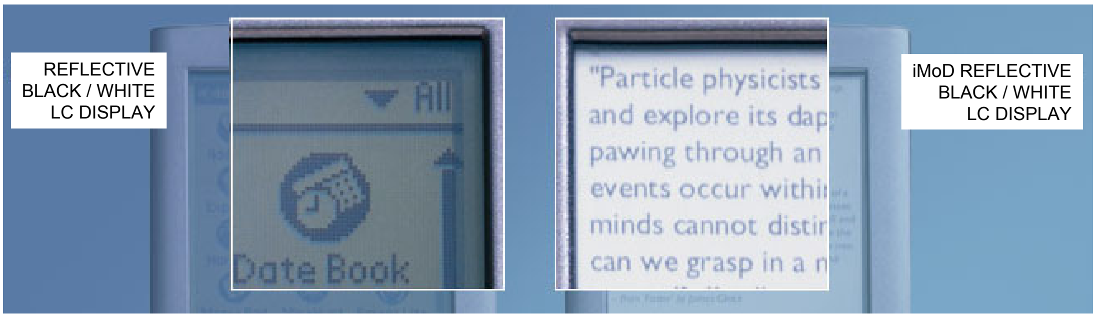


Fig. 7-4. The interference of light for displaying color images.

The simple active microoptical structure provide the functions on ON/OFF modulation, color selection, and memory, while eliminating components such as active matrices, color filters and polarizers. The optical performance of this active microoptical display is superior to commercially reflective LCDs, especially on reflectance and viewing angle. It has approximately twice reflectance than conventional R-LCDs, as shown in Figs. 7-5(a) and (b), with in ±60^{o} viewing angle.



(a)



(b)

Fig. 7-5. (a) Measured reflectance of color reflective displays, and (b) demo photos of B/W reflective displays.

Consequently, active microoptics enables a whole new generation of flat panel displays for portable applications. Based on our fabrication abilities, such as VLSI and TFT-LCD techniques, not only iMoD^{TM} structure but also more optical MEMs approaches may able to be proposed and developed for revolutionizing the mobile display technology.

The great potentials of microopitcal components are gradually shown in the display applications. This optical technology provides a lot of improvements in display systems, and allows the display to be more and more appealing and attractive in various applications. As display devices become indispensable to human beings, more and more novel applications of display show up daily, so do the applications of microoptical components as new design concepts and fabrication technologies emerged, the applications of microoptics are full of immense possibilities. Therefore, the designers and scientists cannot only handily improve performance of display systems, but also easily invent new display systems for vast amount of information communication in these multi-media and Internet era.