

國立交通大學

顯示科技研究所

碩士論文

配向層修飾對 Pi-Cell 光電特性之研究



Critical Voltage Reduction by Alignment Layer
Modification in Pi-Cells

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Pi-Cell 之配向層表面修飾降低轉態電壓之研究

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摘要

近 10 年來，平面顯示器的蓬勃發展，帶動顯示器的革命，成功取代傳統 CRT。在這波平面顯示器熱潮中，由於液晶顯示器具有輕、薄、省能的特性，並且各種尺寸都有其應用產品。因此，成為眾多平面顯示器中的最重要的技術。然而，在大尺寸的應用中，動態影像品質主要受限於液晶的反應時間太長，液晶反應速度成為動態影像優劣的關鍵，動態影像一直無法和傳統 CRT 比較。所以具快速應答的液晶操作模式是近年來被熱烈討論及研究的對象。在各種模式之中，最備受矚目的就是光學補償彎曲(optically compensated bend ,OCB 或稱 Pi-cell)。

Pi-cell 的操作主要是介於 Bend 狀態與垂直的狀態之間，而且這兩種狀態液晶的差異並不大，並且電壓移除後不會有反向流動現象，反應時間會比其他模式快。但 Pi-cell 在操作之前，分子排列成 Splay 狀，操作前通承需要提供偏壓並且持續一段時間，才能正常驅動。本篇論文特別使用能夠聚合的液晶材料，可以降低偏壓，並且改良 Pi-cell 的暗態，進而提升對比度，並且不影響到其反應時間。此外，也將討論此聚合型液晶材料的表面及特性。

Critical Voltage Reduction by Alignment Layer

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Abstract

In the last one decade, flat panel displays have developed vigorously, promote the display revolution, and replace CRT successfully. In this current of flat panel displays, LCDs have the properties of light, thin, power saving, and have products of each size, so LCDs become the most important technology of numerous flat panel displays. However, in the application of large size, the long response time of LC has limited the moving image quality, the response time of LC becomes the key issue of moving image quality, can not compare with conventional CRT. So the operation mode of fast response LC have been discussed and studied hot. In numerous modes, the optically compensated bend (OCB or Pi-cell) mode. The operation of Pi-cell mode is mainly between the bend state and the homeotropic state, and the difference of LC alignment between these two states is not much, and doesn't have the back flow effect after the voltage removed, has the faster response than other mode. But before Pi-cell operates, the LC molecules align in splay, and we usually need to apply a bias voltage for a period of time to operate. This thesis especially uses the liquid crystal material which can polymerize, can reduce the bias voltage, and improve the dark state of Pi-cell, then increase the contrast ratio, and doesn't affect the response time. Besides, we will discuss the surface morphology and some properties of this polymerized liquid crystal material.

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Chapter 1

Introduction and background

1-1 Introduction

With the rapid development of internet and wireless communication, the information is so popular that extend to every individual person. Because of that, portable devices and communication products have been developed so quickly. For example, notebooks, cell phones, digital cameras, GPS, and PDA, etc.. Because LC display has many advantages, such as thin, light weight, low power consumption, no radiation pollution, and the most important, compatible with semi-conductor technology. As the internet and digital information market grow, the application of LC display has grown up fast in recent decades, from early digital watch and calculators with low capacity of information, to modern monitors and portable information products. The technology includes material, equipment, manufacture, and product character's development. Until today, the LC displays are still growing up with amazing speed, and become the lead of planar display market.

1-2 Liquid crystal

In 1888, an Austrian botanist named Friedrich Reinitzer[1], interested in the biological function of cholesterol in plants, was looking at the melting behavior of an organic substance related to cholesterol. (The chemical structure of cholesterol was still unknown. Today we

know that the observed substance was cholesteryl benzoate). He observed, as W. Heintz did with stearin 38 years before, that the substance melted to a cloudy liquid at 145.5°C and became a clear liquid at 178.5°C. In the next year, an important invention of the time was the heating stage microscope by Otto Lehmann[2], a physicist from Karlsruhe, Germany. This microscope allowed control of the temperature of the sample. In a later version, with polarizers added, it became the standard equipment in every liquid crystal research laboratory. He also found out the birefringence character of liquid crystal, the optical anisotropic.

In 1890, discussion with Lehmann and others led to the identification of a new phase of matter called the liquid crystal as fourth state of matter or mesophases.

Liquid crystal phase is between solid state and liquid state. As a result, it has both the solid character and liquid character. When we heat the material from ordered crystalline solid to disordered isotropic liquid, it will have a character between the two. Every molecule has unstable position but similar orientation. The structure is similar to crystal's arrangement, and the liquid character can help the molecule change the position and point direction, the structure of molecule are asymmetric, most rod-liked and disk-liked.

When LC in ordered crystalline solid, because LC has fluid character and asymmetric structure, the material will have uni-axial anisotropy character. That means the refractive index, dielectric constant, and magnetic susceptibility will change when in different orientations. However, display's main application is generated by changing the refraction index and dielectric constant.

Rod-like liquid crystal material can be divided into 3 major categories. That is Nematic, Smectic, and Cholesteric. In this thesis, we don't discuss other type of liquid crystal.

1-2-1 Nematic

This type of liquid crystal has the worst alignment and the most like isotropic. There is

no relationship between molecule's positions. Every molecule can rotate freely around specific long axis. The molecule's main axis (rod-like's long axis) is roughly parallel to each other as (Fig. 1-1).

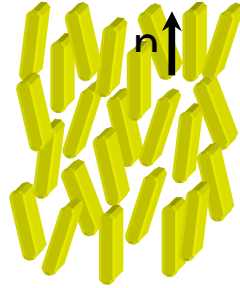


Fig. 1-1:Nematic liquid crystals' alignment, the main axis is about point to the same orientation.

Define a vector **n** to present the overview director around the molecules. We also define a physical parameter to describe the molecules' alignment: Order Parameter S

$$S = \frac{1}{2} \langle 3\cos^2\theta - 1 \rangle \quad (\text{eq. 1-1})$$

θ is the angle between molecule's long axis and **n**. when molecules aligned perfectly parallel, $\theta=0$, and S will be equal to 1. When molecules aligned randomly, $\theta=\text{random}$, S will be 0. Generally, liquid crystal molecules have $0.5 < S < 0.7$. Nematic liquid crystals' viscosity is small, response time is fast. It's the earliest liquid crystals that been used in LC TV, monitor, and all types of display elements[3,4,5].

1-2-2 Smectic

Smectic has two spatial dimension of alignment, they align layer by layer regularly and stake in layer structure, each layer has one degree alignment (Fig. 1-2).

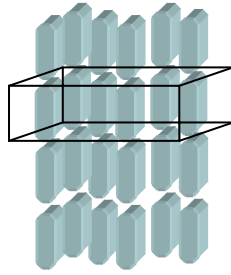


Fig. 1-2:Smectic liquid crystals are aligned in two dimensions and have layer structure.

This kind of liquid crystals has different alignment in different layer. It can be subdivided into A-L 12 different kinds of Smectic liquid crystals, there were named by the time order they were found out. For example, Smectic A phase, Smectic C phase. Generally, this kind of molecules has high viscosity, slow response time when add an electric field. So Smectic liquid crystals seldom been used in displays, their main application is optical data storage materials.



1-2-3 Cholesteric

This kind of liquid crystals is stacked by many layers of nematic liquid crystals, it's a type of nematic liquid crystals, it can also be called as 『chiral nematic liquid crystals』 (n^*), the molecules align in helical plane, each surface is parallel with each other. Each plane is a nematic layer, but they have different orientation of molecule's long axis. Therefore, two plane's long axis has an included angle. When the molecule's long axes in two adjacent planes have the same orientation, the distance between the two planes calls a pitch (Fig. 1-3). From molecule's chirality we can decide the direction of rotation.

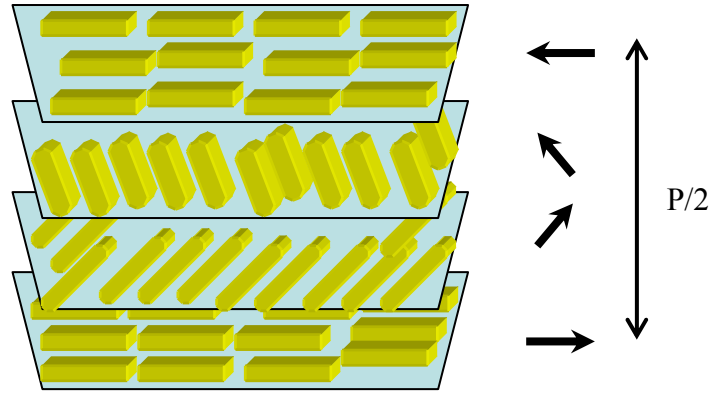


Fig. 1-3:Cholesteric liquid crystals' helical structure, it can reflect the incident light.

Cholesteric liquid crystals' pitch will change with different temperature, pressure, electric field, or magnetic field. Because this kind of liquid crystals has optical rotation, it can reflect the incident light with $2pn$ (n is average refractive index). Therefore, when the temperature is changed, it will happen to have a selective reflection because of different wavelengths and also causes a color variation. As a result, it can be used as a detector of temperature. Besides, the alignment of molecules are easily been effect by the electric field, it also can be used as reflective displays, and electronic paper[6].

1-2-4 Liquid crystal phases versus temperature

The alignment of liquid crystals can be Smectic or Nematic phase, because the phase change can be related to temperature. As follows:

Solid \rightarrow Smectic \rightarrow Nematic \rightarrow Isotropic
 Crystal \rightarrow Liquid Crystal \rightarrow Liquid
 Low temperature \rightarrow High temperature

In Nematic liquid crystals, it can be seemed as many small domains, each domain has molecules with the same orientation, different domain has different director. When light passes though, it causes scattering because different director in the continuous domain. So the

liquid crystals will be milky colored liquid. It only become transparent when all domains have the same orientation.

When the temperature over T_{N-I} , the alignment of molecules will become isotropic and liquid state. It also makes the sample become clear and transparent. This temperature calls clearing point and has significant physical meaning. Consequently, it's an important feature of liquid crystals that molecules will align orderly.

1-3 Liquid crystal optics

Light can be seemed as an electromagnetic wave transparent in space. They don't need medium to propagate, and the direction of electric field is perpendicular to the direction of magnetic field. It also has some physical effect, for example, refraction, diffraction, interference, and polarization. When light has different frequency or wavelength, they will have different color. Besides, we can take the property of light as superposition of each single light. As a result, we will discuss only the monochromatic plane light wave in the following.

1-3-1 Basic properties of light

From Maxwell eq., we can derive wave eq.:

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{E}) + \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = -\mu_0 \frac{\partial^2 \vec{P}}{\partial t^2} - \mu_0 \frac{\partial \vec{J}}{\partial t} \quad (\text{eq. 1-2})$$

For a generalized three dimensional monochromatic plane light wave, it propagate in a uniform dielectric substance, then $\vec{P} = \epsilon_0 \chi \vec{E}$ and $\vec{J} = 0$.

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{E}) + \frac{n^2}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} = 0 \quad (\text{eq. 1-3})$$

The refraction index could be: $v = \frac{c}{n} \Rightarrow n \equiv \sqrt{\mu\epsilon}$

From eq. 1-3, we can get wave function as:

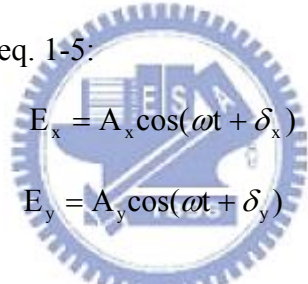
$$\vec{E}(\vec{r}, t) = \vec{A} \cos[\omega t - \vec{k} \cdot \vec{r} + \delta] \quad (\text{eq. 1-4})$$

Since light wave is transverse wave, we can define the direction of polarization is the direction of electric field. The direction of propagation is z, then the electric field of monochromatic plane light wave will vibrate in x-y plane.

Then we can rewrite eq. 1-4 as two vectors perpendicular with each other.

$$\begin{aligned} E_x &= A_x \cos(\omega t - kz + \delta_x) \\ E_y &= A_y \cos(\omega t - kz + \delta_y) \end{aligned} \quad (\text{eq. 1-5})$$

$A_x, A_y, \delta_x, \delta_y$, represents the amplitude of vibration and the phase individually. To describe the polarization of light wave simply, take $z=0$ to see the change of the vibration verses time on the x-y plane, then eq. 1-5:



$$\begin{aligned} E_x &= A_x \cos(\omega t + \delta_x) \\ E_y &= A_y \cos(\omega t + \delta_y) \end{aligned} \quad (\text{eq. 1-6})$$

We can define the phase as: $\delta = \delta_y - \delta_x$. If $\delta = 0$ or π , then

$$E_y = \frac{A_y}{A_x} E_x \quad \text{or} \quad E_y = -\frac{A_y}{A_x} E_x \quad (\text{eq. 1-7})$$

From eq. 1-7, when the electric field direction of light vibrate in $\frac{E_y}{E_x}$ direction, we call it as linear polarization state. We use a new math calculate way to describe the polarization state of light--- Normalized Jones Vector:

$$J = \frac{1}{\sqrt{A_x^2 + A_y^2}} \begin{pmatrix} A_x e^{i\delta_x} \\ A_y e^{i\delta_y} \end{pmatrix} \quad (\text{eq. 1-8})$$

When the light wave is linear polarized ($\delta = 0$ or π), the x axis has an included angle of ψ , then:

$$J_\psi = \begin{pmatrix} \cos \psi \\ \sin \psi \end{pmatrix} \quad (\text{eq. 1-9})$$

and

$$J_{\psi} * J_{\psi + \frac{\pi}{2}} = 0 \quad (\text{eq. 1-10})$$

So the two factor are orthogonal, and when $\psi=0$:

$$J_x = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \text{and} \quad J_y = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (\text{eq. 1-11})$$

The index of J, means the x polarized direction and y polarized direction.

1-3-2 The propagation of light waves in uniaxial medium

Most liquid crystals displays are nematic liquid crystals phase, if we consider thin sliced nematic liquid crystals cell, we can take it as uniformed uni-axial medium. As a result, we are going to discuss the effect when light propagates in the anisotropic uni-axial medium propagate.

In uni-axial medium, we have three refraction indexes as n_x, n_y, n_z .

We have: (1) $n_x = n_y = n_o$, and we call the index as ordinary index.

(2) $n_z = n_e$, we called n_e as extraordinary index.

When $n_e > n_o$, we call the medium as positive uni-axial medium; when $n_e < n_o$, we call the medium as negative uni-axial medium.

When light propagate in uni-axial medium, it will happen to have two propagate mode, the first one will be ordinary wave and extraordinary wave. And we can present the two refractive indexes as:

$$\text{O wave :} \quad n = n_o \quad (\text{eq. 1-12})$$

$$\text{E wave :} \quad \frac{1}{n(\theta)^2} = \frac{\cos^2 \theta}{n_o^2} + \frac{\sin^2 \theta}{n_e^2} \quad (\text{eq. 1-13})$$

θ is the included angle of the propagate direction and z axis(light axis).

Consequently, when light propagate in this medium, the two directions of light will have different propagate velocity and different phase velocity. When light in the medium propagate

for a while, the two parts of light will have phase retardation compare with each other. When the light passes through the medium, the two parts of light will combine together again, so the polarization happens. Therefore the birefringence wave plate uses this theorem to change the polarization of light.

Here are two examples:

I. When the direction of propagation along z axis(light axis):

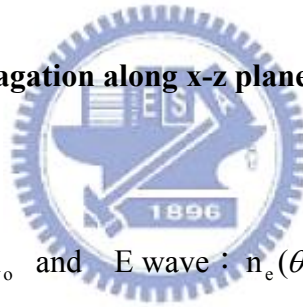
$\theta=0$, substitute into 1-12 and 1-13 :

$$\text{O wave : } n = n_o \quad \text{and} \quad \text{E wave : } n(\theta) = n_o$$

The two has the same phase velocity, $k_1 = k_2 = n_o(\frac{\omega}{c})$ s After light propagate in this two modes for a distance d, from eq. 1-4, the light does not have phase retardation. That means the polarization of light won't change.

II. When the direction of propagation along x-z plane:

From eq. 1-12 and 1-13:



$$\text{O wave : } n = n_o \quad \text{and} \quad \text{E wave : } n_e(\theta) = \left[\frac{\cos^2\theta}{n_o^2} + \frac{\sin^2\theta}{n_e^2} \right]^{-\frac{1}{2}}$$

O wave has wave vector: $k_o = n_o(\frac{\omega}{c})$ s ,

E wave has wave vector : $k_e = n_e(\theta)(\frac{\omega}{c})$ s ,

From eq. 1-8 we know, when light propagate in this medium for a distance d, O wave has a phase transition: $n_o(\frac{\omega}{c})d$, E wave has a phase transition: $n_e(\theta)(\frac{\omega}{c})d$, the two has a phase retardation Γ :

$$\Gamma = [n_e(\theta) - n_o](\frac{\omega}{c})d \quad (\text{eq. 1-14})$$

or

$$\Gamma = \frac{2\pi}{\lambda} [n_e(\theta) - n_o]d \quad (\text{eq. 1-15})$$

From eq. 1-8 we know, this phase retardation can generate a change polarization of light

propagation. LCD's main application uses the similarity of light propagation between liquid crystals and uni-axial medium. Please refer to the next section of the details of the theorem.

(The equations from this section refers to "Elements of Photonics, Volume I: In Free Space and Special Media."[7])

1-4 Structure and operation method of LCD

Generally, LC display can be seemed as two dimensional pixel alignments. Each pixel can be taken as a light switch, LC display use liquid crystals to modulate the polarization of light wave and form a display element. It includes backlight mode, polarizer, LC cell, etc..

Backlight mode includes light source, ELP, diffuser, etc.. Because liquid crystals cannot emit light by itself, so it needs a backlight. In the present market conditions, we often use CCFL and LED as our backlight. But they are not planar light, so they need ELP and diffuser to turn the point light or linear light into uniform planar light.

Polarizer is one of the main component of display. All displays have unpolarized light as their light source. When the light passes the polarizer, the light would be changed into a polarized light with fixed direction. Then we can use LC cell to control the polarization of the light. The function of analyzer is examine the light direction after modulated by LC cell, only some part of the light that has the same polarized direction with analyzer can passes through. So it can cause the change of brightness.

LC cell includes ITO glass, alignment layer, LC, TFT(Thin Film Transistor), color filter, etc.. ITO is a transparent conduct electrode, coated on the upper substrate and lower substrate. We also coat color filter on the upper substrate to have a full colored display. We use lower substrate to have TFT, and supply the voltage for liquid crystals. LC would change the alignment because of the electric field. When we remove the applied voltage, they need a output strength to regain the original alignment of LC. Because of that, we have an alignment

layer to help LC regain the original alignment. We often use polyimide as the material of alignment layer.

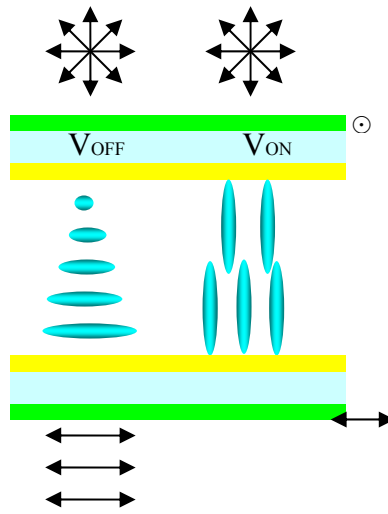


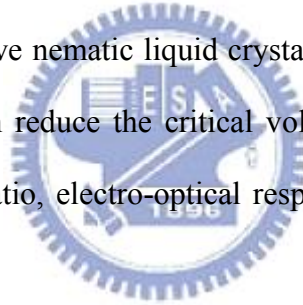
Fig. 1-4: When voltages switch, the alignment of TN LC cell.

Operation theorem: Here we are going to use normally white mode TN LC cell as an example. (Fig. 1-4). We use unpolarized light to have the backlight, when light passes through polarizer, only the light has the same polarized direction with the polarizer can pass through polarizer and enters into LC cell. In the meantime, if we add an electric field on the LC layer (the right figure of Fig. 1-4), then the light axis of liquid crystals will have the same direction with the electric field. From section 1-3-2, the phase retardation will be 0, and the polarization of light will maintain. So the light cannot pass through the analyzer and causes dark points. When we remove the electric field, the LC layer will have phase retardation, so the linear polarized light can pass analyzer and causes bright point (white point). When the light varying from black at the weakest intensity to white at the strongest, we can modulate the light and have grayscale. So we can use LC cell as an optical-electrical switching elements to modulate the light.

1-5 Motivation and objective

Because materials have been improved in recent years, so the liquid crystals can have the response time from 50 ms to now 4ms, but some applications (ex. HDTV) need faster response time, 4ms still can't satisfy the need of high frequency[8]. In 1983, P. J. Bos brought π cell out[9,10], it can be driven by high voltages. After that, Uchida brought out bi-axial retardation film to improve the dark state, and named OCB cell[11,12,13]. He also reduced the driving voltage to 6V, and it can be used in TFT LCD. OCB has the advantages of fast response and wide viewing angle, so it can be used in high frequency display products. However, OCB needs to apply a voltage bigger than critical voltage before operate[14], and sustain for a while to make transition of splay to bend, it's a disadvantage in application.

Here are going to use reactive nematic liquid crystal monomers to improve the original alignment layer, and then we can reduce the critical voltage from 1.8V to 0.7V and won't affect the transmittance, aspect ratio, electro-optical response, and wide viewing angle of π cell.



1-6 Organization of this thesis

The thesis will be presented as following: the second chapter is going to discuss the essential structure of π cell, the reason that why π cell has fast response time, and wide viewing angle. Moreover, the discussion will include how the transition of splay to bend happens, and some method to solve the problem. The third chapter is going to explain the equipments that have been used in this experiment. The fourth chapter describes experimental processes, optical-electronic character, the analysis of result, and discussion. Finally, in Chapter 5, the summary of the results and future work for next research on this subject will be given.

Chapter 2

Overview of π cell

2-1 Introduction

In the year of 1983, the P. J. Bos's team first proposed the operation mode of bend cell, titled π cell, an half-wave plate which can modulate with voltage. After, in the year of 1993, the team of Uchida proposed a cell based on the π cell, add biaxial negative compensation film to reduce the dark state light leakage, and improve the contrast ratio and viewing angle, they titled this cell Optically Compensated Bend (OCB) cell. π cell (or OCB cell) has the advantages of fast response[15] and wide viewing angle[16]. However, because of the structure of π cell, the dark state light leakage is more severe than other mode (like the VA mode), consequently, the contrast ratio is usually worse than other mode. Furthermore, when the applied voltage on the π cell is below critical voltage, the cell will be stable in the splay state; we must offer a voltage larger than critical voltage and hold on a period of time so that the liquid crystal molecules can transit from splay state to bend state. In this chapter, we will introduce the structure of the π cell, and the reasons of these characters we mentioned above.

2-2 The character of π cell

2-2-1 The structure of π cell

Fig. 2-1 is the structure of the π cell. The two polarizer above and under the cell are crossed, and the alignment layers on the two substrate have the same rubbing direction, and make an angle of 45 degree with the two polarizer. In general, the pretilt angle of the alignment layer used in π cell is about in the range of 6~14 degree, such pretilt angle makes the LC molecules align in splay state in a plane without distortion

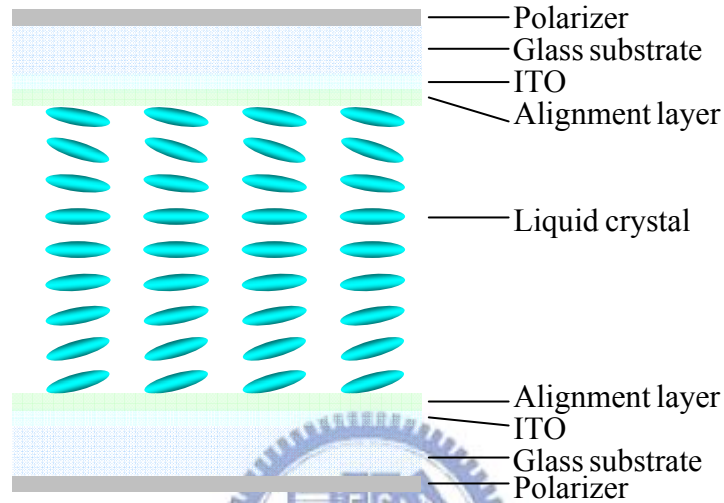


Fig. 2-1: The structure of the π cell.

2-2-2 Fast response

π cell is a fast liquid crystal display mode[17,18,19], this is mainly because the π cell operates between bend state (Fig. 2-2A) and homeotropic state (Fig. 2-2B), the difference of LC alignment between these two state is not much, and the LC molecules align bent in π cell, the LC molecules will rotate in the same direction when switch, we called that flow effect (Fig. 2-3), this is not like TN mode, which must overcome the delay caused by the backflow when changing the distorted alignment in operation process, especially in the relaxation when removing the voltage. So in the operation of π cell, the response time is about 1 ~ 10 ms, faster than TN mode (50 ms) and the response of human eyes (20 ms)

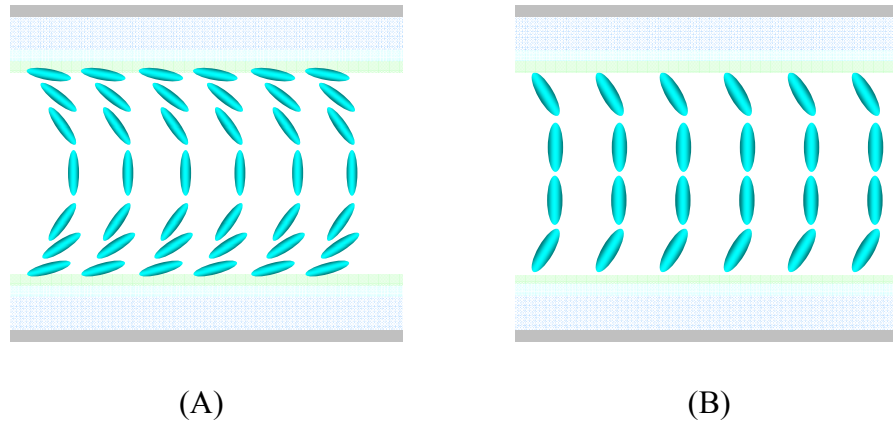


Fig. 2-2: (A) Voff (Vcr), π cell is in the bright state. (B) Von, π cell is in the dark state, the LC alignment between these two state is much like, so the π cell has fast response.

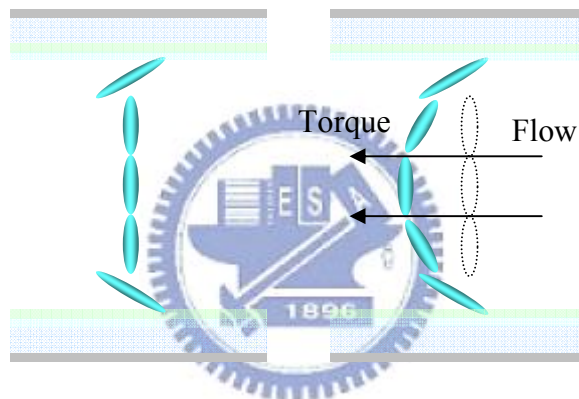


Fig. 2-3: Schematic figure of the dynamics in the π cell. The flow induces the torque to accelerate to relax.

2-2-3 Wide viewing angle

From Fig. 2-4, we can see that when the transmittance is 50%, the curve of TN mode has asymmetric distribution, while the curve of π cell has symmetric distribution. This phenomenon is related to the alignment of LC molecules. Because in the plane of rubbing direction, the alignment of LC molecules is symmetric in the vertical direction, so we will experience the same optical path along the symmetric direction in this plane (Fig. 2-5). There is self-compensated effect in this direction. Therefore, the horizontal viewing angle of π cell is

wider and symmetric than TN mode.

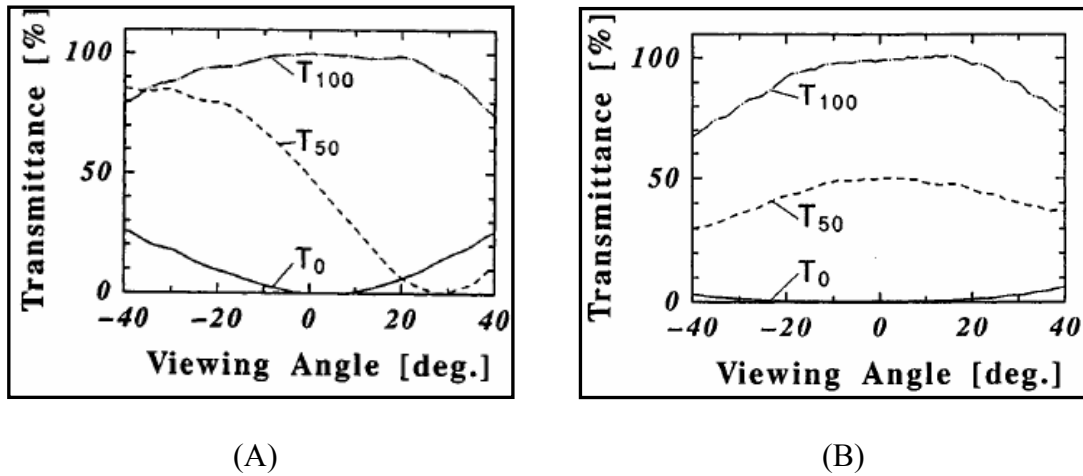


Fig. 2-4: The relation between the horizontal viewing angle and the transmittance of (A)TN mode(B) π cell[11]. TN mode shows asymmetric transmittance, but π cell shows symmetric transmittance.

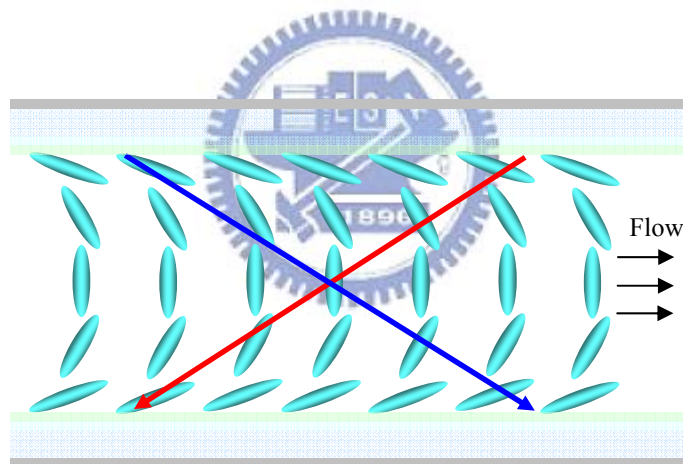


Fig. 2-5: π cell has the symmetric viewing angle in the plane of rubbing direction.

2-2-4 Light leakage in dark state

The alignment layer of π cell usually provides the pretilt angle of 6~14 degree, when applying electric field, the LC molecules near the alignment layer suffer larger constraining strength from the alignment layer, these molecules don't stand up exactly, leads to more severe dark state light leakage (Fig. 2-6). Compare to the dark state of VA mode, the LC

molecules can stand up exactly, so the contrast ratio of π cell is usually less than VA mode in the normal direction. Accordingly, Uchida proposed a biaxial negative type compensation film to improve the dark state of π cell, but the contrast ratio is still not as good as the VA mode.

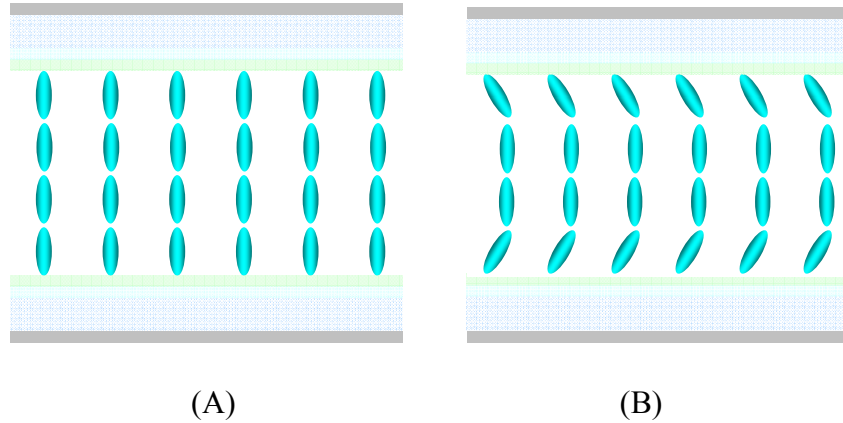
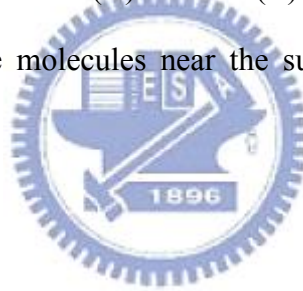


Fig. 2-6: The LC molecules alignment of (A)VA mode(B) π cell in dark state. The major cause of dark state light leakage is the molecules near the substrate in π cell can not stand up exactly.



2-2-5 Phase transition

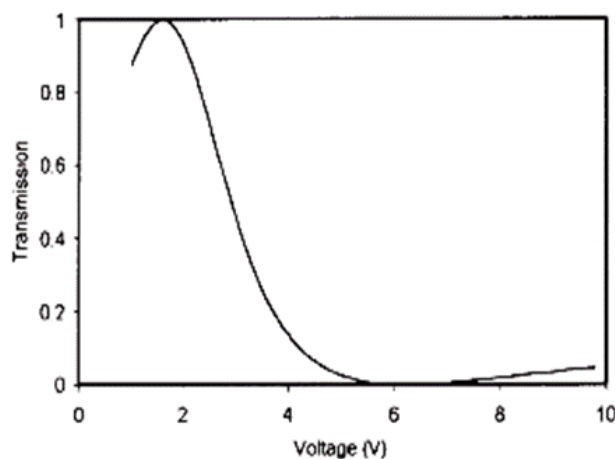


Fig. 2-7: The V-T curve of a general π cell.

The V-T curve of π cell usually looks like Fig. 2-7. The voltage corresponding to the

100% transmittance is called critical voltage (V_{cr}), and the voltage corresponding to the 0% transmittance is called dark state voltage, π cell usually operates between these two voltage.

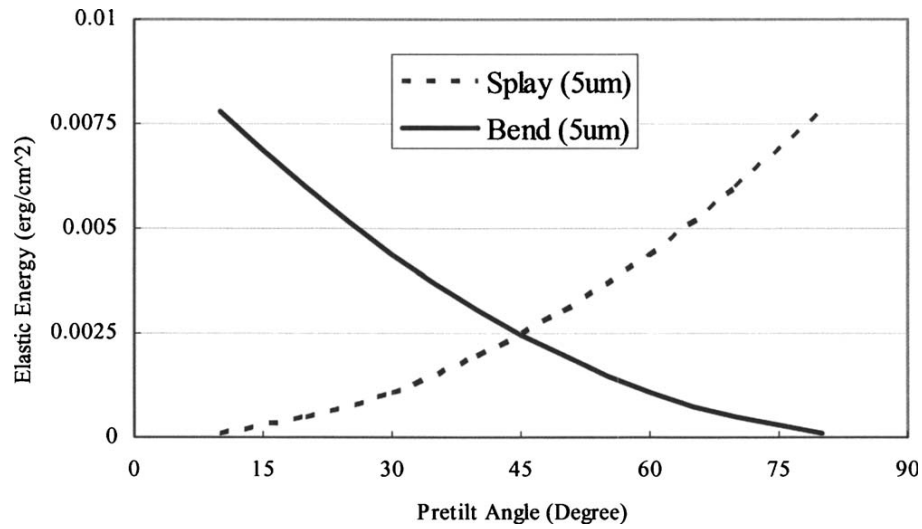


Fig. 2-8: The pretilt angle versus energy distribution of splay state and bend state.

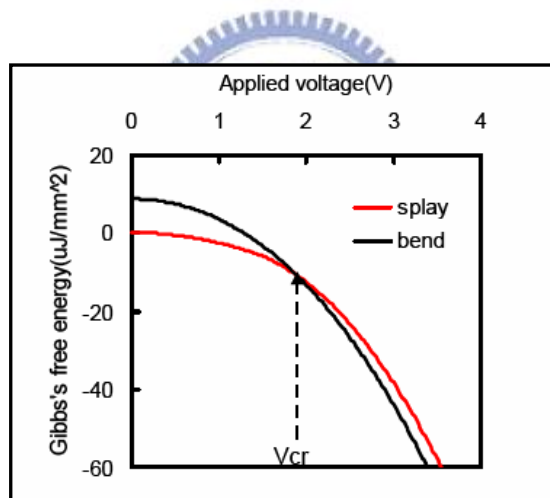


Fig. 2-9: The energy distribution of splay and bend state when applying voltage.

From the energy point of view, when the pretilt angle is low, splay state has lower energy (Fig. 2-8). When the pretilt angle increases, the energy of bend state and splay state becomes closer[20,21]. When the pretilt angle is about 45~50 degree, the energy of these two state almost the same. The pretilt angle of a general π cell is about 6~14 degree, so the beginning state of a general π cell is stable in splay state. Applying voltage on the π cell will change the original energy distribution (Fig. 2-9). Therefore, we usually need to offer a

voltage larger than critical voltage to the π cell, for a long period of time, to enable the π cell transit to bend state, then operate it. This is a problem need to be solved in application.

To improve the problem of phase transition, the common method likes to increase pretilt angle[22,23], generate bend core or chiral dopant[24,25], multi-dimensional alignment[26], offer a twist electric field[27], polymer stabilized[28,29]...etc. Although these method can shorten the transition time from splay state to bend state, but they usually affect other optical properties (ex. worse the dark state), or the fabrication process, driving method become complicated, make the π cell lose its predominance.

2-3 Summary

In this chapter, we introduced the fast response and wide viewing angle properties of π cell, and brought up the problem in dark state and the drawback of needing phase transition of π cell. In the chapter afterward in this thesis, we proposed a new cell structure which can improve the dark state and phase transition problem of a π cell in the same time, and easy to fabricate, make π cell have better performances and advantages.

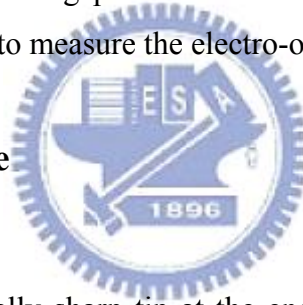
Chapter 3

Measurement systems

3-1 Introduction

In this chapter, the measurement setups used in the experiments were described in the following sections. The surface condition and the film thickness of RMM-19B were observed and measured by utilizing AFM. The transmission spectrum of the empty cell was analyzed by using the spectrometer and the cell gap would be obtained by interferometric method. We assembled the laser optics system to measure the electro-optical properties of π cell.

3-2 Atomic force microscope



AFM consists of an atomically sharp tip at the end of a reflective cantilever across a sample surface with feedback mechanisms that enable the piezo-electric scanners to maintain the tip at a constant force. The scanning motion is conducted by a piezo-electric tube scanner which scans the tip in a raster pattern with respect to the sample (or scans to the sample with respect to the tip). The tip-sample interaction is monitored by reflecting a laser off the back of the cantilever into a split photodiode detector. The photodetector measures the difference in light intensities and then converts to voltage. Feedback from the photodiode difference signal, through software control from the computer, enables the tip to maintain a constant force above the sample. In the constant force mode the piezo-electric transducer monitors real time height deviation. A schematic diagram of this mechanism is depicted in Fig. 3-1.

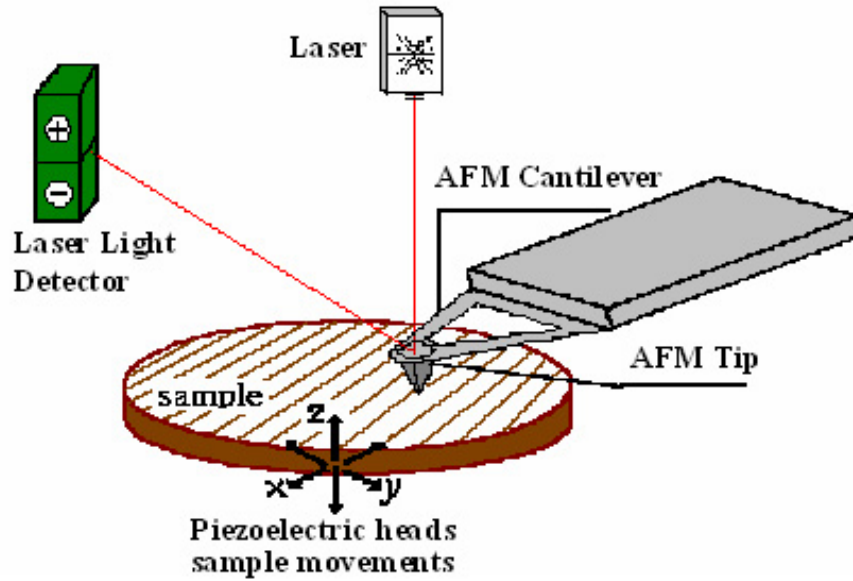


Fig. 3-1: Concept of AFM and the optical lever.

The two most commonly used modes of operation are contact mode AFM and Tapping Mode™ AFM, which are conducted in air or liquid environments.

Contact mode AFM consists of scanning the probe across a sample surface while monitoring the change in cantilever deflection with the split photodiode detector. A feedback loop maintains a constant cantilever deflection by vertically moving the scanner to maintain a constant photodetector difference signal. The distance the scanner moves vertically at each x, y data point is stored by the computer to form the topographic image of the sample surface.

Tapping mode AFM consists of oscillating the cantilever at its resonance frequency and lightly “tapping” on the surface during scanning. The laser deflection method is used to detect the root-mean-square (RMS) amplitude of cantilever oscillation. A feedback loop maintains a constant oscillation amplitude by moving the scanner vertically at every x, y data point. Recording this movement forms the topographical image.

The AFM has several advantages :

1. The AFM provides a true three-dimensional surface profile.

2. Samples viewed by AFM do not require any special treatments (such as metal/carbon coatings) that would irreversibly change or damage the sample.
3. AFM modes can work perfectly well in ambient air or even a liquid environment.
4. AFM can provide higher resolution than SEM.

3-3 Cell gap measurement system

For liquid crystal display, the thickness of a cell gap usually affects the optical performance. We need to measure the empty cell gap, and interferometric method[30] is what we use. The measurement instrument used is UV/Vis spectrometer LAMBDA 650 from Perkin Elmer.

The principle of this method is introduced :

The basic concept of the measurement method is based on the interference of light reflected by the two reflecting surfaces. In Fig. 3-2., R_1 is the reflective index of surface 1 which the incident light pass, and R_2 is the reflective index of surface 2.

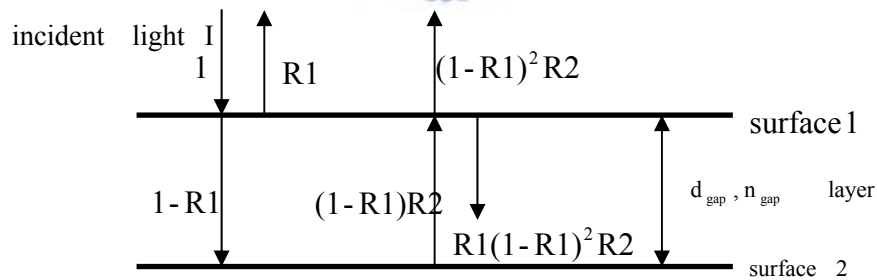


Fig. 3-2: Two reflecting surfaces were separated by a layer causing a light interference.

If the total incident light is $I = \cos \omega t$ and we assume there is no any other absorption of light in surface 1 and 2, then we can write the total reflected light R as

$$R = R_1 \cos \omega t + \sum_{k=1}^{\infty} R_1^{k-1} R_2^k (1-R_1)^{1+k} \cos \omega(t - kt_0) \quad (\text{eq. 3-1})$$

Where $\omega = 2\pi c n_{\text{gap}} / \lambda$ and $t_0 = 2d_{\text{gap}} n_{\text{gap}} / c$, c is the speed of light in vacuum, λ is the

wavelength, d_{gap} is the thickness of the layer, n_{gap} is the refractive index of the layer. The cosine factor in eq. (3-1) for $k > 1$ are caused by internal reflections. Since $R_1 < 1$ and $R_2 < 1$, the magnitude of the cosine factors for $k > 1$ is much smaller than for $k = 1$. Therefore the internal reflection is chosen to be neglected, so

$$R = R_1 \cos \omega t + (1 - R_1)^2 R_2 \cos \left(\omega t - \frac{4\pi n_{gap} d_{gap}}{\lambda} \right) \quad (\text{eq. 3-2})$$

Thus the reflected spectrum is

$$|R(\lambda)|^2 = R_1^2 + [(1 - R_1)^2 R_2]^2 + 2R_1(1 - R_1)^2 R_2 \times \cos(4\pi n_{gap} d_{gap} / \lambda) \quad (\text{eq. 3-3})$$

The periodic term in eq. (3-3) causes an interference pattern. The periodicity of the reflected interference spectrum determined the optical thickness of the cell gap, $n_{gap} d_{gap}$.

If λ_1 and λ_2 are the two wavelengths showing extrema in eq. (3-3), then $\cos(4\pi n_{gap} d_{gap} / \lambda) = \pm 1$ for $\lambda = \lambda_1$ and $\lambda = \lambda_2$. Therefore

$$2n_{gap} d_{gap} = k_1 \lambda_1 / 2 \quad (\text{eq. 3-4})$$

$$2n_{gap} d_{gap} = k_2 \lambda_2 / 2 \quad (\text{eq. 3-5})$$

Where k_1 and k_2 are natural numbers. Suppose $\lambda_1 > \lambda_2$, then

$$k_2 = k_1 + x \quad (\text{eq. 3-6})$$

x is a natural number.

Based on eqs. (3-4), (3-5), and (3-6), we can write

$$n_{gap} d_{gap} = \frac{x \lambda_1 \lambda_2}{4(\lambda_1 - \lambda_2)} \quad (\text{eq. 3-7})$$

The value of $x-1$ indicates the number of extrema in $|R(\lambda)|^2$ between the wavelengths λ_1 and λ_2 . It is better to choose the distance x between the two extrema as large as possible for improving the accuracy of the calculation of $n_{gap} d_{gap}$. The sample data was shown in Fig. 3.3 for a 3.98 μm cell.

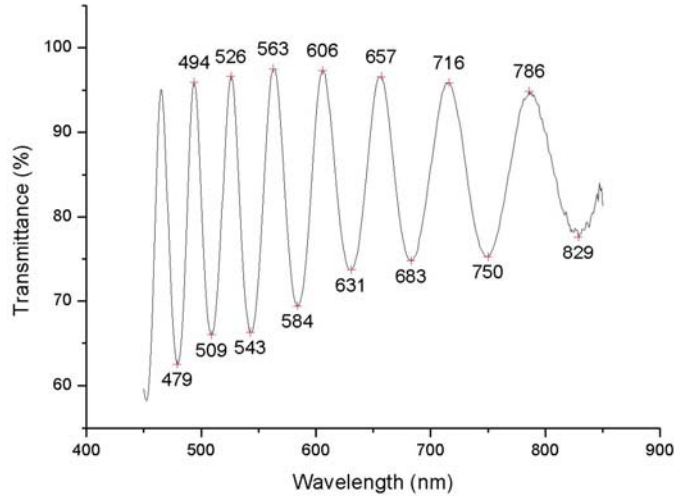


Fig. 3-3: The reflection as a function of wavelength using a air gap of 3.98 μm .

$$n_{\text{gap}} d_{\text{gap}} = \frac{x\lambda_1\lambda_2}{4(\lambda_1 - \lambda_2)} = \frac{12 \cdot 786 \cdot 494}{4 \cdot (786 - 494)} = 3.98 \mu\text{m} \quad (\text{eq. 3-8})$$

3-4 Laser optics systems



Our laser optics system is as in Fig. 3-4. This optical system is responsible for the measurement of electro-optical properties, such as V-T characteristics and response time. First of all, we have to reduce the intensity of laser source within the acceptable range of the photo detector by using a 10% ND filter. Next, the moderate light becomes a polarized light after passing through the polarizer and then enters the LC cell. The LC cell, acted as a phase modulator, changes the phase of the incident polarized light by retardation $\Delta n \cdot d$ (Δn is the birefringence of LC, and d is the thickness of LC). Then the modulated light passes through the analyzer and the light output is received by the photo detector. The driving waveform of FLC is written by ourselves and sent by a waveform generator WFG500 (from FLC Electronics AB). The optical output received by the photo detector can be observed with the oscilloscope (from Tektronix) and quantified data can be read by a multimeter (from Keithley).

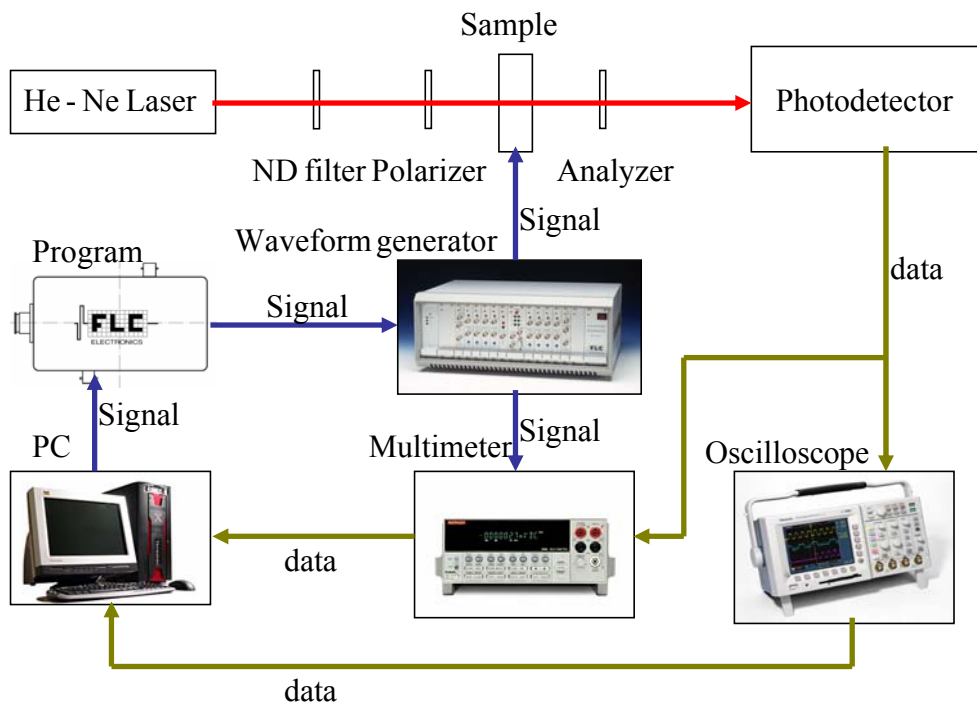
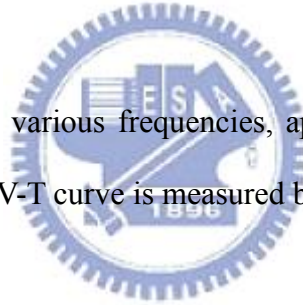


Fig. 3-4: This is a schematic diagram of the laser optics system.

We use a square wave with various frequencies, applying on the cell, to measure the response time of the test cell. The V-T curve is measured by using a 1k Hz square wave.



Chapter 4

Experiments and results

4-1 Introduction

For π cell mode displays, there are two major disadvantages. The first one is that the displays can not directly operate in splay state but only work normally in bend state. In comparison with the other mode displays (TN, VA, IPS), this is the additional problem needed to be conquered. Second, no perfect dark state exists in π cell mode. Because of LC molecules alignment in π cell mode, the light leakage in dark state is more serious than that of the other modes. As a result, the contrast ration of π cell is often lower than that of the others.

In this thesis, nematic acrylate mixture (Merck, RMM-19B) is used to stack above the alignment layer so that the pre-tilt angle is changed. This makes the critical voltage change, which causes the process from splay to bend to become easy and improve the first problem.

Besides, RMM-19B is also a LC material which also provides phase retardation of linearly polarized light. This small changed value improves the original π cell light leakage in dark state and the contrast ration is improved. These issues will be discussed detailed later.

4-2 Cell fabrication process

Fig. 4-1 shows the fabrication process of π cells:

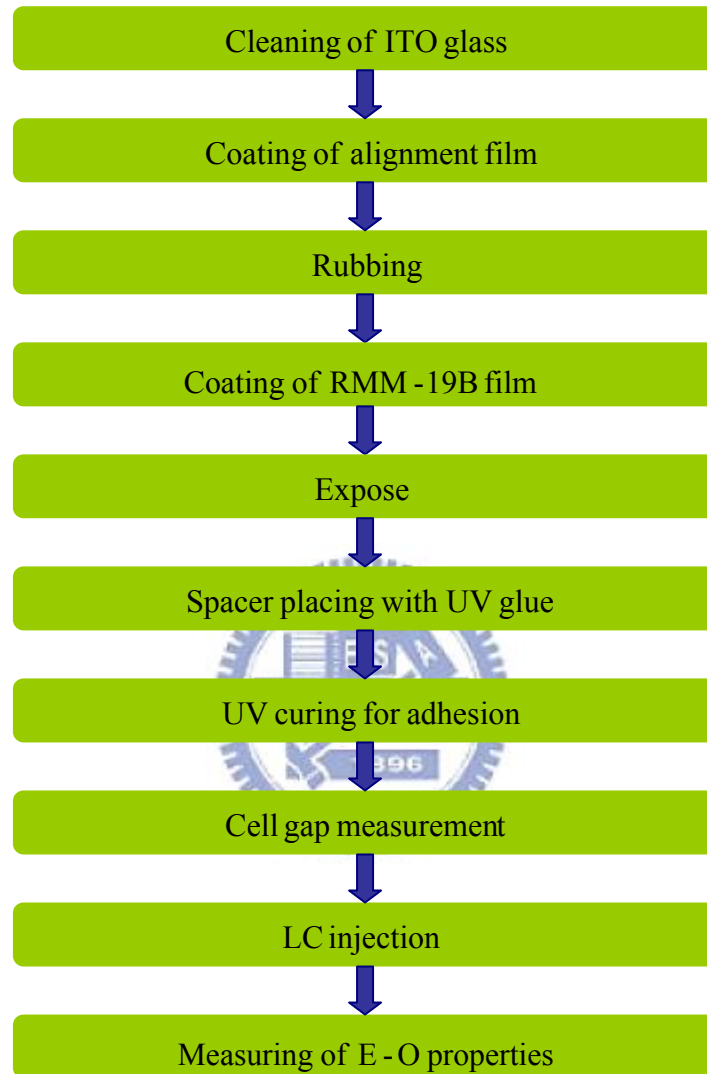


Fig. 4-1: Fabrication process of π cells.

- A. Each ITO glass substrate was cut by 20mm x 25mm and was cleaned by hands with 5 wt% detergent solution. Later each substrate was flushed by DI water until the water flowing along the surface smoothly. All cleaned samples were put into a holder which was soaked into a beaker injected with DI water and vibrated for thirty minutes by ultrasonic vibration equipment. Nitrogen air gun was used to dry the surface of

substrates before they were baked at 110°C for thirty minutes. Finally, UV-Ozone was used to treat the glass substrate for 20 minutes to get better adhesion of alignment layer.

- B. Put each substrate onto the chock of the spin coater. Solvents of the alignment material would be coated first before coating the polyimide (Chisso PIA-5580-01). The injectors filled with the solvent and the polyimide should adopt 0.2um filter to leach particles of the drops. The parameters of spin-coating are shown as Table 4-1.

	Speed	Time
Waiting	0rpm	30s
1st spin	700rpm	20s
2nd spin	5000rpm	60s

Later samples were baked at 220 °C for one hour. The film thickness of alignment layer was measured by AFM (from Digital Instruments) and was about 750Å.

- C. Rubbing the samples with rubbing machine. The rubbing strength was different depending on the LC material, alignment film, and pretilt angle. The rubbing conditions were listed as Table 4-2.

Pile impression	0.2mm
Rotation speed	500rpm
Advancing speed	7.3mm/s

- D. 0.04 grams RMM-19B (Merck) was dissolved in 0.96 grams PGMEA to get a 4 wt% solution. The solution was coated onto a rubbed substrate. The solvent was evaporated at 40°C and the samples were exposed to UV light for 5 minutes at the same time. At least, a polymerized layer was formed and exhibits good splayed alignment characteristic. The

procedure of spin-coating was shown as Table 4-3.

	Time	Speed	
1st spin	20s	500rpm	
2nd spin	60s	RMM-19B-A	RMM-19B-B
		4000rpm	6000rpm

- E. In new cell structure, the top plate used the substrates from step 3 and the bottom plate used those from step 4. 5um spacers were mixed with UV glues (NOA-65, from Norland) to seal the cells. Next, the sealed cells were exposed to a UV lamp for 5 minutes to cure the glues. Finally, empty cells were completed and prepared to be filled in with LCs..
- F. The cell gap of each empty cell was measured by UV-Vis 650, the spectrometer, which was used interferometric method to calculate the cell gap.
- G. Injecting LCs (Table 4-4) by capillary force from the edge of the cell.

n_e	n_o	Δn	$\epsilon_{ }$	ϵ_{\perp}	$\Delta \epsilon$
1.662	1.504	0.158	14.1	4.1	10

- H. Solder the wire at the ITO contact, and then the test cell was available for a mount of electro-optical measurements.

4-3 Polymerizable nematic mixture in π cell

In order to modify the cell structure on alignment surface, polymerizable nematic mixture (Merck, RMM-19B) was used. RMM-19B is a nematic acrylate mixture that can be

polymerized by UV irradiation producing aligned LC polymer film. The mixture is designed to give splayed alignment when coated onto a suitable substrate, and is therefore ideal for preparing optical retardation layers.

RMM-19B solution contains LC molecules and polymerization monomers and these two ingredients would stack and align above the sample after UV light exposure. LC molecules can not move after the curing procedure.

During the evaporation of the solvent, if the evaporation rate is different, the solvent concentration of partial area would not uniform so that LC molecules of thin film may gather together in some areas resulting in thin film defects, as shown in Fig. 4-2. Consequently, evaporation situation of the solvent must be noticed particularly. Generally speaking, well-evaporated thin film would not cause LC molecules to aggregate, as shown in Fig. 4-3. Fig. 4-4 is the result observed by AFM and surface of the sample is uniform. Fig. 4-5 demonstrates our new cell structure.

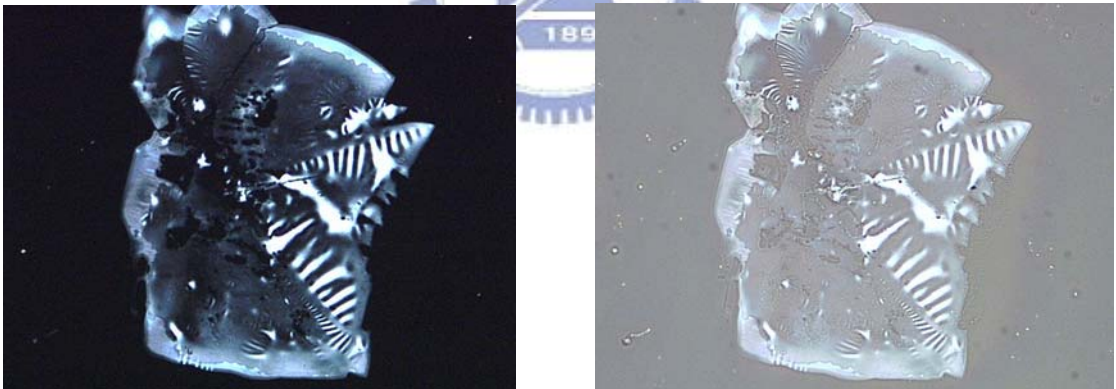


Fig. 4-2: Observation of RMM-19B thin film by POM. LC molecules aggregate in some local areas so that uneven dark or bright state appears in the pictures

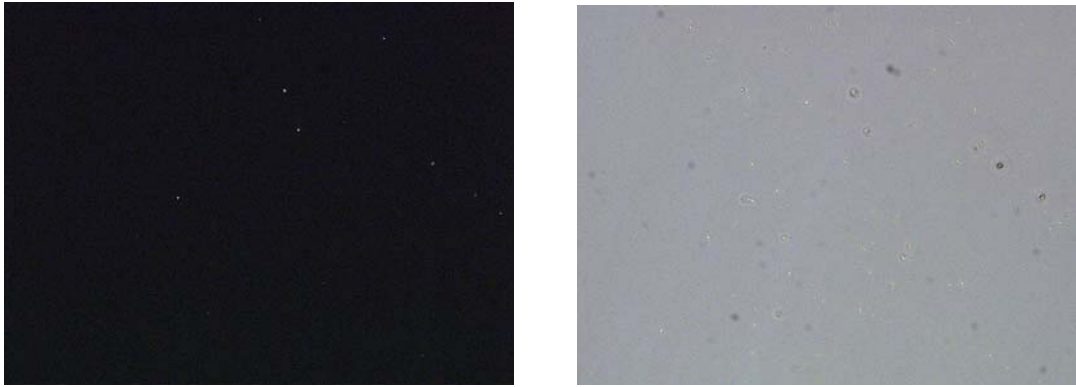


Fig. 4-3: The dark or bright state of RMM-19B thin film observed by POM.

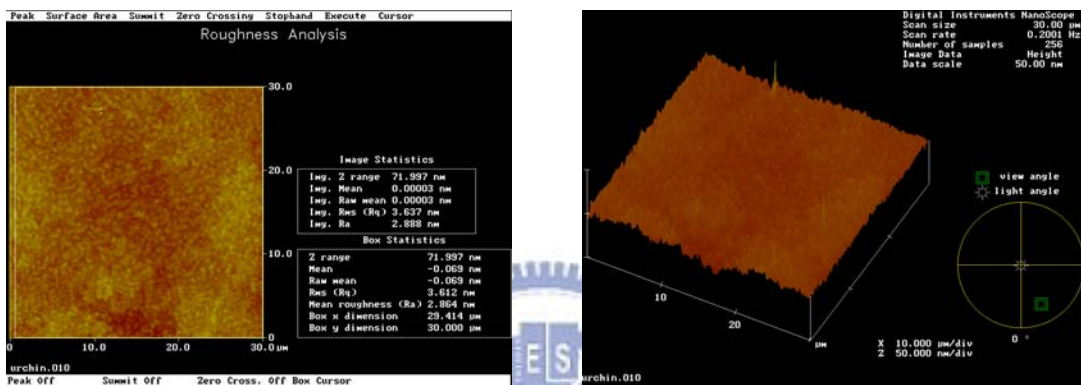


Fig. 4-4: RMM-19B microscopic structure observed by AFM. RMM-19B forms a thin film about 100~200 nm with 3 nm roughness.

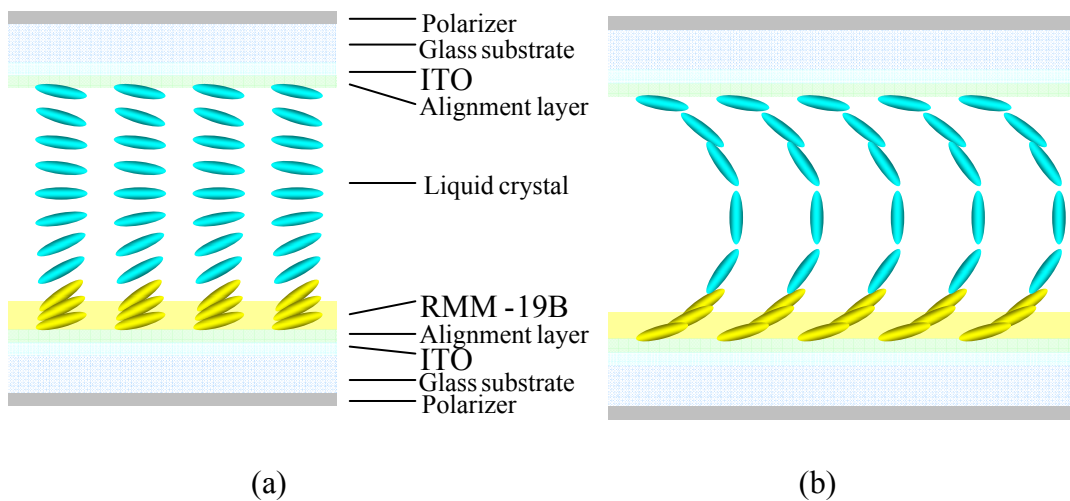


Fig. 4-5: Liquid crystal cell structure and molecules arranged in the surface modified π cell structure. The color band indicated the RMM-19B film. (a) play state ($V=0$); and (b) bend state ($V>V_{cr}$).

4-4 Electro-optical properties measurement and results

4-4-1 EO properties of new cell structure

Sample A is common π cell structure and Sample B uses RMM-19B as the new alignment layer in the bottom plate. The EO properties is measured from zero to ten voltages as shown in Fig. 4-6. Fig. 4-7 is the driving waveform for response time measurement and each pulse is 1 ms.

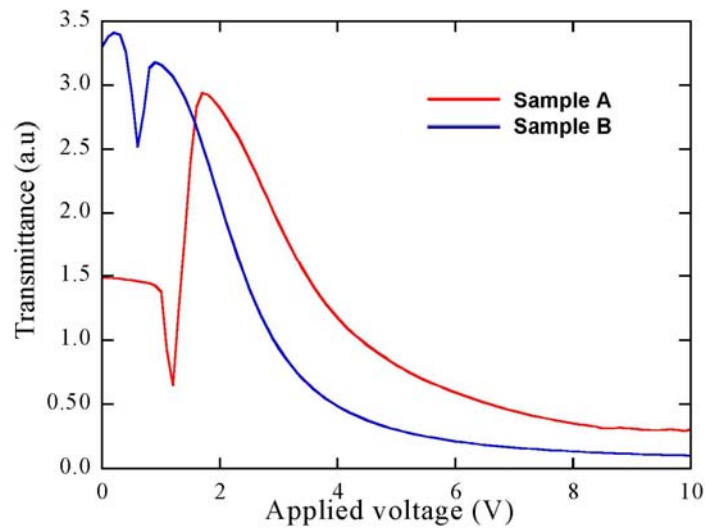


Fig. 4-6: V-T curve of sample A and B.

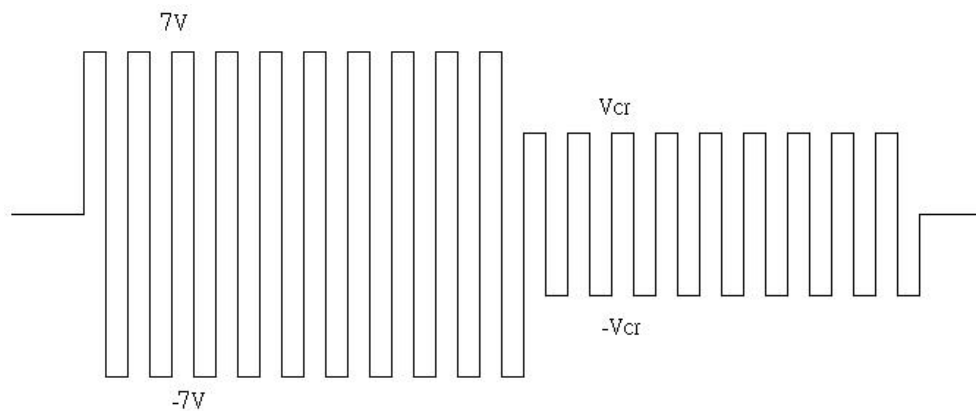
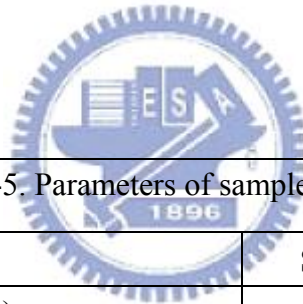


Fig. 4-7: Waveform for response time measurement. The driving voltage of dark state is 7 volts and that of bright state is depending on the V_{cr} of each sample.

About V_{cr} measurement, Sample A has larger V_{cr} than that of Sample B. The top and bottom substrates of Sample A have the same anchoring energy and pretilt angle in the alignment layer. Sample B, in comparison with the A, is using RMM-19B to coat upon the alignment layer of the bottom plate, which probably provides a higher pretilt angle. Such a structure might cause the LC molecules, near the surface of RMM-19B, to much easily rotate with electric field so that we got smaller V_{cr} in π cell.

In response time respect, only 0.4 ms differences between these two cells and the deviation may be from measurement error or affection of new cell structure. No matter what causes the difference, response time of each cell is in the acceptable range so that Sample A or B still keeps π cell fast response time merit.

Table 4-5 shows the cell gap, pretilt angle of bottom plate, V_{cr} , and response time of our samples.



	Sample A	Sample B
Cell gap(μm)	5.0	5.1
Pretilt angle of bottom substrate	10°	--
Alignment layer of bottom substrate	PIA-5580-01	RMM-19B
Critical voltage (V)	1.8	0.9
Response time (ms)	4.4	4.8
Contrast ration	6.5	19.3

Besides, RMM-19B is a material with optical compensation effect so that the dark state of Sample B is improved greatly. Sample A uses general π cell structure and such configuration inherent has no good dark state causing the contrast ratio difference to be very significant. If driving voltages of the dark state is designated as 7 volts, contrast ration for Sample is 6.5 but that for Sample B is 19.3. From this point, RMM-19B has obvious effect in

dark state improvement, which is contributing to compensation film design.

4-4-2 The effect of film thickness

In order to explore if the thickness of RMM-19B will affect the V_{cr} , two samples with varied film thickness are made by adjusting the spin rate. After baking and curing of the substrates RMM-19B-A and RMM-19B-B (Table 4-5), film thickness is determined by Apha-Step and the values are 135 nm for the former and 110 nm for the later, respectively. The relation of thickness versus V_{cr} and response time are listed in Table 4-6.

Table 4-6. The relation of thickness versus V_{cr} and response time in RMM-19B-A and RMM-19B-B.		
	RMM-19B-A	RMM-19B-B
Film thickness (nm)	135 nm	110 nm
Critical voltage (V)	0.7 V	1.4 V
Response time (ms)	< 6 ms	< 6 ms

In traditional π cell setup in, the V_{cr} is around 1.7V to 1.8V. When Rmm-19B is used, the V_{cr} will decrease. The value will be lowered to 1.4V for 110 nm thickness film and to 0.7V for 135 nm. Fig. 4-8 shows the relation of film thickness and V_{cr} and Fig. 4-9 shows the V-T curve of cells with different RMM-19B film thickness. The significant differences between three samples are attributed to the film thickness, which related to the surface pretilt angle. RMM-19B-A and RMM-19B-B possess similar response times within reasonable range of π cell. The similar dark state was also observed.

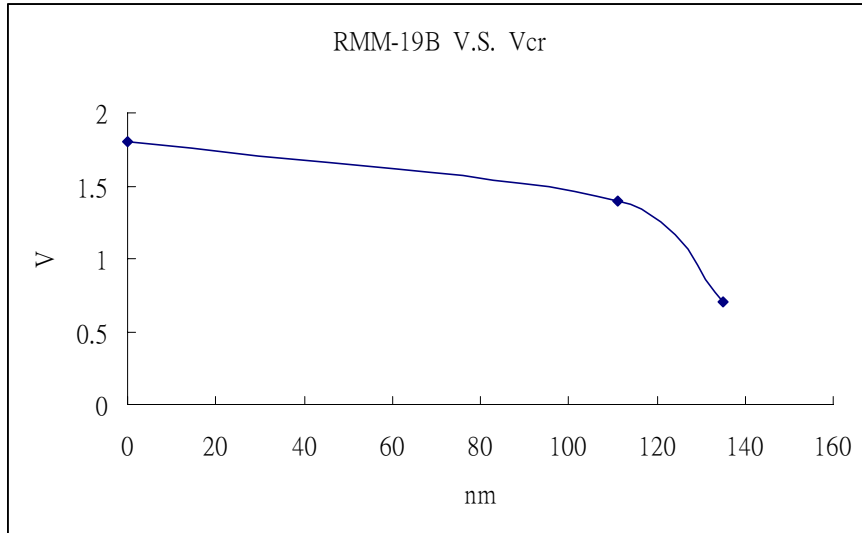


Fig. 4-8: The relation of RMM-19B film thickness and V_{cr} . V_{cr} will decrease with the increasing of film thickness.

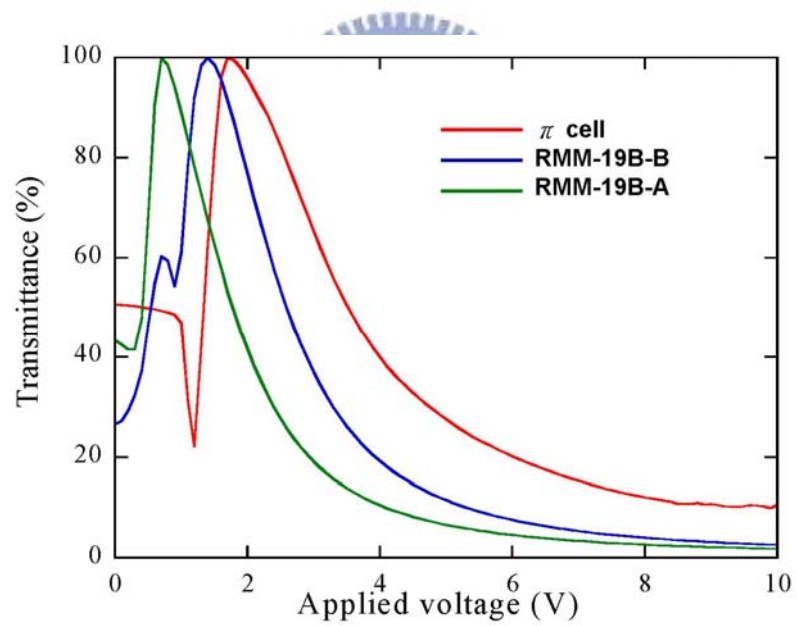


Fig. 4-9: V-T curves for three samples with different film thickness.

4-4-3 Response time measurement

	Cell Gap	τ_{on}	T_{off}	Response Time
Without RMM-19B	5.02 μ m	3.8ms	0.5ms	4.3ms
With RMM-19B	5.06 μ m	4.4ms	0.4ms	4.8ms
Without RMM-19B	2.5 μ m	1.3ms	0.2ms	1.5ms
With RMM-19B	2.5 μ m	1.4ms	0.2ms	1.6ms

To get better performance in LCD displays, reducing the response time of LCs is a choice. By lowering cell gap, LCs' response time can be lowered. But if the coating of RMM-19B would have negative effect in response time lowering is not sure. Therefore, we lower the cell gap and compared the cells with or without RMM-19B. As shown in Table 4-7, when cell gap reduces to 1/2 times, response time would lower to 1/3 times, which successfully declines below 2ms. And the existence of RMM-19B thin film does not affect response time.

4-5 Summary

The surface modified π cell structure with polymerizable nematic film effectively lowers V_{cr} , increases driving voltage range of gray scale, improves light leakage problem of dark state, increases the contrast ration of π cell to three times, and make the design of compensation film easy. Besides, lowering cell gap can effectively lower response time which would not be affected if RMM-19B is used to get good characteristics mentioned above. Thus, the new cell structure has the great advantages in the active matrix TFT-LC display.

Chapter 5

Conclusions

5-1 Summary

The research key point of this thesis is the structural improvement of π cell. Using RMM-19B above the alignment layer makes the critical voltage drop from 1.8 V to the range of 0.7 V to 0.9 V, therefore we can maintain the bend state of the π cell by applying a smaller bias voltage, it is power saving for LC cell, coincident with the demand of display in general. In addition, the operation voltage range of the gray scale broaden from the range of 1.8 V to dark state voltage originally, to the range of 0.7 V to dark state voltage, this makes the gray scale operation easier. In the part of the dark state, using RMM-19B effectively reduces the light leakage of dark state, successfully improves the original poor dark state of π cell, and the design of the compensation film becomes easier. Without the compensation film and use 7 V as the dark state voltage, the measured contrast of the π cell increases from 6.5 to 19.3. In the part of the response time, reduce the cell gap to 2.5 μm makes the response time of the LC be below 2 ms. And in the condition which the thickness of RMM-19B is in the range of 100 nm to 135 nm, it doesn't affect the response time. The new structure of π cell has better performance and faster response time, and will be suitable for the applications of high class products, like HDTV, medical treatment display, etc.

5-2 Future works

In this thesis, we found that RMM-19B can improve the transition process and the dark state. But the new π cells still will transit between splay and bend states. Further research on how to use RMM-19B to drop the critical voltage to 0 V so that new π cells will not need the transition from splay to bend will be continued. Furthermore, if the pile of RMM-19B on the alignment layer changes the pretilt angle so that the V_{cr} is lowered or if there are another factors affecting the decreasing of V_{cr} is not confirmed. Advanced survey on this topic would be discussed in our future work.



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