Chapter 1

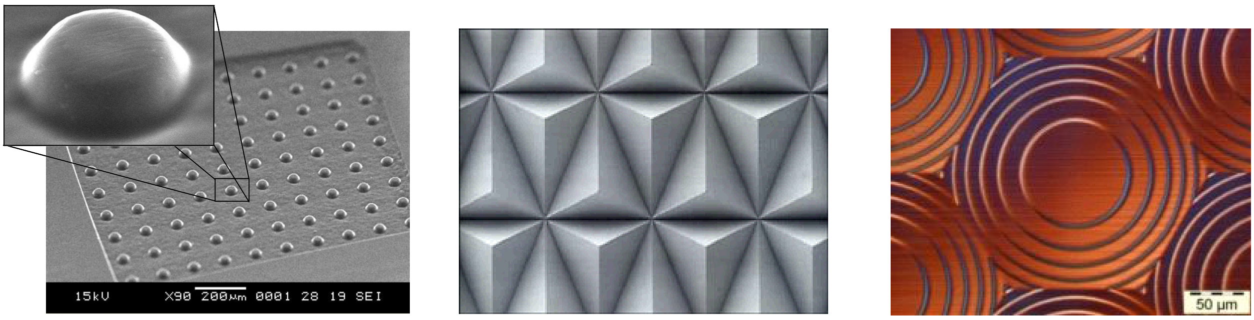
Introduction

Microoptics[1], [2], enabling the collection, distribution, or modification of light, is an effective method to shape and influence light with very small structures and components. Liquid-crystal displays (LCDs)[3], [4] are light-controlling devices, which rely on the optical properties of liquid-crystal materials to control the output light from an external source. Among LCDs, reflective/transflective types become popular technologies for mobile and low-power applications under ambient illumination. Microoptics is a key technology to further improve the performance, minimize the size, and reduce the cost to meet the applications of portable LCDs.

1.1 Microoptics

Traditional passive optical components are used in optical systems to collect, redistribute, or modify optical radiation. Refractive and reflective components, such as lens, prism and mirrors are well-known and already have been used for centuries. As the development of microelectronic and miniaturization of components for compact and light-weight systems, various novel technologies have been developed to shrink the size of optical components.

Concurrently, micro-refractive optical components, such as microlens(Fig. 1-1(a)) and microprism(Fig. 1-1(b)) with diameter of 1mm to a few microns, can now be fabricated with high quality, using techniques such as graded-index[5], [6], [7], [8], photothermal[9], [10], thermal reflow[11], [12], and photoresist 'sculpture' [13], [14]. In parallel, diffractive-optics has emerged from holography with the assistance of computer generated holography and precise tooling technologies. Typical diffractive optical elements (DOEs), as shown in Fig. 1-1(c), have multilevel microreliefs (‘binary optics’) or continuous relief and amplitudes of a few microns. Following the development of VLSI fabrication methods and the associated tooling technologies, various fabrication methods, such as VLSI Lithography / patterning / etching techniques, laser writing, and plastic modeling, etc. have been developed to fabricate the DOEs for practical applications. Through the rapid development of design and fabrication technologies mentioned above, novel microoptical structures can be realized to complement and exceed the applicability of the traditional lenses, prisms, and mirrors. Almost any structure and shape, including asymmetric sphere, can be manufactured, providing high degree of flexibility for design. Moreover, DOEs are in the form of planar structure, resulting in more versatile applications and system integration.



(a) (b) (c)

Fig. 1-1. Microoptical Components: (a) microlens, (b) microprisms, and (b) DOEs.

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. It is a key technology to meet the needs of miniaturization, cost reduction, and improved performance. Microoptics is also a quintessential enabling technology for various electrooptical systems, as shown in Fig. 1-2, which has become the important technique for building compact optoelectronic system. Especially in electronic display systems, microoptical components also contribute various novel devices that bring more flexibility in system design to increase the overall performance, thus, offering more appealing display devices.

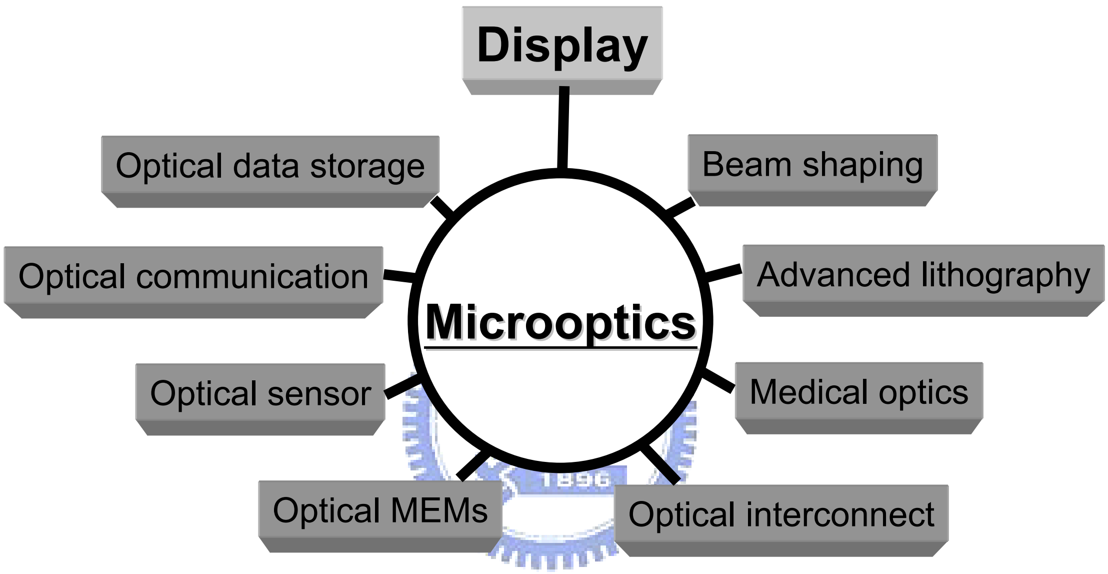


Fig. 1-2. The applicable applications of Microoptics [15].

1.2 Liquid-crystal displays (LCDs)

Since the last decade of the 20th century, display technology has been progressing rapidly. With the popularization of computer, internet and wireless communication, multimedia application display devices and tremendous information interchange become parts of our live, and the demand of technologies of displaying mass information in pictures and contents becomes imperative. Liquid crystal display

(LCD) is the most successful display device due to it has the desired features of thin format, compact size, light weight, and high image quality. All these desired properties of LCD can fulfill the requirements of the applications including desktop monitor, notebook, television, digital camera, portable information apparatuses, etc. With the developments of these various applications, LCDs have become the most important information displays nowadays.

LCD does not emit light itself; therefore, a “transmissive type” color liquid crystal display was demonstrated by Sharp Corporation in 1989 [16]. As implied by the name, transmissive LCD equipped with an illuminator called a backlight system disposed at the rear surface thereof. Thus, the amount of light from the backlight which “transmits” through the liquid crystal panel is controlled by the liquid crystal panel in order to realize images, as shown in Fig. 1-3.

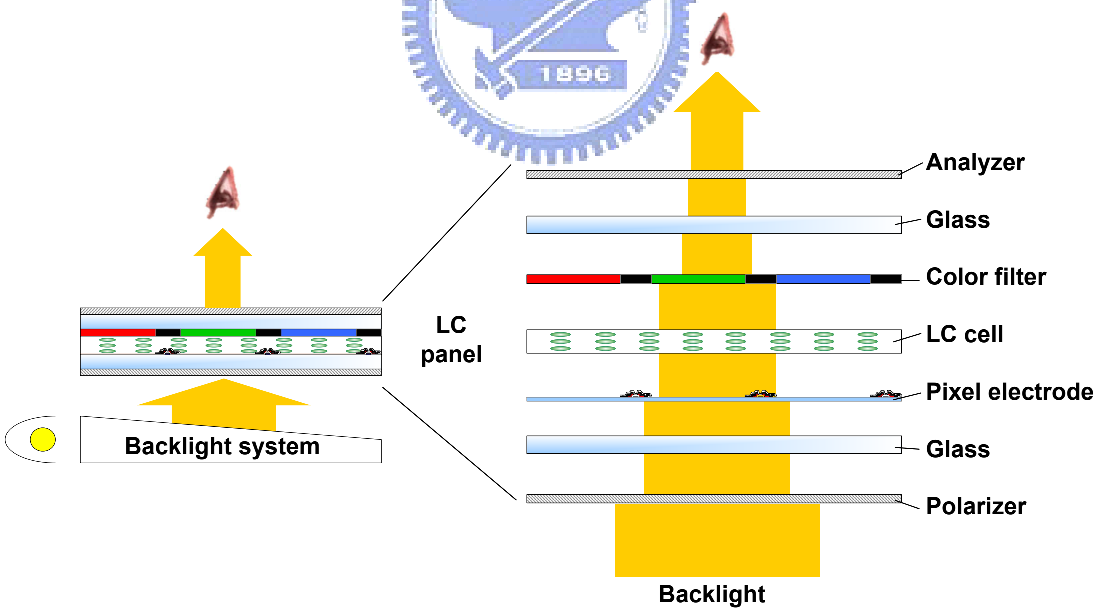


Fig. 1-3. A transmissive type LC display with backlight system and the light transmittance after light passes through each component of the LCD.

The transmissive type LCDs are advantageous in thinness, brightness, high contrast ratio and good color saturation. However, the requirement of backlight results in high power consumption. Besides, the devices in the LCD embodiment including polarizer, pixel electrode, LC cell, color filter, and analyzer will absorb or block the backlight. Therefore, a typical transmissive LCD device has transmittance of about only 8%, as shown in Fig. 1-3, transmittance after light passes through each device of the display. For yielding adequate brightness with low transmittance, the driving voltage of backlight system has to be increased, thus results in much higher power consumption. Moreover, the transmissive LCD becomes too difficult to observe while they are used under bright ambience, which is so called "wash-out" phenomenon. For example, in direct sunlight, the intensity of the surface reflection is much stronger than that of the backlight; thus the images are wash-out, as the photo shown in Fig. 1-4. Therefore, transmissive LCDs, which require high power consumption and cannot be readable at outdoor environment, are only limited for desktop monitor or TV applications.

Fig. 1-4. Demo photos of a transmissive type LCD at the indoor and outdoor environment.

1.3 Portable LCDs - Reflective/transflective LCDs

The wireless internet, cellular phones, digital cameras, digital camcorders, and vehicle displays are revolutionizing our society, leading to demand for multimedia connectivity wherever we go. These portable devices require low power consumption and sunlight readability, where of transmissive type LCDs cannot achieve easily. Consequently, reflective and transflective LCDs were proposed for mobile applications[17].

1.3.1 Reflective LCDs

In order to solve the problems in the transmissive type LCDs, a "reflective" type color LCD was proposed by T. Uchida in 1995[18]. The reflective type LCDs are provided with a reflector formed on one of pair of substrate in place of backlight, so that the ambient light is reflected to show the images, thereby obtaining display light proportional to an amount of ambient light, as illustrated in Fig. 1-5. Thus, reflective type LCDs will not wash out under bright environment and the images can be observed distinctly. Further, the reflective LCD is advantageous of light weight and low power consumption due to the elimination of the backlight. For the above reasons, the reflective LCDs are particularly suitable as the devices for the mobile devices.

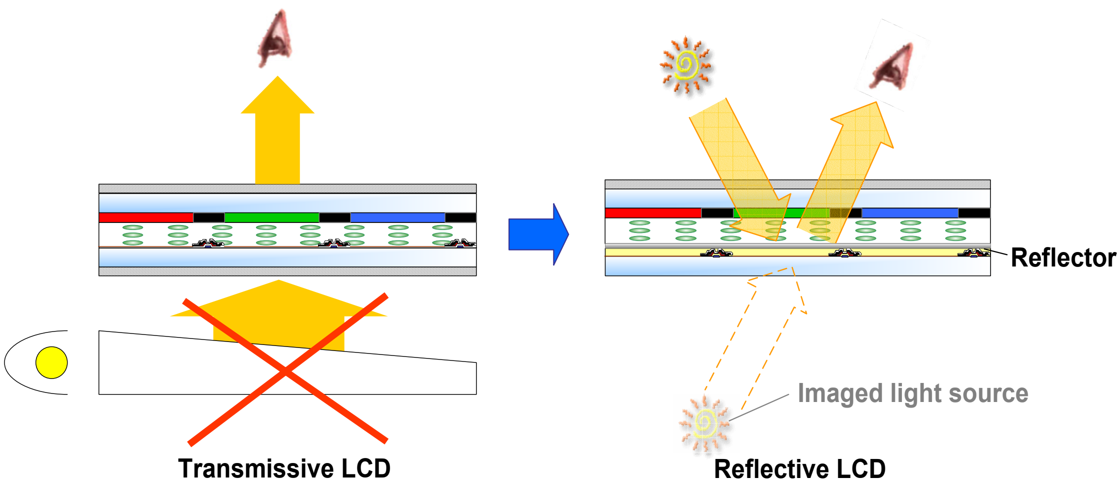


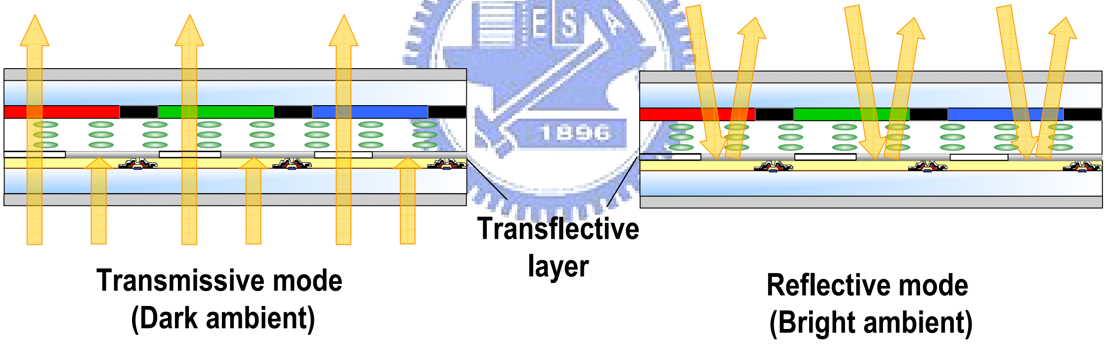
Fig. 1-5. Schematic plot of a reflective type LCD using ambient light as the light source to display the image.

Due to the rapid growth of portable display market, several reflective LCD technologies have been actively pursued, including mixed-mode twisted nematic LCDs (MTN-LCDs), super-twisted nematic LCDs (STN-LCDs), polymer dispersed liquid crystal (PDLC), and cholesteric LCDs (Ch-LCDs), etc. Each technology has its own applications, such as MTN-LCDs for personal digital assistants (PDAs), STN-LCDs for cellular phones, PDLC for smart cards, and Ch-LCD for e-books. In these applications, low power consumption, high brightness, high contrast ratio, and low cost are critical. However, most of the reflective LCDs still suffer from inadequate brightness and contrast ratio (CR). Additionally, the reflective LCDs use the ambient light for images, the display luminance particularly depends on the surrounding environment, and it always loses its visibility in dark ambient.

1.3.2 Transflective LCDs

When the ambient light is dim, the reflective LCD is not readable if no built-in light is available. To overcome this problem, a configuration which realizes both the transmissive and reflective mode display in one liquid crystal device has been disclosed by Sharp Corporation in 1998[19] and named “transflective” type LCDs, as shown in Fig. 1-6. 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. In a bright ambience, the incident light on the T sub-pixel is absorbed by the lower polarizer and the device works as a reflective display. In a dark ambient, the backlight transmits the T sub-pixels and the device works as a transmissive display.

However, the liquid crystal cell gap for R and T portions are the same. While the cell gap is optimized for R portions, as a result, the light transmittance for the T mode is lower than 50% due to the transmissive light only propagating the LC layer once in T portion, and resulting in different optical path difference compared with the ambient light. Besides, a challenge of such a transflective display is the issue of matched color saturation between the R and T images. For R mode, the light transverses the color filters twice. However, the light transmits color filters only once in the T mode. To have the same color saturation, the color filters in the T portions should have double pigment concentration as compared to those of the R portions, however, it increases the fabrication complexity. Moreover, the backlight system is utilized as the light source in the dark environment, the reflective region can be regarded as a block that backlight cannot pass through, thus reducing backlight utilization efficiency.



(a) (b)

Fig. 1-6. A device configuration of a transflective LCD. (a) transmissive mode using in dark ambient, and (b) reflective mode using in bright ambient.

1.4 Microoptics in portable LCDs

The reflective and transflective LCDs have been widely used on portable devices. However, low brightness and poor contrast ration are the two major issues for reflective LCDs, and inadequate transmittance and unmatched color saturation are the disadvantages for transflective ones. Therefore, microoptical components, which meet the needs of miniaturization and performance improvement, bring various novel optical designs to enhance the image quality for portable LCDs.

1.4.1 Microoptics in reflective LCDs

Conventional reflective LCDs with metallic reflectors reflect modulated light for viewing. Under oblique illumination, the specular reflection of planar reflector reflects the oblique incident light to its corresponding reflection angle. Consequently, the viewers cannot perceive the brightest image near the normal direction, a typical viewing region for common viewers, as shown in Fig. 1-7. Moreover, the brightest reflected image is at the glare angle where surface reflection from the front glass interferes with image, thus, degrades the contrast.

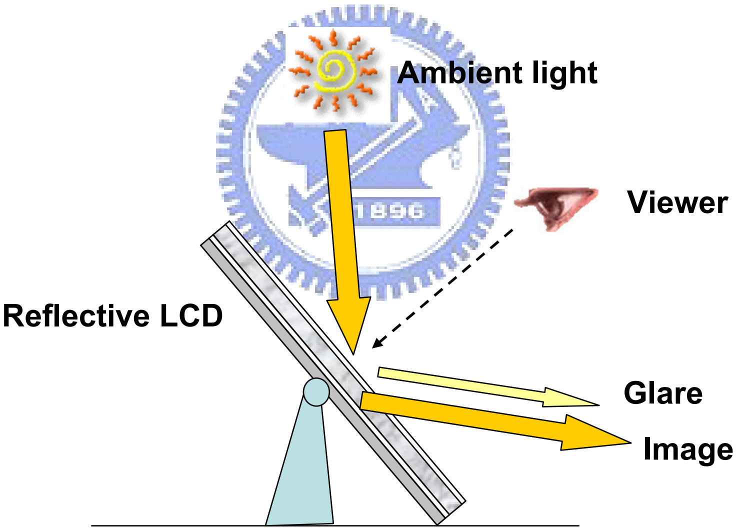


Fig. 1-7. Typical office illumination and the reflected light distribution of reflective LCDs.

Many methods have been reported for improving the brightness and contrast ratio of reflective LCDs. The two successful methods of microoptics in reflective LCDs are rough surface reflector[20] and micro-slant reflector (MSR)[21]. Rough surface reflector as depicted in Fig. 1-8, implemented on the inner side of the rear substrate can scattered the reflective light into wider viewing region. Therefore, the observer can see a brighter image in the normal direction. Additionally, the TFT structures are hidden beneath the reflector. Thus, the aperture ratio is greater than 90%, and can further increase the brightness. The micro-slant reflector, as shown in Fig. 1-9, is formed as an asymmetrical slant reflector, which can shift the peak of the reflected light away from specular direction by ~12°. Therefore, a contrast ratio in the range 20~30:1 has been achieved[21]. Due to the optical gain, the reflectance normal to the surface is about 0.4X over the MgO standard white, which is around 4 times brighter than a LC cell with a mirror reflector.

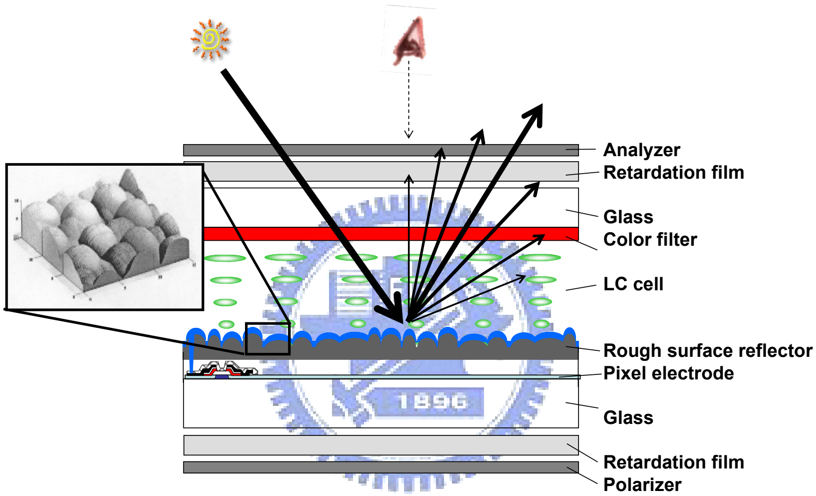


Fig. 1-8. Optical configuration of a reflective LCD with the rough surface reflector[20].

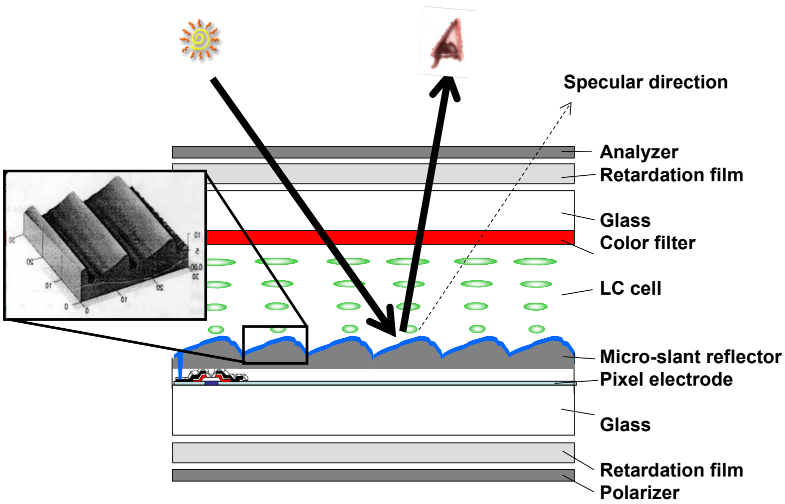


Fig. 1-9. Optical configuration of a reflective LCD with the micro-slant reflector[21].

1.4.2 Microoptics in transflective LCDs

The transflective LCDs with same cell gap for transmissive and reflective portion have the issue of low transmission efficiency. To overcome the issue, Sharp Corporation proposed a new micro-structure named double-cell gap structure[22], [23] in August, 2000, where the cell gaps for R and T sub-pixels are d and 2d, respectively, as shown in Fig. 1-10. As the liquid crystal in R region fulfills a λ/4 condition, those of the liquid crystal in T region fulfills a λ/2 condition due to its double thickness. Therefore, employing a λ/4 retardation film between the polarizer and liquid crystal, the optical path difference in both R and T regions are the same. As a result, both R and T sub-pixels have high light efficiency.

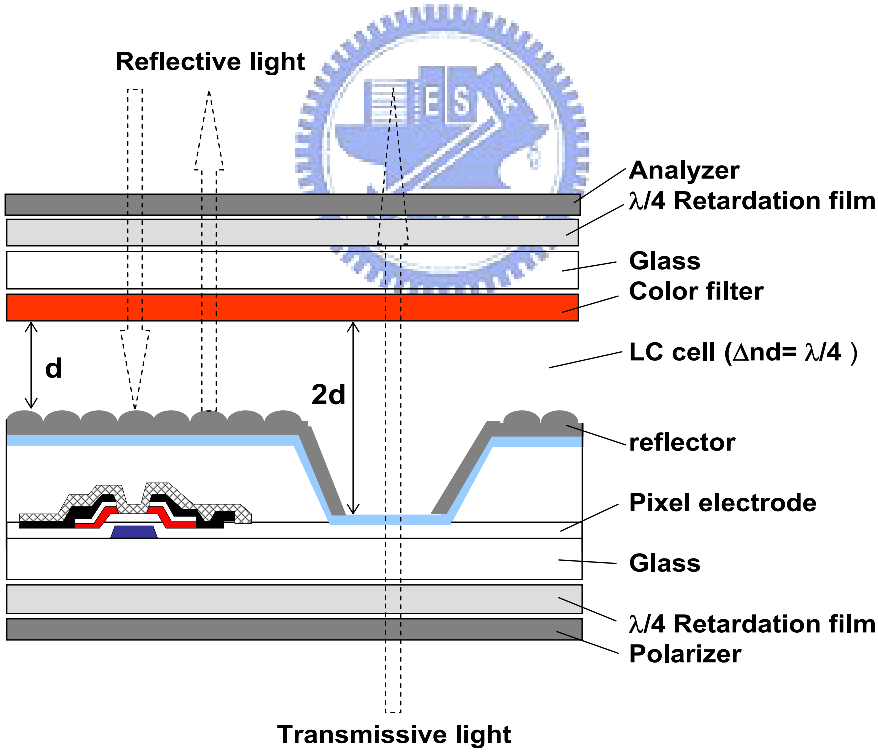


Fig. 1-10. Optical configuration of a transflective LCD with double-cell gap micro-structure to increase the transmissive light efficiency[22], [23].

1.5 Motivation and objective of this thesis

New generation mobile communication and personal information systems, such as mobile phone, hand-held personal computer (HPC), digital camera, and game-boy player have progressed rapidly. Low-power bright full-color displays are essential for above applications. Reflective and transflective LCDs are of advantageous of those requirements. However, these portable LCDs still exist several issues needed to be improved.

In this thesis research, three novel microoptical components, light control film, image-enhanced reflector, and micro-tube array, were designed to further improve the main issues of conventional portable LCDs for yielding high image quality. The theories of the microoptical devices were studied and developed for optimizing their optical performance. Additionally, the economical fabrication technologies, such as semiconductor process with stamp molding and half-tone mask technology, were developed and utilized to reduce the steps of the process and lower the cost.

Several microoptics in portable LCDs reported can provide the reflective image with higher brightness and better contrast[20], [21]. However, the microstructure, such as rough surface and micro-slant reflector require very complex fabrication process which may result in a very high cost. Therefore, we proposed a low-cost film named “light control film (LCF)” which can be easily laminated onto the top surface of reflective LCDs to collect and re-direct the incident light from multi-direction for much enhanced brightness, contrast ratio, viewing angle, and uniformity. The LCFs can be either constructed with multidirectional asymmetrical microlens array or random gratings. In our design, the Moiré pattern, color dispersion, surface scattering effects were considered and been successfully avoided. Moreover, LCFs are easily fabricated by standard semiconductor processes on Si wafers used as stampers. The structure is then duplicated on a thin transparent plastic film by injection/stamping molding. By using these well-developed fabrication processes, the designed structure can be produced economically and reproducibly in large volume, and is an effective means of enhancing the image quality of portable LCDs.

In transflective LCDs, the double cell gap micro-structure increases the transmissive light efficiency. However, due to the different cell gap thickness of reflective (R) and transmissive (T) portion, the R and T images have different response time, and the light leakage at the edge of R and T portion reduces the contrast ratio. Additionally, the issue of unmatched color saturation still exists. Consequently, an "image enhanced Reflector (IER)" was proposed. It is built upon the transmissive region of a single cell gap transflective LCD to guide the backlight to follow the similar paths of reflective light. Consequently, the R and T image of this novel transflective LCD can yield high optical efficiency, same response time, and matched color saturation. Additionally, a very reliable, convenient and cost-effective technology, half-tone mask technology which can form microoptical elements with continuous profile and high optical performance by using only one mask, was developed and used to fabricate the IER structure.

The image enhanced reflector (IER) can be applied for not only general transflective TFT-LCDs but also for cholesteric LCDs. Conventional reflective cholesteric liquid crystal display (Ch-LCD) is a strong contender for e-papers and e-books, yet it only can be operated on reflective mode under bright ambience. To enable a display to be useable from dark to bright sunlight conditions, transflective display is a good option. However, the conventional transflective approach cannot be applied to the cholesteric displays. We demonstrated a transflective Ch-LCD by placing an image-enhanced reflector above the transmissive part to reflect the backlight into the reflection pixels. This IER design functions equally well for both monochrome and full color cholesteric displays. Due to the similar paths of transmissive and reflective light, the same bright state for both reflective and transmissive channels can be obtained. Thus, the Ch-LCD maintains same color image with good readability in any ambience.

The LCFs and IER can much enhance the reflective and transmissive image in portable LCDs. However, in conventional transflective LCDs the reflective area is regarded as a block that backlight cannot pass through, thus much degrades the backlight utilization efficiency. Consequently, "micro-tube array (MTA)" was proposed to collect the backlight into the transmissive area to increase the backlight utilization efficiency. The micro-tube structure is similar to a reversed funnel for allowing most backlight enter the tube from larger bottom aperture and be collected to smaller upper aperture so that light efficiency of the backlight can be increased substantially. As a result, area ratio of the reflective region to the transmissive region can be redistributed for optimizing the image quality. On the other hand, the backlight system with a lower power can be utilized to achieve the same illumination as conventional transflective LCDs. Therefore, a novel portable LCD which utilizes LCF and IER to enhance the reflective and transmissive image, and MTA to increase the backlight efficiency, is demonstrated and become more attractive and competitive in the portable display applications.

1.6 Organization of this thesis

The thesis is organized as following: The theories of microoptics and portable LCDs are presented in **Chapter 2.** Basic diffractive optical component designs, such as Fresnel microlens, and grating, are described in this chapter. Additionally, this chapter also represents the working principle of various portable LCDs, such as MTN-LCDs, STN-LCDs, PDLC, and Ch-LCDs. In **Chapter 3,** the fabrication technologies of microoptics are summarized, and the major instruments used to characterize the microoptical components and the performance of display system are described. Using light control film for enhancing the reflective image quality are demonstrated in **Chapter 4.** In this chapter, the optical design for avoiding color dispersion, moiré pattern, and surface scattering are also described. To suppress the issues of conventional transflective LCDs, image enhanced reflector, which can yield high light efficiency, same response time, and matched color saturation for transflective LCDs, is shown in **Chapter 5.** Moreover, with image enhanced reflector, a full color transflective cholesteric LCD, which is the first Ch-LCD in the world displaying similar image quality for transmissive and reflective mode, is also presented in **Chapter 5**. In **Chapter 6**, micro-tube array for increasing the backlight utilization efficiency in transflective LCDs to further improve the image quality is presented. Finally, discussions and summary of this dissertation, and recommendations for the future works are given in **Chapter 7**.