國立交通大學

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碩士論文

設計與製作具寬頻譜反射之反射式膽固醇液晶顯示器

Design and Fabrication of Wide Band Reflection Reflective Cholesteric LCD

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中華民國九十四年六月

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國立交通大學 電機資訊學院
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摘要

當網路和電腦相關的產業持續成長時，電子資訊顯示產業成為一個廣大的市場。高亮度、高可閱讀性、廣視角、低功率消耗和高色彩飽和度是顯示器的主要考量因素。反射式液晶顯示器使用外在環境光當作光源，不需要使用背光模組。因此，低功率消耗和輕巧是反射式液晶顯示器的主要優點。在許多種類的反射式液晶顯示器當中，雙穩態反射式膽固醇液晶顯示器由於具有低功率消耗、低製造成本和不錯的可閱讀性等優點，近來受到很多的注意。反射式膽固醇液晶顯示器適合低製造成本、高解析度、較長的閱讀時間和較小的功率消耗等應用。

然而，由於膽固醇液晶材料的限制，反射頻譜通常只有窄頻譜的反射，所以此顯示器通常只能呈現單一色彩的影像。單一色彩的影像通常不能滿足使用者的需求。黑白顯示器通常才是使用者所希望看到的。為了解決膽固醇液晶顯示器窄頻譜反射的問題，我們提出一個叫做“全頻譜反射”的方法來改善這個問題。這個方法的特性是用膽固醇液晶和下板反射板的兩個反射頻譜疊加在一起來加大整個膽固醇液晶顯示器的反射頻譜。寬頻譜的反射可以呈現白色的影像而不是只有單色的影像。此外，這個方法的暗態是利用膽固醇液晶在圓錐狀態的散射效應

和偏光板的濾光作用來產生。因此，黑白反射式膽固醇液晶顯示器可以被實現出來，將來便能藉此製作出彩色的顯示效果。

我們藉由液晶模擬軟體“DIMOS”建立一套模擬模型來分析此反射式膽固醇液晶顯示器的特性。我們使用反射綠光、紫外光、紅外光波段膽固醇液晶材料來最佳化此顯示器的光學特性。從模擬的結果得知，使用反射紫外光波段的膽固醇液晶顯示器可以具有寬頻譜的反射而成為黑白的顯示器。

根據模擬的結果，我們使用傳統液晶顯示器的製程來製造膽固醇液晶顯示器的樣品。我們使用四種不同的配向條件和三種不同的膽固醇液晶材料來找出最佳性能的樣品。

最後，我們使用“ConoScope”來測量製造的膽固醇液晶顯示器的光學性質，例如：反射頻譜、反射率、對比和視角分佈。從量測的結果得知，使用“全頻譜反射”方法的膽固醇液晶顯示器可以達到寬頻譜反射的特性來實現黑白的顯示器。因此，使用這個方法大大提升膽固醇液晶顯示器的影像品質。使得膽固醇液晶顯示器對使用者具有較佳的可閱讀性。具有低功率消耗、低製造成本、好的影像品質、大的視角分佈等優點的黑白反射式膽固醇液晶顯示器能被實現，並適合於電子書或是電子紙張的應用。

Design and Fabrication of Wide Band Reflection Reflective Cholesteric LCD

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Abstract

As the Internet and the computer related industries growth continues, the electronic information display is a large market. High brightness, high readability, wide viewing angle, low power consumption and high color saturation are the main concerns. Reflective LCDs utilize ambient light as the light source, thus they do not need backlight modules. Low power consumption and light weight are main advantages of reflective LCDs. Among all reflective LCDs, bistable reflective cholesteric LCDs (Ch-LCDs) have received much attention recently because of their advantages of lower power consumption, low cost, and good readability. This kind of display is ideally applicable for those required low cost, high resolution, and long using time with low power consumption.

However, due to the limitation of cholesteric LC materials, the reflective spectrum is narrow band. Therefore, the display is usually monochromic appearance, which often can not satisfy the user’s requirement. Black and white displays are the least desired for viewers. In order to solve the problem of narrow band reflection, a new method “Full Spectrum Reflective Method” is proposed. The characteristic of this method is to use two reflective spectra: one is the spectrum of cholesteric LC, the other is the spectrum of reflector compensating each other to broaden the spectrum of the display. Wide band reflection can display white images instead of monochromic images. Besides, the dark state is created by cholesteric’s scattering effect in focal conic state and polarizer’s filtration effect. Therefore, black and white reflective cholesteric LCD can be demonstrated. Furthermore, the full color mode can be realized.

By LCD simulation software “DIMOS”, we established a simulation model used to characterize the features of the reflective Ch-LCDs. We utilized green band, UV band, and infrared band Ch-LC materials to optimize the optical properties of Ch-LCDs. From the simulation results, Ch-LCD with UV band Ch-LC can be wide band reflection, thus, enabling a black and white display.

Based on the simulation results, we fabricated Ch-LCD test cells with conventional LCD fabrication process. We utilized four rubbing conditions and three different Ch-LC materials to find out the best performance of test cells.

Finally, we used “ConoScope” to measure the optical properties of fabricated Ch-LCDs, such as reflective spectra, reflectance, contrast ratio, and viewing angle. From the measured results, Ch-LCDs with full spectrum reflective method can obtain wide band reflection property to realize black and white displays. Therefore, this method improves the image quality of Ch-LCDs greatly. The displays have better readability. With the advantages of low power consumption, low cost, good image quality, and wide viewing angle, the reflective Ch-LCDs are suitable for electronic books (E-Books) or electronic papers (E-Papers) applications.

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這本論文的完成，對我而言，可說是研究過程中辛苦的結晶。首先，最感謝指導教授 謝漢萍教授兩年來細心的指導，提供良好的學習環境讓我能專心投入研究工作，此外，老師在語言能力上的要求，也讓我努力去加強，在做人處事上也都有明顯的進步，並且學到很多寶貴的技術和經驗。

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Chapter 1

Introduction

1.1 Display Technology

Since the last decade of the 20th century, display technology has been progressing rapidly. With the popularization of internet, computer and wireless communication, multimedia application display devices and mass information interchange become parts of our live, and the demand of technologies of display mass information in contents and pictures are getting more imperative. Electronic displays are key element for information display. As an interface between viewer and information devices, electronic displays are demanded to have sufficient information contents and be operated in various properties, such as high brightness, high contrast ratio, wide viewing angle, high resolution, fast response, and portability, etc. To satisfy the different demands, diverse display technologies have been demonstrated in the past years, such as cathode ray tubes (CRTs), liquid crystal displays (LCDs), plasma display panels (PDPs), field emission displays (FEDs), and organic light emitting diode (OLED) displays[1]. Among these display technologies, liquid crystal display (LCD) is the most successful display device due to the desired features of compact size, light weight, thin format, and high image quality.

1.2 Liquid Crystal Displays (LCDs)

LCD can fulfill the requirements of the applications including notebook, desktop monitor, digital camera, television, etc. With the developments of various applications, LCDs have become the most important information displays nowadays.

LCD does not emit light by itself, therefore, a “transmissive type” liquid crystal display was demonstrated by Sharp Corporation in 1989[2]. Transmissive LCD equipped with a backlight system which is disposed at the rear surface. Therefore, the amount of the light from the backlight which transmits through the liquid crystal panel is controlled by the liquid crystal in order to display images. The components of the display compose of backlight, polarizer, circuit plate, liquid crystal, and color filter, as shown in Fig. 1-1.

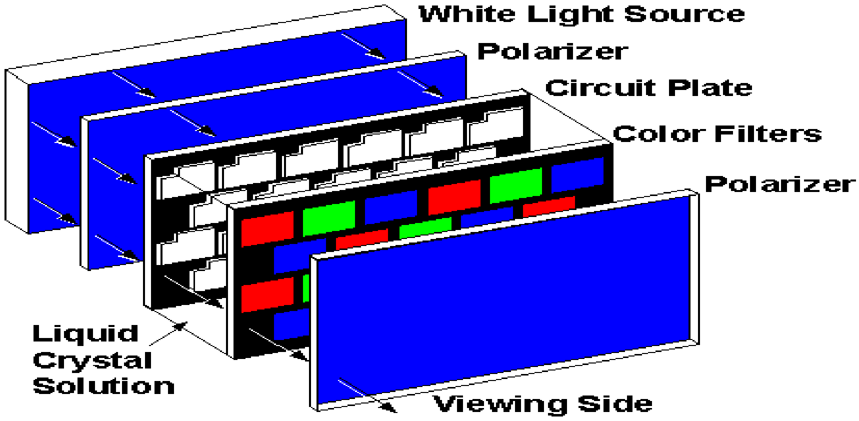


Fig. 1-1. Transmissive type LCD.

The transmissive type LCDs have advantages of high brightness, high contrast ratio, and high color saturation. However, the requirement of backlight results in high power consumption. Besides, the components of the LCD including polarizer, pixel electrode, LC cell, color filter, and analyzer will absorb the backlight. Therefore, the transmittance of a typical transmissive LCD is about 8%. For obtaining adequate brightness with low transmittance, the driving current of the backlight has to be increased, thus results in higher power consumption. In addition, transmissive type LCDs are difficult to observe under bright circumstance, which is so called “wash-out” phenomenon. Therefore, transmissive type LCDs are suited for desktop monitors instead of portable displays.

1.3 Portable LCDs - Reflective LCDs

The cellular phones, digital cameras, electronic books (E-books), and vehicle displays are revolutionized our life, leading to demand for multimedia activities wherever we go. These portable devices need sunlight readability and low power consumption, where of transmissive type LCDs can not achieve easily. Therefore, reflective LCDs are proposed for portable applications.

The “reflective” type LCD was proposed by T. Uchida in 1995[3] to solve the problems in the transmissive type LCDs, as shown in Fig. 1-2. The reflective type LCDs are provided with a reflector formed on the substrate in place of backlight, so that the ambient light is reflected to display images, thereby obtaining display light proportional to the amount of the ambient light. For the reason, the reflective type LCDs do not wash out under bright environment and the images can be observed distinctly. Moreover, reflective LCDs have advantages of low power consumption, light weight and low cost due to the elimination of the backlight system. Thus, reflective LCDs are particularly suitable for outdoor applications, such as cellular phones, electronic books (E-books), and digital cameras.

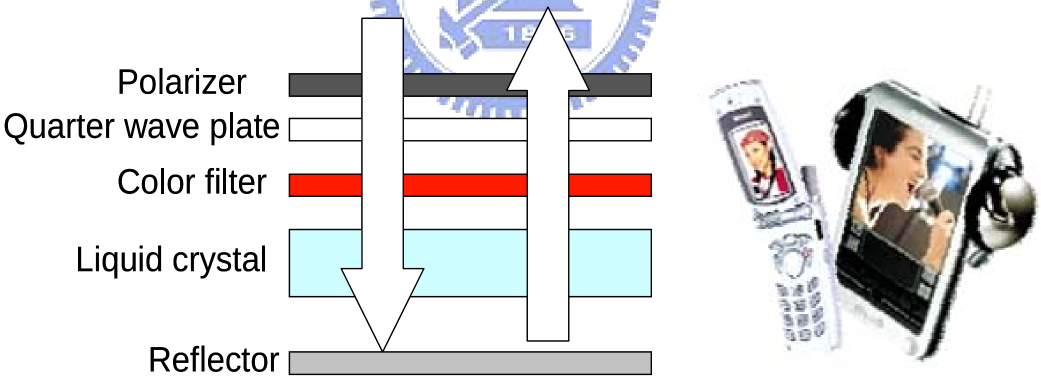


Fig. 1-2. Reflective type LCD.

However, since reflective LCDs use ambient light to display images, the display brightness depends on the surrounding environment, and they lose their visibility under dark environment. Besides, the purity of ambient light varies with the environment. Therefore, the reflective LCDs can not provide sufficiently high image quality of brightness, contrast ratio, and color saturation for portable devices. Accordingly, further improvement in contrast ratio and brightness is necessary.

1.4 Transflective LCDs

In order to solve the problems of both transmissive and reflective type LCDs, a new display construction which has both transmissive and reflective modes in one liquid crystal device is proposed by Sharp Corporation in 1998[4] and named “transflective type LCD”, as shown in Fig. 1-3. The transflective LCD splits each sub-pixel into reflective and transmissive regions to display images in any ambience. In reflective region, a reflector is disposed at the rear glass surface to reflect ambient light. In transmissive region, the light of backlight can pass through the LC layer to display images.

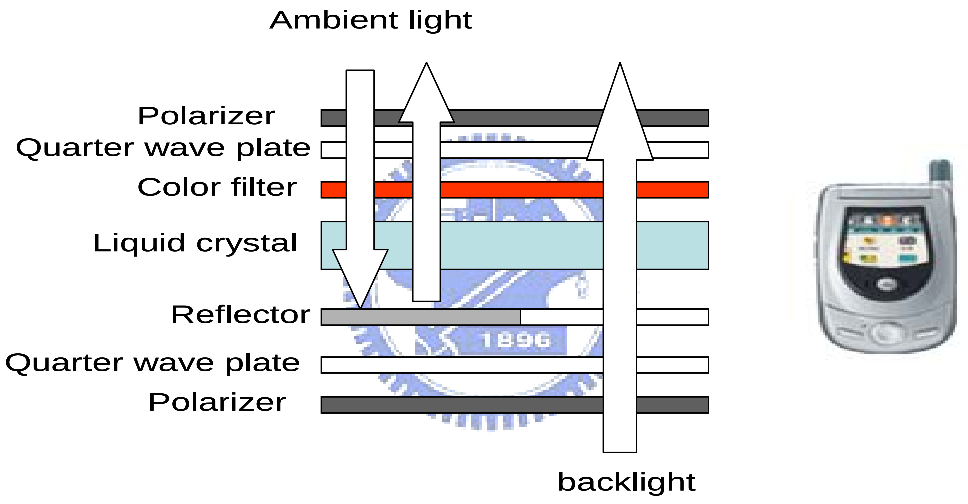
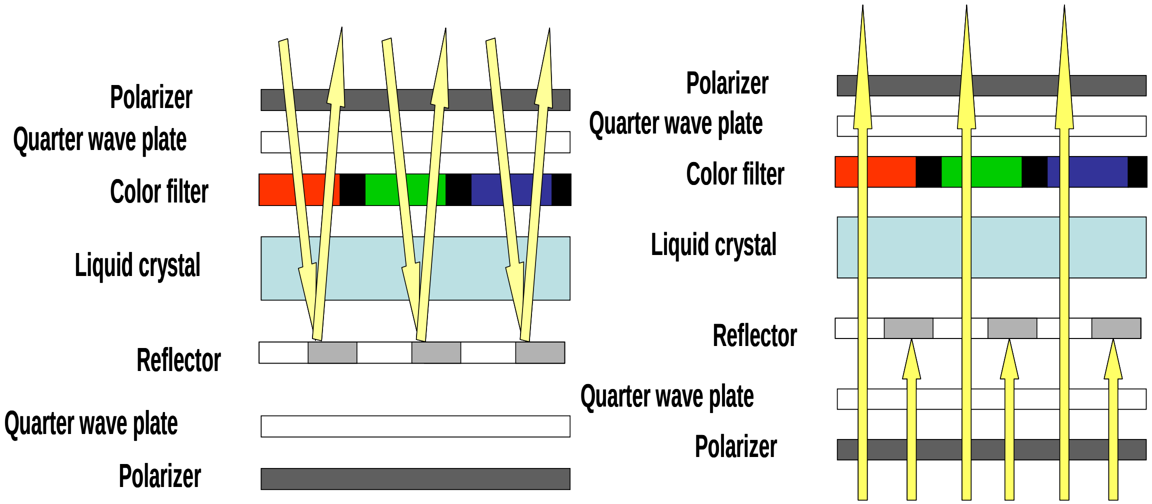


Fig. 1-3. Transflective type LCD.

In a bright ambience, the reflector reflects the ambient light to display images during the reflective mode, as shown in Fig. 1-4(a). On the other hand, in a dark ambience, the backlight transmits the transmissive sub-pixels and the device works as a transmissive display, as shown in Fig. 1-4(b). However, the liquid crystal cell gaps for reflective and transmissive regions are the same. As a result, the ambient light and backlight have different optical path difference due to the backlight propagates the LC layer once in transmissive region. Therefore, the light transmittance for the transmissive mode is lower than 50% of the reflective mode.



(a) Reflective mode (b) Transmissive mode

(Bright ambient) (Dark ambient)

Fig. 1-4. Operation principle of the transflective LCD (a) reflective mode (b) transmissive mode.

For reflective mode, the light passes through the color filter twice, as shown in Fig. 1-4(a). Nevertheless, the backlight transmits the color filter only once in transmissive mode, as shown in Fig. 1-4(b). Thus, the optical path of ambient light and backlight should be designed to match color saturation.

1.5 Cholesteric Liquid Crystal (Ch-LC)

The cholesteric (Ch) phase is a liquid crystal phase exhibited by doping chiral molecules. The LC molecule structure is shown in Fig. 1-5.

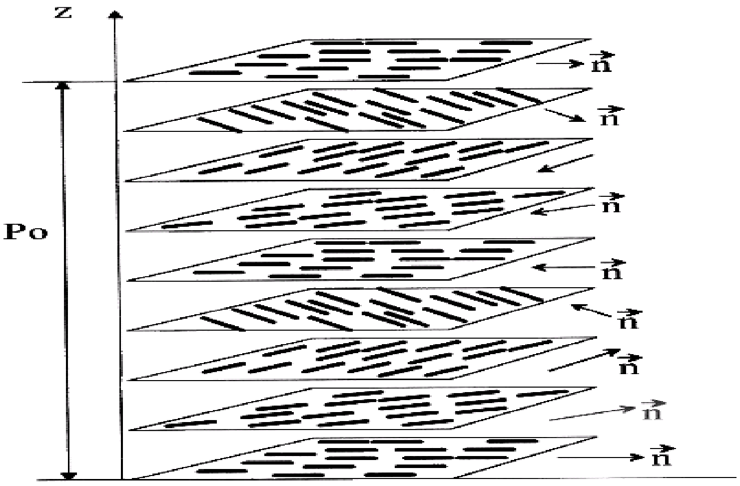


Fig. 1-5. Cholesteric LC molecule structure.

The cholesteric LC molecule is a helical structure. Along the helical axis, the LC director $\vec{n}$ on the two neighboring plane are twisted slightly with respect to one another. The distance along the helical axis for the director to rotate 2π is called the pitch P_0.

The state of cholesteric liquid crystal is characterized by the direction of helical axis as shown in Fig. 1-6. In the planar state, the LC molecules are oriented in helices with a periodicity and the helical axis is perpendicular to the cell surface as shown in Fig. 1-6(a).

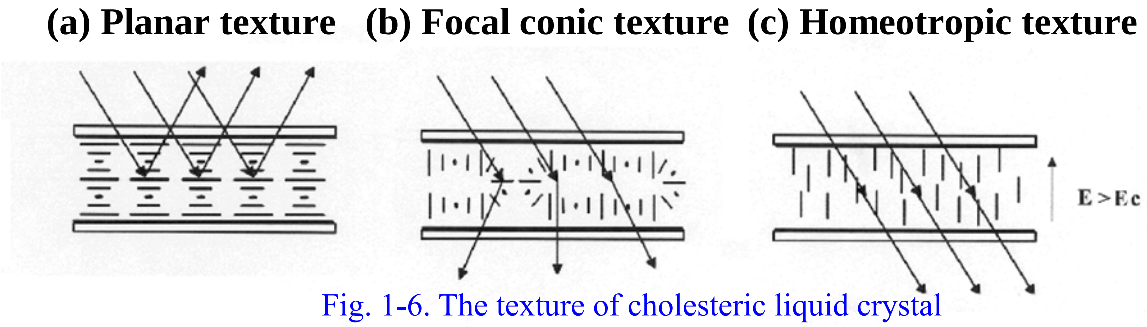

(a) Planar texture (b) Focal conic texture (c) Homeotropic texture

Fig. 1-6. The texture of cholesteric liquid crystal
(a) Planar, (b) Focal Conic and (c) Homeotropic texture.

Light with the wavelength matching the pitch of the helix is reflected and the display appears in bright state. The central wavelength of the reflected light is determined by $\lambda_0 = p \times n$[5], where p is the pitch of Ch-LC and n is the average refractive index of Ch-LC. Additionally, the bandwidth of the reflected light, $\Delta\lambda$, is proportional to the birefringence of Ch-LC, Δn. If the reflected light in the visible light range, the LC has a bright colored appearance. For applying the voltage, the LC changes from planar state to focal conic state, which scatters the incident light and displays dark images. In focal conic state, the helical axis is more or less parallel to the cell surface, as shown in Fig. 1-6(b). The focal conic state is characterized by its highly diffused light scattering appearance caused by a distribution of small, birefringence domains, at the boundary between those domains the refractive index is abrupt changed. This state has no single optic axis. The focal conic state is typically milky-white (i.e., white light scattering). Both planar state and focal conic state can coexist in the same panel. When the applied field is larger than a critical field Ec, the helical structure is unwound and the directors of liquid crystal align in the normal direction of the cell, as shown in Fig. 1-6(c). The state is called homeotropic state.

With the proper surface alignment or dispersed polymer, both planar state and focal conic state can be stable at zero electric field. This is called “bistable” phenomenon of Ch-LC[6]. Due to the bistable property of Ch-LC, the power source can be eliminated for maintaining images. Therefore, the power consumption of Ch-LCD is much lower than other kind of displays.

The operation principle of cholesteric LCDs are illustrated in Fig. 1-7. In the voltage-off state, the Ch-LC reflects colored light if the Bragg condition ($\lambda_0 = p\times n$) is satisfied. The bandwidth $\Delta\lambda$ of the reflected light is equal to $p\times\Delta n$[6]. Due to the helical structure of the Ch-LC material, circularly polarized light with the same handedness as the helical structure is reflected strongly because of the constructive interference of the reflected light[7]. While circularly polarized light with the opposite handedness as the helical structure is not reflected because the light does not match the Bragg condition. An incident unpolarized light is decomposed by Ch-LC right and left hand circular polarized components with one component reflected and the other transmitted[8], respectively. The transmitted light is absorbed by the black paint layer coated on the rear substrate, as shown in Fig. 1-7(a). When applying a voltage, the periodic helical structures of Ch-LC are changed to focal conic state[9]. Therefore, the Bragg reflection is interrupted due to the scattering effect of focal conic state. The incident light is absorbed by the black paint layer and a dark state is obtained, as shown in Fig. 1-7(b).

Although cholesteric liquid crystals are only bi-stable, they can exhibit gray scale because of their multi-domain structure[10],[11]. Starting from the imperfect planar state, some domains can be changed to the focal conic state at lower voltage than other domains.

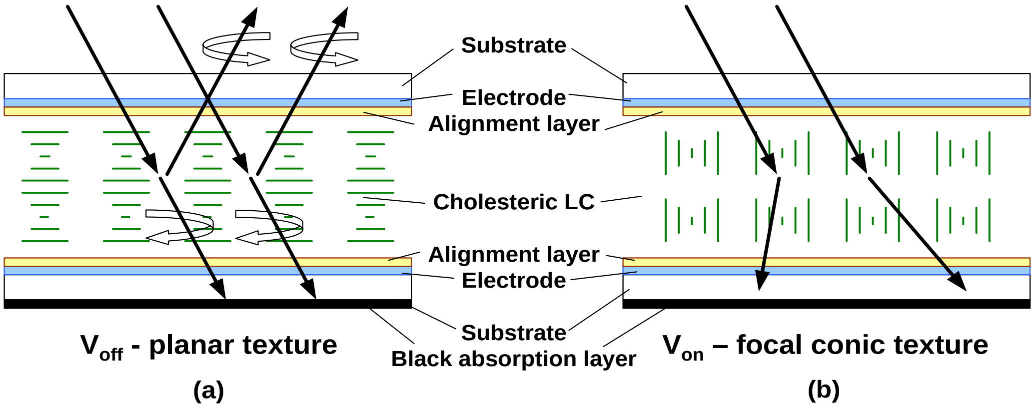


Fig. 1-7. The basic operation principle of a reflective cholesteric LCD at (a) Voltage-off and (b) Voltage-on state.

Once a domain has been changed to the focal conic state, it remains the state even after the applied voltage is turned off. Fig. 1-8 shows microphotographs of the gray scale of a cholesteric display.

From right to left, the gray scale is achieved by applying voltage pulses with increasing amplitude, and the reflectance decreases. The domain size is about 10um. The typical pixel size of Ch-LCD is about 100um. A cholesteric domain has only two stable states at zero field. It is either in the planar state or in the focal conic state. In a Ch-LCD, the domains in the planar state have the same optical properties, independent of the states of other domain

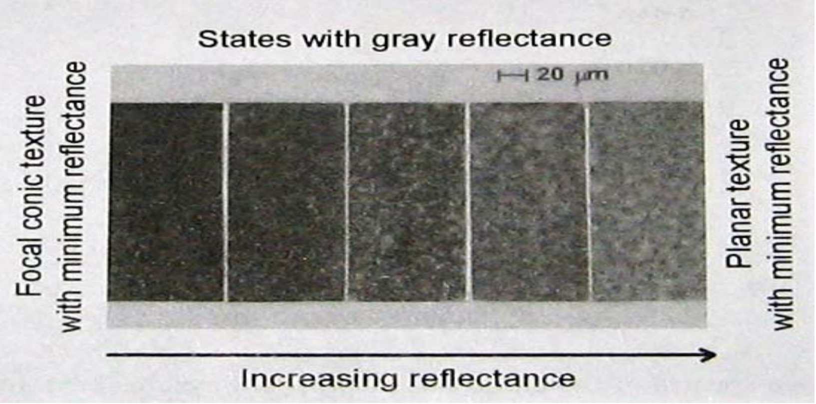


Fig. 1-8. The microphotographs of the gray scale of the cholesteric display[12].

The human eyes like full color spectrum in many applications. For example, white color information is written on the dark background. With the development of the flat panel displays, more and more displays with neutral color come into being, such as black-and white STN displays and active matrix TFT (AMTFT) displays. Unfortunately, both of these approaches have some disadvantages and limitations. The AMTFT displays are not true zero field image storage systems, because they require constant power input for image refreshing. The STN displays do not possess inherent gray scale capability as a result of the extreme steepness of the electro-optical response curve of the display. The AMTFT devices use semiconductors to provide memory effects and require expensive processing.

Compared with STN and TFT displays, cholesteric displays have many obvious advantages. First, the memory effect can make the display unlimitedly high resolution while STN is very hard to reach that many scan lines, and TFT needs to use storage capacitor to hold the voltage thus decreases the aperture ratio of displays. Besides, the power consumption of cholesteric displays is much lower than other displays due to the memory effect. Secondly, cholesteric displays have lower manufacturing cost, simpler production process and higher yield than both STN and TFT displays. Thirdly, the display performance such as viewing angle is better than STN displays. Additionally, sunlight readability makes cholesteric displays suitable for mobile devices applications.

1.6 Motivation and Objective of this Thesis

As described above, the conventional reflective cholesteric liquid crystal displays (Ch-LCDs) have advantages of low power consumption, light weight, wide viewing angle, and low cost. However, due to the limit of birefringence of cholesteric liquid crystal material, the bandwidth of reflection light is usually narrow band, resulted in single color images. Single color display is not appealing to users.

In order to solve the problem, a novel method for reflective Ch-LCDs “full spectrum reflective method” is proposed to improve the performance of the displays. The characteristic of the method is to use a wide band reflector and polarizers and quarter wave plates to broaden the spectra of reflected light. The two reflective spectra components, one reflected by Bragg reflection of cholesteric liquid crystal, and the other reflected by the wide band reflector, are compensatory each other and will meet together to emanate to viewer as full gamut of visible light. Thus, it can appear white in bright state. On the other hands, the black state is created by Ch-LC’s scattering type depolarization effect and polarizer’s filtration effect in focal conic texture. Therefore, a black and white reflective Ch-LCD can be realized. Black and white display is more desired for users. In addition, since the reflected light is white, the conventional color filters can be patterned for obtaining full color displays.

Based on the advantages of reflective Ch-LCD for low power consumption, long-term image memory, light weight, low cost, and good sunlight readability, this display is ideal suitable for hand-hold device application. By the full spectrum reflective method, black and white reflective Ch-LCD can be achieved instead of monochromic display. This method improves image quality of conventional reflective Ch-LCD greatly, making it suitable for electronic book or electronic paper application.

1.7 Organization of this Thesis

The thesis is organized as following: the principles and the features of the cholesteric LCD will be presented in **Chapter 2.** In **Chapter 3,** the LCD fabrication processes including cell process such as polyimide (PI) printing, rubbing, spacer dispense, sealant dispense, assembly, hot press and LC injection will be presented**.** Besides, the major measurement equipments used to characterize the fabricated the Ch-LCD are illustrated. In **Chapter 4,** the simulated results including reflective spectra, reflectance and color appearances of different cholesteric LCs used to verify and optimize our design will be presented. About the experimental results, several Ch-LCD samples fabricated by simulated results are demonstrated. Based on the measurement results, some optical properties of the samples are discussed in **Chapter 5.** Some applications of Ch-LCD are discussed in **Chapter 6.** Finally, the conclusion of the thesis is given in **Chapter 7.**

Chapter 2

Principle

2.1 Optical Properties of Cholesteric Liquid Crystals

Cholesteric liquid crystals have two stable states at zero electric field: the reflecting planar state and the scattering focal conic state. Microphotographs of the planar state and the focal conic state are shown in Figs. 2-1(a) and (b). When a cholesteric liquid crystal is in the planar texture, there is a periodic structure of the refractive index in the cell normal direction[13]. The liquid crystal exhibits Bragg reflection at the wavelength $\lambda_0 = p \times n$ for normally incident light, where p is the pitch of Ch-LC and n is the average refractive index of Ch-LC. The reflection is strong and multiple reflections inside the liquid crystal is important. The bandwidth of the reflected light given by $\Delta\lambda = p \times \Delta n$[6], where $\Delta n = n_e - n_o$ is the birefringence. Circularly polarized light with the same handedness as the helical structure of cholesteric LC is reflected strongly because of the constructive interference of the light reflected from different positions, while circularly polarized light with the opposite handedness to the helical structure is not reflected because of the destructive interference of the light reflected from different positions. If the normally incident light is unpolarized, then the maximum reflection from the cholesteric LC is 50%.

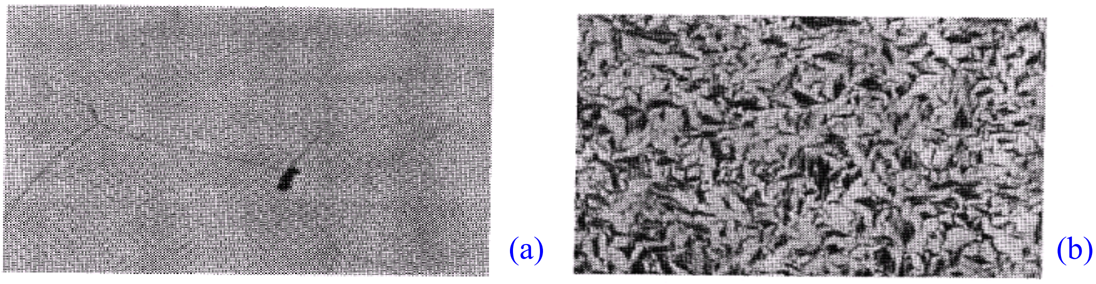
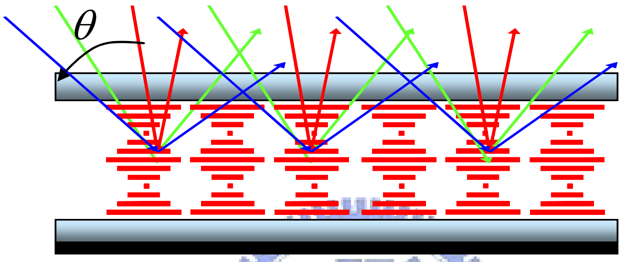

(a) (b)

Fig. 2-1. Microphotographs of (a) the planar and (b) the focal conic states.

2.2 Viewing Angle of Cholesteric Displays

When light is obliquely incident at the viewing angle θ on the cholesteric liquid crystal, as shown in Fig. 2-2, the central wavelength of the reflected light is given by $\lambda = p \times \bar{n} \times \cos\theta$[14], where θ is the incident angle with the normal direction. When θ is increased, the reflected light is shifted to a shorter wavelength, the reflection band becomes broader and the peak reflection becomes higher. The shift of reflection band is undesirable for display applications, because the color of the reflected light changes with the viewing angle.



$$\lambda = \bar{n}P\cos\theta$$

Fig. 2-2. Viewing angle of cholesteric liquid crystal displays.

For the perfect planar state, there is a concern of viewing angle for incident light at an angle θ, the reflected light is only observed at the corresponding viewing angle. These problems can be partially solved by using an alignment layer or dispersing a small amount of polymer in the liquid crystal which gives weak homogeneous anchoring or homeotropic anchoring. The dispersed polymer and the alignment layer produce defects and create a multi-domain structure[15], as shown in Fig. 2-3.

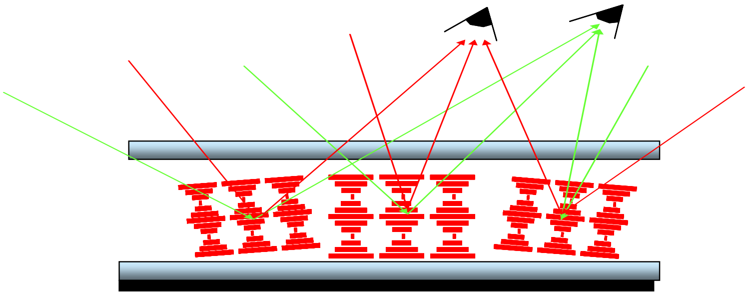


Fig. 2-3. Multi-domain structure of cholesteric liquid crystal displays.

In this structure, the helical axis in the domains is no longer exactly parallel to the cell normal but distributed around the normal direction. In this imperfect planar state, for incident light at a given angle, light reflected from different domains are in different directions, as shown in Fig. 2-3. For the ambient light, light reflected from different domains can be observed at one location. Because the observed light is a mixture of different colors, the colors observed at different viewing angle are not very different. Therefore, this multi-domain structure improves the viewing angle of the cholesteric display[16]. Furthermore, the dispersed polymer or alignment layer stabilizes the focal conic state at zero field. The display stabilized by polymer is called the polymer-stabilized cholesteric display and the one stabilized by the alignment layer is called the surface-stabilized cholesteric display[17][18].

2.3 Cell Design of Cholesteric Displays

When a cholesteric liquid crystal is in the planar state, it reflects narrow band light. When it is in the focal conic state, it is scattering light. In order to achieve high contrast ratio, it is desirable that the backward scattering of the focal conic state can be minimized. It is also desirable that the light from the back of the display can be controlled. Therefore, a color absorption layer is required to coat on the back plate of the display[19], as shown in Fig. 2-4.

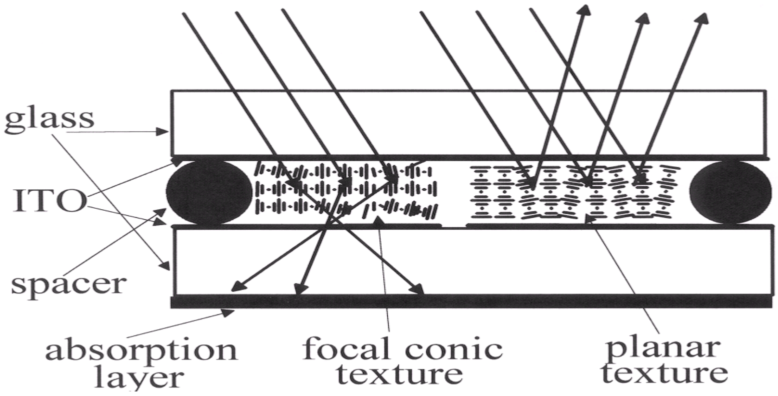


Fig. 2-4. Cell structure of the cholesteric display.

A black appearance is made with a black absorption layer[20]. The display has a bright color appearance when the liquid crystal is in the planar state and a black appearance when the liquid crystal is in the focal conic state. A white reflective display is made with a color absorption layer[21]. For example, the liquid crystal reflects yellow color light and the absorption layer reflects blue color. When the liquid crystal is in the planar state, yellow light is reflected from the cholesteric liquid crystal and blue light is reflected from the absorption layer. Therefore, the display has a white appearance. When the liquid crystal is in the focal conic state, only blue light is reflected from the absorption layer. Thus, the display has a blue appearance in dark state. Higher contrast can be achieved by putting the absorption layer inside the cell on top of the back plate.

The reflection of a cholesteric liquid crystal display depends on the cell thickness. For perfect planar state, 3um cell thickness is sufficient to obtain the saturated reflection from the liquid crystal with birefringence $\Delta n \geqq 0.2$. In reflective cholesteric displays, because of the defects produced by the alignment layer or dispersed polymer, usually 5um cell thickness is required to obtain a saturated reflection.

In polymer-stabilized bistable cholesteric displays, it is preferable to mix the cholesteric liquid crystal with a few percent of the monomer. Then the cells are irradiated by UV light for photopolymerisation of the monomer. A blacker focal conic state can usually be obtained by polymerizing the monomer in the homeotropic state in the presence of an applied voltage[22].

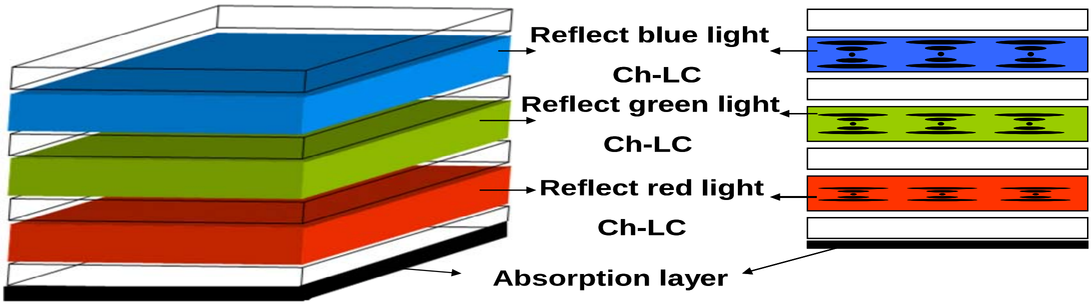
In surface-stabilized bistable cholesteric displays, either weak homogeneous alignment layers or homeotropic alignment layers can be used. When homeotropic alignment layers are used, the focal conic state appears darker and the response time becomes shorter, but the reflection of the planar state is lower[23].

Liquid crystal materials with large Δn and Δε are always desirable. When Δn is large, a smaller pitch of liquid crystal can be used, so the cell gap can be reduced. Therefore, the driving voltage can be reduced. When Δε is large, the driving voltage also can be reduced. For display applications, the cholesteric liquid crystal is a mixture of a nematic liquid crystal and chiral dopants. The components should be chosen carefully such that the cholesteric phase temperature range is wide and the pitch does not shift with temperature.

2.4 Color of Cholesteric Displays

For a conventional reflective cholesteric display, only a single color can be displayed. In order to become multiple color displays, there are several methods proposed to obtain multiple colors: U.S. Patent 6,377,321 by stacking multiple layers of cholesteric liquid crystals with different pitches, U.S. Patent 6,061,107 and U.S. Patent 5,949,513 by using one layer of cholesteric liquid crystals partitioned in plane, etc.

For the stacking method, multiple color displays can be made by stacking three layers of cholesteric liquid crystals with three different pitches reflecting red, green, blue light[24], as shown in Figs. 2-5.(a) and (b).



(a) Structure (b) Cross section

Figs. 2-5.(a) Structure and (b) Cross section of stacked type of Ch-LCD.

One cholesteric layer with the three colors is fabricated first. Then they are glued together. A potential issue of the stacked approach is parallax, i.e. the incident light and reflected light pass through different pixels. Parallax leads to color mixing which becomes a serious issue for high-resolution displays. In order to reduce parallax, thin substrates, preferably substrates with conducting coating on both sides should be used to decrease the distance between the liquid crystal layers. Because of the high reflection of the electrodes, the stacking order from bottom to top should be red, green and blue. The reflection spectrum of a three-layer cholesteric display is shown in Fig. 2-6. Without using a polarizer, the reflectance is about 30%~35%, and its contrast ratio is in the range of 5-10 within 60° viewing cone. However, the stacked method is still too complex and the cost is high.

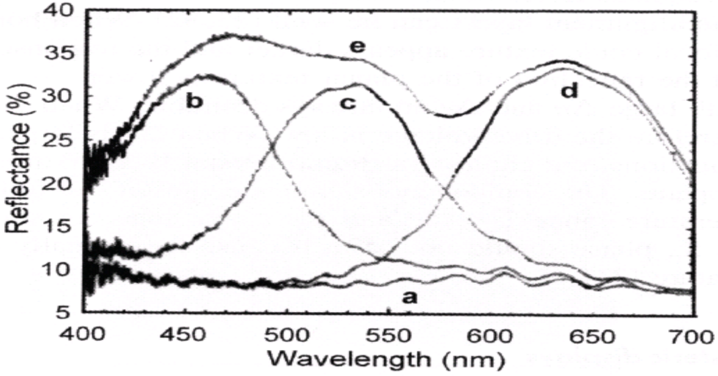
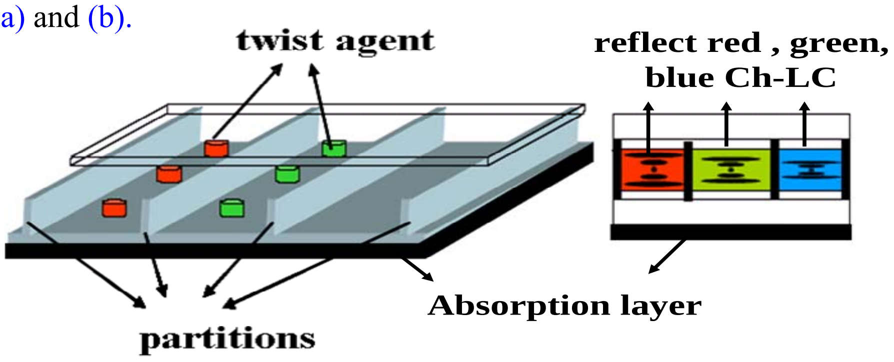


Fig. 2-6. Reflection spectrum of the stacked multiple color cholesteric display. Curve a: all off, curve b: blue on, curve c: green on, curve d: red on, curve e: all on[25].

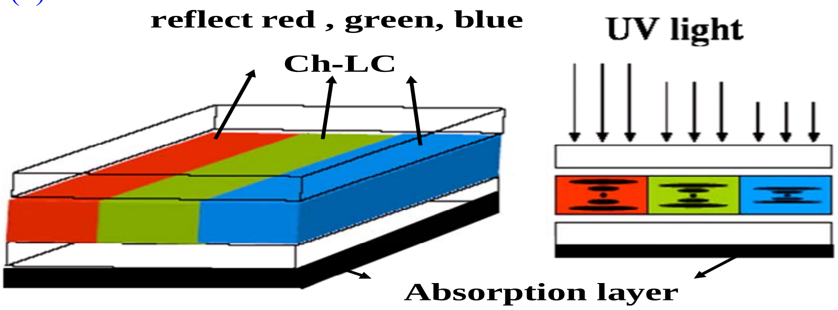
Other methods to achieve multiple colors, such as partition LC, the different pitches of LC must be used. The different pitches can be achieved by two methods. The first method, three cholesteric liquid crystals with different pitches by depositing different twist agents are put into empty cells with partitions[26], as shown in Figs. 2-7.(a) and (b).



(a) Structure (b) Cross section

Figs. 2-7.(a) Structure and (b) Cross section of different pitches of Ch-LCD.

The second method is photo color tuning[27]. A photo-sensitive chiral dopant is added to the liquid crystal. The dopant undergoes a chemical reaction under UV irradiation and thus its chirality changes, and the pitch of the liquid crystal changes. By varying the irradiation time, different pitches can be achieved, as shown in Figs. 2-8.(a) and (b).



(a) Structure (b) Cross section

Figs. 2-8.(a) Structure and (b) Cross section of different UV light curing of Ch-LCD.

The main drawback of one layer multiple color displays is that the reflection is low when only one color is on and the other colors are off.

2.5 New Method for Wide Band Reflection- Full Spectrum Reflective Method

Current cholesteric displays are utilizing Bragg reflection theory, one of the intrinsic properties of cholesteric liquid crystal. In Bragg reflection, only a portion of the incident light with the same handedness of circular polarization and within the specific wave band which generates a monochrome color display can reflect back to the viewer. In order to improve the image quality of single color cholesteric displays, a new configuration "Full Spectrum Reflective Method" is proposed, as shown in Fig. 2-9.

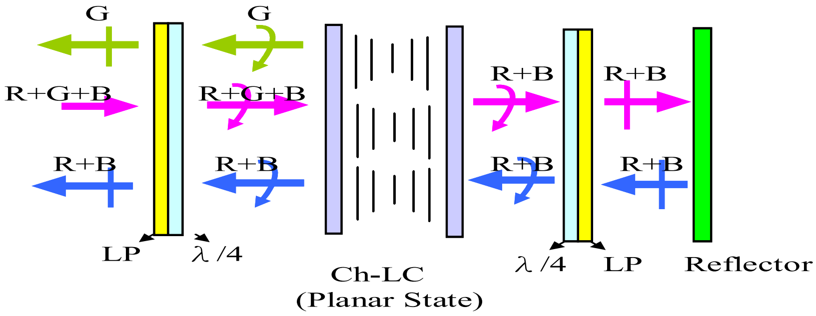


Fig. 2-9. Configuration of full spectrum reflective method.

The wide band reflective cholesteric LCD consists of a Ch-LC cell, a full band reflector, and two circular polarizers which are composed by a linear polarizer (LP) and $\lambda/4$ plate. In bright state, the Ch-LC in planar state reflects the light component with the same handedness as Ch-LC, like green light component and the reflective bandwidth and wavelength are determined by the helical pitch and birefringence of Ch-LC. Besides, the remaining light component out of the selective bandwidth, like red and blue light component passes the LC, and is reflected by a full band reflector without changing the polarization state. Consequently, the two components: one reflected by the Bragg reflection with a center wavelength λ_0 of Ch-LC, and the other reflected by the reflector, are compensatory each other and combine together by the viewer to perceive as full band of visible light, as shown in Fig. 2-10.

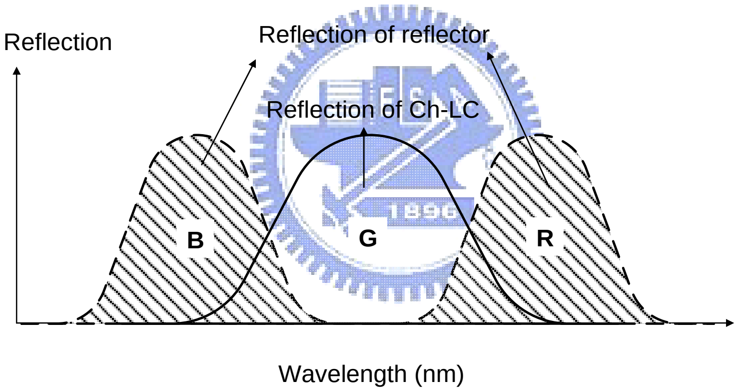


Fig. 2-10. Schematic plot of full spectrum reflective method.

When the Ch-LC is tuned in invisible Bragg reflection wavelength, for example in infrared wavelength range, a full spectrum of visible light will be reflected by the full band reflector. Therefore, the viewer still perceives full visible spectra of white images.

In dark state, the incoming light reaches a circular polarizer with the same handedness of the Ch-LC and is cut more than 50%. The rest of light goes to the Ch-LC with focal conic texture and is depolarized by the scattering effect of the LC material and assume 60% of incoming light can pass through the Ch-LC. Then the unpolarized light passes a linear polarizer is reduced by more than 50%, then is reflected by the reflector and further passes through a circular polarizer, located between the reflector and the Ch-LC cell. The remaining light passes through the Ch-LC cell again is depolarized by the scattering effect of the focal conic texture, and then is cut by more than 50% again by the front circular polarizer. Finally, only small portion (about 5%) of total light can reach to the viewer. As a result, by use of scattering effect of Ch-LC in focal conic texture and filtration of the polarizers results in dark state of the display, as shown in Fig. 2-11.

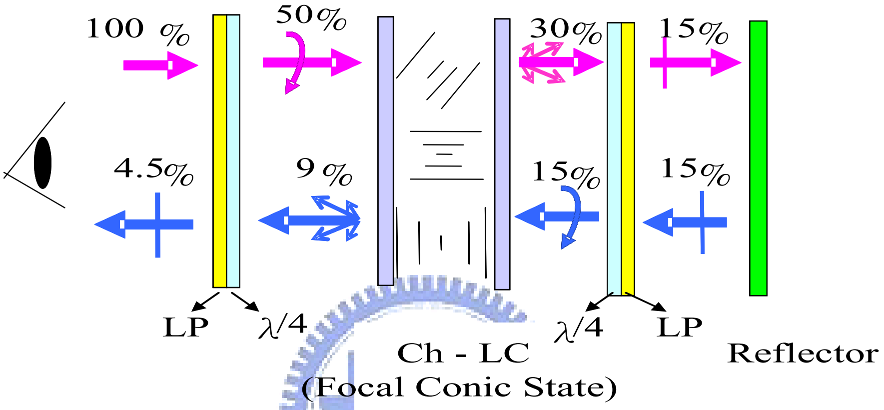


Fig. 2-11. Configuration of the wide band Ch-LCD in dark state.

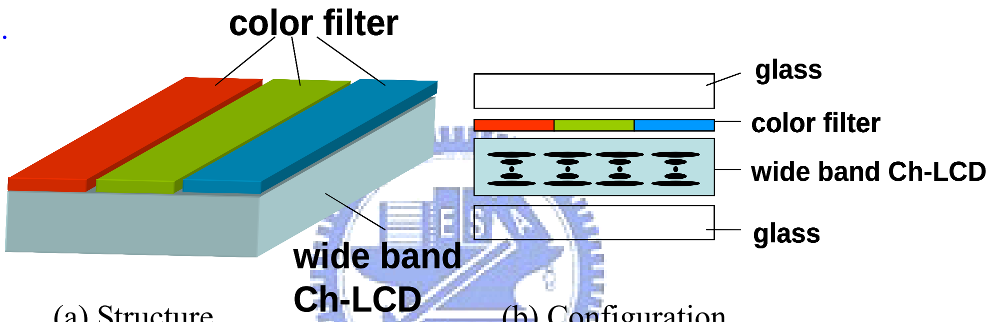
The full spectrum of reflective cholesteric display can be realized both in visible and invisible spectra, for example, infrared wave band. The optical scattering effect in the infrared wavelength is the same as in the visible wavelength range, which is dependent on the pitch of the liquid crystals and refractive index so that the display obtains the same optical “dark” state. On the other hand, the optical “bright” state is still the full gamut of visible light reflected by a full band reflector. A reflective cholesteric display that works in infrared wavelength will have very fast response time and low driving voltage for the reason of lower viscosity and longer helical pitch of liquid crystal.

Using the full spectrum reflective method, both the two optical paths should have the same angular distribution and mutually matching over a wide viewing angle so that the display looks white in the planar texture. There are two approaches to match the two paths. First, the distribution of Ch-LC itself is designed to single domain planar structure by means of surface treatment such as rubbing the surface of the glass coated with polyimide. Second, the reflector then is designed in the way of a mirror surface. The two reflected lights enable display to exhibit white color within certain viewing angle.

In order to improve the viewing angle of the Ch-LCD, a diffusing layer coated on the front polarizer surface, which is functioned as an anti-glare layer, can realize the large viewing cone. Other approach is to obtain multi-domain planar structure by controlling the surface rubbing condition to assure the wide angle distribution of reflective light. And the reflector is then designed with a specific surface condition, thus, wide reflective distribution can be achieved. In the case of infrared Ch-LC, the angular distribution of the display is entirely dependent upon the reflector because the reflective film will reflect all the visible white light with predetermined angular distribution.

The black and white reflective Ch-LCD introduces a novel way to realize real video display with higher brightness and contrast ratio. Conventional reflective Ch-LCD with video rates does not look bright because of most of the incoming light being absorbed by the back black absorption material. The transition time is limited by the domain size of the Ch-LC so that the total reflection of the display at high switching speed is not as good as low driving speed. By utilizing the full spectrum reflective method, light out of the selective reflection bandwidth can be used. Therefore, the total brightness of the display is enhanced even in the video rate driving speed. The other parameter that benefit to the video rate is the longer wavelength of the selective reflection and low threshold voltage of the display, for example, the infrared wave band Ch-LC. The black and white reflective Ch-LCD with lower driving voltage and lower viscosity liquid crystal formulation due to the longer helical pitch of Ch-LCD will result in a faster driving speed. While the red color monochrome Ch-LCD looks poor for conventional display mode although the driving voltage is lower than that of other wave band monochrome displays. Therefore, by using full spectrum reflective method, a reflective black and white Ch-LCD with video speed can be achieved.

The black and white display can be easily converted to a full color display in the same way as a reflective STN or a reflective TFT display does. By using conventional color filter process to coat the red, green, and blue three color filters on the Ch-LCD, the full color Ch-LCD can be readily achieved, as shown in Figs. 2-12.(a) and (b).



(a) Structure (b) Configuration

Figs. 2-12.(a) Structure and (b) Configuration of full color Ch-LCD.

Besides, the full spectrum reflective method also can be used for transflective displays. The configuration of display is shown in Fig. 2-13.

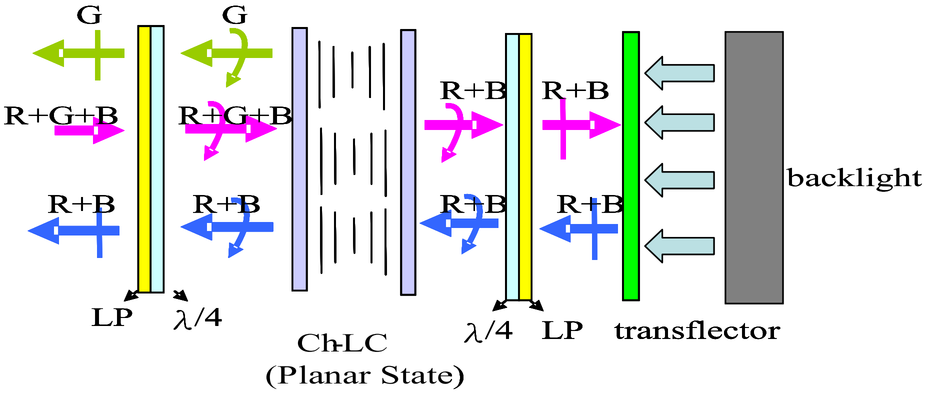


Fig. 2-13. Transflective Ch-LCD with full spectrum reflective method.

The transflective display structure includes a Ch-LC cell, two circular polarizers, a transflective reflector and backlight. The transflective Ch-LCD basically has the same structure as the black and white full spectrum reflective display as concerned. The difference is an addition of the backlight system and the half-reflection-half-transmission reflector. The backlight can be turned on in a dim ambient light. The transflective display's principle is described as following. When the display works in the planar state, the light beam emitted by the backlight passes the transflective film and reaches the second circular polarizer and consequently becomes circular polarized. The polarized light then reaches the Ch-LC cell, a portion of the light which is Bragg reflected by the Ch-LC will pass through the second circular polarizer and the rest of it will move toward to pass the first circular polarizer without attenuation. At this time, the viewer can observe a monochromic bright light, which is different from the full spectrum reflective method mentioned above. When the Ch-LC is in the focal conic texture, the light emitted from the backlight passes the transflective film and the second circular polarizer being by cut more than 50%, consequently, becomes circular polarized. The remaining light reaches the Ch-LC cell with focal conic state and is depolarized by the scattering effect of Ch-LC. The depolarized light further passes the first circular polarizer with more than 50% loss. The light rays out of the display's front surface are kept a large angle distribution due to the scattering of Ch-LC. Therefore, the viewer's eye can only collect a small portion of light. Thus, by use of filtration of polarizers and scattering effect of Ch-LC, the display can yield dark state, though the darkness is not as good as the reflective mode because of shorter optical path of backlight.

When the display works in combination of backlight and transflective reflector, the optical performance such as contrast ratio is still good enough and the brightness is much higher than reflective mode. Therefore, even in bright or dark ambience, the transflective Ch-LCD still has good readability.

2.6 Summary

Compared with other display technology, the full spectrum reflective mode or transflective mode Ch-LCD has several advantages.

1. High display quality:

The integration from monochromic to full spectrum reflective black and white display and to full color display makes the Ch-LCD more human friendly while maintaining the advantages of the conventional Ch-LCD's, such as long term zero field memory effect, large viewing angle, sunlight readability and so on. The black and white reflective Ch-LCD is highly desirable for high information content electronic newspapers and electronic books.

2. Low power consumption and low driving voltage:

Because the Ch-LCD with full spectrum reflective method has long time memory effect at zero voltage without continuous refresh, the overall power consumption is much lower than STN or TFT displays. Therefore, low power consumption makes the display be the best candidate for the portable electronic displays. Besides, the driving voltage of Ch-LCD is reversed to reflection wavelength of liquid crystal, the longer wavelength of reflection the lower driving voltage. The full spectrum reflective method allows the Bragg reflection of Ch-LC to be chosen in long visible wavelength or even in the infrared wavelength. If the infrared wavelength of 750nm is chosen, the threshold voltage then becomes half of the green color. Besides, the cell thickness "d" is direct proportional to the threshold voltage. In the conventional Ch-LCD's, the cell gap has to meet the requirement of the reflectivity or brightness of the display in the planar state, but in the method the cell gap is only required by sufficiently depolarization efficiency in the focal conic state. Thus, this method allows the cell gap to be much thinner than former displays so that the voltage can be further reduced. These two factors mentioned above solve high voltage operation problem of conventional Ch-LCD's. So, the display can be compatible with normal STN or TFT drivers.

3. High dynamic driving speed:

The characteristic of long wavelength reflection of Ch-LC reduces the amount of the chiral nematic material to the nematic LC material so as to decrease the viscosity of the Ch-LC. Therefore, the response time of Ch-LC is reduced greatly. Meanwhile, the cell gap reduction further reduced the response time of Ch-LC. As a result, the driving speed is much faster than the conventional Ch-LCD's.

4. High productivity:

In some application the display is required zero voltage memory effect but no special demand for driving speed such as electronic books, information boards, and mobile phones. The full spectrum reflective Ch-LCD working at long helical pitch may allow larger cell gap of liquid crystal. The bigger cell gap allows larger tolerance and higher yield of LCD fabrication process. The monochromic Ch-LCD is usually designed to use 3.5um cell gap to fit the standard STN driver. With the present technology, the cell gap can be enlarged to 5um, which is the standard STN cell gap. Thus, the display can achieve the same display cell gap at the same driving voltage compared with STN displays. Consequently, the productivity can be improved because of low cost and high yield of fabrication process.

5. Better display mode:

Transflective display is an important expansion on the basis of the prior reflective display. The conventional reflective Ch-LCD uses black coating layer attached to the back of the display. Thus, the display only relies on the ambient light to display images, which is not visible in dark ambience. However, the transflective Ch-LCD can use in bright or dark ambience. It is a breakthrough for Ch-LCDs.

Chapter 3

Fabrication and Measurement Instruments

3.1 Introduction

The Ch-LCD test cells are used to evaluate the performance of the full spectrum reflective method. The embodiment including several LCD fabrication processes will be shown in the following sections, and the measurement technologies and instruments which are available to develop the Ch-LCD will be introduced in this chapter.

First, the LCD fabrication processes including cell process such as polyimide (PI) printing, rubbing, spacer dispense, sealant dispense, assembly and hot press will be used. Besides, the electro-optical characteristics and performance of the Ch-LCD test cells, such as reflective spectrum, reflectivity, brightness, and contrast ratio were measured by LCD measurement instrument "ConoScope"[28]. The major features and principles of the instrument will be illustrated in this chapter.

3.2 LCD fabrication process

The LCD fabrication processes including cell process such as polyimide (PI) printing, rubbing, spacer dispense, sealant dispense, assembly, hot press and LC injection will be used to fabricate the Ch-LCD test cells. The detailed fabrication processes are listed below.

(a) Substrate preparation: For the display application, the glass is widely used as a substrate. In the fabrication, the glass with about 0.7mm thick was chosen. After the initial cleaning, the polyimide (PI) was printed on the glass substrate, as shown in Fig. 3-1. Before rubbing, the PI layer must be cured.

(b) Rubbing: Using roller to roll on the PI film to produce mechanical force to rearrange the orientation of PI film. Therefore, LC molecules will be aligned naturally with the micro-groove of PI film surface for the lowest energy, as shown in Fig. 3-2.

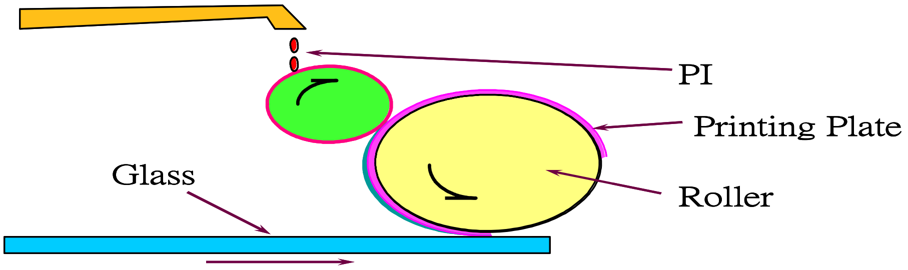


Fig. 3-1. PI printing process.

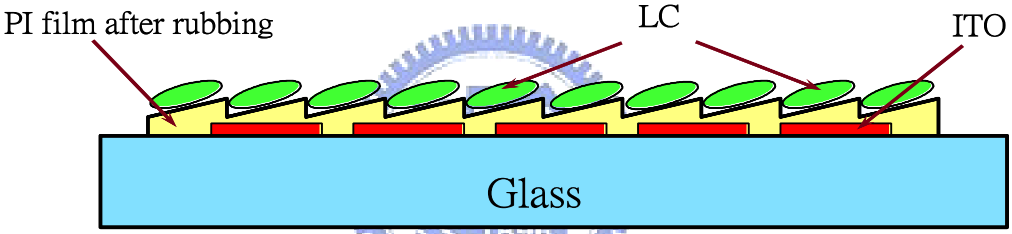


Fig. 3-2. Illustration of rubbing process.

(c) Spacer dispense: Dispense spacer uniformly on the glass substrate to support the top and bottom glass and maintain a uniform cell gap of LCD. The operation principle of spacer sprayer is using high pressure N_2 to atomize spacer solution and using high temperature to dry the spacer. Then the spacers deposit on the glass substrate. The process is shown in Fig. 3-3.

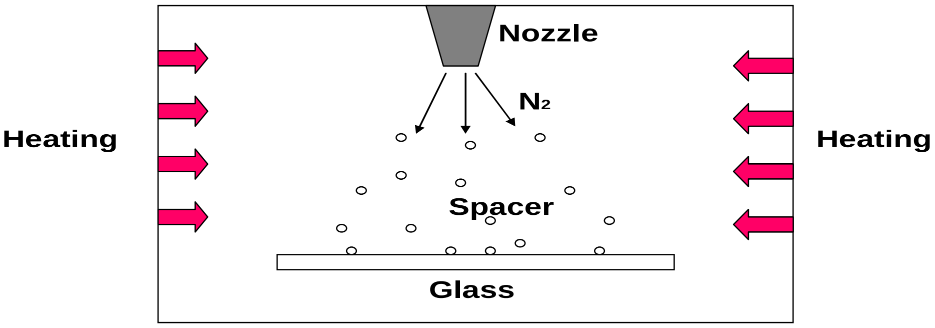


Fig. 3-3. Operation principle of spacer sprayer.

In order to maintain uniform cell gap of LCD, spacer dispensing uniformity and density must be taken into consideration. Besides, some defects of the process like spacer cohesion or spacer break must avoid.

(d) Sealant dispense: Dispenser draw the sealant into special pattern to support top and bottom glass substrates to form a frame of cell to hold liquid crystal. Besides, dispensing Ag sealant can connect the common electrode of top and bottom glass substrate to create electric field between the liquid crystal cells. The process flow of dispenser line is shown in Fig. 3-4.

Fig. 3-4. Process flow of dispenser line.

The sealant break checker can confirm the condition of sealant pattern, such as the position or width of sealant.

(e) Alignment: By use of high precision CCD camera to align the top and bottom glass substrates. Besides, using UV glue to fix the glass substrates.

(f) Hot press: Pump high vacuum to press the sealant to form cell gap of LC, and heat the sealant to harden to form fixed cell gap. The process flow is below:

Align substrates->Pre pump vacuum->First stage hot press->Second stage hot press. In addition, some hot press process parameters are listed in Tab. 3-1.

Tab. 3-1. Process parameters of hot press.

Hot press	First stage(Gap shaping)	Second stage(Sealant hardening)
Purpose	Assembly accuracy	Gap uniformity
Temperature	110~120℃	140~150℃
Pressure	1.0~1.2 kg/cm^2	1.2~1.5 kg/cm^2
Pressure time	320sec	320sec

(g) Liquid crystal injection: After precisely assembly of top and bottom glass substrates, the cell structure is initially finished. In order to inject LC into the cell, usually using "low pressure vacuum injection method". The LC cells are put into vacuum chamber with low pressure (about 3×10^{-3} torr). The vacuum chamber structure is shown in Fig. 3-5. The chamber has a pump to achieve vacuum condition. Besides, the LC container is put on the elevator. Therefore, the LC container can rise to contact LC cells. Then a gas is injected into the chamber. By use of pressure difference between the chamber and the cell, the LC can be injected into the gap. With proper injection pressure and time, the LC can perfectly fill into the cell gap. Finally, UV glue is used to seal the hole of cell gap.

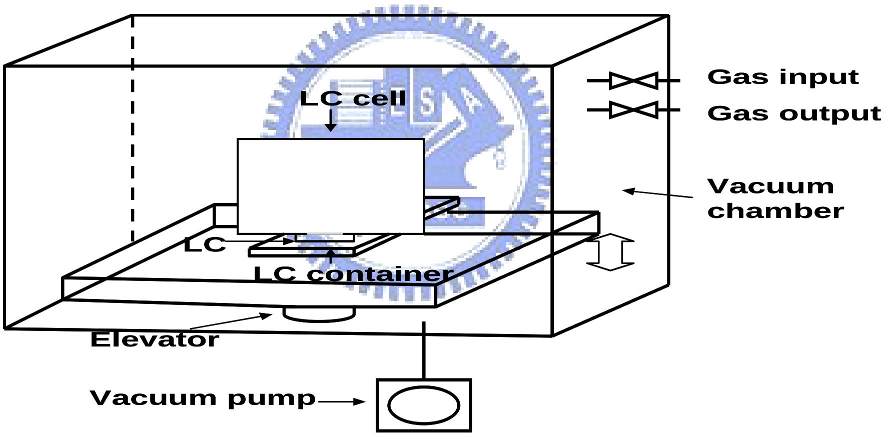


Fig. 3-5. Configuration of LC injection machine.

The LC injection steps are shown in Fig. 3-6. (a) Pump can draw gas out to achieve vacuum condition. (b) With high vacuum condition, LC cell contacts with LC material. (c) A gas is drawn into the chamber to raise the pressure in chamber, thus LC can fill into the cell gap. (d) Resume normal pressure condition, and LC can perfectly fill into the cell gap.

(h) Isotropic: By using heat treatment to activate LC molecules, and cooling rapidly. LC molecules can align correctly on the rubbing PI microgrooves.

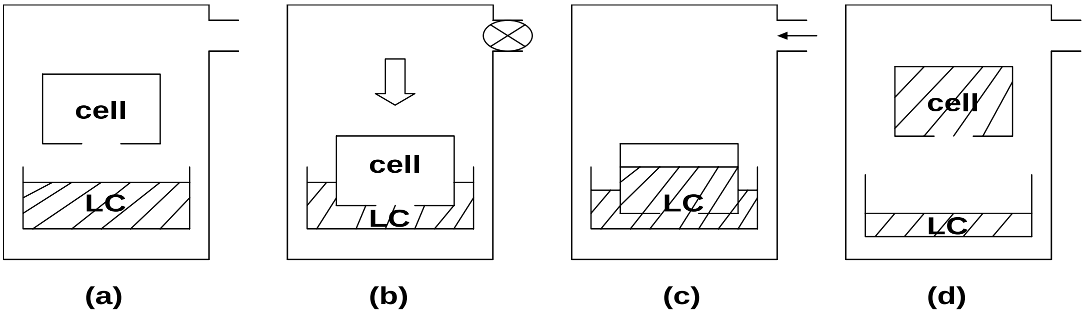


Fig. 3-6. Operation steps of LC injection. (a) Pump gas out to lower pressure in chamber. (b) LC cells contact with LC material. (c) LC material injects into cell gap. (d) Back to normal pressure condition.

Finally, all the cell fabrication steps are organized in Fig. 3-7.

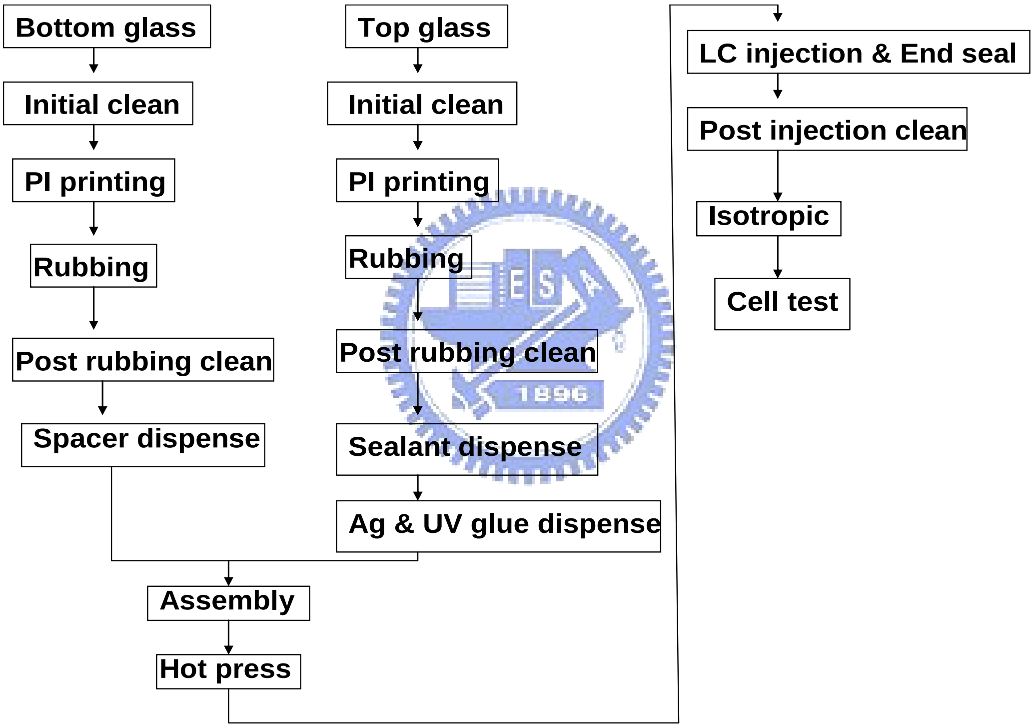


Fig. 3-7. Cell fabrication process steps flow.

3.3 Measurement System

After the preliminary fabrication of LCD test cells, we used a measurement instrument “ConoScope”[28] to measure the electro-optical properties of the test cells.

3.3.1 ConoScope

(a) Introduction:

The ConoScope is a novel measurement system designed for evaluation of the photometric and colorimetric properties of LCDs and other visual display devices versus viewing direction.

The key component of the instrument is a special wide-aperture transform lens with the measuring spot located in its front focal plane. The lens transforms the direction of propagation of elementary of parallel beams coming from the measuring spot in such a way that they converge in the rear focal plane of the lens to form a colorful 2-dimensional transform pattern. In this transform pattern, each element corresponds to one specific direction of light propagation. The transform pattern is projected on an electronic camera (CCD-array detector) and analyzed with respect to intensity (e.g. luminance) and chromaticity.

Spectrum and temporal luminance variations can be measured from “focal plane detection” using a sensitive spectrometer and a fast photometer, respectively.

The ConoScope offers the advantage of simultaneous recording of light intensity or chromaticity versus direction of light propagation, thus drastically reducing the time required for the viewing cone analysis of visual display units.

(b) Applications:

The ConoScope can be used for visual performance evaluation, such as simultaneous measurement of luminance and chromaticity versus viewing direction. Evaluation of measurement data like luminance, contrast ratio, color shift, gray scale and many characteristics can be obtained.

(c) Working principle:

The conoscopic instruments are based on the conoscopic method where a cone of elementary parallel light beams C, transmitted by the sample S (located in the front focal plane of the transform lens L_1) and originating from the measuring spot is collected simultaneously over a large solid angle by the lens L_1, as shown in Fig. 3-8.

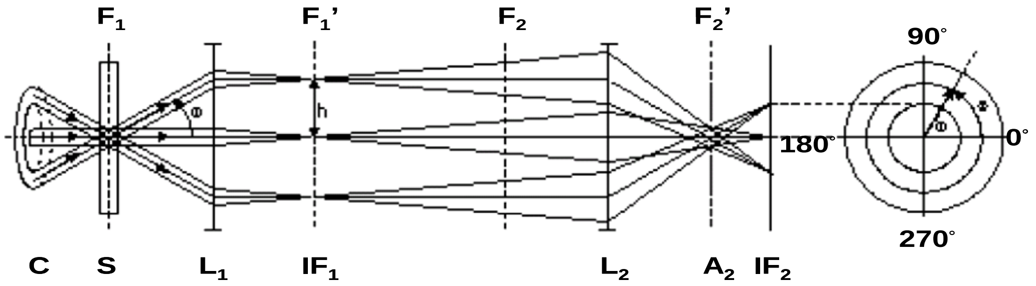


Fig. 3-8. The concept of a conoscopic receiver.

A pattern IF_1 (i.e. conoscopic figure) is generated in the rear focal plane F_1'of the lens L_1 with the intensity of each area element corresponding to the intensity of one elementary parallel beam with a specific direction of light propagation.

The light propagating parallel to the optical axis of the conoscopic receiver forms the center of the circular pattern IF_1 and the beams with constant angle of inclination appear as concentric circles around the center with the radius of the circles being proportional to the inclination.

In the pattern IF_1 the directional intensity distribution of the cone of elementary parallel light beams C is transformed into a two-dimensional distribution of light intensity and color with each location in the pattern corresponding to one direction of light propagation. The second optical system L_2 optionally projects the transform pattern IF_1 on a CCD detector array for evaluation of the directional intensity distribution, as shown in Fig. 3-9.

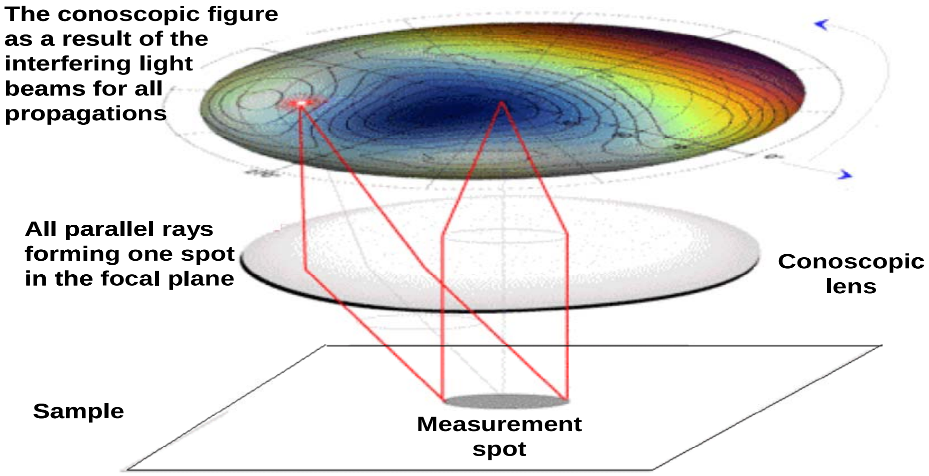


Fig. 3-9. Illustrations of ConoScope detector.

Besides, whenever a display is illuminated under all directions, surface reflections may not be avoided. The ConoScope has introduced a novel illumination device “DRI-2” to illuminate reflective devices under homogenous distributed, diffuse conditions, at the same time avoiding specular reflections.

The mask in DRI-2 is rotating during the measurement, thus generating a conical illumination with a shadowed zone, corresponding to the mask orientation. The system records only the shadowed zone, thus avoiding the specular components as the detector does not measure into the light source.

3.4 Summary

We have introduced conventional LCD cell process in this chapter, such as PI printing, rubbing, spacer dispense, assembly and hot press, etc. The reflective Ch-LCD test cells are fabricated with the conventional cell processes. Besides, the working principles of the LCD measurement instrument “ConoScope” are also introduced. The electro-optical characteristics and performance of the Ch-LCD test cells, such as reflective spectrum, reflectivity, brightness, and contrast ratio were measured by “ConoScope”.

Chapter 4

Simulation Results and Discussions

4.1 Introduction

Based on the principle described in chapter 2, we established a simulation model used to characterize the features of the reflective cholesteric LCD using full spectrum reflective method.

First, the reflective spectra were analyzed for Ch-LCD. Besides, three different kinds of Ch-LC material parameters were utilized to simulate electro-optical properties of Ch-LCD. After that, the configuration of optical components was designed and optimized. Further, various Ch-LC materials and the arrangements of the optical components were also discussed and compared. Finally, Ch-LCD test cells were designed based on the simulation results.

4.2 Simulation Software

The LCD simulation tool “DIMOS”, developed by autronic-MELCHERS GmbH company[28] was used to design the optimized reflective Ch-LCD configuration and simulate its optical properties. It is assumed that the LCD is composed of plane parallel layers where the lateral extensions are much larger compared to the thicknesses of the single layer, thus, we only consider one spatial variation of the layer parameters along the layer normal.

The structure of DIMOS can be divided into three parts: the database, the simulation and visualization. The database holds all the materials, layers, light sources and session data. Users are allowed to define and change materials and layers in database. The simulation comprises all methods for calculation of the static and dynamic director profiles as well as the routines for calculating the optical output quantities. Visualization has several types of representations: data lists, 2d and 3d plots, colored polar diagrams, color chart and so on.

The LC materials in DIMOS are optically uniaxial. In addition to the parameters of the uniaxial medium, the elastic parameters K_1, K_2, and K_3, and the natural pitch are needed.

The cholesteric layer in DIMOS is a uniformly twisted structure with the helical axis normal to the layer surface. The helical pitch is small compared to the thickness so that the layer is periodic. When the light enters the Ch-LC layer, this periodicity causes constructive multiple reflections within a certain wavelength region, the Bragg reflection band.

Besides, the choice of the calculation method is crucial. Among the various methods for calculating LC cell optics, matrix methods are very suitable. DIMOS offers two methods, 4×4 matrix method and 2×2 matrix method. The 4×4 matrix method is the most generic method for multilayer optics[29]. As long as the stack is composed of birefringent homogeneous layers, the calculated quantities like transmittance and reflectance can be well derived[30]. In other words, these results are the exact solutions of Maxwell's equations. Inhomogeneous layers like LC layer are approximated by a series of homogeneous slabs. Since this method takes into account multiple reflections, more or less strong modulations of the reflectance and transmittance curves can be observed.

The 2×2 matrix method neglects multiple reflections making the calculation simpler and faster[31]. Only single reflections at the interfaces are considered. A disadvantage of this method is that the light reflected from the entire multilayer is not considered. An important fact is that the transmittance curves are fairly smooth. This is because multiple reflections are neglected. Multiple reflections play an important role in periodic media like cholesteric LC. 2×2 matrix method is not suitable for the type of materials.

4.3 Simulation of Reflective Spectrum

To simulate the reflective spectrum of green band cholesteric LC, we use the following LC material parameters: n_o=1.509, n_e=1.698, ε_o=4.1, ε_e=14.3, pitch=0.343um, cell gap d=5um. DIMOS allows a spatial varying pitch by defining pitch values at certain levels within the layer. We want to define a uniformly twisted cholesteric layer with 15 full turns. Uniform twist is described by constant pitch of Ch-LC.

Next we define the variation range for optics calculations. Define only one variation: the wavelength of reflective light from 400nm to 700nm with 1 nm increment.

The simulated reflective spectrum result is shown in Fig. 4-1. From the simulation, we find that the reflection band begins roughly at 510nm and ends at 590nm. The center wavelength of reflected light is 550nm, the green light band. Because the birefringence of Ch-LC material is small, the reflected light usually has narrow band reflection. Therefore, it is only a monochromic display. From the simulation, the bandwidth of reflected light is about 80nm.

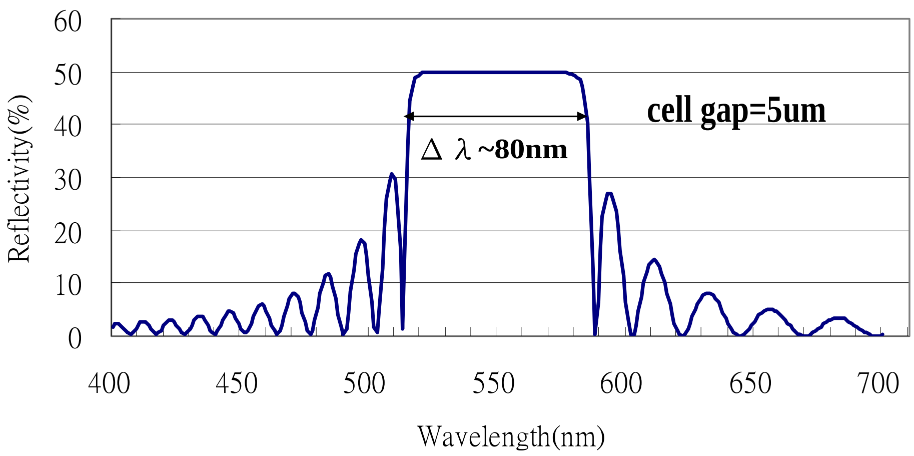


Fig. 4-1. Simulated reflective spectrum of green band Ch-LC. (d=5um)

If we change the cell gap to 10um and 15um, the simulated reflective spectrum results are shown in Figs. 4-2. and 4-3.

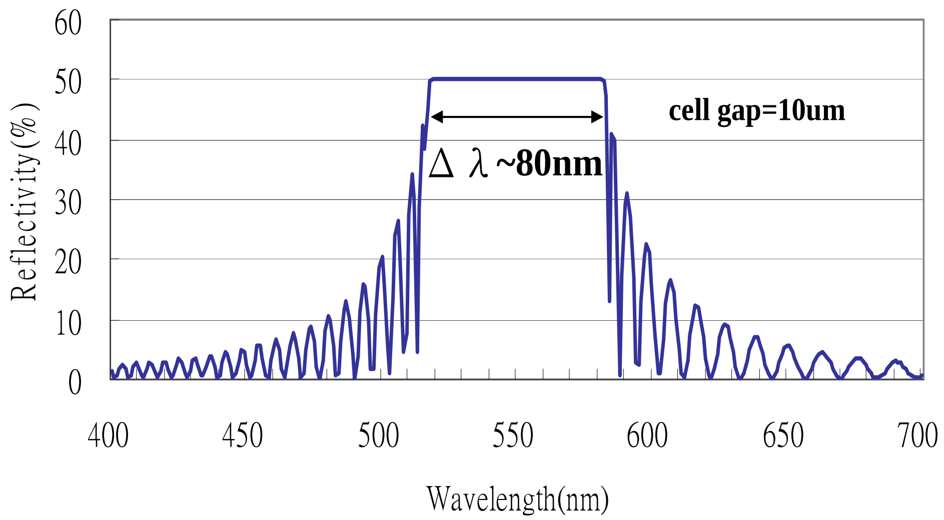


Fig. 4-2. Simulated reflective spectrum of green band Ch-LC. (d=10um)

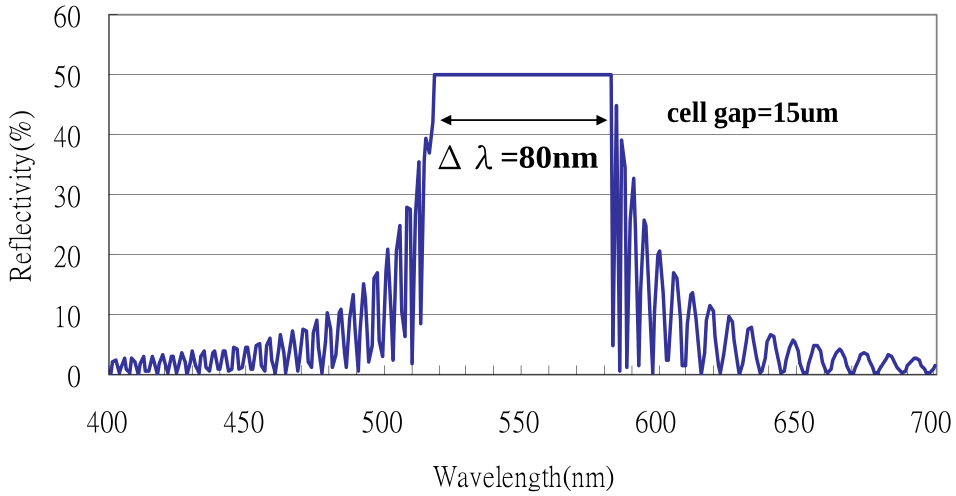


Fig. 4-3. Simulated reflective spectrum of green band Ch-LC. (d=15um)

From these simulations, we find that the reflective spectrum becomes more and more a rectangle as cell gap increases. In other words, the reflected light becomes to focus on central wavelength range. However, bandwidth of reflective spectrum is almost the same. It is still a narrow band reflection. Therefore, increasing cell gap of Ch-LC can not broaden the reflective spectrum greatly.

Afterwards, we try to simulate other reflection band Ch-LC material. We choose reflection band in shorter wavelength range, UV band Ch-LC. We use the following

LC material parameters: n_o=1.5061, n_e=1.6724, ε_o=6.5, ε_e=23.3, pitch=0.126um, cell gap d =5um. We define the variation range for optics calculations: the wavelength of reflective light from 150nm to 250nm with 1 nm increment. The result is shown in Fig. 4-4.

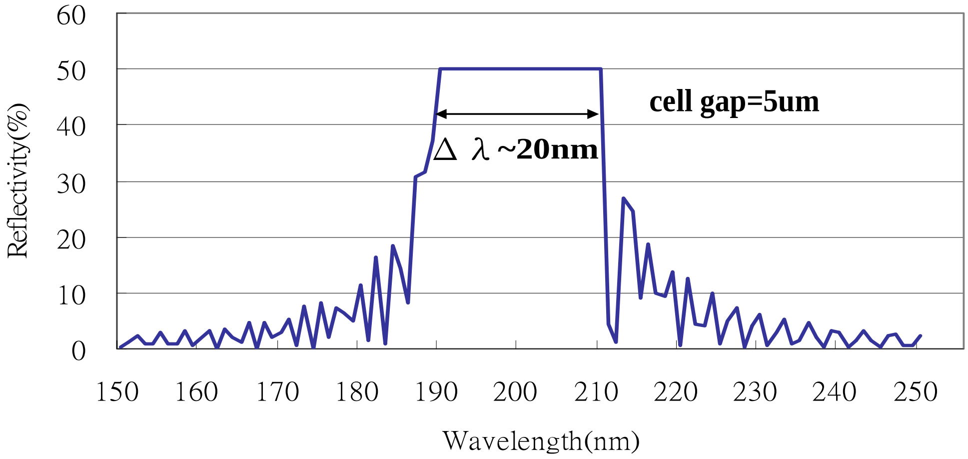


Fig. 4-4. Simulated reflective spectrum of UV band Ch-LC. (d=5um)

From the simulation result, the center wavelength of reflected light is 200nm, the UV light range. The bandwidth of reflected light is about 20nm. For wide band reflection, the performance of UV band Ch-LC is still not suitable.

Thus, we try to simulate other reflection band Ch-LC. We choose reflection band in longer wavelength range, infrared band Ch-LC. We use the following LC material parameters: n_o=1.517, n_e=1.749, ε_o=6.5, ε_e=23.3, pitch=0.459um, cell gap d =5um. We define the variation range for optics calculations: the wavelength of reflective light from 600nm to 900nm with 1 nm increment. The result is shown in Fig. 4-5.

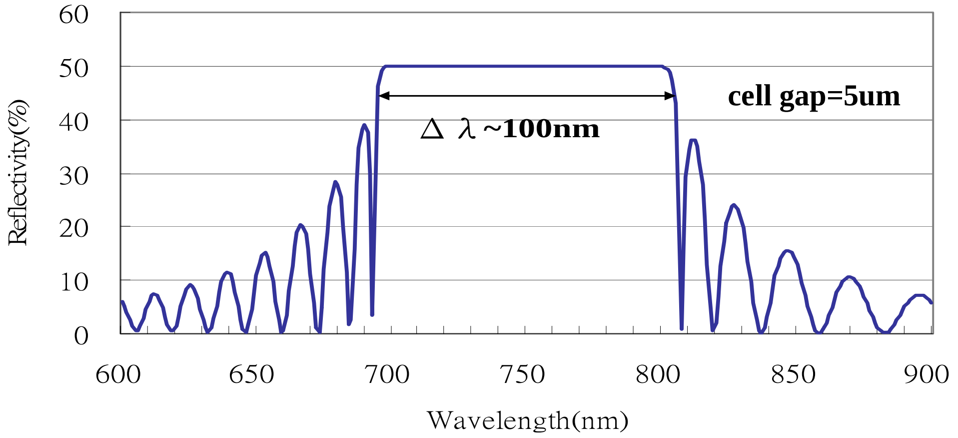


Fig. 4-5. Simulated reflective spectrum of infrared band Ch-LC. (d=5um)

From the simulation result, the center wavelength of reflected light is 750nm, the infrared light range. The bandwidth of reflected light is about 100nm. The bandwidth is larger than UV band Ch-LC and green band Ch-LC. But for wide band reflection, the performance of infrared band Ch-LC is still not suitable.

Narrow band reflection is the intrinsic property of Ch-LC material. Because Ch-LC only reflects specific band of light, and most of other bands are absorbed. Therefore, it is usually monochromic appearance. As described in chapter 2, we proposed a new method "Full Spectrum Reflective Method" to broaden the reflective spectrum in order to fabricate black and white display. Thus, we do some simulations to verify the method.

Conventional Ch-LCD usually utilizes black absorption layer to yield dark state. However, out of selective reflection band light is absorbed. The reflective spectrum is totally determined by Ch-LC. Thus, our new method utilizes reflective layer instead of black absorption layer. Out of selective reflection band light can be reflected by reflective layer to compensate the spectrum of Ch-LC. Besides, the dark state is obtained by the filtration of polarizers. Here we utilize green band Ch-LC material to simulate. The simulation results are shown in Figs. 4-6.(a)(b)(c)(d).

Fig. 4-6(a) is simulated configuration of proposed Ch-LCD.

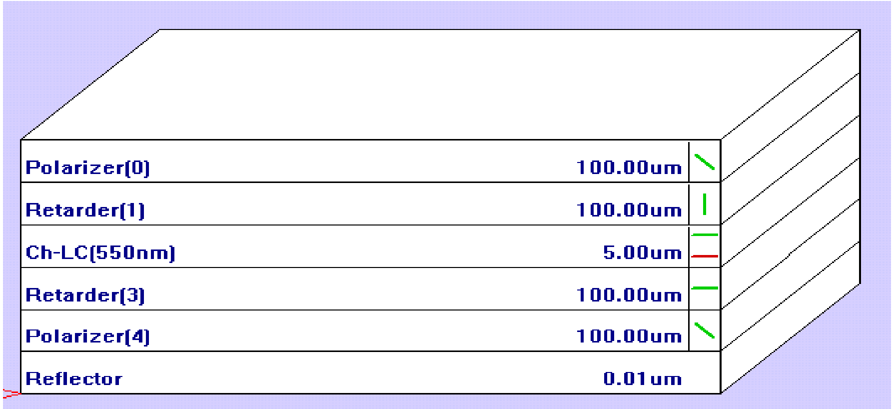


Fig. 4-6(a). Simulated configuration of proposed Ch-LCD.

Fig. 4-6(b) is the simulated spectrum of reflector.

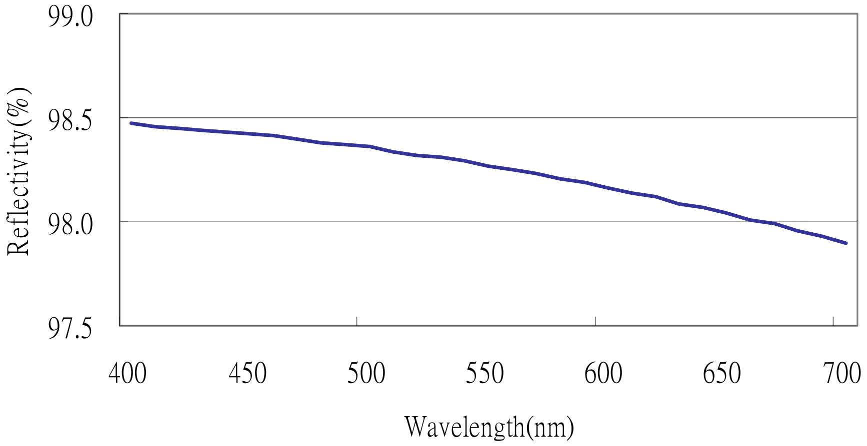


Fig. 4-6(b) The simulated spectrum of reflector.

The reflectivity of the reflector in DIMOS is 98.5%~98% over the visible band range, thus, the reflector can be assumed an ideal wide band reflector.

The spectrum of proposed Ch-LCD is simulated in Fig. 4-6(c). From the result, we can find the spectrum covers three parts: 400nm~500nm (blue light), 500nm~600nm (green light), and 600nm~700nm (red light). But higher reflectivity is in red light range. Therefore, the color of the Ch-LCD is slightly shifted to red light range. The color distribution is illustrated in CIE 1931 color coordinate, as shown in Fig. 4-6(d).

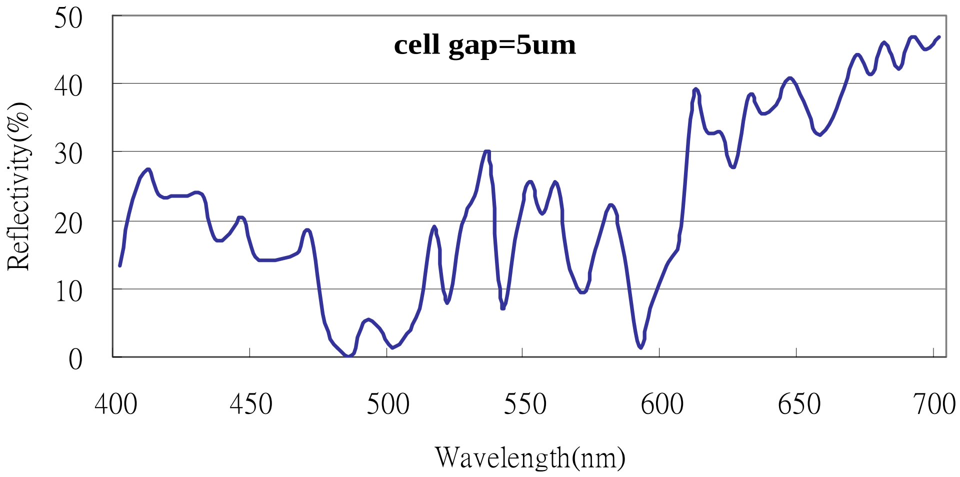


Fig. 4-6(c). Simulated reflective spectrum of green band Ch-LCD. (d=5um)

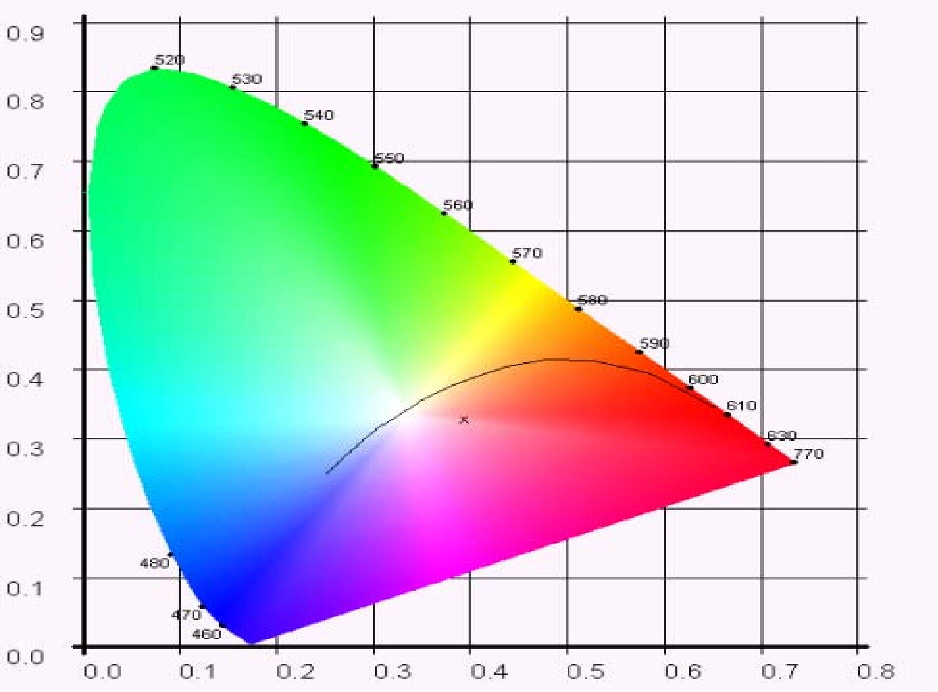


Fig. 4-6(d). Color profile of green band Ch-LCD.

Then we utilize UV band Ch-LC material to simulate full spectrum reflective method. The simulated Ch-LCD configuration is shown in Fig. 4-7. The simulated spectrum is shown in Fig. 4-8.and the color distribution is illustrated in CIE 1931 color coordinate, as shown in Fig. 4-9.

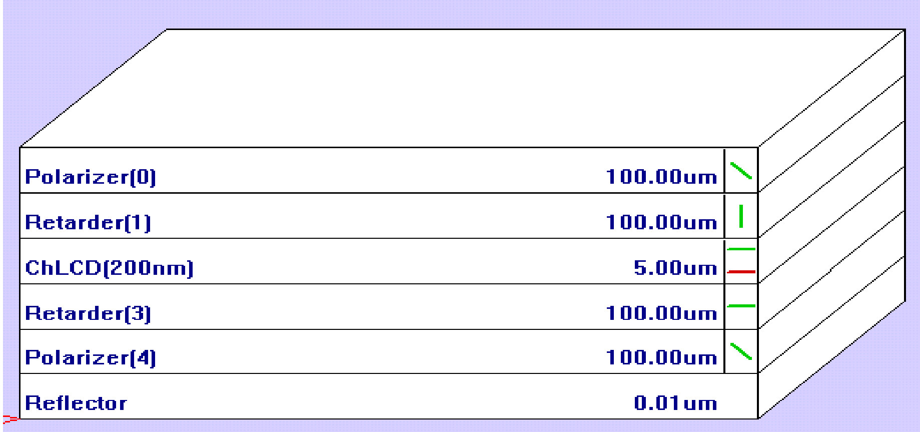


Fig. 4-7. Simulated configuration of UV band Ch-LCD.

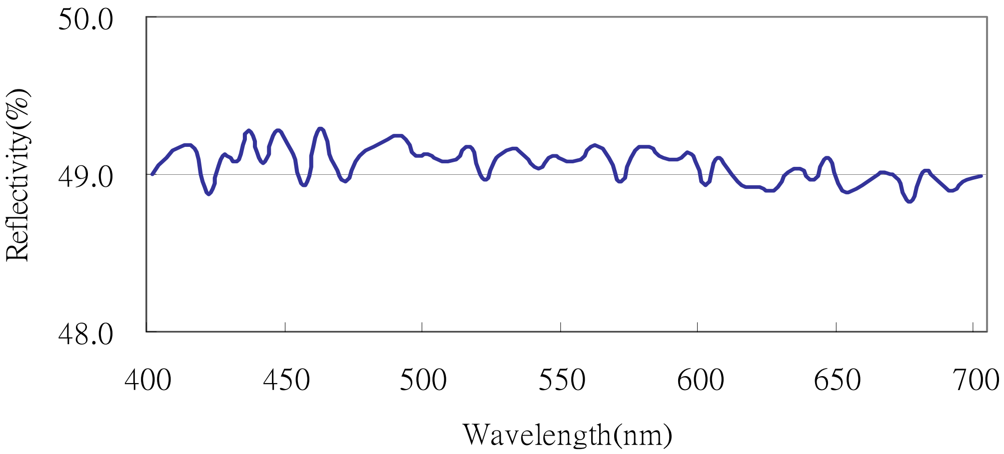


Fig. 4-8. Simulated reflective spectrum of UV band Ch-LCD.

From the simulation results, the reflective spectrum can cover all visible light range and has high reflectivity. Thus, it can display white images in bright state, as shown in Fig. 4-9. Though the UV band LC reflects invisible light, out of selective reflection band light is reflected by the wide band reflector. In other words, the spectrum is mainly determined by the wide band reflector instead of Ch-LC material. By this method, the spectrum can be broadened greatly to become black and white reflective Ch-LCD.

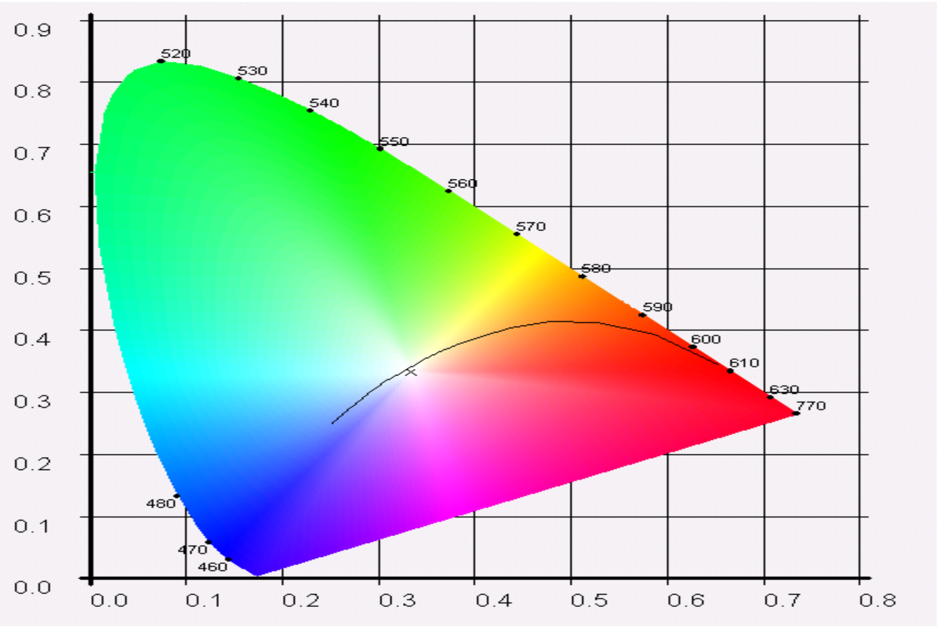


Fig. 4-9. Color profile of UV band Ch-LCD.

Besides, we also simulate infrared band Ch-LC with this method. The simulated configuration is shown in Fig. 4-10.and the simulated spectrum is shown in Fig. 4-11. Besides, the color profile of the display is illustrated in CIE 1931 color coordinate, as shown in Fig. 4-12.

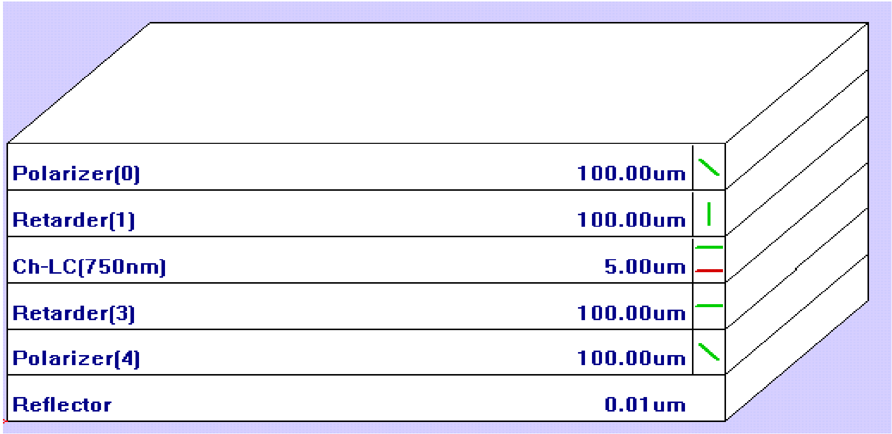


Fig. 4-10. Simulated configuration of infrared band Ch-LCD.

From the simulated reflective spectrum, reflective light covers all visible light range and the reflection peak is in the green light range. Therefore, the color of the display is slightly shifted to the green light range, as shown in Fig. 4-12. Besides, the reflectivity of the infrared band Ch-LCD is about 20%, which is lower than UV band and green band Ch-LCD.

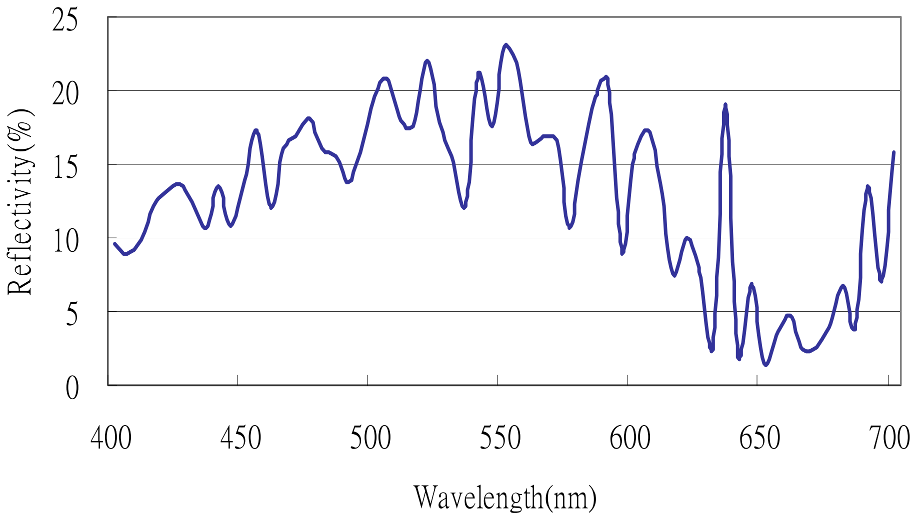


Fig. 4-11. Simulated reflective spectrum of infrared band Ch-LCD.

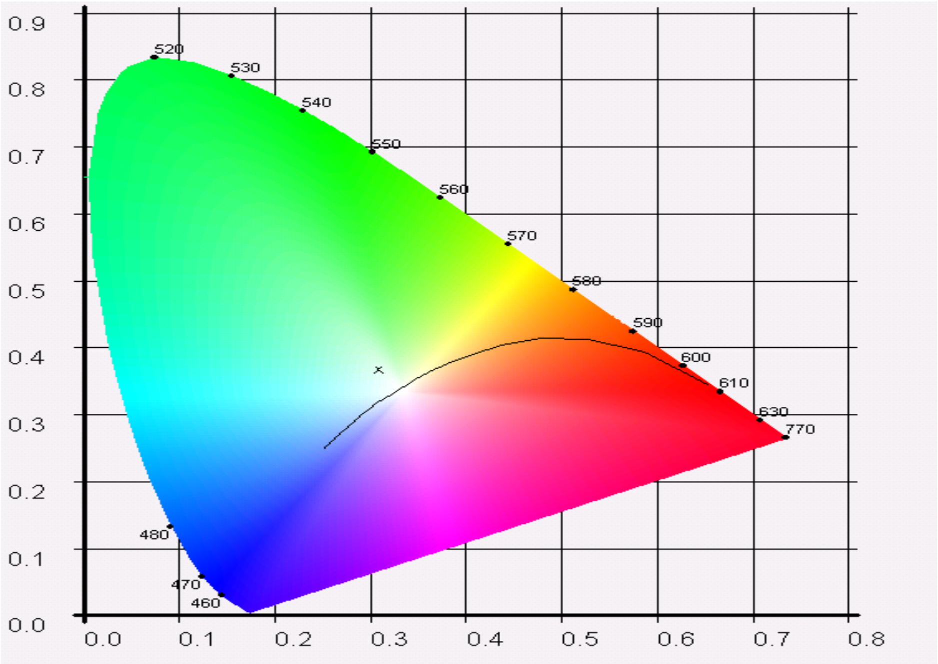


Fig. 4-12. Color profile of infrared band Ch-LCD.

4.4 Summary

Finally, we make some comparisons and conclusions about full spectrum reflective method with green light band, UV light band, and infrared light band different Ch-LC materials. Our objective is to have a broad band reflection of Ch-LCD in bright state. In DIMOS simulation, the full spectrum reflective method can actually broaden the reflective spectrum of Ch-LCD. In term of reflective spectrum, the proposed method with UV band Ch-LC material has the widest reflection band, which can cover all visible light bands. As a result, The Ch-LCD can appear white images instead of monochromic images. Therefore, this method can improve image quality of Ch-LCD. In addition, reflective brightness is an important issue for reflective display application. In term of reflectivity, the reflectivity of conventional Ch-LCD is close to 50%. However, full spectrum reflective method utilizes extra polarizers and retardation films to compensate the reflective spectrum. Thus, the reflectivity of this method is lower than conventional Ch-LCD’s. Among the three Ch-LC materials, UV band Ch-LC material has the highest reflectivity of 49%, which is much close to reflectivity of conventional Ch-LCD’s. Therefore, full spectrum reflective method with UV band Ch-LC material can achieve broad band reflection and high reflectivity. The comparisons of the new method with the three Ch-LC materials are listed in Tab. 4-1.

Tab. 4-1. Comparisons of three Ch-LC performances.

	Green band Ch-LC	UV band Ch-LC	Infrared band Ch-LC
Spectrum	Narrow band	Full visible band	Broad band
Color	Slight shift to red light	White appearance	Slight shift to green light
Reflectivity	About 25%	About 49%	About 20%

Chapter 5

Experimental Results and Discussions

5.1 Introduction

According to previous described fabrication in chapter 3 with conventional LCD fabrication process, reflective Ch-LCD test cells are fabricated. We choose 3 inch in diagonal and 0.7mm thickness glass substrate. In term of rubbing process, we utilize four different conditions: no rubbing, top and bottom rubbing (parallel direction), top and bottom rubbing (reverse direction), bottom rubbing. The cell gap of test cell is expected to 3.5um to lower the driving voltage of Ch-LC.

Besides, we utilize different reflection band Ch-LC materials. MDA-00-3461 Ch-LC (central wavelength=550nm, green light band) and MDA-02-3885 Ch-LC (central wavelength=200nm, UV light band) were provided by MERCK company[32]. RDP-95155ChBZ1 Ch-LC (central wavelength=750nm, infrared light band) was provided by DAINIPPON INK AND CHEMICALS company[33]. The detail specifications of the three Ch-LC materials are listed in Tab.5-1.

Tab. 5-1. Specifications of three Ch-LC materials.

	Green band Ch-LC	UV band Ch-LC	Infrared band Ch-LC
Clearing Point	92℃	51℃	82℃
Optical Anisotropy	$\Delta n=0.2578$ $n_o=1.5140$ $n_e=1.7718$	$\Delta n=0.1663$ $n_o=1.5061$ $n_e=1.6724$	$\Delta n=0.232$ $n_o=1.517$ $n_e=1.749$
Dielectric Anisotropy	$\Delta\varepsilon=11.2$ $\varepsilon_0= 4.4$ $\varepsilon_e=15.6$	$\Delta\varepsilon=16.8$ $\varepsilon_0= 6.5$ $\varepsilon_e=23.3$	$\Delta\varepsilon=10.8$ $\varepsilon_0= 4.3$ $\varepsilon_e=15.1$

5.2 Measurement Results

We utilize measurement instrument "ConoScope" to measure the electro-optical properties of the fabricated Ch-LCD test cells. The reflectivity, reflective spectrum, color appearance, viewing angle, contrast ratio, and voltage response were measured and will be discussed.

5.2.1 Measured Reflective Spectrum and Reflectivity

First, we measured green band Ch-LCD with conventional and full spectrum reflective method, respectively. The test cells are both no rubbing process. Fig. 5-1. shows the measurement results, (a) is the spectrum of conventional method and (b) is spectrum of full spectrum reflective method. The central wavelength of green band Ch-LCD is 560nm and the bandwidth is about 80nm if 20% reflectivity is acceptable. The peak reflectivity is about 50%. With the proposed method, the bandwidth can increase to 150nm. However, the peak reflectivity is decreased to 40%, because the absorption effect of extra polarizers and retardation films.

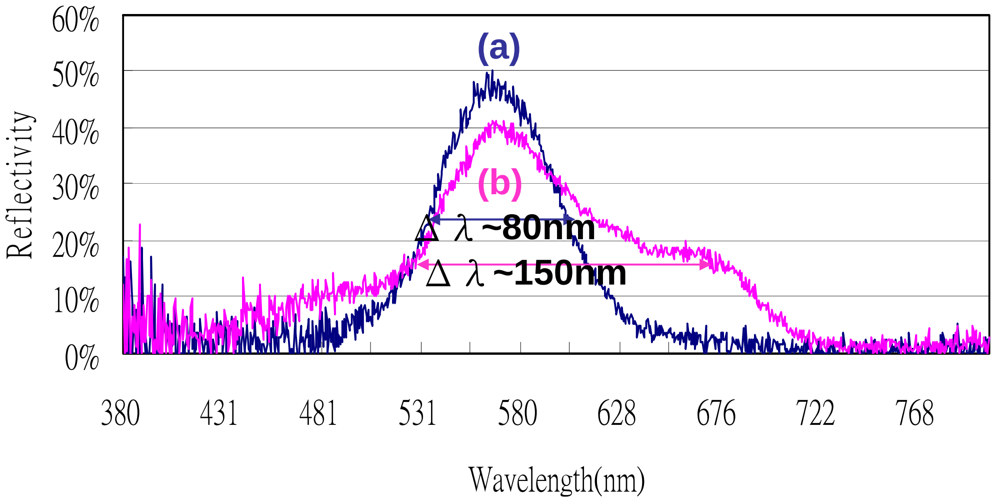


Fig. 5-1. Measured reflective spectrum of (a) conventional and (b) full spectrum reflective method.

Second, we measured UV band Ch-LC with full spectrum reflective method. We use four different rubbing conditions test cells. Fig. 5-2. shows the spectrum of no rubbing condition. From the measurement, the spectrum with 20% reflectivity covers from 470nm to 690nm. It is a wide band reflection to display white images in bright state. Besides, the reflectivity is about 50%, which is close to the conventional Ch-LCD with high reflectivity.

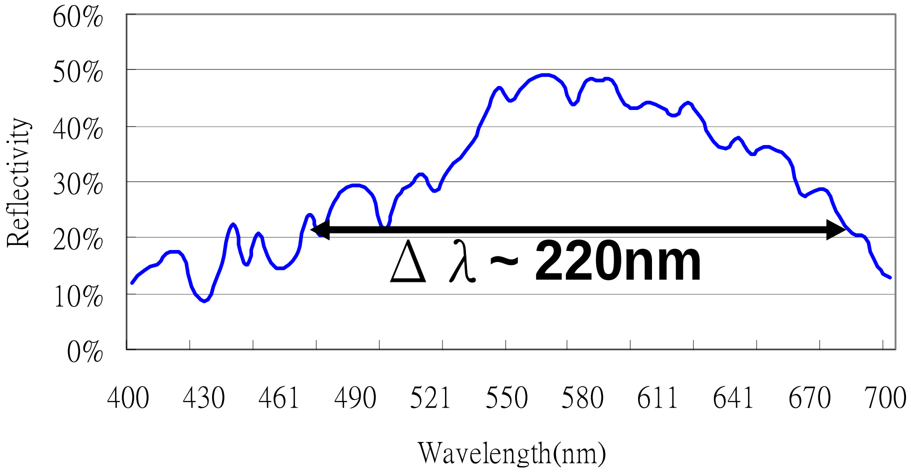


Fig. 5-2. Measured reflective spectrum of UV band Ch-LCD.
(no rubbing condition)

Then we measured reflective spectrum of top and bottom glasses with parallel rubbing direction condition, as shown in Fig. 5-3.

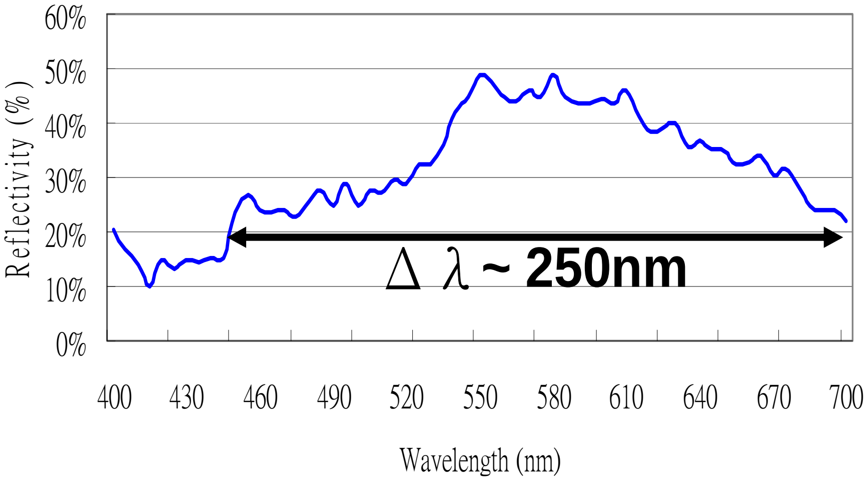


Fig. 5-3. Measured reflective spectrum of UV band Ch-LCD.
(parallel rubbing direction condition)

The reflective spectra of reverse rubbing direction condition and only bottom rubbing condition are shown in Figs. 5-4 and 5-5, respectively.

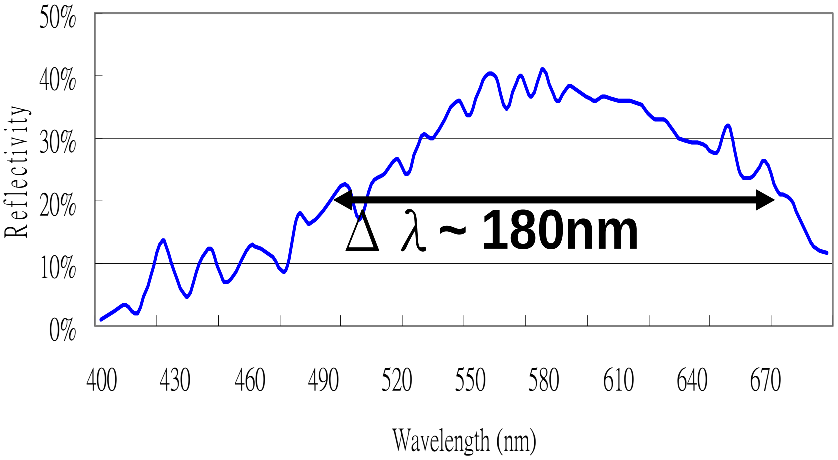


Fig. 5-4. Measured reflective spectrum of UV band Ch-LCD.

(reverse rubbing direction condition)

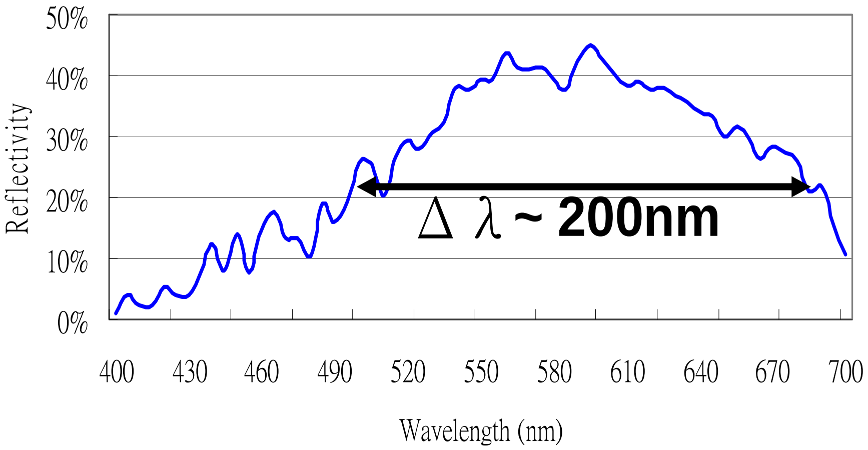


Fig. 5-5. Measured reflective spectrum of UV band Ch-LCD.

(bottom rubbing condition)

Compared with the four rubbing condition, the spectra are all wide band reflection over visible light band. Besides, test cell of both surfaces rubbed with parallel direction has higher reflectivity. Thus, different rubbing conditions can affect the reflective spectrum of the displays. Because the domains in the planar texture of bistable reflective Ch-LCD are created by introduction of defects, which are introduced from the surfaces of the cell structure. The surface of typical Ch-LCD is usually an unrubbed polyimide (PI) alignment layer. The non-homogeneity of the surface results in non-uniform liquid crystal alignment. Therefore, the planar texture has many defects.

These defects reduce the on-axis brightness of the displays as well as the degree of circular polarization. However, the defects play an important role in the viewing angle and the bistability of the display. The viewing angle is increased because of the wide distribution of the helical axes. The reflection from the unrubbed PI layer of the planar texture is diffuse and is nearly lambertian. Therefore, the appearance of the display is close to printed paper. This is a highly desirable property making this kind of display an ideal choice for electronic paper application.

The distribution of the helical axes and the defects are controlled to increase the brightness near the surface normal while maintaining a good viewing angle. A balance is obtained between the defect density, domain size, and distribution. Thus, the result has a brighter texture than conventional bistable planar texture and has a wide viewing angle. The defects control is achieved by rubbing the PI layer.

There are several methods to enhance the brightness of the display. The display can be made by using hybrid alignment, only one of the two PI surfaces is treated. Depending on which surface is treated, near the viewer or farther from the viewer, has an impact on brightness and appearance. When the surface near the viewer is treated, the display has a bright and shiny appearance, but the viewing angle is decreased. However, when the surface away from the viewer is treated, the display is bright and more diffusive appearance.

Rubbing the PI surfaces also can have an impact on the polarization state of the reflected light. Contrary to the conventional thought, the reflected light from a stabilized planar texture, from an unrubbed cell is not actually circularly polarized.

The degree of polarization is quite low. Because there are large number of defects in the planar texture. The scattering from the defects results in reflected light that is not circularly polarized. However, the degree of polarization can be increased by treating the PI layers to reduce the number of defects.

It is instructive to compare the microscopic domain structures that have various rubbing conditions. Three planar texture photographs are shown in Fig. 5-6. Fig. 5-6(a) is for a conventional planar texture with unrubbed surface alignment. Small randomly aligned domains can be clearly seen. Fig. 5-6(b) is the hybrid aligned cell where one surface is a rubbed PI layer and other is an unrubbed PI layer. The photograph is taken from the rubbed side. The small domain structure seems to be better defined. In addition, there are some larger domains spread randomly between the smaller domains. It is these larger domains that increase the degree of circular polarization, and increase the brightness of the display. Fig. 5-6(c) is the photograph for the cell with both surfaces rubbed. It shows large planar domains with very few defects.

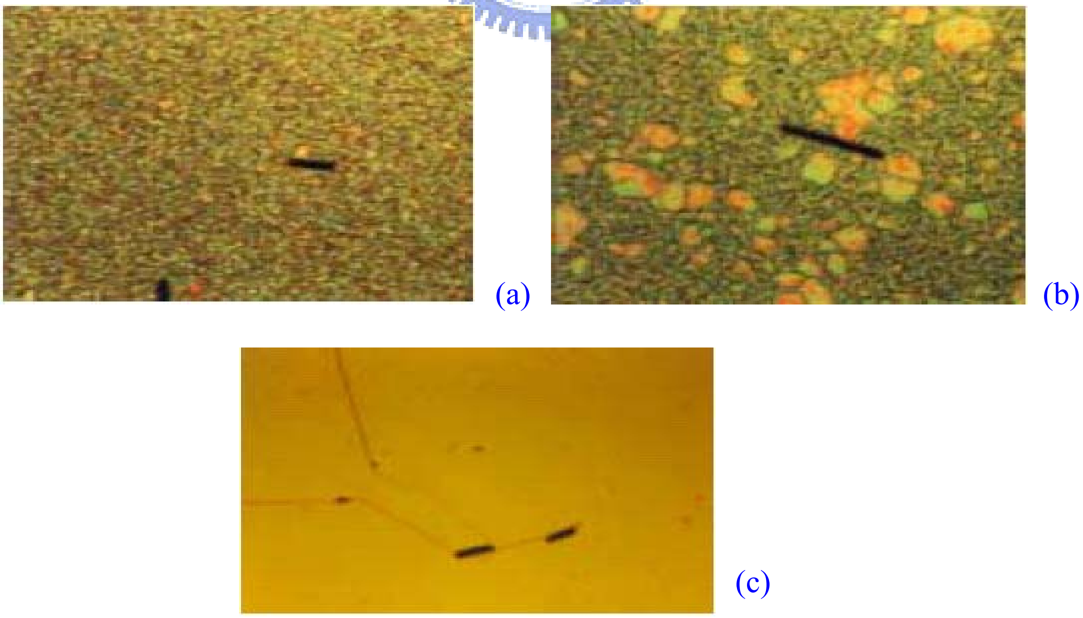

(a)
(b)
(c)

Fig. 5-6. Microscope texture photographs for the planar texture with various rubbing conditions. (a) both surfaces unrubbed (b) only one surface rubbed and (c) both surfaces rubbed.

Besides, we also measured the reflective spectra of Ch-LCD with infrared band LC material with four rubbing conditions. Fig. 5-7 shows the spectrum of no rubbing condition. The peak reflectivity is about 40% and the spectrum can cover all visible light band to reflect white light in bright state. In addition, compared with UV band Ch-LCD, the bandwidth of infrared band Ch-LCD is narrower than UV band Ch-LCD.

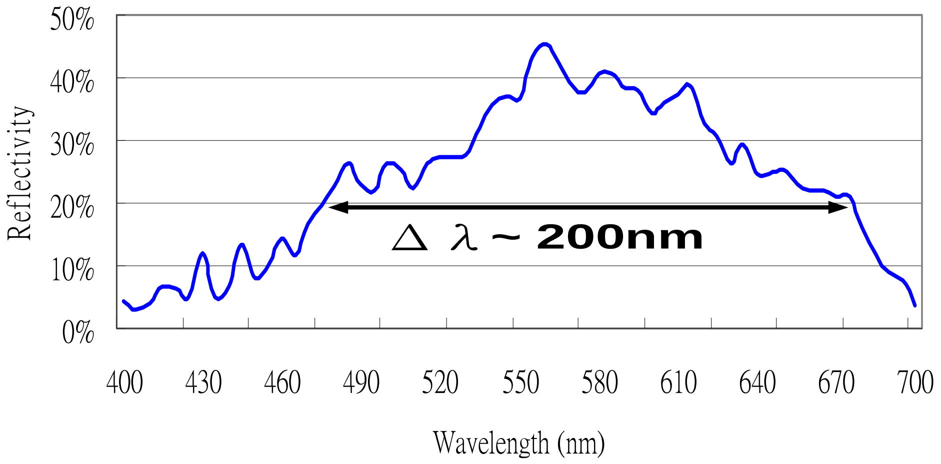


Fig. 5-7. Measured reflective spectrum of infrared band Ch-LCD.
(no rubbing condition)

Other spectra of rubbing condition are shown in Figs. 5-8, 5-9 and 5-10.

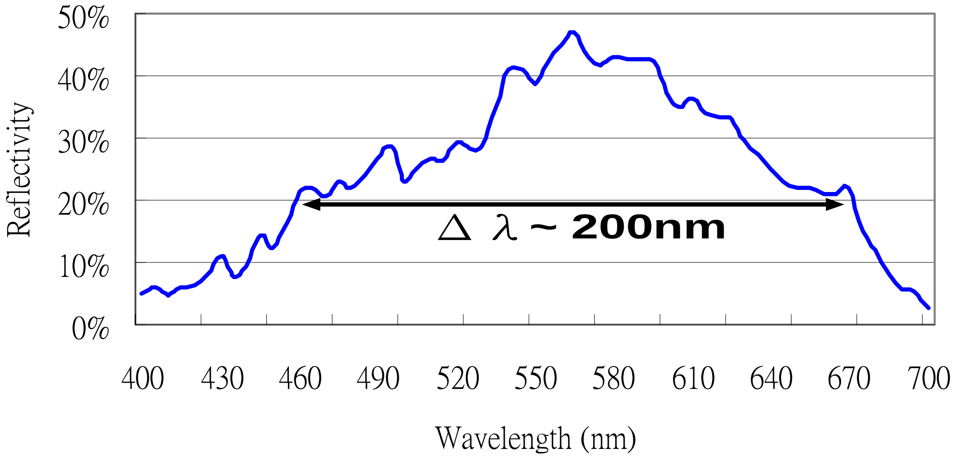


Fig. 5-8. Measured reflective spectrum of infrared band Ch-LCD.
(parallel rubbing direction condition)

As described in UV band Ch-LCD, the reflectivity of rubbed test cell is larger than unrubbed test cell. Thus, by rubbing process, the brightness of Ch-LCD can be improved.

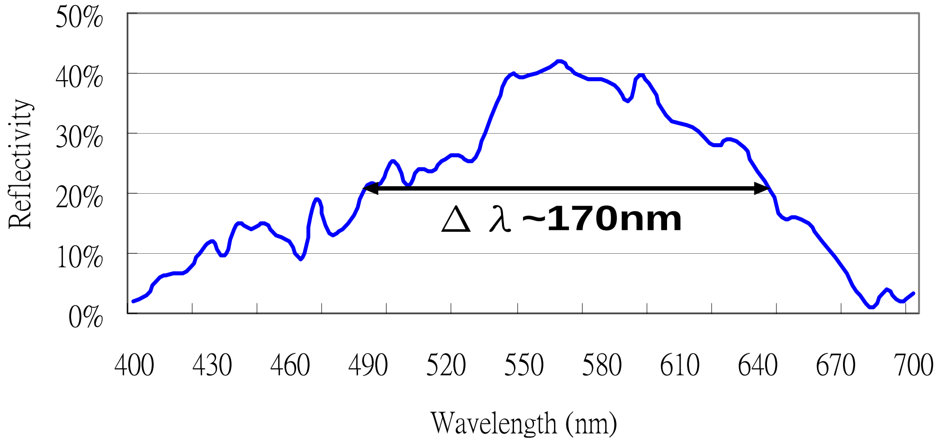


Fig. 5-9. Measured reflective spectrum of infrared band Ch-LCD.
(reverse rubbing direction condition)

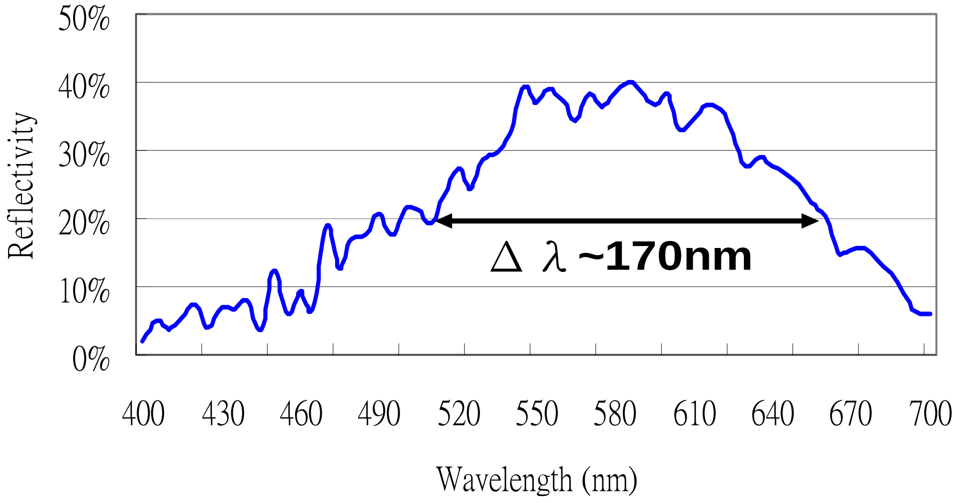


Fig. 5-10. Measured reflective spectrum of infrared band Ch-LCD.
(bottom rubbing direction condition)

Among the four rubbing conditions, test cell of both side rubbed with parallel direction has higher reflectivity about 45% than others.

Conventional cholesteric displays reflect a narrow bandwidth due to the limited birefringence of Ch-LC. However, by utilizing full spectrum reflective method, the spectrum can be broadened to produce wide band reflection. Based on the measurement results, Ch-LCDs with UV band or infrared band LC materials have wide band reflection in bright state. Besides, brightness is an important issue for reflective displays. In term of reflectivity, UV band Ch-LC material of both surfaces rubbed with parallel direction has the highest reflectivity of about 50%, in good agreement with the simulation results shown in chapter 4. Thus, it is wide band reflection with high brightness. Therefore, Ch-LCD can be a black and white display instead of a monochromic display.

In addition, we also use four different rubbing conditions to fabricate the test cells. From the measurement results, both surfaces rubbed with parallel direction condition has the highest brightness. The result agrees with the expectation. Because when LC molecules align well by rubbing process, the defects can be reduced greatly in planar texture. Most of ambient light can be reflected by cholesteric LC molecules instead of scattering. Therefore, the brightness can be improved.

5.2.2 Measured Reflectance distribution

Reflectance is important factor of displays. We use diffuse light source to measure reflectance of the test cells. Fig. 5-11 shows the measurement result of conventional Ch-LCD with green band Ch-LC material

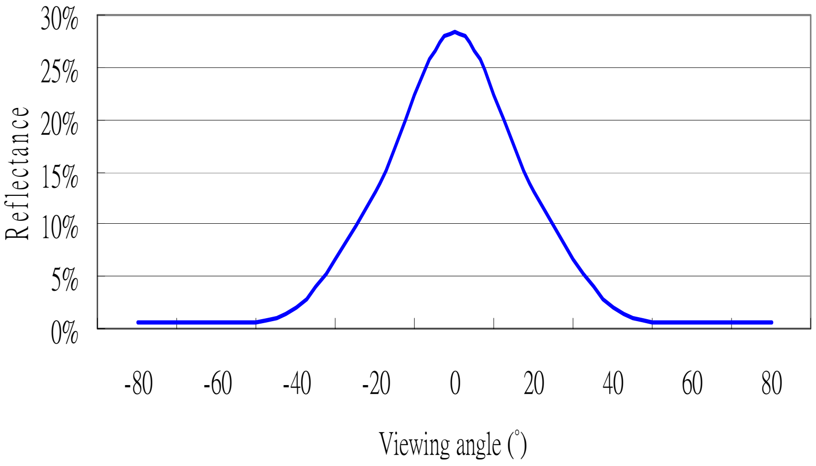


Fig. 5-11. Reflectance distribution of conventional Ch-LCD.

From the measurement results, we find reflectance distribution of conventional Ch-LCD is ±40° and the peak reflectance is 28%. The brightness of light source is about 1900 nits.

We also measured Ch-LCD with full spectrum reflective method. The results are shown in Fig. 5-12.

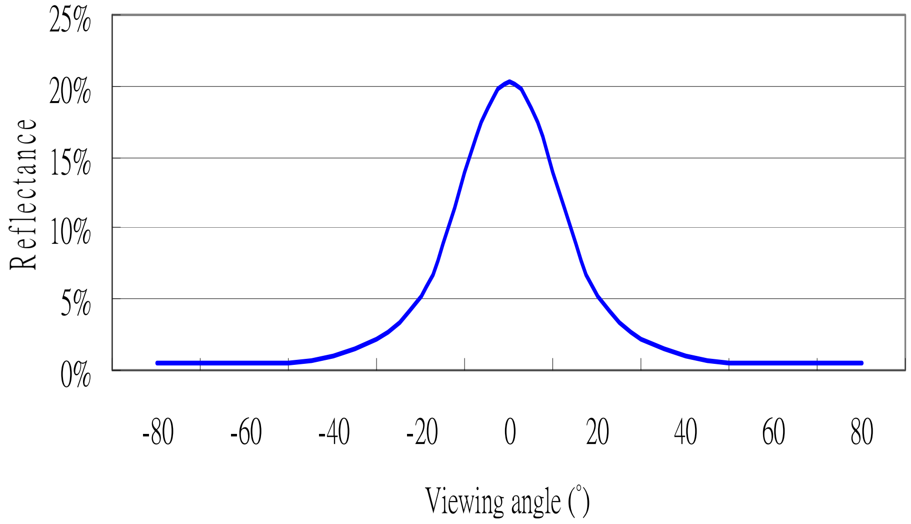


Fig. 5-12. Reflectance distribution of Ch-LCD with full spectrum reflective method.

The reflectance distribution of Ch-LCD with full spectrum reflective method is ±35° and the peak reflectance is 20%. Compared with the reflectance distribution of two methods, the reflectance of full spectrum reflective method is smaller than conventional method, because new method utilizes polarizers and retardation films to yield dark state. Therefore, some light are absorbed by the optical films.

Besides, we also measured full spectrum reflective method with UV band LC material. The results are shown in Fig. 5-13. The test cell is both surfaces rubbed condition. From the measurement results, the reflectance distribution is ±70° and the peak reflectance is 45%. Compared with reflectance distribution of green band and UV band Ch-LC material, the reflectance distribution of UV band Ch-LC material is much larger than green band Ch-LC material. The performance is acceptable for reflective displays application. The reflected light angle distribution of Ch-LCD with reflection in invisible band is larger than reflection in visible light band, because the reflection is mainly determined by the wide band reflector instead of Ch-LC material. Therefore, the reflectance distribution can be improved.

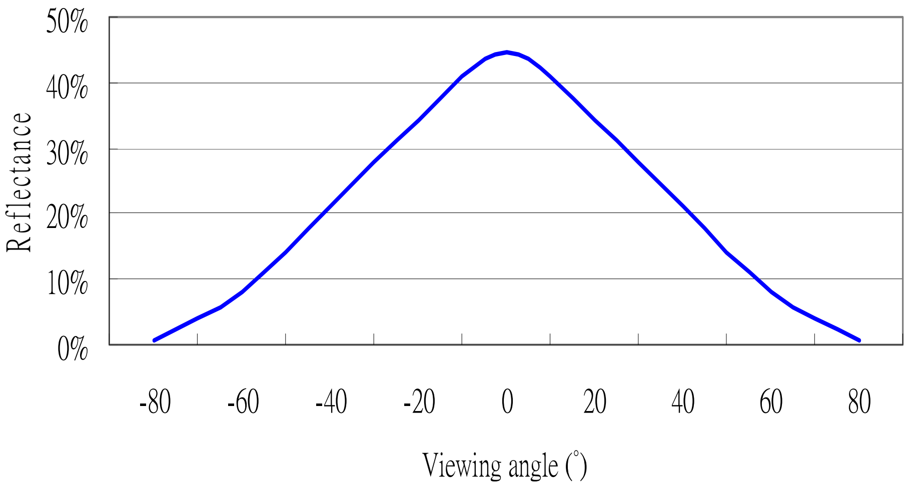


Fig. 5-13. Reflectance distribution of Ch-LCD with UV band Ch-LC material.

The reflectance distribution measurement results of no rubbing test cell are shown in Fig. 5-14.

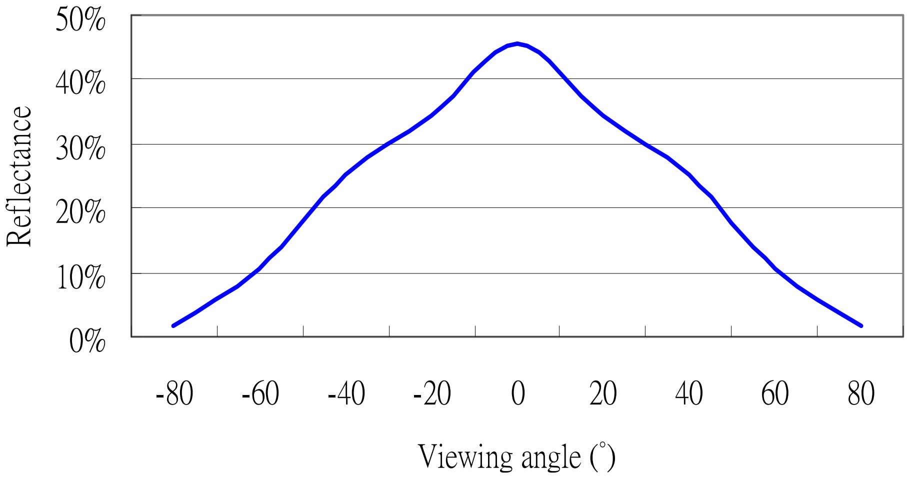


Fig. 5-14. Reflectance distribution of Ch-LCD with UV band Ch-LC material. (no rubbing condition)

Base on the measurement results, the reflectance distribution of unrubbed test cell is similar to the results of both surfaces rubbed test cell.

In addition, the measured reflectance distribution results of Ch-LCD with infrared band Ch-LC is shown in Fig. 5-15. The test cell is no rubbing.

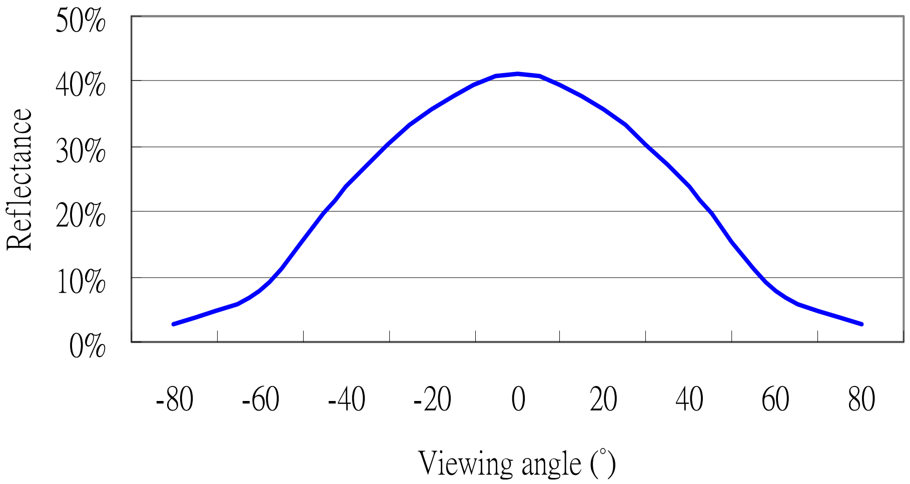


Fig. 5-15. Reflectance distribution of Ch-LCD with infrared band Ch-LC material. (no rubbing condition)

From the measurement results, the angle distribution is ±80° and the peak reflectance is 40%. Besides, we also measured Ch-LCD with infrared band Ch-LC with both surfaces rubbed condition, and the results are shown in Fig. 5-16.

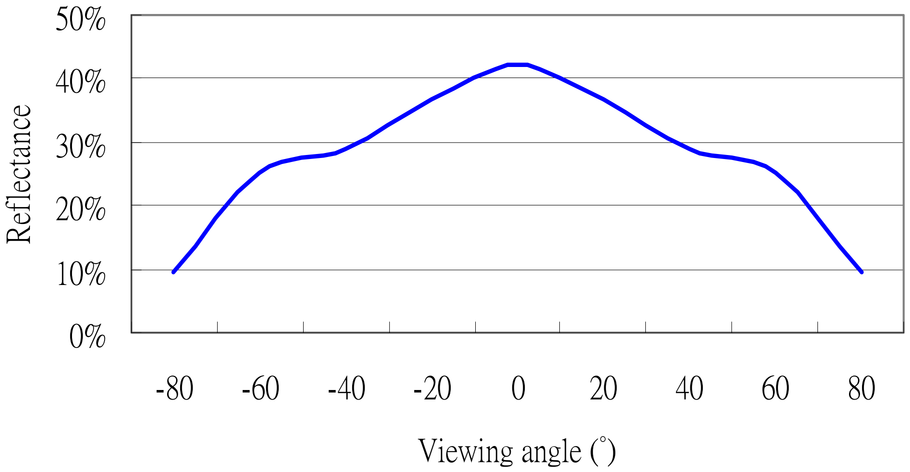
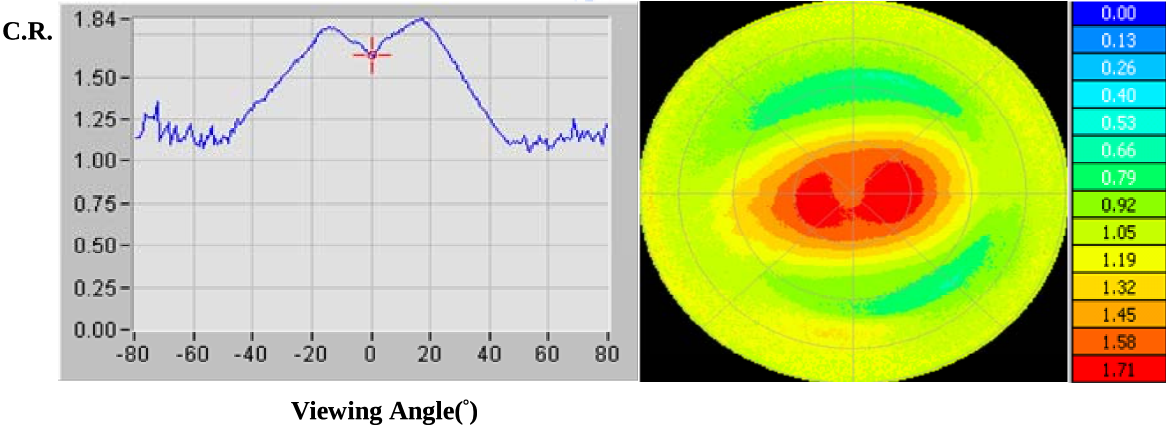


Fig. 5-16. Reflectance distribution of Ch-LCD with infrared band Ch-LC material. (both surfaces rubbed condition)

So far, we have measured reflectance and angle distribution of Ch-LCD with green band, UV band, and infrared band Ch-LC materials. Several observations in the last few paragraphs have shown that reflectance and angle distribution of UV band or infrared band are larger than conventional Ch-LCD. Above all, Ch-LCD with UV band LC has the highest reflectance of 45%, and Ch-LCD with infrared band Ch-LC has the widest angle distribution of ±80°. These measurement results lead to the conclusion that Ch-LCD with reflection in invisible band Ch-LC material has high reflectance and wide angle distribution properties. The performances of Ch-LCD are good enough for reflective display products applications.

5.2.3 Measured Contrast Ratio

Contrast ratio (C.R.) is also an important factor of displays. C.R. is defined by the brightness of bright state divides into the brightness of dark state. We measured the C.R. of the test cells with three different Ch-LC materials. Figs. 17 (a) and (b) show the C.R. distribution of conventional Ch-LCD with green band Ch-LC, respectively.



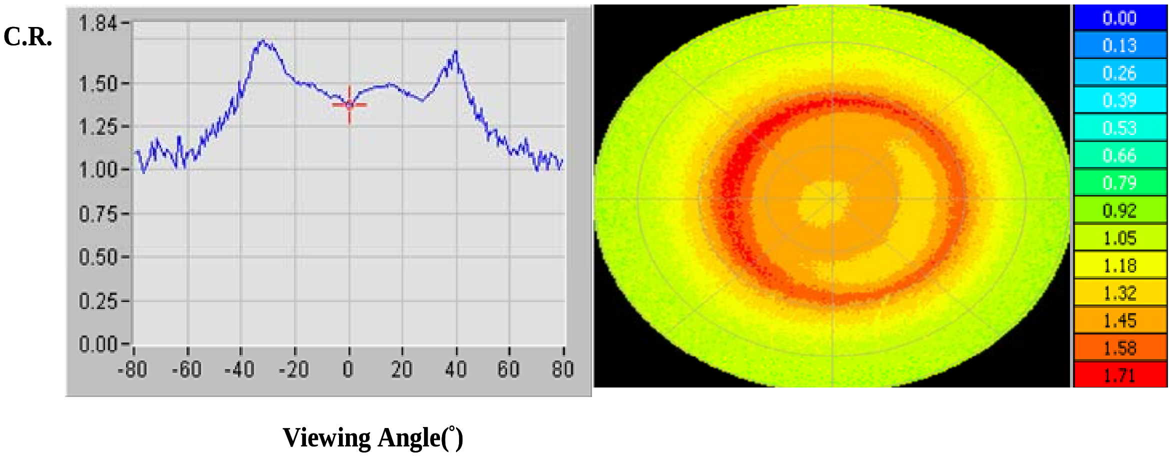
(a) (b)

Fig. 5-17 (a) C.R. cross-section distribution and (b) C.R. distribution of conventional Ch-LCD.

The measurement results were that the C.R. of conventional Ch-LCD was about 1.8 within viewing angle ±40°, which is very low for usage. The reason for poor C.R.

of conventional Ch-LCD is narrow band reflection resulting in monochromic display.

The measured C.R. of Ch-LCD with full spectrum reflective method is shown in Figs. 5-18 (a) and (b), respectively.

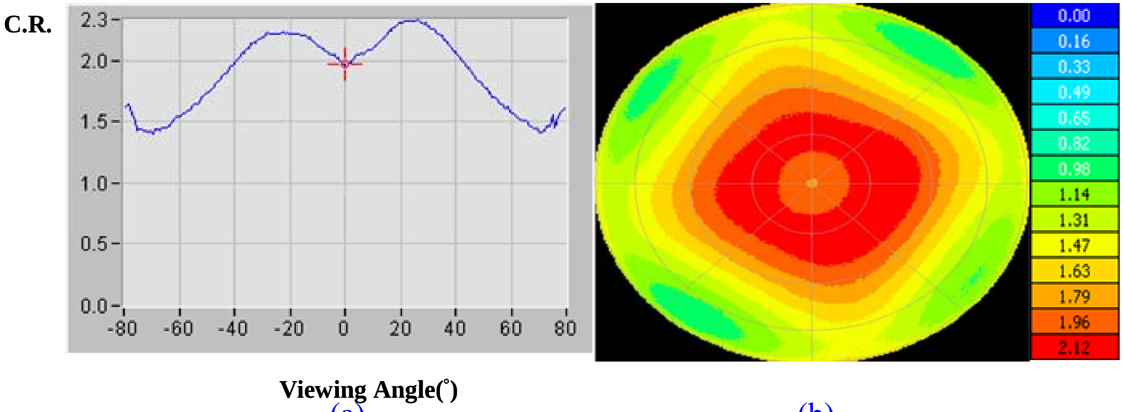


(a) (b)

Fig. 5-18 (a) C.R. cross-section distribution and (b) C.R. distribution of Ch-LCD with full spectrum reflective method.

Compared the C.R. of conventional Ch-LCD and full spectrum reflective method, the results are almost the same. One explanation for the result may be that full spectrum reflective method with green band Ch-LC can not yield wide band reflection in bright state. In other words, it is still a monochromic display. Therefore, the C.R. does not improve a lot.

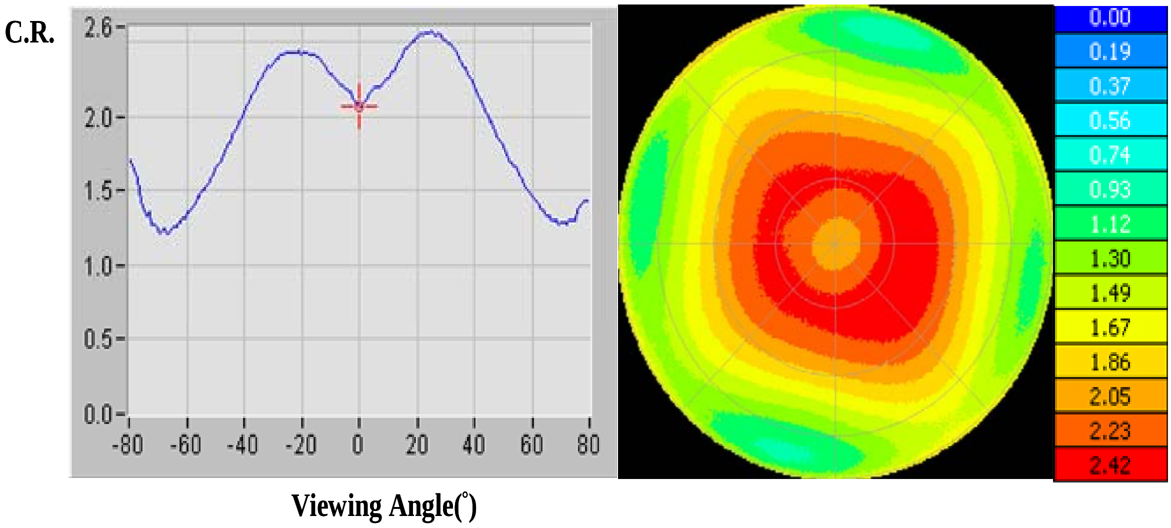
The C.R. of Ch-LCD with UV band Ch-LC is shown in Figs. 5-19 (a) and (b), respectively.



(a) (b)

Fig. 5-19 (a) C.R. cross-section distribution and (b) C.R. distribution of Ch-LCD with UV band Ch-LC.

From the measurement result of no rubbing condition test cell, the C.R. is about 2 within viewing angle ±40°. In addition, we also measured C.R. of both surfaces rubbed test cell. The result is shown in Figs. 5-20 (a) and (b), respectively.



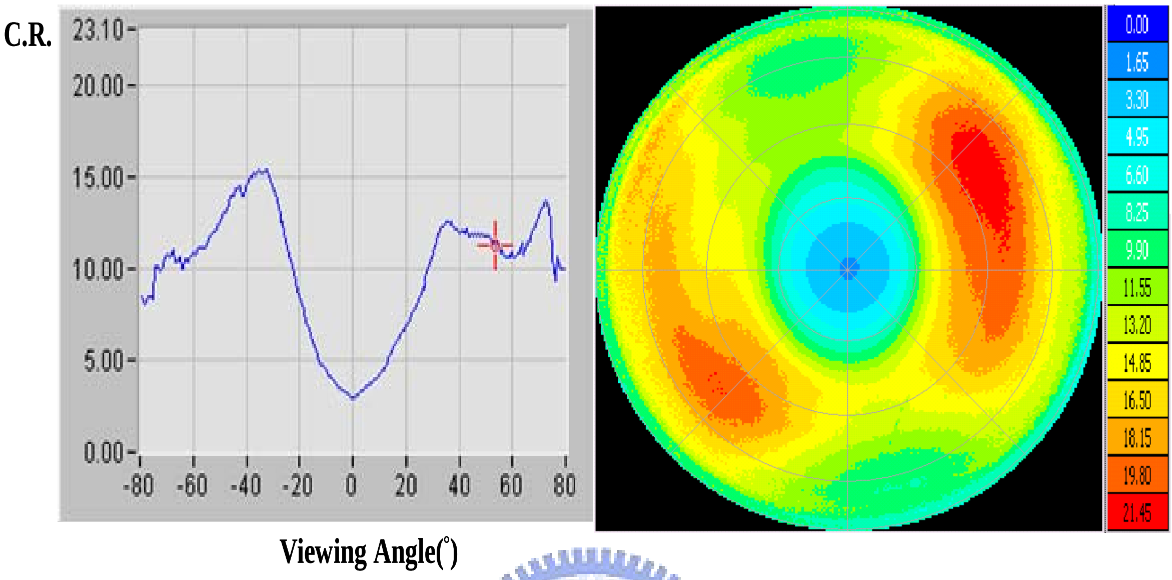
(a) (b)

Fig. 5-20 (a) C.R. cross-section distribution and (b) C.R. distribution of Ch-LCD with UV band Ch-LC. (both surfaces rubbed condition)

Based on the measurement results, it can be concluded that the C.R. of no rubbed and both surfaces rubbed conditions are almost the same. Besides, the C.R of UV band Ch-LCD is higher than green band Ch-LCD. There are good reasons for thinking that UV band Ch-LCD can have wide band reflection in bright state thus the brightness can be improved. However, the dark state of full spectrum reflective method is not as good as conventional method using black absorption layer. Therefore, the C.R. can not improve significantly.

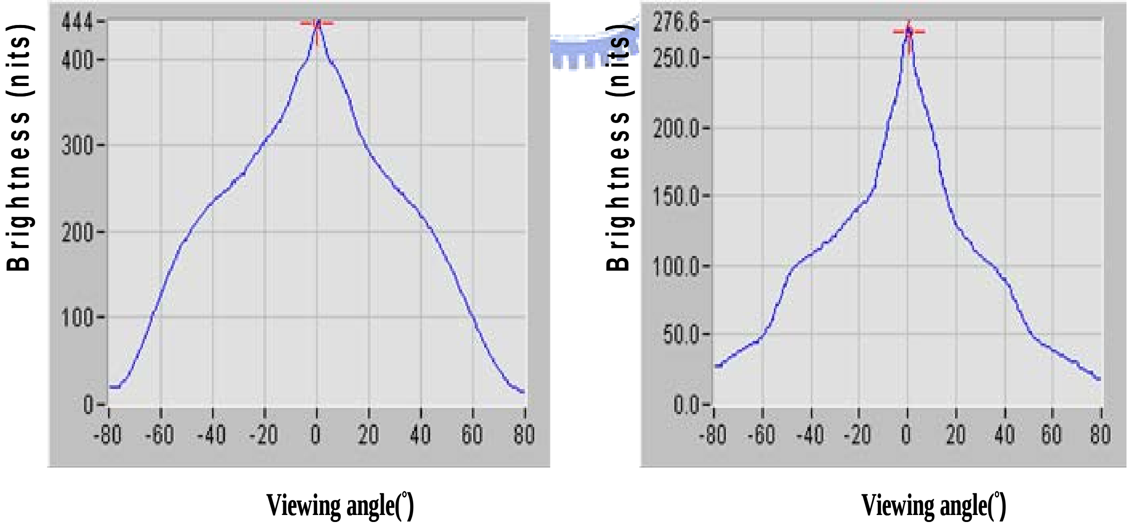
We also measured the C.R. of infrared band Ch-LCD, and the result is shown in Figs. 5-21 (a) and (b), where the C.R. of infrared band Ch-LCD is about 10-15 within viewing angle ±20°~ ±80°. The C.R. is much higher than green band or UV band Ch-LCD. Based on the brightness measurement result above, the brightness of UV band and infrared band Ch-LCD are almost the same. However, the C.R. of infrared band Ch-LCD is much higher than UV band Ch-LCD. Accordingly, the infrared band

Ch-LCD may have darker state than UV band Ch-LCD. In order to verify the result, we also measured the dark states of them. The results are shown in Figs. 5-22 (a) and (b), respectively.



(a) (b)

Fig. 5-21 (a) C.R. cross-section distribution and (b) C.R. distribution of Ch-LCD with infrared band Ch-LC. (no rubbing condition)



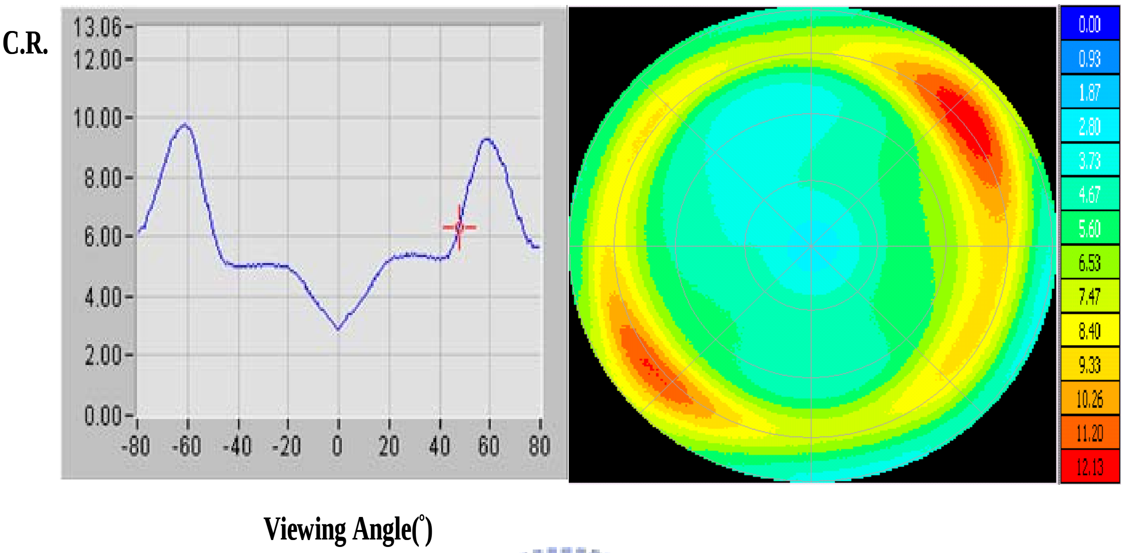
(a) (b)

Fig. 5-22. (a) Dark state of UV band Ch-LCD and (b) Dark state of infrared band Ch-LCD.

Based on the results of Figs. 5-22 (a) and (b), there are sufficient evidences to show that the dark state of infrared band Ch-LCD is actually darker than UV band

Ch-LCD. Therefore, the darker state results in higher C.R. of infrared band Ch-LCD.

In addition, we also measured infrared band Ch-LCD with both surfaces rubbed condition. The results are shown in Figs. 5-23 (a) and (b), respectively.



(a) (b)

Fig. 5-23 (a) C.R. cross-section distribution and (b) C.R. distribution of Ch-LCD with infrared band Ch-LC. (both surfaces rubbed condition)

From the measurement results, we find that the C.R. of infrared band Ch-LCD with both surfaces rubbed condition is about 5-10 within viewing angle ±20°~ ±80°.

So far, we have seen the measured C.R. of three different Ch-LC materials. Observations have shown that Ch-LCD with full spectrum reflective method has higher C.R. than conventional Ch-LCD. Above all, Ch-LCD with infrared band Ch-LC material has the highest C.R. about 10-15. These measurement results lead to the conclusion that Ch-LCD with full spectrum reflective method not only has wide band reflection, but also has high C.R. than conventional method.

5.2.4 Measured Voltage Response

Voltage response is also an important property of displays. Therefore, we measured the curve of reflectance versus voltage of the Ch-LCD test cells. The measurement result of green band Ch-LCD is shown in Fig. 5-24. From the result, the

Ch-LCD initially has about 23% reflectivity at zero voltage. When applying voltage is larger than 12V, the reflectivity would decrease with increasing voltage. When applying voltage about 16V, the image switches to dark state. Thus, the threshold voltage of the Ch-LCD is about 16V. When applying voltage is larger than 26V, the reflectivity would increase with increasing voltage. When apply voltage about 30V, the image recovers to bright state. In other words, the image can be switched states between 12V to 30V.

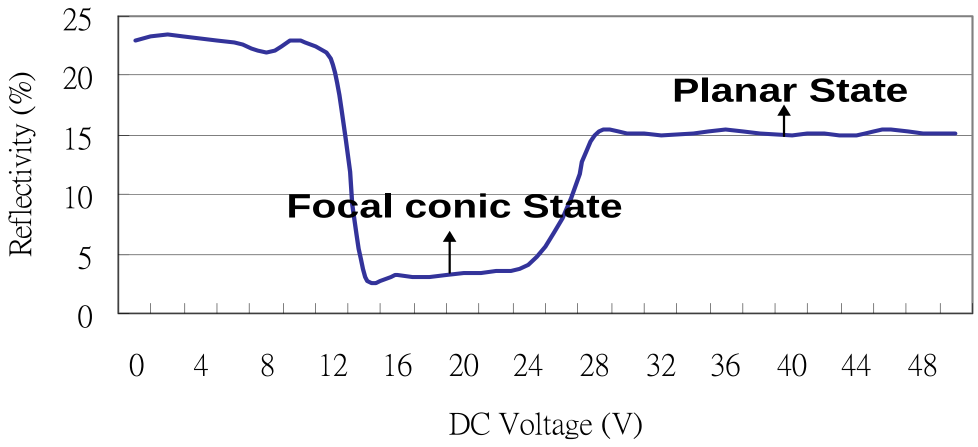


Fig. 5-24. Reflectance versus DC voltage curve of green band Ch-LCD.

Besides, the voltage versus reflectance curve of UV band Ch-LCD is shown in Fig. 5-25.

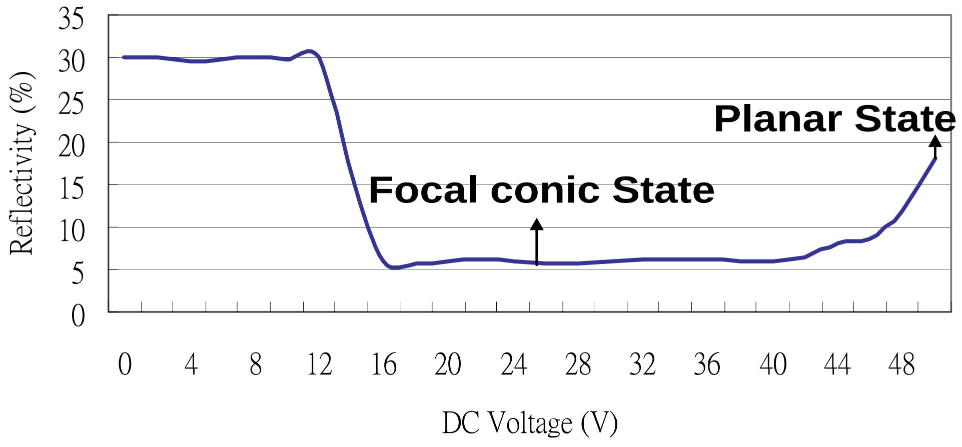
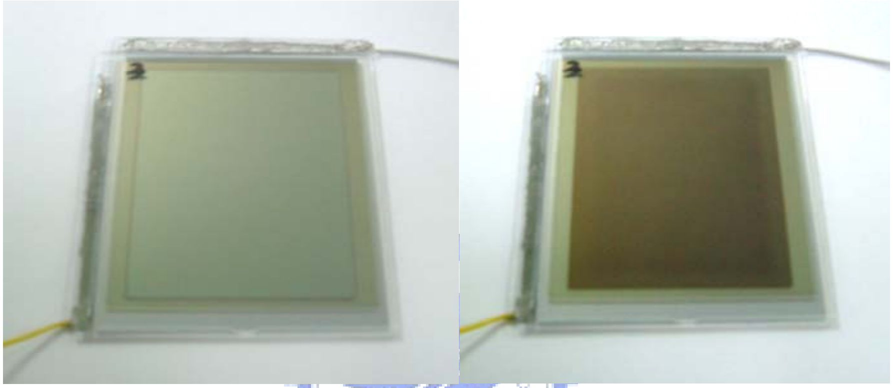


Fig. 5-25. Reflectance versus DC voltage curve of UV band Ch-LCD.

From the results, the threshold voltage of the Ch-LCD is about 18V and recover voltage to bright state is about 50V. The photographs of the bright state and the dark state of the display are shown in Figs. 5-26.(a) and (b), respectively. Compared with the result of green band Ch-LCD, the operation voltage of UV band Ch-LCD is larger than green band Ch-LCD. For the reason stated in chapter 2, the operation voltage is reversed to the reflected light wavelength of Ch-LC. Because of the wavelength of UV band Ch-LC is shorter than green band Ch-LC, thus the operation voltage of UV band Ch-LC is larger than green band Ch-LC.



(a) (b)

Fig. 5-26. The photographs of UV band Ch-LCD (a) bright and (b) dark state.

In addition, the DC voltage versus reflectance curve of infrared band Ch-LCD is shown in Fig. 5-27.

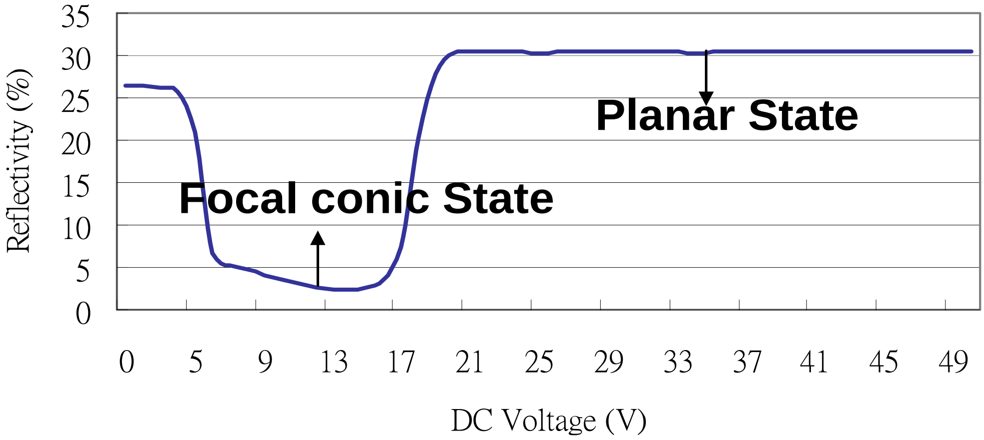
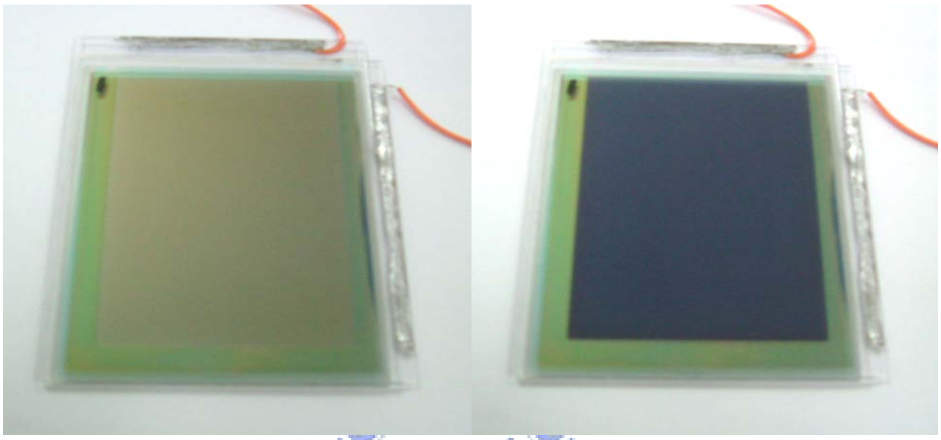


Fig. 5-27. Reflectance versus DC voltage curve of infrared band Ch-LCD.

When applying voltage is larger than 4V, the reflectivity decreases with increasing voltage. When apply voltage about 12V, the image switches to dark state. Thus, the threshold voltage of the Ch-LCD is about 12V and recover voltage to bright state is about 22V. The photographs of the bright state and the dark state of the display are shown in Fig. 5-28, respectively.



(a) (b)

Fig. 5-28. The photographs of infrared band Ch-LCD (a) bright and (b) dark state.

The lower operation voltage makes infrared band Ch-LCD compatible with standard driver IC. The operation voltage of infrared band Ch-LCD is much lower than green band or UV band Ch-LCDs. For the reason given above, longer reflected light wavelength of infrared band Ch-LC, resulting in lower operation voltage. Low voltage operation is important for practical applications. Therefore, infrared band Ch-LCD is more suitable for applications.

5.3 Future Application - Transflective Ch-LCD

Purely reflective displays have poor performance in low ambient lighting conditions, consequently, auxiliary lighting is required. A transflective display is usually the most elegant solution. A transflective display can be used in a transmissive mode with a backlight and also in a purely reflective mode without the backlight. It is well known that bistable Ch-LCD is usually used in a fully reflective mode. However, with proper design, Ch-LCD can be used in a fully reflective mode as well as a fully transmissive mode. This greatly enhances the usefulness of the cholesteric display technology by enabling its use in low ambient lighting conditions.

The schematic illustration of the transflective Ch-LCD is shown in Fig. 5-29.

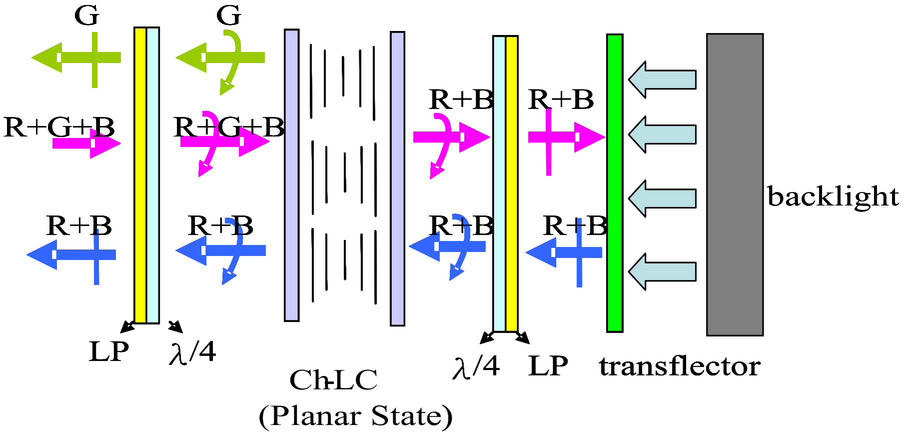
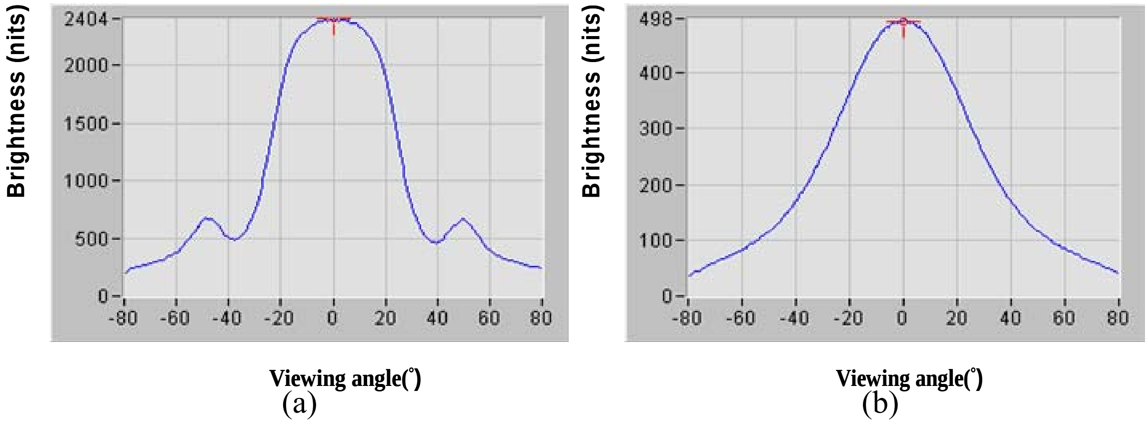


Fig. 5-29. Schematic illustration of the transflective Ch-LCD.

The operation principle of the transflective Ch-LCD has already stated in chapter 2, thus we only show the measurement results here. We use standard CCFL as the backlight. The brightness distribution of the backlight and transmitted light brightness of the transflector are shown in Figs. 5-30. (a) and (b), respectively. We can find the peak brightness of the backlight is about 2400 nits and transmitted light brightness of the transflector is about 500 nits. Therefore, the transmittance of the transflector is about 20%.



Figs. 5-30. (a) Brightness of the backlight and (b) Transmitted light brightness of the transflector.

In reflective mode, the backlight is off and the display is just like reflective Ch-LCD as described before. We use UV band Ch-LCD sample here. The measured brightness and viewing angle distribution is shown in Fig. 5-31.

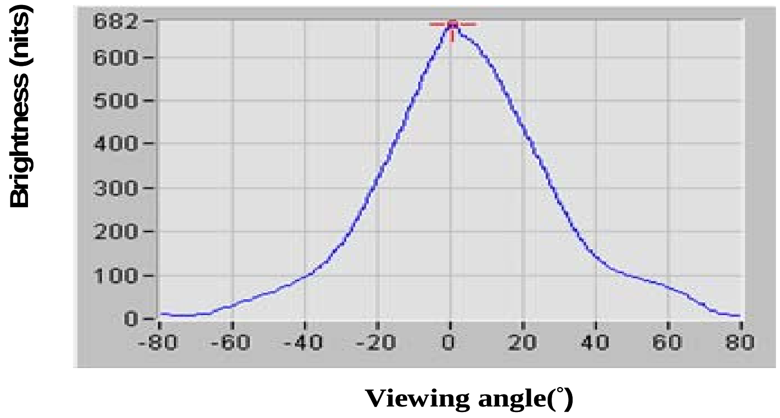


Fig. 5-31. Brightness distribution of reflective mode.

From the result, we find the brightness of the reflective mode is lower than pure reflective Ch-LCD as measured before, due to that the transflector film is not a perfect reflector. Thus, some light transmits through the film instead of reflection by the film. However, in bright ambience, the brightness of the display is sufficient.

The C.R. of the display in reflective mode is about 2, as shown in Fig. 5-32.

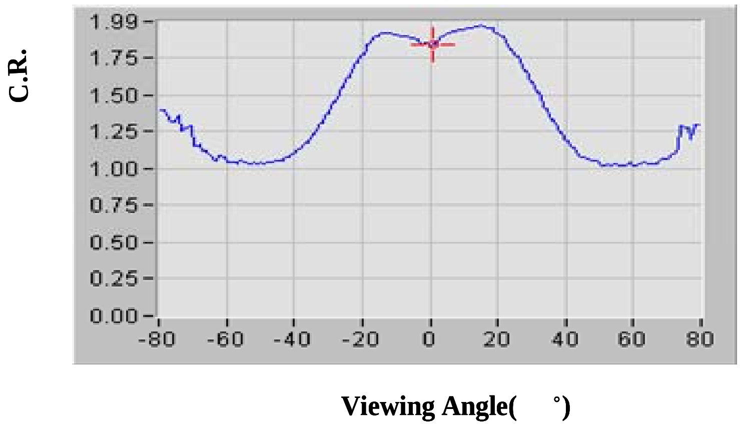
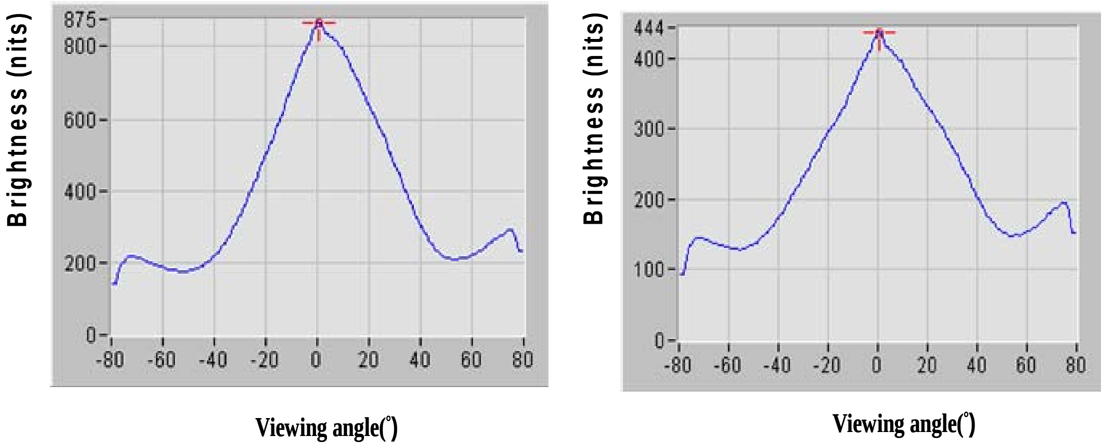


Fig. 5-32. C.R. distribution of reflective mode.

In dark ambience, the display works in transmissive mode, and the backlight turns on. When the display is in the planar state, the light from the backlight is reflected by the Ch-LC of planar state. The light is then absorbed by the polarizer. When the display is in the focal conic state, the light from the backlight is weakly scattered by the Ch-LC of focal conic state and emerges from the display. The result is a bright state from the focal conic state and a dark state from the planar state. The measured brightness of bright and dark states are shown in Figs. 5-33. (a) and (b), respectively.



(a) (b)

Figs. 5-33. The brightness of (a) bright and (b) dark states.

From the measured results, the display can provide higher brightness than reflective mode. The measured C.R. of the display is shown in Fig. 5-34. The C.R. of the transmissive mode is about 2.

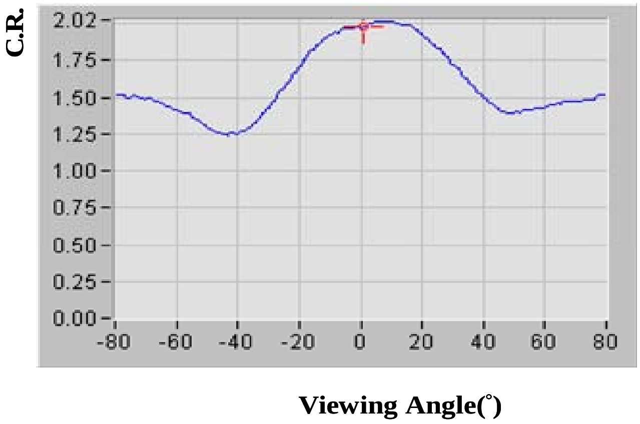
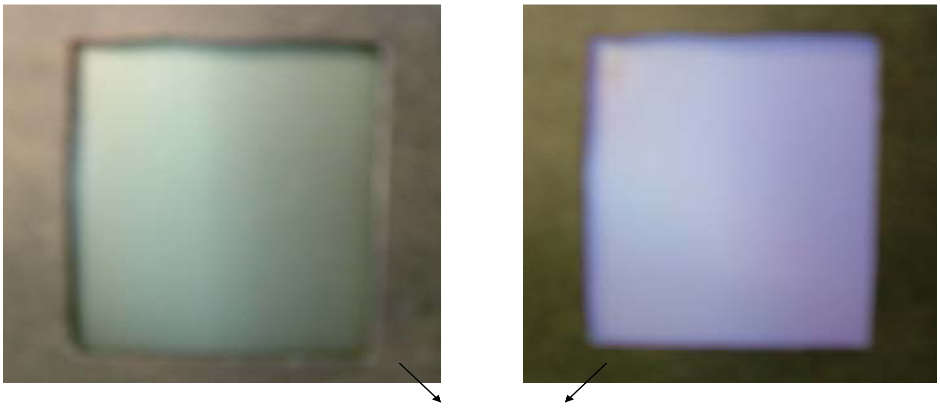


Fig. 5-34. The C.R. of the transmissive mode.

Based on the measurement results, we find the brightness and C.R. of the transmissive mode are close to the reflective mode. However, purely reflective

Ch-LCD has poor readability in dark ambience. The transflective Ch-LCD can provide accept performance in dark ambience. The photographs of reflective mode and transmissive mode are shown in Figs. 5-35.(a) and (b), respectively.



(a) (b)

Fig. 5-35. The photographs of (a) reflective mode (b) transmissive mode.

The photographs are taken in zero field conditions. Fig. 5-35.(a) is a photograph taken of the reflective mode in conventional office lighting. Fig. 5-35.(b) is a photograph taken of the transmissive mode in a nearly dark room. The photographs demonstrate that the transflective Ch-LCD yields sufficient brightness in both situations.

5.4 Summary

After the whole fabrication of the Ch-LCD test cells, a measurement system “ConoScope” was utilized to measure the reflective spectra, brightness and contrast ratio. Based on the measurement results, Ch-LCDs with UV band or infrared band LC materials have wide band reflection in bright state. Therefore, the black and white reflective Ch-LCD can be demonstrated. The C. R. of Ch-LCD with infrared band LC material is about 10~15. The contrast is sufficient for reflective display applications. In term of driving voltage, Ch-LCD with infrared band LC material has low driving voltage of 22V, which is much lower than conventional Ch-LCD’s. The infrared band Ch-LCD has advantages of high contrast and low driving voltage. Besides, the transflective Ch-LCD can yield reasonable contrast in both the transmissive mode as well as the reflective mode. This extends the cholesteric display technology to enable its use to low ambient lighting conditions.

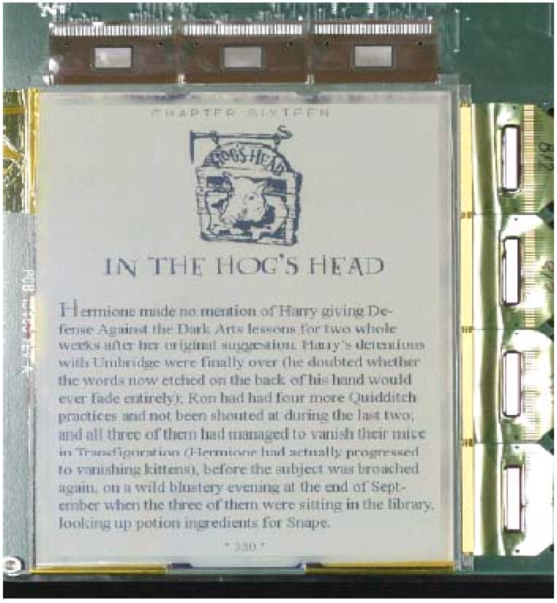
Chapter 6

Applications

6.1 Introduction

As the Internet and computer related industries growth continues, the electronic publishing is a huge market. People can download articles or books from the Internet. However, everyone wants to read them like a real book instead of the images on a bulky monitor.

The electronic book (e-book) is a reading device, as shown in Fig. 6-1. This portable reading machine is mostly employed to read all types of electronic publications like news, books, textbooks and all Internet related information.



CHAPTER SIXTEEN

IN THE HOG'S HEAD

Hermione made no mention of Harry giving Defense Against the Dark Arts lessons for two whole weeks after her original suggestion. Harry's detentions with Umbridge were finally over (he doubted whether the words now etched on the back of his hand would ever fade entirely); Ron had had four more Quidditch practices and not been shouted at during the last two; and all three of them had managed to vanish their mice in Transfiguration (Hermione had actually progressed to vanishing kittens), before the subject was broached again, on a wild blustery evening at the end of September when the three of them were sitting in the library, looking up potion ingredients for Snape.

~ 330 ~

Fig. 6-1. Photograph of latest black and white reflective Ch-LCD[35].

Nowadays, it is known that handheld devices, such as e-books, palm PCs, mobile phones, etc., are high volume markets. All kinds of handheld devices are battery operated. The power consumption is one of the key issues.

6.2 E-Book Application

As a portable electronic product, low cost and good performance are of first important. Low power consumption is the second important issue. Comfortable holding and easy carrying is another important requirement. In order to meet all the basic requirements, bistable reflective Ch-LCD is the best solution to e-book application. Due to the image-memory of Ch-LCD, the e-book based on it will not only be the lowest cost for CPU and its peripheral components, it will also consume extremely low power.

The e-book is usually made up of the CPU, the memory, the display, the battery, and some peripherals like AC link (include touch screen, audio), the PC link, USB, etc. The display is the key component for e-book. A low power consumption display can dramatically reduce the battery size. The image-memorized Ch-LCD makes it to be one of the best candidates for e-book due to its real low power consumption and its paper-like static image without any flicker.

The e-book should have such features as portability, superior readability, and lightweight. The built-in Internet connection allows you easily to download documents. The e-book can hold up to 100K pages on removable memory card.

Reflective Ch-LCD is the most power saving display and one of best performance displays due to its memory effect. As discussed above, Ch-LCD maintains the images under zero external applied voltage. The power is consumed only when the images are changed. The energy dissipation per update is about 50mJ for VGA resolution and less than 100mJ for 720×720 resolution. When you view the images 10 seconds longer or more, the other displays like STN-LCD or AM-LCD will consume 20 more times energy than Ch-LCD. If you read the VGA image on Ch-LCD spending one minute, you can save 250 times the energy of other refreshing reflective LCD consumes.

6.3 The Driving Scheme of E-Book

The driving voltage is an important issue for applications. The electro-optical response of Ch-LCD is shown in Fig. 6-2. The curves are obtained under zero field condition after driving.

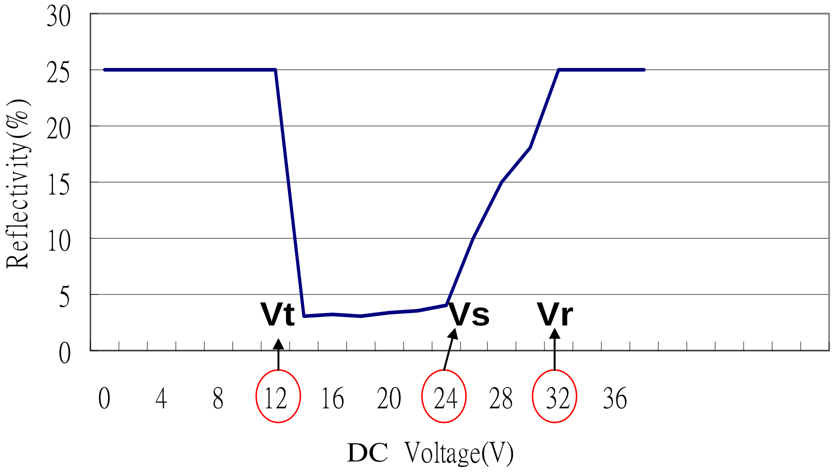


Fig. 6-2. Electro-optical response of Ch-LCD.

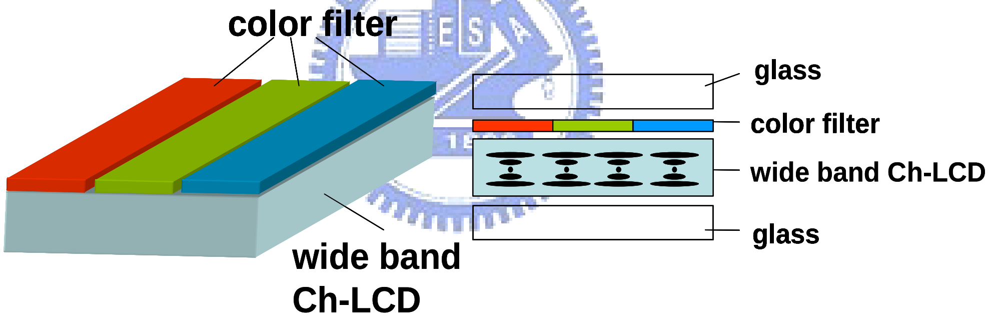
We use three pulses to drive Ch-LCD, which is passive matrix driving method. A 32V high voltage pulse with 2ms wide is applied to drive the whole display to the field induced nematic state. After a short relaxation, a low voltage pulse about 12V is applied to drive the display to an incomplete focal conic state. We call these two stages as image erasing. Right after image erasing to dark state, we address the display row by row by using a 32V high pulse with about 0.3 ms wide to planar "bright" state and a 24V pulse with 0.3 ms wide to focal conic "dark" state.

Threshold voltage Vt is defined that the LC can change from planar state to focal conic state. At the high voltage pulse Vr, the LC is driven to the nematic structure by the end of the pulse but then relax quickly to the planar reflecting state when the voltage is suddenly dropped to zero. The low voltage pulse Vs is to drive the LC to incomplete focal conic state after image erasing to a focal conic dark state. The three pulse driving method can not only be easily implemented by standard STN driver, but also achieves high addressing speed.

6.4 Full color cholesteric displays

Full color displays are more appealing to user. Conventional full color Ch-LCD was fabricated by stacking three layers of RGB (Red, Green and Blue) colors of cholesteric cells, as described in chapter 2. However, there are some drawbacks of the method. Stacking three cholesteric cells results in the device thick and heavy and parallax will decrease the resolution.

Our approach to full color application is to achieve a broad band reflection covering the entire visible spectrum, i.e., from 450 to 650 nm. We used full spectrum reflective method to realize a black and white reflective cholesteric display. Since the reflected light is white, so we can pattern conventional color filters for obtaining full color displays, as shown in Fig. 6-3. The fabrication processes are compatible with conventional process.



(a) (b)

Figs. 6-3.(a) Structure and (b) Configuration of full color Ch-LCD.

6.5 Summary

Finally, we summarize the advantages of Ch-LCD e-book products.

1. Long-term image memory.
2. Low power consumption.
3. Real static images: No flicker.
4. Lightweight.
5. Wide viewing angle: ±80° can be achieved.
6. Low cost.

7. No image parallax.

8. Excellent sunlight readability.

However, full color ability and low operation voltage are important issues for future application. For full color application, we proposed full spectrum reflective method to achieve a black and white cholesteric display. With wide band reflection in bright state, the reflected light is white. Therefore, by conventional color filters process, full color reflective cholesteric displays can be realized. Besides, high operation voltage about 50V is a drawback of cholesteric displays. From the experimental results, we find the operation voltage of infrared band cholesteric LC can be below 25V, thus the display can be compatible with standard driver IC. As a result, the low operation voltage full color cholesteric displays are more suitable for E-book application.

Chapter 7

Conclusions

As the Internet and the computer related industries growth continues, the electronic information display is an important technology. High brightness, high readability, wide viewing angle, low power consumption and high color saturation are the main concerns. Low power consumption and light weight are main advantages of reflective LCDs. Among all reflective LCDs, bistable reflective Ch-LCDs are best solution to e-book application due to the merits of lower power consumption, low cost, and good readability. However, due to the limitation of cholesteric LC materials, the reflective spectrum is narrow band. Therefore, the display is usually monochromic appearance, which often can not satisfy the user's requirement. Black and white displays are the least desired for viewers. In order to solve the problem of narrow band reflection, a new method "Full Spectrum Reflective Method" is proposed. The characteristic of this method is to use two reflective spectra: one is the spectrum of cholesteric LC, the other is the spectrum of reflector compensating each other to broaden the spectrum of the display. Wide band reflection can display white images instead of monochromic images. Besides, the dark state is created by cholesteric's scattering effect in focal conic state and polarizer's filtration effect. Therefore, black and white reflective cholesteric LCD can be demonstrated. A typical LCD cell process was utilized to carry out the Ch-LCD test cells due to its convenient manufacturing process. Finally, "ConoScope" was utilized to characterize the properties of the fabricated test cells and compared with simulation results.

In the simulation, we established a simulation model by LCD simulation software "DIMOS" used to characterize the features of the reflective Ch-LCDs. We utilized green band, UV band, and infrared band Ch-LC materials to optimize the optical properties of Ch-LCDs. From the simulation results, Ch-LCD with UV band Ch-LC can be wide band reflection, thus, enabling a black and white display.

In the experiments, "ConoScope" was utilized to measure reflective spectra, reflectance, contrast ratio, viewing angle and voltage response. In term of reflective spectra, UV band Ch-LCD has the widest reflective spectrum and high reflectance of 50%, which agreed with the simulated results. In term of contrast ratio, infrared band Ch-LCD has the highest C.R. of 10, which is much higher than conventional reflective Ch-LCD's. Therefore, the proposed method can improve the image quality of Ch-LCD. Besides, high operation voltage about 50V is the drawback of conventional Ch-LCD's. However, by using infrared band Ch-LC material, the operation voltage can be decreased to 25V, which can be implemented by standard STN driver. As a result, the cost and manufacturing yield can be improved.

We used full spectrum reflective method to achieve wide band reflection covering the entire visible spectrum to realize black and white reflective cholesteric displays. For full color applications, since the reflected light is white, so we can pattern conventional color filters for obtaining full color displays.

Finally, it can be concluded that UV band or infrared band Ch-LCDs with full spectrum reflective method can have advantages of wide band reflective spectra, high contrast and low driving voltage. The Ch-LCDs are suitable for E-books applications.

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