LC/POLYMER COMPOSITES, SCATTERING PROPERTIES
AND APPLICATION IN DISPLAYS

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LIST of Glossary

LCPC – liquid crystal polymer composite
PSLC – polymer stabilized liquid crystal
PDLC – polymer dispersed liquid crystal
PSCT – polymer stabilized cholesteric texture
PSNLC – polymer stabilized nematic liquid crystal
LWGP – light waveguide plate
PLWG – polarizing light waveguide
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CHAPTER 1

Introduction

In this dissertation, liquid crystal (LC) molecules were used as the main building block for research and invented devices. LC molecules have amazing physical and chemical properties because they exist in a phase between liquid and crystal. Depending on their intrinsic properties and their interaction with surroundings, different states of LCs can exist. The beauty of LCs is that position and orientation of the majority of LC molecules can change by their interaction with proper surroundings materials or by an applied electric field. LC molecules also have a birefringence. In the last couple of decades, studies of the optical birefringence properties of LC molecules, in addition to change of position and reorientation by applied electric field have led to useful electro-optical devices for human beings such as liquid crystal displays (LCDs).

During these years, much effort was made to improve the quality and light efficiency of LCDs. In recent years, large LCD companies are looking for a new generation of LCDs for broader application. Additionally, the light efficiency of LCDs is inherently poor since the LC cell is often sandwiched between crossed polarizers, which leads to a minimum loss of 50%. We carried out research on the design and fabrication of new generation LCD devices for broad application. In addition, we focused on solving the current LCD’s light efficiency problem, which would lead significant advancement for LCD industry.

In this work, LC/polymer composites were used to design and fabricate four novel LC devices to bring new generations of LCD and improving the light efficiency of current LCD technologies significantly. These devices are LC/polymer diffuser, bistable light shutter, active and passive polarizing light waveguide plate (PLWG). These invented LC devices were used to create a transparent display for the new generation of LCDs. A
bistable light shutter was created for application in reflective display as well as smart windows. A PLWG for improving LCDs fundamental light extraction design was fabricated that can dramatically increase the light efficiency of current LCD technology from 50% to 83%. The results obtained here can be used as a base for deeper understanding and improvement on these invented devices. The dissertation is divided as follows:

In Chapter 2, various LC properties such as LC phase, and dielectric properties are introduced. Cholesteric LC is introduced and different states and transition between the states are discussed. Propagation of light in LC media and cholesteric LCs are described. Finally, the main principles of device fabrication with LC/polymer composites and their optical scattering properties are discussed.

In Chapter 3, the new idea of using polymer stabilization of cholesteric LC for transparent displays is introduced. Polymer networks can stabilize the state of the cholesteric LC; in that way the devices can either scatter the incident light or become optically transparent with applied voltage. This light shutter was modified and used as a light diffuser to make the transparent display.

In Chapter 4, two new techniques for making bistable LC light shutters are discussed. Bistable light shutters made by cholesteric LC polymer composites can be used for smart windows and low power consumption displays. In Chapter 5, the novel concept of using an active PLWG as a diffuser for LCDs is reported. Current LCD diffusers provide unpolarized light, but a PLWG can produce partially polarized light and therefore can increase light efficiency by greater than 50%. A PLWG is highly desirable as a diffuser for transparent displays since PLWGs can increase the light efficiency of displays.

A passive PLWG plate is introduced in Chapter 6. This type of waveguide can be used in regular LC displays (LCDs). Different scattering properties of PLWG were studied. The advantage of this technique is that the light efficiency of current display technology can be increase without applying voltage. This technique is a breakthrough in LCD design.
The results presented in this dissertation is summarized in the following presentations and publications:


- **A. Moheghi**, G. Qin, J. Jiang, S. Afghah, Deng Ke Yang “Scattering behavior in LC/Polymer composites”, in preparation


CHAPTER 2

Fundamental of Liquid Crystal and Device Fabrication

2.1 Liquid Crystal

Three main phases of matter are known: solid, liquid and gas. In solids, molecules have both positional and orientation order, and their positions are fixed. Liquids are isotropic media that have uniform physical properties in all directions and can flow. Gases are compressible and their molecules have no orientational and positional order. Liquid crystals (LC) are a phase of matter that is between liquid phase and crystal phase. They have some properties of liquids and some properties of solids. LCs possess a certain degree of orientational order and positional relationships between the molecules [1]. LCs are organic compounds composed of molecules that are elongated and rod like (calamitic) or flat and disc-like (discotic). This dissertation exclusively studied rod-like LCs, which are composed of molecules that are typically five or more times longer (~2-10 nm) than their width (~0.5 nm). One of the simplest and most common LCs is pentylcyanobiphenyl, more commonly known as 5CB, as shown in Fig 2.1. 5CB has a permanent dipole from the cyano group CN.

![Figure 2.1 5CB](image-url)
Although the molecules themselves are not cylindrical, they can still be regarded as such because of the rapid rotation about the long axis (~GHz) due to thermal motion. In non-ferroelectric LC phases the dipole has an equal probability to point either up or down, so the cylindrical representation has no head or tail. The basic molecular components considered necessary for liquid crystallinity are a flexible tail(s) and a rigid core(s). If the molecule is purely rigid, then it will directly transform from an isotropic liquid to a crystalline solid. However, if it is completely flexible, then it cannot maintain orientational order over a long enough length scale. The balance of these two components creates LCs phases [2].

The macroscopic orientation of rod-like LCs is defined by the director ($\vec{n}$). The director points along the direction of the average orientation of the long axis; the alignment of individual molecules can deviate from the director. The director is a double-arrowed vector because of the symmetry; there is an equal probability of a molecule to point up or down. However, the director is often specified as a single-arrowed vector for convenience and it is simply noted that $\vec{n}$ and -$\vec{n}$ are equivalent. In this dissertation, the orientation of LC refers to the director orientation rather than the orientation of an individual molecule.

### 2.2 LC phases

LCs have different phases. Generally, LCs divide into two main categories: Lyotropic LC in which phase changes are due to different concentrations of the LC molecules and thermotropic LCs in which phase changes are induced by changing temperature. In this
dissertation, thermotropic LCs were used because of their electro-optic properties and their application in display and light shutter industries. Different phases for thermotropic LCs can be defined in a sequence given by increasing temperature. They are mainly the smectic and either nematic or cholesteric phases. In the nematic phase the molecules do not possess positional order but have a long-range orientational order; they tend to be parallel to a common axis that is defined by the director of LC ($\bar{n}$). [3]

Nematic LCs are the most widely used LCs in display applications. Molecules can translate in all the three directions and can rotate freely around the long molecular axis [1]. Deformations of nematics are described by the free energy density [3] [4]:

$$F = \frac{1}{2} K_1 (\text{div} \bar{n})^2 + \frac{1}{2} K_2 (\bar{n} \cdot \text{curl} \bar{n})^2 + \frac{1}{2} K_3 (\bar{n} \times \text{curl} \bar{n})^2,$$

where $K_1$, $K_2$, and $K_3$ are elastic constants associated with splay, twist, and bend deformations of LCs, respectively.

In LC cells $\bar{n}$ can have different orientations of polar angle with respect to bounding substrates (xy plane): parallel to the substrates (planar alignment $\Theta_s=0^\circ$), perpendicular (homeotropic alignment, $\Theta_s=90^\circ$), or tilted ($90^\circ > \Theta_s > 0^\circ$) depending on the alignment set at the LC/bounding substrate interface by the aligning material (buffed polymer film, for example), Fig 2.2, (for the simplicity we assume that the azimuthal angle, $\varphi_s$, is equal to $0^\circ$). At the nematic/surface interface the phenomenon called anchoring appears [3, 4]. Typically anchoring stems from anisotropic character of molecular interactions such as van der Waals interactions between the LC molecules and those of the aligning material.
Strength of anchoring is characterized by the anchoring coefficient $W$, which is equal to the work per unit area required to deviate the director from the preferred orientation by a certain angle [4].

![Diagram of LC's Director](image)

**Figure 2.2** Different orientation of LC’s Director $\vec{n}$, (a) homogeneous or planar, (b) homeotropic, and (c) tilted.

Homogeneous anchoring can be achieved by mechanically rubbing the surface of the LC cell substrate, which is mostly ITO (indium tin oxide) coated glass, with a cotton ball or cloth. The rubbing creates micro-grooves along the rubbing direction. When the LC is aligned parallel to the grooves, there is no orientational deformation. If the LC were perpendicular to the grooves, there would be orientational deformation, resulting in an increased elastic energy. Therefore, the LC will be homogeneously aligned along the rubbing direction. The problem with alignment created in this way is that the anchoring strength ($10^{-5} \text{ J/m}^2$) is weak. Rubbed polyimides are used as a homogeneous (planar) alignment layer. The rubbing not only creates the micro-grooves but also aligns the polymer chains. The intermolecular interaction between the LC and the aligned polymer chains also favors parallel alignment and thus increases the anchoring energy. The anchoring strength can become as high as $10^{-3} \text{ J/m}^2$. Furthermore, pretilt angles of a few
degrees of LCs can be generated. Homeotropic anchoring can be achieved using SE1211 homeotropic alignment layer. The intermolecular interaction between the surfactant and the LC promotes the homeotropic alignment and lead LCs to align perpendicular to cell surfaces.

Anchoring phenomena are responsible for restoring the director orientation in a cell when the electric field is switched “off”. When the field is switched “on”, anchoring prevents the LC molecules from being completely reoriented.

Smectic LCs are another phase of thermotropic LCs. In a smectic phase, the molecules are arranged in a layered structure with a well-defined interlayer spacing [3] and possess a long-range orientational order as well as a positional order in one direction. While there are numerous types of smectic phases, Smectic A (SmA) and smectic C (SmC) are the most commonly observed. In SmA phase the director is perpendicular to the layer plane. In SmC the director is tilted within the layer; the tilt value varies depending on the material and temperature.

Cholesteric or chiral nematic is another phase of LCs that was frequently used in this research. If chiral compounds such as cholesterol esters are added to nematic LCs, the nematic phase changes into the chiral-nematic or cholesteric phase. In cholesteric LCs, the director twist in space around an orthogonal helical axis, on a plane perpendicular to the helical axis. Molecules are aligned with their long axes parallel to a common direction, similar to that in nematic LCs. A cholesteric LC is shown in Fig. 2.3. The director is rotated (twisted) along the helical axis tracing out a left-handed or right-handed helical path depending on the properties of the chiral dopant. The distance along the helical axis along which LC director twists 360° is called the pitch. Pitch is usually on the order of the wavelengths of visible light. The pitch depends on the amount of chiral dopant (fraction by weight) in the mixture and its helical twisting power (HTP) according to the relationship.
\[ P = \frac{1}{HTP \cdot C}, \] 2-2

where \( C \) is the concentration of the chiral dopant. The HTP is the “degree” of chirality, a measure of how much twist can be induced by the dopant and has units of \( \mu m^{-1} \). The HTP can vary with between types of dopants as well as the type of host. Cholesteric LCs exhibit optical rotation, and selective reflection. Moreover, cholesteric LCs are used in polymer stabilized LCs which will be discussed in coming chapters of this dissertation.

Figure 2.3 Cholesteric LC

A cholesteric LC molecule can be regarded as a screw, instead of a rod, in considering its physical properties. After considering the symmetry where \( \vec{n} \) and \(-\vec{n}\) are equivalent, the generalized elastic energy density for cholesteric LC is given by:

\[ f_{\text{elastic}} = \frac{1}{2} K_1 (\text{div}\vec{n})^2 + \frac{1}{2} K_2 (\vec{n} \cdot \text{curl}\vec{n} + q_0)^2 + \frac{1}{2} K_3 (\vec{n} \times \text{curl}\vec{n})^2, \] 2-3
where $q_0$ is the chirality. The axis around which the director twists is called the helical axis and is chosen to be parallel to $z$ here. The pitch, $P_0$, is related to the chirality by:

$$P_0 = \frac{2\pi}{q_0}.$$  \hfill (2.4)

Depending on the chemical structure, the pitch of a cholesteric LC could take any value from a few tenths of a micron to infinitely long. Nematic LCs can be considered as a special case of cholesteric LCs with an infinitely long pitch [2].

### 2.3 Dielectric properties of LCs

The main reason that LCs are of great importance in display applications is their response to externally applied electric fields. Their direction can be easily changed by electric fields produced by application of a few volts across the LC cells. They are either dielectric or ferroelectric materials with high resistivity and thus consume little energy. When the LCs reorient, their optical properties change dramatically because of their large birefringence.

The anisometric shape of molecules is responsible not only for the orientational ordering but also results in anisotropic properties of LCs along the director and perpendicular to it. Optical anisotropy (birefringence) of LCs $\Delta n = n_e - n_o$ results in double refraction of light passing through a slab of LC material [5]. Here $n_e$ and $n_o$ are the LC refractive indices for
the light propagating perpendicular to $\mathbf{n}$ (extraordinary wave) and parallel to $\mathbf{n}$ (ordinary wave), respectively. Anisotropy of dielectric constants $\Delta \varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ leads to the response of $\mathbf{n}$ to an external electric field $\mathbf{E}$. Here $\varepsilon_\parallel$ and $\varepsilon_\perp$ are the dielectric constants of LC in the directions parallel and perpendicular to $\mathbf{n}$. LCs reorient in externally applied electric fields because of their dielectric anisotropies. The electric energy, part of the free energy, of a LC depends on the orientation of the LC director in the applied electric field and is given by:

$$f_{\text{elastic}} = -\frac{1}{2} \Delta \varepsilon_0 (\mathbf{E} \cdot \mathbf{n})^2.$$  \hspace{1cm} 2-5

Under a given electric field, the LC is considered to be in an equilibrium when the total free energy is minimized. When a nematic LC is confined, such as when it is sandwiched between two parallel substrates with alignment layers, the orientation of the LC director is determined by the anchoring condition in the absence of an external field. When an external electric field is applied to the LC, it will reorient because of the dielectric interaction between the LC and the applied field. If the dielectric anisotropy is positive ($\Delta \varepsilon > 0$), the LC tends to align parallel to the applied field. If $\Delta \varepsilon < 0$, it tends to align perpendicular to the field. This field-induced reorientation of the LC is referred to as the Freedericksz transition [1]. The electrical field-induced director reorientation is a very important phenomenon for practical applications.
2.4 Cholesteric LC different states

Cholesteric LCs can exhibit different states depending on the effects of surface anchoring, cell thickness, and applied fields. The cholesteric LC can be switched from one state to another by applying electric fields or by applying pressure. There are many possible transitions among the states [2]. In order to design drive schemes for the different light shutters made from cholesteric LCs, it is essential to understand these transitions. The cholesteric LCs considered here have positive dielectric anisotropies unless otherwise specified. The main states of cholesteric LCs are discussed below.

2.4.1 Planar texture

The planar texture (state) is probably the most important and most well known texture (state). In this case, the helical axis is oriented parallel to the normal of the LC cell substrates. When the surfaces impose a preferential alignment direction for both top and bottom boundaries, the number of turns will be quantized, allowing only an integer number of half turns. The oily streak defect can be observed in this state; most of the time it is formed during the filling process and can be observed between spacers. Figure 2.4 presents the planar texture.
2.4.2 Fingerprint texture

In the fingerprint texture, the helical axis is parallel to the substrates. When the pitch is long, the layered structure can be easily seen, which resembles fingerprint. Usually, this texture can be obtained either by applying a field to the planar texture or by having homeotropic boundary conditions. However, in the latter case, it depends on the ratio of the cholesteric pitch to the cell gap. If this ratio is larger than a critical value, then the LC will behave as a homeotropically oriented nematic. The Fingerprint texture is shown in Fig 2.5.
2.4.3 Focal conic texture

In focal conic state, the cholesteric LC is broken into domains in which the helical axis of different domains points in different directions, but the pitch remains the same. For this reason, there is a mismatch of the refractive index between domains and, therefore, the texture scatters light. Focal conic texture is shown in Fig 2.6.

![Figure 2.6 Cholesteric LC in the focal conic state](image)

2.4.4 Homeotropic texture

The homeotropic texture is the simplest texture. In this case, a high electric field is applied to a cholesteric LC with a positive dielectric anisotropy and the helix is unwound so all the molecules will point along the field. This configuration is trivial for light and under crossed polarizers the texture is dark because direct incident light just sees ordinary reflective index of cholesteric LC molecules. Homeotropic texture is shown in Fig 2.7.
2.5 Transition between cholesteric LC states

When the cholesteric LC experiences different electric fields and anchoring conditions, transitions between cholesteric LC states will occur as discussed in the following subsections.

2.5.1 Transition between planar state and focal conic state under a given electric field and boundary conditions

A LC system in equilibrium is in a state with minimum free energy. In considering the states of the cholesteric LC, the energies involved are the elastic energy of the deformation of the LC director, electric energy, and the surface energy. In both the planar and focal conic states, the helical structure is preserved. In the planar state, the elastic energy is zero because there is no director deformation, while in the focal conic state, the elastic energy
is positive because of the bend of the cholesteric layers. In the planar state, the electric energy is zero because the LC director $\mathbf{n}$ is perpendicular to the field everywhere, while in the focal conic state, the electric energy is negative because the LC is parallel to the applied field in some regions. The elastic energy is against the planar–focal conic (P–F) transition while the electric energy favors the transition. When the applied field is sufficiently high, the planar state becomes unstable and the LC transforms from the planar to the focal conic state. Once the transition occurs, because of an energy barrier, some disturbance is necessary to drive the focal conic back to the planar texture. This can be accomplished either by strong anchoring or by an electric field.

Once the cholesteric LC is in the focal conic state, it may remain there, depending on the surface anchoring condition of the area around the cholesteric LC. In bistable cholesteric LC where either weak tangential or homeotropic alignment layers are used or polymers are dispersed in the LC, the LC remains in the focal conic state when the applied voltage is turned off. This property is discussed more in Chapters 3 and 4. If the cell has strong homogeneous alignment layers, the focal conic texture is unstable and the LC relaxes slowly back to the planar texture.

### 2.5.2 Transition between the focal conic state and homeotropic state

When the LC is in the focal conic state and the externally applied electric field is increased, more LC molecules are aligned parallel to the field. The LC is gradually
switched to the fingerprint state. When the applied field is increased further, the pitch of
the LC becomes longer. When the applied field is above a threshold value $E_c$, the helical
structure is unwound, the pitch becomes infinitely long, and the LC is switched to the
homeotropic state. In the fingerprint state. The free energy is given by [2],

$$f_{\text{Electric}} = \frac{1}{2} \Delta \epsilon \epsilon_0 E^2 \sin^2 \theta - \frac{1}{2} \Delta \epsilon \epsilon_0 E^2. \quad 2-6$$

where $\theta$ is the angle between cell normal and directors. The critical field that unwinds the
helical structure is given by [2]:

$$E_c = E_0 = \frac{\pi^2}{P_0} \sqrt{\frac{K_{\alpha\alpha}}{\epsilon_0 \Delta \epsilon}} \quad 2-7$$

The fingerprint state to homeotropic transition is reversible. The LC can transform directly
from the homeotropic state back to the fingerprint state. The transition is, however, a
nucleation process and therefore is slow (on the order of 100 ms). There is also a
hysteresis where the transition occurs only when the applied field is decreased below a
threshold that is lower than the threshold to unwind the helical structure. If there are no
nucleation seeds, the formation of helical structure in the middle of the homeotropic state
always causes the free energy to increase; i.e., there is an energy barrier against the
homeotropic–fingerprint (H-F) transition. Experiments have shown that the threshold $E$ of
the H-F transition is about 0.9Ec. For the LC in the homeotropic state, when the applied field is decreased, there are two relaxation modes. One is the H-F mode in which the LC relaxes into the fingerprint state and then to the focal conic discussed in the previous section. The other is the H-P mode in which the LC relaxes into the planar state [6, 7].

If \( K_3 = \frac{K_{33}}{K_{22}} = 2 \), we have \( E_{HP} = 0.45 \) Ec which is lower than the critical field for unwinding the helix. The non-normalized critical field of the homeotropic state to planar-state transition is [2]:

\[
E_{HP} = \frac{2}{\pi} \sqrt{\frac{K_{22}}{K_{33}}} E_c. \tag{2-8}
\]

If the LC is in the homeotropic state and the applied field is reduced, there are two possible relaxation modes. If the applied field is reduced to the region \( E_{HP} \langle E \langle E_{HF} \), then the LC will relax slowly into the fingerprint state and then to the focal conic state when the applied field is reduced further. If the applied field is reduced below \( E_{HP} \), then the LC will relax quickly into a transient planar state and then to the stable planar state. The way to switch the LC from the focal conic state to the planar state is by first applying a high field to switch it to the homeotropic state, and then turning off the field quickly to allow it to relax to the planar state.
2.6 Propagation of Light in Cholesteric LCs

By solving the electromagnetic wave equation of light in cholesteric LC media with the pitch near the wavelength of the light, the result is that the cholesteric LC reflects circularly polarized light with the same handedness and the same periodicity as the helical pitch. Reflection edge bands, \( \lambda_1 \) and \( \lambda_2 \), are calculated as below in equation 2-8 for normal incident light as

\[
\begin{align*}
\lambda_2 &= \sqrt{\varepsilon_0} P = n_e P, \\
\lambda_1 &= \sqrt{\varepsilon_\perp} P = n_o P.
\end{align*}
\]

The width of this reflection band is

\[
\Delta \lambda = \lambda_2 - \lambda_1 = (n_e - n_o)P = \Delta n P.
\]

For light that is circularly polarized with the same helical sense as the helix of the LC, the angle between the electric vector of the light and the LC director is fixed as the light propagates along the helical axis. Light rays reflected from different positions are always in phase and they interfere constructively which results in strong reflection.
2.7 LCs/polymers

LC/polymer composites (LCPCs) are a relatively new class of materials that are used in various technologies such as in displays, light shutters, and optical fiber telecommunications. They consist of low molecular-weight LCs and high-molecular-weight polymers, which are phase-separated from each other. According to the morphology, LCPCs can be divided into two sub-groups: polymer-dispersed LCs (PDLCs) and polymer-stabilized LCs (PSLCs). In PDLCs, the concentration of the LC and polymer are about the same, and the LC exists in droplets that are dispersed in polymer. In PSLCs, the polymer forms a sponge-like structure. The concentration of the LC is much higher than that of the polymer in PSLCs, allowing the LC to form a continuous medium. LCPCs can also be divided into two subgroups according to the application; scattering device and non-scattering device. In a scattering device, the polymer produces or helps to produce a poly-domain structure of the LC in one field condition. The domain size must be comparable to the wavelength of visible light in order for scattering to occur. The material is highly scattering because of the large birefringence of the LC. In another field condition the LC is aligned unidirectionally along the applied field or can stay in planar texture of cholesteric with reflection band farther than visible light and the material becomes transparent. In a non-scattering device, the LC is used to stabilize states of the LC. In this research, PSLCs were used to design and fabricate different optical LC devices.
2.7.1 Scattering Properties of LCPCs

The scattering of LCPCs is caused by the spatial variation of refractive index in the materials [8]. In PSLCs, the scattering is due to the refractive index mismatch between the LC and the polymer network as well as between LC domains. A precise calculation of the scattering of LCPCs is very difficult because of the birefringence of the LCs, dispersion in domain size, and irregularity of domain shape. In this dissertation, we discuss only qualitative behavior of PSLCs scattering.

In PSLCs, the polymer concentration is usually less than 15% of the total mixture. The monomer used may be mesogenic with rigid cores similar to those of LC molecules [9-12]. Before polymerization, the mixture of the monomer and the LC is in a LC phase. The polymerization environment is anisotropic due to the aligning effect of the LC on the monomer and the anisotropic diffusion of the monomer in the LC. Anisotropic fiber-like polymer networks are usually formed, which mimic the structure of the LC during the polymerization. Because the LC and monomer are homogeneously mixed and in LC phase during the polymerization, external fields and surface alignment techniques can be applied to create various polymer network structures. After polymerization, polymer networks tend to stabilize the LC state in which they are formed. In a PSLC, the LC near the polymer network tends to align along the polymer network. The strength of the interaction between the LC and the polymer network is proportional to the surface area of the polymer network. The surface area of the polymer network can be increased by using higher polymer concentrations or producing smaller lateral size polymer networks.
2.7.2 Methods of making PSLCs

PSLCs are usually made from mixtures of LCs and monomers that can be directly dissolved in the LC. Photo-initiated polymerization is fast in the other of first couple of minutes and more popular and it was the method of polymerization for all experiments in this research. The monomer is usually acrylate or methyl acrylate because of its fast reaction rate. A photo-initiator was also added to the mixture. The concentration of the photo-initiator added was typically 1–10% of the monomer. When irradiated under UV light, the photo-initiator produces free radicals that react with the double bonds of the monomer and initiate the chain reaction of polymerization. The monomer is polymerized to form a polymer network. The lateral size of the polymer network is on the order of submicrons. The morphology of the polymer network is affected by the following factors: structure of the monomer, UV intensity, photo-initiator type and concentration, and the temperature. The lateral size of polymer networks is determined by the polymerization rate, mobility, and concentration of monomers [13]. Polymer networks with smaller lateral sizes can be obtained with higher polymerization rates, which can be achieved with higher UV intensities or high photo-initiator concentrations or higher polymerization temperature. In this research, LC/polymers composites were used to design and fabricate different novel light shutters. These combinations were used to report a new display backlight diffuser device that will significantly increase the light efficiency of current LCD technology.
CHAPTER 3

Transparent Display using Polymer-stabilized Cholesteric

Texture Normal-mode Light Shutter

3.1 Introduction

Transparent display is an emerging new display technology [14-20]. It has great potential for advertising display application. Transparent display can be operated in two modes: transparent mode and display mode. In the transparent mode, it is transparent and the scene behind it can be seen. In the display mode, transparent displays images as a regular TV. One of the critical components of the transparent display is a switchable diffuser (or reflector) that can be switched between a transparent state and a diffusion (scattering) state. In the transparent state, the diffuser appears as a piece of glass. In the diffusion state, it appears milky and guides light from ambient light or backlight (or edgelight/edgelit) to the LC panel.

Several switchable diffusers have been reported. Examples include PDLCs [14, 15]. PDLCs scatter light in the absence of applied voltages and become transparent when a voltage is applied. They, however, usually suffer from two drawbacks. First when they are in the transparent state, they are only transparent for normal incident light and are hazy for obliquely incident light; thus they have a narrow viewing angle. Second, when they are in the scattering state, the backward scattering is weak and less than 20%. Another
example is cholesteric LC [16]. Cholesteric LC is reflective planar state in the absence of applied voltage and switched to the transparent homeotropic state when a voltage is applied. Although the reflectance of a single layer cholesteric LC can be as high as 50%, its reflection bandwidth is usually only around 50 nm and cannot cover the entire visible light region. In this chapter we introduced a new concept for a switchable diffuser with modified normal mode PSCT [21-25]. In the transparent state, normal mode PSCT has a very high transmittance and a large viewing angle. In the scattering state, it has a diffused reflectance higher than 30% in the entire visible light region.

In Chapter 2 different states of the cholesteric LC were explained. The PSCT normal-mode light shutter is made from a mixture of cholesteric LC and a small amount of monomer and photo initiator. The pitch of the cholesteric LC is a few microns. No special cell surface treatment is needed. Polymerization occurs while a high voltage is applied on the LC cell, which unwinds the cholesteric structure and reorients the LC molecules to the homeotropic state (perpendicular to the substrate) and the polymer network is formed perpendicular to the cell surface in the direction of homotropically aligned LCs under the high field as shown in Fig. 3.1 After polymerization, when the PSCT normal-mode light shutter is in a zero field state, the LC tends to have a helical structure, while the polymer network tends to keep the LC director parallel to it. The competition between these two factors results in the focal conic texture as shown in Fig. 3.1 (a). In this state, the material has a polydomain structure and is optically scattering. When a sufficiently high electric field is applied across the cell, the positive dielectric anisotropic LC is switched to the
homeotropic texture as shown in Fig. 3.1 (b). Incident light just sees the ordinary reflective index of LCs and is not scattered and therefore the cell is transparent.

Figure 3.1 Schematic diagram of the switchable normal mode PSCT diffuser. (a) Scattering state, (b) transparent state.

Because the concentration of the polymer is low and both the LC and the polymer are aligned in the cell normal direction, the PSCT normal-mode light shutter is transparent at almost any viewing angle. In order to scatter visible light strongly, the size of the focal conic domain size has to be around the wavelength of the light. The main factors affecting the domain size are the pitch, polymer concentration, and curing UV intensity. The drive
voltage is mainly determined by the pitch and the dielectric anisotropy of the LC. Faster responses can be achieved with a shorter pitch.

In this research, PSCT normal mode light shutter was used as a switchable diffuser for transparent LC displays. It can be switched between a transparent state and a milky scattering state by applying voltage.

3.2 Experiments

The optical properties of the PSCT are controlled by the morphology of the polymer network, the helical pitch of the cholesteric LC, and the cell thickness.

This research evaluated the performance of the normal mode PSCT with the following experiments:

A- The chiral dopant concentration was varied (which also varied the pitch),

B- The monomer concentration was varied,

C- The UV curing intensity was changed,

D- Cell thickness was varied,

For each experiment, all the other parameters were kept fixed and just one parameter varied. The LC cell was made from two parallel ITO coated glass plates. A homeotropic alignment layer SE1211 was spin coated on ITO on both internal surfaces of the LC cell. An ITO layer on the cell surface as the electrode would work for normal mode PSCT but the stability of the focal conic texture is better when homeotropic alignment was used. The LC/monomer mixture was filled into the cell and cured under 1.4mw/cm² UV light for 30 minutes with an applied 50 Vac-850 Hz electric voltage. While curing, the LC molecules
aligned parallel to the electric field because they had positive dielectric anisotropy and molecules dipole wanted to align in the direction of electric field. Monomers created a polymer network by the help of photo initiators in the direction of LC molecules, which was perpendicular to the cell surfaces. The LC used was BL038 (Merck which is positive LC from EMD). The characterizing parameters of mixture are:

- BL038: $\Delta n=0.272$, $\Delta \varepsilon=16.9$ in 20$^\circ$C, Chiral dopant is R811 with the helical twisting power (HTP) of 10 $\mu m^{-1}$
- Monomer is RM257 (Merck) with chemical structure is shown in Fig. 3.2 below:

![Figure 3.2 Monomer RM257 Chemical structure](image)

- We used BME (Benzoin methyl ether) photo initiator from Sigma Aldrich for polymerization. Its chemical structure is shown in Fig. 3.3.

![Figure 3.3 Photo initiator BME](image)

Reflection and transmission behavior of PSCTs were considered as two important parameters of electro-optic behavior of PSCTs. In the transmission measurement, a photo-
detector with the collection angle of $4^\circ$ was placed directly behind the PSCT cell. The measured transmission was normalized to the incident light before the cell. In the reflection measurement, the photo-detector was placed at the same side as the incident light and at $30^\circ$ with respect to the cell normal. The measured reflection was normalized to that of a regular white copy paper. Electro-optical set up for measurement of transmission vs. voltage behavior is shown in Fig 3.4.

![Electro-optical set up for measurement](image)

**Figure 3.4 Schematic of electro-optic set up for PSCT experiment**

### 3.3 Results

All calculations of the contrast ratio used the maximum transmission and the minimum transmission as found in the T-V curve like the one shown in Fig. 3.5. When the voltage was removed gradually, the contrast ratio was lower than that when the voltage was
removed suddenly. This is because the transition from the homeotropic texture to the focal conic texture is not a homogenous transition (occurring everywhere simultaneously), but is a nucleation process that starts at defects in the sample such as spacers and the strands of the polymer network [26]. As voltage decreases slowly, the focal conic texture grows from just a few places so it forms larger domains. If the voltage is removed suddenly, the domains form in many more places at once and therefore the average domain size tends to be smaller, which scatters light better.

3.3.1 Effect of monomer concentration

Polymer concentration plays an important role in the electro-optic behavior of PSCTs. Switching time, threshold voltage, and hysteresis are the important parameters that are affected by polymer concentration in the PSCTs. In order to find the best monomer concentration in mixture, other parameters were held fixed while making the PSCT and electro-optic properties were compared for different monomer concentrations. We used a mixture consisting of 97% E44 (Merck) LC and 3% chiral dopant S1011 (Merck). This ratio makes a cholesteric LC with the pitch of 1.075 μm. Four mixtures with 4 monomer concentrations of 1.3%, 2%, 3%, and 4% of total weight of the LC and chiral dopant were made. Mixtures were filled into the 10 μm ITO coated cells. The cells were UV cured with intensity of 1.4 mw/cm² UV light for 30 minutes while applying 50Vac, 1kHz electric voltage.

As mentioned before, in PSCT normal mode, the polymer network and LC were perpendicular to the cell surface.

Transmission vs voltage for different monomer concentrations was measured; see Fig. 3.5.
The cell with 4% monomer or lighter stayed in the transparent homeotropic state after UV curing and removing voltage. This means that the alignment effect of the polymer is strong enough to overcome the effect of cell surface anchoring and the helical structure. In this case, the strong anchoring of the polymer networks keeps LCs molecules parallel to them in the homeotropic state and the cell remains in the transparent homeotropic state. For 1.3% and 2% of monomers as shown in Fig. 3.5, the contrast ratios were 5 and 6, respectively. For the cell with 3% monomer, the contrast ratio was the highest and was 90. So for the rest of the work, PSCTs with 3% of monomers were chosen.

3.3.2 Effect of chiral dopant concentration

In order to study the effect of chiral dopant concentration, which leads to changing the pitch of the cholesteric texture, two different mixtures with pitches of 800 nm and 500 nm were made and filled into the 24 μm ITO coated LC cell normal mode PSCT.
In transparent display, reflection from diffuser in off state is an important parameter since we do not have any dark background as in regular TV state. Transmission and reflection measurement geometry is shown in Fig 3.6.

120 Vac, 1 kHz electric field was applied to the cells during curing. Their transmission vs applied voltage is shown in Fig. 3.7 and Fig 3.8.

The transmission and reflection vs. applied voltage of the cell with thickness of 24 μm and helical pitch of 800 nm were measured. The threshold voltage of this sample is 90 V. The transmittance of voltage-on state is 87%. If the applied voltage is turned down gradually, the reflectance is 18%. If the voltage is turned off suddenly, the reflectance is 25%. The difference is probably due to that when the voltage is turned off suddenly, smaller domains form, which cause higher backward scattering.

The threshold voltage of the cell with thickness of 24 μm and helical pitch of 500 nm is about 120 V. The transmittance of voltage-on state is 86%. The reflectance of the voltage-off state is increased to 32%. These results show that increasing the helical pitch is an efficient way to increase the reflectance of the scattering state.
The results show that unwinding cholesteric LCs with a shorter pitch needs a higher voltage than those with a longer pitch. The contrast ratio of the 500 nm pitch sample is higher. The reason is due to the smaller focal conic domains, which leads to the higher scattering of incident light.

Figure 3.7 Electro-optical response of the PSCT cell with 24 μm cell gap and 800 nm pitch, (a) T vs V, (b) R vs V
3.3.3 Effect of the Cell thickness

The effect of different cell thickens on transmission vs. voltage (T vs V) and reflection vs voltage (R vs V) was measured. Two different mixtures with the same polymer concentration and pitch were made. The same method was used for UV curing and making PSCT. The measured T vs V and R vs V for the mixture of PSCT with pitch 500 nm filled in cells with 24 μm cell thickness is Fig. 3.8. Similarly, T vs V and R vs V for the mixture of PSCT with pitch 500 nm filled in cells with 14 μm cell thickness is shown in Fig. 3.9.
The driving voltage for the cell with 14 μm thickness and 500 nm pitch is 72 V. The transmittance of the voltage-on state is 88%. The reflectance of the voltage-off state is 13%. A comparison of the result for T vs V and R vs V for the mixture with 500 nm pitch in the 24 μm shows that the cell with the 24 μm thickens has a higher contrast ratio and reflection. Thicker cells have more focal conic domains and can scatter light more.

Figure 3.9 Electro-optical response of the PSCT cell with 14 μm cell gap and 500 nm pitch., (a) T vs V, (b) R vs V
Figure 3.10 Photograph of the PSCT cell with 24 μm cell gap and 800 nm pitch. (a) voltage off, (b) voltage on.

Figure 3.10(a) shows a photograph of the PSCT cell in the voltage off state. It appears quite white due to its high reflectance. Figure 3.10(b) shows a photograph of the PSCT cell in the voltage on state. It is very transparent and the scene behind it can be seen well.

3.4 Performance in edgelit display

We tested the PSCT diffuser with a LED edgelight. In this set up, light generated by an array of LEDs couple in one of the edges of the PSCT. Normal mode PSCT was used as a waveguide. When PSCT is in a focal conic state, it will scatter light and act like a diffuser. Figure 3.11 shows edge coupling in 4x4 inch PSCT normal mode. Output light on the screen indicates behaviors of the PSCT waveguide. When voltage is on and the PSCT is in transparent state, LC molecules are homeotropic; edgelight just sees one reflective index and will be guided in the cell. No light comes out of the cell as shown in Fig. 3.11(a).
When voltage is off, the PSCT normal mode is in focal conic state and will scatter light from the surface as shown in Fig. 3.11 (b).

Figure 3.11  Edge coupling in PSCT. (a) Transparent state edgelight, (b) scattering state edgelight,

3.5  Edgelite scattering dependence to distance in scattering state and transparent state.

In order to measure the intensity of scattered light in different positions from edgelit, a detector is placed on top of the PSCT diffuser and the intensity of scattered light in different positions from edglight is measured. The measurement set up is shown in Fig 3.12.
The measurement shows that the intensity of the scattered light will decrease as the position get farther from the edglight. Measurement starts from 0.5 cm of edglight. The edge from 0 cm to 0.5 cm was covered in order to avoid measuring the direct light from the LEDs. The result is shown in Fig. 3.13. When voltage is on, because of the homeotropic state of LCs, edge light propagates through the cell. The intensity of the scattered light is low, and independent of the distance from the light source.

![Edgelight scattering dependence on distance](image)

**Figure 3.12** Measurement set up for edglight scattering dependence on distance

**Figure 3.13** Edglight scattering dependence on distance
Figure 3.14 (a) shows a photograph of the PSCT cell in the voltage on state. It waveguides light through it and no light comes out. The scene behind it can be seen well. Figure 3.14 (b) shows a photograph of the PSCT cell in the voltage off state. It waveguides light and scattered the light out. It blocks the scene behind it.

![Photograph of the PSCT cell when edgelight. (a) voltage on, (b) voltage off.](image)

3.6 Summary and final product

We developed a transparent advanced super dimension switch (ADS) LC display with a switchable PSCT diffuser. Figure 3.15 shows a photograph of the display. When the PSCT is in the scattering state, the display appears as a regular display and the scene behind the display cannot be seen as shown in Fig. 3.15 (a). When the PSCT is in the transparent state, the scene behind the display can be seen as shown in Fig. 3.15 (b). It has an excellent viewing angle.
3.6.1 Impact

We developed a switchable diffuser for transparent LC displays. It was made from polymer stabilized cholesteric LC. It has a good performance of high transmission transparent state and high reflection scattering state as well as a large viewing angle.

![Photograph of the ADS transparent display with the PSCT switchable diffuser. (a) PSCT in scattering state, (b) PSCT in transparent state.](image)

Figure 3.15. Photograph of the ADS transparent display with the PSCT switchable diffuser. (a) PSCT in scattering state, (b) PSCT in transparent state.
CHAPTER 4
Bistable Salt and Bent Core Cholesteric LCs Light Shutter

4.1 Introduction

LCs have been used to make various light shutters and switchable windows [27] [2]. As was mentioned in Chapter 2, examples are PDLCs and PSCTs [24, 28-31]. They exhibit two optical states: transparent and opaque. They are usually in the opaque state in the absence of applied voltage and become transparent when a voltage is applied. They are monostable in that a voltage must be applied to sustain one of the optical states. When they are used as large size architectural switchable windows, they consume a great deal of energy when voltage is applied for a prolonged period. In order to save energy, bistable switchable windows are highly desirable, which can be either in the transparent or opaque state without applied voltages.

PSCT is one of the switchable windows technologies. The cholesteric LC possesses a helical structure in which the elongated LC molecules twist spatially around an orthogonal axis-called the helical axis. The optical properties of a cholesteric LC sandwiched between two parallel substrates depend on the direction of the helical axis with respect to the substrates. It exhibits three textures (states) with different optical
properties due to different orientations of the helical axis. The first texture is the planar texture in which the helical axis is perpendicular to the substrates and the LC reflects light at the wavelength \( \lambda = \frac{(n_e + n_o)}{2}P \) with the bandwidth \( \Delta \lambda = (n_e - n_o)P \), where \( n_e \) and \( n_o \) are the extraordinary and ordinary refractive indices of the LC, respectively and \( P \) is the pitch of cholesteric LC. The second state is the focal conic state in which the LC forms a poly-domain structure where the helical axis varying randomly from domain to domain; the LC is optically scattering. The third state is the homeotropic state in which the helical structure is unwound by externally applied voltages with the LC molecules aligned perpendicular to the substrate; the LC becomes transparent. Cholesteric LCs can be operated in various modes. As discussed in Chapter 3, one example of PSCT is the PSCT normal mode light shutter, which is in the opaque focal conic state without applied voltages and which changes to the transparent homeotropic state when a sufficiently high voltage is applied. Another example is the PSCT reverse mode light shutter, which is in the transparent planar state (reflecting infrared light) without applied voltages and which changes to the opaque focal conic state when a voltage is applied [24] [9]. A third example is the dual frequency PSCT bistable mode light shutter, which can be either in the opaque focal conic state or in the transparent homeotropic state in the absence of applied voltages. When a low frequency voltage is applied, the LC exhibits positive dielectric anisotropy and changes from the focal conic state to the homeotropic state. When a high frequency voltage is applied, the LC exhibits negative dielectric anisotropy and changes from the homeotropic state back to the focal conic state. The problem with the dual
frequency LC is that the cross frequency (when the dielectric anisotropy changes from positive to negative) changes significantly with temperature and the frequency is high (>10 kHz) such that the capacity effect of the LC film becomes so severe that large power suppliers are needed [32, 33]. In this chapter, we report two novel bistable mode cholesteric LC light shutters, which has advantages over the current LC light shutters.

4.2 Bistable Optical Light Shutter by Doping Salt

4.2.1 Overview

This shutter is operated between the transparent planar state and the scattering focal conic state. A low frequency (60 Hz) voltage pulse switches the shutter from the transparent state to the scattering state and a high frequency (2 kHz) voltage pulse switches it back to the transparent state.

4.2.2 Experiment and results

The cholesteric LC used in our experiment was a mixture of 95% nematic host HNG-7058 (HCCH, China) and 5% chiral dopant R811 (Merck). The mixture has a negative dielectric anisotropy. The pitch is 0.66 µm and thus reflects light at a wavelength
around 1.1 μm. The cholesteric LC is then doped with Salt tetrabutylammonium bromide \([(C_4H_9)_4N^+Br^-}\) (TBAB, Sigma Aldrich), whose chemical structure is shown in Fig. 4-1.

![Chemical structure of Slat tetrabutylammonium bromide (TBAB)](image)

**Figure 4.1 Chemical structure of Slat tetrabutylammonium bromide (TBAB)**

The mixture was filled into cells that consisted of two parallel glass substrates with transparent ITO electrode. The inner surface of the substrates was coated with PI2555 (Du-Point) and rubbed for a homogeneous alignment of the LC. The cell thickness was controlled by 10 μm spacers.

The novelty of the bistable light shutter is setting abnormal responses of the LC to applied voltages, depending on the frequency of the voltage. The applied voltage has two effects on the LC. First, the LC has a negative dielectric anisotropy. When a voltage is applied across the cell, independent of the frequency, it tends to align the LC perpendicular to the electric field, namely, parallel to the cell substrate. This is the dielectric interaction effect. Second, the LC has ions due to the doped salt. When a voltage is applied across the cell, it makes the ions move along the electric field direction, namely, perpendicular to the cell substrate. The motion of the ions produces turbulence and tends to align the LC along their moving direction. Conversely, the voltage tends to align the LC perpendicular to the cell substrate. This is the turbulence effect [34]. These two effects of the applied voltage
complete each other [26, 35-37]. The strength of the latter effect depends on the frequency of the applied voltage. At a low frequency, the ions follow the electric field. The motion is sufficiently large and the aligning effect of the turbulence is dominant. The overall effect of the applied voltage is to align the LC perpendicular to the cell substrate. At a high frequency, the ions cannot follow the electric field due to their limited mobility. The aligning effect of the dielectric interaction is dominant. The overall effect of the applied voltage is to align the LC parallel to the cell substrate.

The operation of the bistable light shutter is schematically shown in Fig. 4-2. The liquid crystal is initially in the planar state as shown in Fig 4-2 (a), where the LC is

![Figure 4.2 Schematic diagram of the operation of the bistable light shutter. (a) Transparent planar state, (b) Scattering focal conic state.](image-url)
parallel to the cell substrate. Because the LC reflects infrared light, it is transparent in the visible light region. A polarizing optical microphotograph of the planar state is shown in Fig. 4.3(a). When a low frequency (60 Hz) voltage is applied across the cell, the turbulence effect dominates and tends to align the LC perpendicular to the cell substrate, while the LC tends to retain the helical structure due to the intermolecular interaction. The net result is that the LC is switched to the focal conic state as shown in Fig. 4.2 (b), where the helical structure is retained and, in some regions, the LC becomes perpendicular to the cell substrate. The focal conic state is a multi-domain structure and the LC becomes scattering. A polarizing optical microphotograph of the focal conic state under 40 V is shown in Fig. 4.3(b). When the low frequency voltage is removed, the LC remains in the focal conic state, because the helical structure is preserved in both the planar and focal conic state. There is an energy barrier between these two states and the focal conic domains cannot rotate back to the planar state even though the surface alignment layer favors the planar state. A polarizing optical microphotograph of the focal conic state at 0 V is shown in Fig. 4.3 (c). Nevertheless, it is different from that under the applied voltage. The focal conic domain size at 0 V is larger than that under the applied voltage. When a high frequency voltage is applied, the dielectric interaction effect dominates and tends to align the LC parallel to the cell substrate. Thus the LC is switched back to the planar state. When the applied voltage is removed, the LC remains in the planar state.
When the salt TBAB is doped into the LC, it disassociates into positive and negative ions and changes the electric resistivity of the LC. Using an LCR meter (Hewlett Packard 4284A), we measured the resistances of cells of 1 cm² area with various TBAB concentrations. When the concentration of TBAB was 0%, the resistance of the cell at 60 Hz was 648 KΩ. When the concentration of TBAB was 3% the resistance decreased to 55 KΩ.

We measured the electro-optical response of the bistable cholesteric LC light shutter. In the measurement, a green He–Ne laser at the wavelength 532 nm was used and a photodiode was used as the detector. In the measurement, a voltage pulse with the time interval of 2 s was applied, and the transmission was measured 1 min after the removal of the pulse. Note the transmission was measured at 0 V. Voltage pulses with a frequency of 60 Hz drove the LC from the transparent planar state to the opaque focal conic state. The

Figure 4.3 Polarizing optical microphotographs of the liquid crystal in the bistable cholesteric light shutter. (a) Planar state, (b) Focal conic state under 40 V, (c) Focal conic state at 0 V.
transmittance of the material after removal of the applied voltage vs. the amplitude of the applied voltage pulse is shown in Fig. 4.4. Initially the LC was in the planar state with high transmittance (90%). The light loss was mainly due to the reflection at the glass–air interfaces. For the cell without salt, when voltage was applied, there was no turbulence and the transmittance remained unchanged. For the cells with salt, turbulence was induced when a voltage was applied. When the amplitude of the applied voltage pulse was below 20 V, the induced turbulence was not large enough to change the state of the LC, and the transmittance remained high. When the voltage was increased above 20 V, the LC was switched from the planar state to the focal conic state, and the transmittance decreased. Both the amount of the LC that switched to the focal conic state and the domain size depended on the amplitude of the voltage pulse and the concentration of TBAB.

![Graph](image)

**Figure 4.4** Transmission at 0 V as a function of the amplitude of the applied voltage pulse with a frequency of 60 Hz.
As the voltage and the TBAB concentration were increased, the turbulence became more violent; more LC was switched to the focal conic state and the formed focal conic domain size decreased. Therefore, the transmittance decreased. Note that the scattering efficiency of the LC depended on the focal conic domain size. The material was most scattering when the domain size was slightly larger than the wavelength of the light. When the concentration of TBAB was 0.5%, the domain size was too large and the scattering was not strong. When the concentration of TBAB was 3.0%, the domain size was too small and the scattering was not strong either. When the concentration of TBAB was 2.0%, the performance was optimized. When the applied voltage was 70 V, the minimum transmittance of 4% was obtained. The transmittance-voltage curve had a shoulder around 40 V for the cells with the TBAB concentrations of 0.5% and 2.0% and a local peak for the cell with the TBAB concentrations of 3.0%. This phenomenon was probably due to the dual effects of the voltage with the frequency of 60 Hz. The first effect is the turbulence effect, which caused the LC to reorient away from the original direction (parallel to the cell substrate) and led to a decrease of the transmittance. The second effect was the dielectric interaction, because of the negative dielectric anisotropy, which tended to align the LC parallel to the cell substrate and caused the transmittance to increase. These two effects had different voltage-dependences and competed against each other.
Voltage pulses with a frequency of 2 kHz drove the LC from the opaque focal conic state to the transparent planar state. At this frequency, the dielectric interaction dominated and the turbulence was very weak. The transmittance of the material after removal of the applied voltage vs. the amplitude of the applied voltage pulse is shown in Fig. 4.5. Initially the LC was in the focal conic state with low transmittance. The initial transmittances of the cells doped with different concentrations of TBAB were different as described in the above paragraph. For the cell without salt, the initial transmittance was high, and remained high when voltage was applied. For the cells with salt, the initial transmittance was lower, because they were driven into the scattering focal conic state by the low frequency voltage pulse. When the amplitude of the applied voltage high frequency pulse was below 5 V, the dielectric interaction was too weak to change the state of the LC, and the transmittance
remained low. When the voltage was increased above 5 V, the LC began to reorient from the focal conic state to the planar state, and the transmittance increased. When the voltage was increased to 25 V, the LC was completely switched back to the planar state and the transmittance after the pulse restored to 90%. At this frequency, the effect of turbulence was negligible, and therefore the behavior of the LC was independent of the concentration of TBAB, except that the initial focal conic states of cells doped with different concentrations of TBAB were different.

The bistable cholesteric light shutter doped with 2% TBAB had the best performance. Its time dependence of the electro-optical response to voltage pulses is shown in Fig. 4.6.

![Graph showing transmission as a function of time with two voltage pulses applied.](image)

**Figure 4.6** Transmission as a function time when two voltage pulses with the different frequencies were applied in sequence.
Initially the LC was in the planar state with high transmittance. After 5 S, a 2 S wide voltage pulse with an amplitude of 65 V and frequency of 60 Hz was applied, which switched the LC to the focal conic state with lower transmittance. Note that the transmittance after the pulse was low than that during the pulse. The transmittance became stable 10 s after the removal of the pulse. After 65 S, a 1 S wide voltage pulse with an amplitude of 22 V and frequency of 2 kHz was applied, which switched the LC back to the planar state. The transmittance became stable 15 S after removal of the pulse.

Photographs of the bistable cholesteric LC light shutter are shown in Fig. 4.7. No voltage was applied when the two photographs were taken. When the shutter was in the transparent state, the scene behind it can be seen. When it was in the opaque state, the scene behind it was blocked.

4.2.3 Discussion and conclusion

In practical applications such as privacy control, thermal stability of the light shutter is very important. It is highly desirable that its optical properties remain stable in a wide temperature region. There are three important properties that may change with temperature. The first one is the stability of the states. For the bistable light shutter reported here, both the transparent planar state and scattering focal conic state are stable at 0 V as long as the material is in the cholesteric phase (from 20 C° to 80 C°). The second one is the transmittance. The transmittance of the planar state is high and independent of
temperature. The transmittance of the focal conic state remains relatively constant up to an temperature 10° below the cholesteric–isotropic transition temperature. The third one involves the switching voltage stet. The two important parameters of the switching voltages are the amplitude and the frequency. For the low frequency voltage to switch the LC from the planar state to the focal conic state, both frequency and amplitude remain approximately constant in the LC phase. For the high frequency voltage to switch the LC from the focal conic state to the planar state, the amplitude remains approximately constant while the frequency is about 1 kHz and increases moderately with temperature. This is an important advantage over regular dual frequency LC light shutters. For regular dual frequency LCs, the dielectric anisotropy is positive at low frequencies and negative at high frequencies. The frequency where the dielectric anisotropy changes from positive to negative is usually higher than 1 kHz and increases dramatically with temperature.

In summary we developed a novel approach to make a bistable light shutter by doping salt TBAB into a cholesteric LC with negative dielectric anisotropy. The salt enables different electro-optical responses to voltages with different frequencies. The shutter exhibits two stable states at zero voltage: a transparent planar state and a scattering focal conic state. It is switched from the planar state to the focal conic state by a low frequency (60 Hz) voltage pulse, which produces turbulent motion of the ions created by the salt, and is switched back to the planar state by a high frequency (1 kHz) voltage pulse under dielectric interaction. Both the low and high frequency voltages are easy to generate. This technology can be used to make a low power consumption switchable architectural
window, because no voltage is required to sustain either the transparent state or the opaque state.

4.3 Bistable Optical Light Shutter by doping Bent Core Liquid Crystals

4.3.1 Introduction

As mentioned in Chapters 3 and current Chapter, one of the applications of cholesteric LCs is in optical shutters and switchable windows. Especially, when a low optical haze is important, PSCTs are superior to PDLC. Moreover, due to the possibility of stability of both planar and focal conic states at zero electric field in PSCTs, the feasibility of low power consuming electrical windows has been demonstrated. These properties allow for
great applications such as in reflective displays [38], mirrorless lasers [39], and light intensity and color modulators [40-42]. In this section, a new method for making bistable light shutters is reported. Here, we report another novel method to create a bistable light shutter by doping bent core liquid crystals into negative dielectric anisotropy PSCLC. When a low frequency \((f \leq 60 \text{ Hz})\) voltage is applied, the shutter is switched to the scattering focal conic state. When a higher frequencies \((f \geq 200 \text{ Hz})\) voltage is applied, the shutter is switched to the transparent planar state. The planar state and focal conic state are stable at 0 V.

### 4.3.2 Experiments and results

The components of the prepared mixtures were chiral dopant R1011, nematic reactive mesogen RM257, negative dielectric anisotropy nematic liquid crystal ZLI-4330 \((\Delta \varepsilon = -1.9)\), all from Merck, the bent core component mm73 and photoinitiator Benzoil Methyl Ether (from Sigma Aldrich). Chemical structure for mm73, is shown in Fig. 4.8. This was synthesized by Professor Quan Li’s group at the Liquid Crystal Institute. The resultant pitch of the mixture was 1.1 \(\mu\)m. The light shutter cell was made from two indium thin oxide (ITO) glass substrates that were coated with a homogeneous alignment layer PUD026 (Mflex), which had relatively low anchoring strength (polar: \(10^{-5} \text{ J/m}^2\), Azimuthal: \(10^{-6} \text{ J/m}^2\)). The gap between the two substrates was maintained with 16 \(\mu\)m silica fibers.
Different concentrations of the bent core LC were doped into the mixture. The sample doped 7.5% of mm73 was found to have the best bistability behavior and will be explained in the rest of this chapter.

The resistivity of the samples was measured by using a LCR meter (Hewlett Packard 4284A). The result is shown in Fig. 4.9. The sample containing 7.5% of the mm73 component had the lower resistivity, about 100 times lower than the cell without the bent core dopant. The resistivity difference means that higher ion density in the sample doped with the bent core LC plays an important role in layer angulations of the planar texture.

We first applied a low frequency (3 Hz ≤ f ≤ 200 Hz) voltage and studied the electro-optical properties. When the applied electric filed was 2 V/μm, it resulted in a partial change of the planar structure and produced the Helfrich deformation [36]. Helfrich deformation is caused by the ion movement. However, if the field was increased further, the motion of the ions became larger, which created turbulence and caused a strong flow that broke the planar cholesteric LC layers into small focal conic domains. This texture
exhibits light scattering because the created domain sizes are comparable with the wavelength of visible light.

Figure 4.9 Resistivity dependence vs applied frequency, (a) cell without bent core dopant, (b) cell with bent core dopant
Then cell thickness was varied to determine what is the best thickness for having the highest contrast ratio between the transmissive planar state and the scattering focal conic state. The tested cells had thicknesses of 10 μm, 16 μm, 20 μm, and 25 μm, respectively. The cell with 10 μm thickness did not have a good focal conic state because there were fewer focal conic domains. The cells with thicknesses 20 μm and 25 μm appeared yellowish due to the high concentration of bent-core in the mixture, despite the fact that they had more focal conic domains since they are thicker. The 16 μm cell thus was the best one and was chosen for the experiment. The bistable planar and focal conic states of the light shutter also depend on the bent core dopant concentration. Lower concentrations of bent core dopant did not produce a strongly scattering focal conic state, while higher concentration produces a yellowish color of the shutter in the transparent state. Negative liquid crystal ZLI 4330 was used for this experiment.

The presence of a strong homogeneous alignment layer on the surfaces of the light shutter tends to switch the LC from the focal conic state back to the planar state. By using PUD026, a weak anchoring homogeneous alignment layer, the focal conic domains will be stable. PI2555 and PVA alignment layers were tried but the anchoring strength of these alignment layers was too strong so that they switched the LC from the focal conic state to the stable planar state. As shown in Fig. 4.10, the transmission vs. time curve of the sample with bent core dopant and no polymer network shows that the material becomes transmissive ($T>80\%$) again 30 S after the removal of a 60 V, 60 Hz pulse.
Polymer network is a good candidate to stabilize the focal conic state. We added a monomer with different concentrations to the mixture, then photopolymerized them in the focal conic state to stabilize this state after removing the low frequency voltage.

While in the curing process, a 26 V\text{rms} voltage with frequency of 30 Hz was applied to the cell to create turbulence. We assumed that the turbulence in the cholesteric LC was caused by a high number of ions coming from the bent core dopant. We also assumed that the turbulence effect may create random polymer domains in the cell for stabilizing the LC in opaque state. The cell was photo-cured under 1.4mW/cm\textsuperscript{2} UV for 30 minutes in the focal conic state. Unlike the sample with no polymer, the focal conic state in the presence of polymer is stable after removing 60 Hz voltage pulses, which leads to a stable opaque state.

![Figure 4.10 Transmission vs Time after applying 60 Hz pulse for 3 S to a cell without monomer](image)
As shown in Fig. 4.11, for the cell with 0% monomer, after applying 60 V/ 60 Hz pulses for 6 S that switched the LC to the focal conic state caused by turbulence, the transmission went back to its original value after several seconds. The surface anchoring of the planar alignment forces the LC to go back to its minimum free energy state (the planar state).

For the sample with 4.4% monomer, after curing, the opaque state was obtained after applying 60 V, 60 Hz pulses for 6 S. The motion of the ions created the focal conic domains and it appears that the polymer network keep the LC molecules in the focal conic state after the removal of low frequency voltages. The transparent state was obtained by applying strong enough high frequency pulses. The LC was switched to the planar state by applying 200 Hz (Δt_{pulse}=10 S) 80 V pulses. At this high frequency, the dielectric interaction is dominant and the LC tends to align perpendicular to the applied electric field. The applied voltage switched the LC to the planar state. The LC remained in the planar state after the electric field was removed due to surface anchoring. The shutter was transparent in this state. Monomer concentrations of 8.4% and 11% were also tested and shown to enable the bistable behavior. In these cases, the transmittance of the transparent state was lower compared to the sample with 4.4% monomer concentration. The refractive index mismatch between the polymers and the LCs explains this difference. The transmission in the focal conic state was also lower (better contrast ratio) since the effect of polymer stabilizing is stronger for a higher concentrations of monomer in the focal conic state.
4.3.3 Frequency dependence of transitions

Switching between states in our bistable light shutter depends on the frequency. In order to find the frequency range for switching, different frequencies were applied to a 2x2 in$^2$ cell with 4.4% monomer and 7% bent core dopant, and the resulting electro-optical behavior was measured. Turbulence effects occurred at lower frequencies. For finding the working frequency range for switching the LC from the transparent planar state to the scattering focal conic state, 3 Hz, 20 Hz, 40 Hz, and 60 Hz voltage pulses were applied to the cell gradually. The resulting transmission versus voltage curves are shown in Fig. 4.12. These results indicate that the light shutter switched from the transparent state to the scattering
state when the applied voltage was high. The minimum transmittance was obtained with the frequency of 3Hz. A lower frequency voltage caused stronger turbulence since ions can move more freely at lower frequency [34]. Because 60 Hz is the most popular power source frequency and can be used to switch the light shutter to the scattering state, we used this frequency in our future experiments. Also note that the transmittance of the scattering state depends on how the applied low frequency voltage is turned off. When the applied voltage was turned off suddenly, the transmittance was lower than that when the applied voltage was turned off gradually.
Figure 4.12 Switching from planar state to focal conic state and its frequency behavior, blue lines are voltage increasing, red lines voltage decreasing a) 3 Hz, b) 20 Hz, c) 40 Hz and d) 60 Hz

The lowest frequency of the electric field, that can switch the LC from the focal conic state to the planar state is also of interest. To find this frequency, different frequencies of 150 Hz, 175 Hz, 185 Hz, and 200 Hz were used to switch the bistable cell in the scattering state obtained by applying the 60 Hz, 50 V voltage and then removing it
suddenly. Voltage was increased or decreased gradually. All the measurements of the transmission vs voltage curves were done with the cell in the focal conic state with 6% transmittance. The transmission versus voltage curve for transition between the focal conic state to the planar state with applied voltage at different frequencies is shown in Fig.4.13. This result shows that the lowest frequency to obtain the planar state with high transmittance is 200 Hz.

Figure 4.13 T vs V for transition between focal conic state to planar state with different frequencies, a) 150 Hz, b) 170 Hz, c) 185 Hz, and d) 200 Hz.
The main reason for creating turbulence, which leads to the breaking of planar cholesteric state in our bistable light shutter, is explained by the increase in ions density as a result of doping the mixture with mm73 bent core. Ions may come from impurities during the synthesis process of mm73 dopant. We do not think that the mm73 molecules directly play a role in creating bistability and turbulence although the addition of the bent core molecules may change the viscosity of the mixture and lead to a lower switching frequency to obtain the transparent planar state. Furthermore, the experiment shows that the sample with monomer cured in the turbulence state is interesting. Generally, in the regular polymer stabilized liquid crystal, the polymer networks are created in the planar state or the homotropic state. The polymer network formed in the mixture doped with mm75 behaved differently. The fact that polymers enhances the stability of the focal conic state is interesting and differs from typical polymer stabilized liquid crystal devices as we mentioned in Chapters 3. The presence of mm73 produces a change in the morphology of the polymer network, possibly caused by ionic effects or, less likely, interactions between bent core and polymers molecules. Fig. 4.14 (a) and (b) compare the SEM images of the polymer network in the samples with and without mm73, respectively. For the cell without mm73 bent core dopant and same curing condition mentioned above, the typical morphology of PSCLC consisted of submicron polymer fibrils, as shown in Fig. 4-14(a). Interestingly, in the cell with the mm73 bent core, no polymer network was observed and the polymers shrank into spherical domains or random polymer domains. The result was confirmed by observing the polymer network with a polarizing optical microscope.
Another method was used to verify the effect. Two nematic mixtures consisting of 4% RM257, one with no mm73 and another doped with mm73, were prepared and photocured without applying voltage on cells with homogeneous PUD 027 alignment layers. After the curing, the textures were examined under an optical microscope with crossed polarizers at isotropic temperature (100°C). As shown in Fig. 4.15 (a), the sample without mm73 bent core formed fibers along the rubbing direction of the PUD 027 alignment layer, which means that the network has mimicked the nematic texture in homogenous state. On the other hand, Fig. 4.15 (b) shows the formed polymer circles and polymer domains in the cell with a mm73 bent core. They are distributed randomly, similar to the polymer domains observed in the SEM images.

![Figure 4.14 SEM image of polymer structure for the PSCLC sample with (a) 0% mm73 (b) 7% mm73](image-url)
The random polymer morphology may be explainable through effects of the strong turbulence during UV curing. Strong turbulence destroys polymer networks and creates such random polymer domains. It has also been reported that the presence of charge carriers (ions) drastically changes the dynamics of the polymerization, specifically during the propagation step.

The stability enhancement of the focal conic texture in the presence of the polymer domains can be justified by the presence of the created polymer spheres in the material; when the low frequency pulse is removed, the alignment layers on the surfaces tend to retrieve the LC in the planar texture. As shown before, in the case of the sample

![Microscopic images of polymer structure for the polymer stabilized nematic sample with (a) 0% mm73 (b) 7% mm73](image)

**Figure 4.15** Microscopic images of polymer structure for the polymer stabilized nematic sample with (a) 0% mm73 (b) 7% mm73

without polymer, the transmissive planar texture recovers in less than 30 S. However, the presence of polymer domains in the bulk provides a random aligning effect on the surrounding molecule, which competes with the surface alignment. This effect stabilizes the focal conic state. The schematic illustration in Fig. 4.16 (a) shows a physical
interpretation of this phenomenon. Figure 4-16 (b) and (c) show photographs of the actual device in the transmissive and opaque states at zero electric field, respectively.

4.16 (a) Schematic figure of bent core doped PSCLC textures after applying (left) high (right) low frequency, (b) Transparent state, (c) opaque state of the device at zero electric field.
Parameters and specifications of bistable light shutter doped with bent core liquid crystal are shown in Table 4-1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1- Switching time to the focal conic state</td>
<td>Less than 100 ms</td>
</tr>
<tr>
<td>2- Switching time to the planar state</td>
<td>Less than 6 S</td>
</tr>
<tr>
<td>3- Focal conic state 5 minutes after low frequency voltage pulse</td>
<td>8% transmission</td>
</tr>
<tr>
<td>4- Planar state 5 minutes after high frequency voltage pulse</td>
<td>80% transmission</td>
</tr>
<tr>
<td>5-Needed frequency for changing to states</td>
<td>60 Hz for focal conic state and 200 Hz for planar state</td>
</tr>
</tbody>
</table>

**Table 4-1 Parameters of bistable bentcore light shutter,**

### 4.3.4 Conclusion

We demonstrated a convenient novel approach for fabrication of a bistable PSCLC device that can be employed for low power consuming optical shutters and window applications. By adding a small amount of bent core liquid crystal, a hydrodynamic instability and consequently, turbulence is created so that the cholesteric liquid crystal can be switched from the transmissive planar texture to the opaque focal conic state. This phenomenon is described by the increase of the mixture conductivity due ions in the bent core additive. Moreover, the presence of the bent core component leads to a bead-like morphology of the polymer network. This structure produce a long time stability of focal conic state after the
electric field is removed. Low power consumption and low applied frequency pulses are the advantages of using this new method of dynamic scattering for switching liquid crystal states.
CHAPTER 5

Active Polarizing WaveGuide Plate (PLWG)

5.1 Introduction:

LC displays (LCDs) have become the leading technology for information displays. They are used in a wide array of applications from smart phones, e-readers, and digital cameras to computer monitors and televisions because of their advantages of having a high resolution, high brightness, the ability to be incorporated into a flat panel, their light weight, and their low manufacturing cost [2, 43]. In an LCD, the LC does not emit light but modulates the intensity of the light produced by the edgelight or backlight [2, 43, 44]. Edgelit LCDs have the advantages of being compact and lightweight. In an edgelit LCD, a point light source (such as an LED) is placed at the edge of the display. The light source produces unpolarized light that is coupled into a light waveguide plate (typically plastic or glass plate) with a refractive index higher than that of the surrounding air. When the light hits the interface between the waveguide and air (with incident angles larger than a critical angle $\theta_c$), it is totally reflected by the interface and continues to propagate through the waveguide. In order to lead light out of the waveguide, scattering particles are dispersed within the waveguide [43, 45-49]. When light hits a scattering particle, it will change propagation direction and hit the interface with an angle smaller than the critical angle and, thus, comes out of the waveguide. The waveguide thus produces two-dimensional illumination for the LCD. For current light waveguide plates, there is, however, the problem that the light coming out of the waveguide plate is unpolarized. A
polarizer must be used to convert the unpolarized light into polarized light such that the LC can modulate its intensity. In this process, more than half of the light is absorbed by the polarizer and thus is wasted.

There have been efforts to develop light waveguide plates that can produce polarized light for the purpose of improving light efficiency of LCDs [50, 51]. The technologies, however, have not been commercialized ten years after their invention, likely due to the considerable manufacturing cost. In this chapter we report a novel light waveguide plate made from a polymer-stabilized nematic LC film [9, 10, 12]. The LC has a randomly-oriented microstructure in a vertical plane defined by rubbing direction of the alignment layer. The LC has a poly-domain microstructure with a domain size comparable to the wavelength of visible light. The orientation of the LC is more or less uniform in each domain. The orientation of the LC is confined in a vertical plane perpendicular to the plate. The azimuthal angle of the LC orientation remains the same, but the polar angle (defined with respect to the normal of the plate) varies from domain to domain [52, 53]. It scatters the light with polarization in the plane, but not the light with polarization perpendicular to the plane. The incident light produced by the edgelight is unpolarized and can be decomposed into two components with orthogonal linear polarizations. Only the component with polarization in the LC plane is scattered out, thus the waveguide plate converts the unpolarized light produced by the edgelight into linearly polarized light by selective scattering.

As mentioned in previous chapters, polymer networks formed in LCs are anisotropic and affect the orientation of LCs. They tend to align the LC in the direction of their fibrils. They are used to stabilize desired LC configurations and control the electro-optical properties of LC devices. Polymer networks have been used to improve the performance, such as drive voltage and response times, of conventional LC devices such as twist nematic (TN) and in plane switching (IPS) displays.

The polymer-stabilized homogeneously aligned nematic LC (PSNLC) light shutter is made from a mixture of a nematic LC and diacrylate LC monomer. Cells with antiparallel homogeneous alignment layers are filled with the mixture and then
photopolymerized in the nematic phase. The polymer network formed, like the liquid crystal, is structured parallel to the cell surface. The nematic LC has a positive dielectric anisotropy. Figure 5.1 schematically shows how the shutter works. In Fig. 5.1(a), when there is no applied voltage across the cell, the LC and the polymer network are homogeneously aligned in the $x$-direction [2].

![Figure 5.1. Schematic diagram showing how the polymer-stabilized homogeneously nematic LC light shutter works.](image)

We first consider the case where light incident on the PSNLC perpendicularly goes through the material, it encounters the same refractive index in the LC and polymer regions and, therefore, it passes through the material without scattering. In Fig. 5.1(b), the voltage applied across the cell tends to align the LC in the $z$-direction while the polymer network tries to keep the LC in the $x$-direction. As a result of the competition between the applied field and the polymer network, the LC is switched into a multi-domain structure. The LC molecules orient along the same direction within each domain but vary from domain to domain. The directions of the domains are random in the $x$-$z$ plane. When light polarized in the $x$ direction, goes through the cell, it encounters different refractive indices in different domains and is therefore scattered. When light polarized in the $y$ direction,
goes through the cell, however it always encounters the ordinary refractive index of the LC because the LC is oriented in the $x$-$z$ plane and it can thus pass through the cell without scattering. In the section below we will consider light incident on the edge of the liquid crystal layer as in the waveguide.

5.2 Experiment and results

In our experiment, a mixture was created from 95.8% weight nematic LC E44 (from Merck), 3.9 % bifunctional monomer HCM-009 (from HCCH, China), and 0.3% photo-initiator BME (from Polyscience). The mixture had a positive dielectric anisotropy ($\Delta \varepsilon > 0$) and was filled into a cell consisting of two parallel glass substrates with transparent ITO electrodes. A layer of polyimide was spin coated, baked and rubbed on top of the ITO electrode to act as a homogeneous alignment layer for the LC. The cell thickness was controlled by $10 \ \mu m$ spacers. The cell was then irradiated with UV light to photo-polymerize the monomers in the absence of an applied voltage. The formed polymer network was anisotropic and parallel to the LC, as shown in Fig. 5.2. Such a system is an active light waveguide plate (LWGP) whose optical properties can be varied by applying voltages.

After the polymerization, both the LC and polymer network in the PLWG was in the homogeneous state along the alignment layer rubbing direction in the absence of applied voltage, as shown in Fig. 5.2 (a). The polymer network had a strong aligning effect on the
LC and tended to keep the LC in a homogenous state [10, 12, 25, 54]. The ordinary and extraordinary refractive indices of the LC and polymer network were close to each other, respectively, allowing the PLWG to act as a uniform optical medium and not scatter light, no matter where light was incident on it and what the polarization of that light was. Light propagated through the PLWG without scattering. When a voltage was applied across the cell, an electric field perpendicular to the plate surface was generated. The electric field tended to align the LC in the vertical direction (the z direction) because of the positive dielectric anisotropy of the LC, while the polymer network did not reorient and tended to keep the LC in the horizontal direction (the x direction). Because the positions of the polymer fibers were random, the LC was switched into a polydomain structure as shown in Fig. 5.2 (b). Because the aligning forces of the electric field and polymer network were in the xz plane, the LC only reoriented in the same plane.

In different domains, the reorientation of the LC was different. The PLWG is now a non-uniform optical medium. The LC might scatter light dependent on the polarization of the incident light. If the incident light was polarized in the y direction (ray 2 shown in Fig. 5.2 (b)), it encountered the same refractive index, the ordinary refractive index of the LC molecules in different domains, and thus would not be scattered. When it hit the interface of the PLWG with a large angle, defined with respect to the normal of the PLWG, the light would bounce between the two interfaces of the PLWG due to total internal reflection and thus propagate through the PLWG.
Figure 5.2 Schematic diagram of the active polarizing light waveguide plate. (a) voltage off state, (b) voltage on state.

If the incident light had polarization in the \(xz\) plane (ray 1 as shown in Fig. 5.2(b)), on its way back propagating through the waveguide, it would encounter different refractive indices in different domains and thus would be scattered. The propagation direction changed. When it hits the interface of the PLWG at a small angle, it is refracted out of the
plate; thus, the light coming out of the PLWG is linearly polarized in the $x$ direction. For the unscattered light with polarization in the $y$ direction, it can be reflected backwards with its polarization rotated to the $xz$ plane when it hits the combination of a quarter wave plate and a reflector at the other end of the plate. On its way back, it becomes scattered and came out of the PLWG with polarization in the $x$ direction.

We first characterized the polarization dependence of the scattering of the polarizing LWGP. In the experiment, an unpolarized laser beam was incident on the PLWG at normal angle. A polarizer and then a photodetector were placed directly behind the PLWG as shown by the inset in Fig.5-3. The collection angle of the detector was 4°. The polarizer was rotated to check the polarization of the light after the PLWG. In the absence of applied voltage, the LC was in the uniform homogeneous state and did not scatter. The unpolarized laser light passed through the PLWG and its polarization remained unpolarized. The intensity of the light was high and varied slightly when the polarizer was rotated as shown in Fig 5.3 (a). The variation was probably due to the fact that the ordinary refractive indices of the LC and polymer network were not exactly matched. When an AC voltage of 20 V was applied, the LC was switched to an inhomogeneous scattering state and became scattering.

The unpolarized incident light can be considered as a combination of linearly polarized light in two orthogonal directions. For the component with polarization perpendicular to the $xz$ (LC) plane, the encountered refractive index was the ordinary refractive index of the LC, independent of the orientation of the LC in the $xz$ plane, and this component therefore passed through the PLWG without scattering. For the component
with polarization parallel to the $xz$ plane, the encountered refractive index varied from domain to domain, dependent on the orientation of the LC in the $xz$ plane, and therefore it was scattered away from the original propagation direction. Therefore, the unscattered light was linearly polarized in the direction perpendicular to the rubbing direction. When the polarizer was rotated, the transmission oscillated between 0% and 30% as shown in Fig. 5.3 (b), which indicated the transmitted light was linearly polarized.

![Figure 5.3 Transmission vs. polarizer angle of the active polarizing LWGP. (a) voltage = 0 V, (b) voltage =20 V](image)

The transmission vs. voltage of the waveguide plate for normal incident light is shown in Fig. 5-4. When there was no polarizer and the unpolarized laser light beam was normally incident on PLWG, the component of light with polarization parallel to the rubbing direction was scattered and the other component with polarization perpendicular to the rubbing direction passed through. We expect around 50% of the light is scattered and the
transmission decreased from 74% to 35% as the applied voltage was increased from 0 V to 20 V. When a polarizer was placed after the PLWG with its polarization axis perpendicular to the rubbing direction, the detector measured the intensity of the incident light component with polarization perpendicular to the liquid crystal plane. This light component only sees the ordinary reflective index of the LC. The transmission does not change with the applied voltage when the polarizer direction was parallel to the rubbing direction. In that case the detector measure the intensity of the incident light component with polarization parallel to the LC plane. This component sees different extra-ordinary reflective indices of the LC in different domains when a voltage is applied. The transmittance changed from 33% to 0% when the applied voltage was increased from 0 V to 20 V.

Figure 5.4 Transmission vs Voltage for normal incident light with 4° collection angle. 1 S delay between pulses with 1 kHz frequency
We then studied the optical properties of the polarizing LWGP with edgelight illumination. In this experiment, three point white LEDs were installed on the edge of the PLWG. The light was coupled into the LWGP. When light propagated through the PLWG, some light was scattered out of the plate. A polarizer and a photodetector were placed on top of the PLWG as shown by the inset in Fig. 5.5. The distance between the LWGP and the detector was about 1 cm. The light scattered out of the PLWG was polarized. The detector was placed at a position 1 cm from the LED edgelight. The scattered light intensity depended on both the voltage applied and where the edgelight was installed. The results of measurements performed when the LED edgelight was installed at the edge perpendicular and parallel to the alignment layer rubbing direction are shown in Figs. 5.5 (a) and 5.5 (b), respectively. In the absence of an applied voltage, the LC was in the homogeneous state and the scattered light intensity was low. The weak scattering was probably due to incomplete relaxation of the LC. When the voltage was applied, the LC switched to a multi-domain structure. When the voltage was turned off, the LC tended to relax back to the initial homogeneous state. The relaxation was incomplete because the LC cannot fully relax back to the initial homogeneous state, and therefore there was weak scattering even when the voltage was turned off. When 20 V was applied, the LC was switched to the poly-domain state and the scattered light intensity became strong. The measured scattered light intensity varied when the polarizer was rotated, indicating that the scattered light was partially polarized. When the edgelight was installed at the edge perpendicular to the rubbing direction and the applied voltage was 20 V, the maximum scattered light intensity was 120 arbitrary units and the contrast ratio between the
intensities of the two components of the scattered light with polarization parallel and perpendicular to the rubbing direction was 1.76:1. When the edgelight was installed at the edge parallel to the rubbing direction and the applied voltage was 20 V, the maximum scattered light intensity increased to 250 units and the contrast ratio was 2.5:1. The different light outputs in these two geometries were due to the different encountered refractive indices. The LC was confined in the plane (the LC plane) predetermined by the alignment layer rubbing and the plate normal. When the LED was installed on the edge parallel to the rubbing, the light propagation direction was perpendicular to the LC plane; when the LED was installed on the edge perpendicular to the rubbing, however, the light propagation direction was parallel to the LC plane.

The intensity of the light scattered out of the PLWG also depended on the distance from the LED edgelight. The scattered light intensity was measured at various positions on top of the PLWG and is shown in Fig. 5.5. In the experiment, three LEDs were installed, evenly distributed, along the edge. The light intensity first increased slightly with the distance from the edgelight. It peaked at a position 2.5 cm away from the edge before light intensity decreasing with increasing distance. When the distance was short (close to the edge where the LEDs were installed), the light was mainly from the central LED (the other two LEDs did not contribute much), and therefore the scattered light intensity was low. As the light propagated through the waveguide plate, more and more light was scattered out, and thus its intensity decreased with the increasing distance. Therefore, light coming out of the plate decreased with the distance. Due to the
aforementioned two factors, as the distance increased, the scattered light intensity increased first and then decreased.

Figure 5.5 Scattered light intensity as a function of the distance from the edgelight. (a) edgelight installed on the edge perpendicular to the rubbing, (b) edgelight installed on the edge parallel to the rubbing. //: polarizer parallel to rubbing,

The measured intensity at different positions vs. the polarizer angles is shown in Fig. 5.6 when. The scattered light intensity was maximum when the polarizer was at an angle of 90° (where the transmission axis of the polarizer was parallel to the light propagation direction inside the waveguide).
Figure 5.6 Intensity dependence on polarizer angle and position when the edge light was installed on the edge perpendicular with rubbing direction

Figure 5.7 shows the light intensity at different positions vs the polarizer angles. The scattered light intensity was a minimum when the polarizer was at an angle of 90° (where the transmission axis of the polarizer is parallel to the light propagation direction inside the waveguide plate).
Figure 5.7 Intensity dependence on the polarizer angle and position when the edge light was instilled on the edge parallel to the rubbing direction

We constructed a 2x2 in² prototype of the PLWG. The behavior of the PLWG under different polarizer angles for normally incident light is shown in Table 5-1. The pictures were taken with different edgelit directions and conditions (on or off), rubbing directions, polarization directions in front of the light shutter, and with and without voltage applied across the shutter. Based on the polarizer direction and scattering behavior of the PLWG, the scene behind the PLWG was clear when the polarizer was perpendicular to the rubbing direction (Pictures# 2, 3, 6, 7, 10, 11, 14, and 15). When the polarizer was parallel to the rubbing direction, the observed scattering was high and the scene behind the PLWG was blocked for rest of the pictures in Table 5-1.
Table 5-1 The Behaviors and properties of the Active PLWG with different polarization directions for normal incident light

<table>
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<tr>
<th>Picture number</th>
<th>Edge light</th>
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<th>Polarizer direction</th>
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5.3 Discussion and conclusion

In the polarizing LWGP, one component of the incident light is strongly scattered out of the plate with polarization parallel to the alignment layer rubbing direction. The other component, with polarization perpendicular to the rubbing, is weakly scattered and most of it is waveguided to the other edge of the plate. This light can be recycled by placing a quarter-wave plate followed by a reflector at the other edge. When the light is reflected, its polarization is rotated 90° and the light is then scattered out of the plate. The achieved contrast ratio between the intensities of the two components of light coming out of the PLWG with the two orthogonal polarizations is about 2.5:1, which is decent but not optimal. The contrast ratio can be improved by reducing the scattering of the light with
polarization perpendicular to the rubbing direction. This scattering is mainly caused by the imperfect orientation of the polymer network and imperfect matching between the ordinary refractive indices of the LC and the polymer network. Although the contrast ratio is not very high, the polarizing LWGP still can significantly improve the light efficiency of edgelight LCDs. The partially polarized light coming from the plate can be converted into completely polarized light by placing a linear polarizer on top of the PLWG. Assuming the polarizer is perfect, when a regular LWGP is used, the light efficiency of the LCD is 50%. When the polarizing LWGP with contrast ratio of 2.5:1 is used, the light efficiency is increased to $2.5/(2.5+1) = 71\%$. The PLWG is switchable and suitable for transparent LCDs, which can be operated in either transparent or display modes. When no voltage is applied to the active PLWG, it is transparent and scenes behind the display can be seen. When a voltage is applied, it becomes milky and blocks the scenes behind it.

In summary, we developed a novel polarizing light waveguide plate for edgelit LCDs. It can convert unpolarized light into polarized light by selective scattering. It can significantly improve the light efficiency of LCDs.
CHAPTER 6
Passive Polarizing Light WaveGuide Plate

6.1 Introduction

LC displays (LCDs) are widely used for mobile devices such as smart phones, tablets, and digital cameras because of their advantages of flat-paneled, high resolution, high brightness, and lightweight [43] [2] [55, 56]. In mobile devices, the LCD is edgelit by having a point light source (such as an LED) installed on the edge of the display [44]. The edgelight produces unpolarized light that is coupled into a light waveguide plate (LWGP) with a refractive index higher than that of the surrounding air. The light bounces between the two air-plate interfaces, due to total internal reflection, and propagates through the light waveguide plate. Scattering particles are dispersed in the plate to scatter light out of the plate to illuminate the display [44, 45, 47-49]. The scattering property of the particles is independent of light polarization; therefore, the light coming out of the plate is still unpolarized. The unpolarized light is converted by a film polarizer into linearly polarized light for the display to operate properly. In the conversion process, more than 50% of the light is absorbed by the polarizer. This process wastes a lot of energy and moreover causes overheating problems. As battery life is very important for mobile devices, it is highly desired to have more energy efficient LCDs so that the devices do not have to be recharged as often.

In Chapter 5, we reported an active polarizing light waveguide (PLWG) plate made from polymer stabilized nematic LC film [57]. The plate is transparent in the absence of applied voltage. When a voltage is applied across the plate, the LC is switched
to a scattering state where the LC is selectively scattering [9, 53, 57]. Light with polarization in one direction is scattered out of the plate and light with polarization in the orthogonal direction keeps propagating through the plate, thus the waveguide plate converts the unpolarized light produced by the edgelight into linearly polarized light by selective scattering. This switchable waveguide plate is suitable for transparent displays; it is, however, not good for regular transmissive LC displays because a voltage must be applied to enable the scattering, which costs energy.

In this Chapter, we report on a stable polarizing light waveguide plate whose selective scattering is stabilized by a polymer network. We name it a "passive polarized light waveguide plate" (PLWG). No voltage is needed to sustain the scattering, making it suitable for regular transmissive LC displays. This passive PLWG will significantly increase the light efficiency of the current LCDs. As mentioned in Chapter 5, passive PLWGs will create polarized light scatter out from the backlight diffuser in displays which can partially eliminate one of the polarizers in current transmissive LCD technology without applying any voltage. The details of the design and fabrication of the invented passive PLWG are reported and discussed in this Chapter.

6.2 Principles

The PLWG consists of two parallel glass substrates with ITO electrodes and homogeneous alignment layers. The alignment layer is rubbed along the $x$ direction. A mixture of a nematic LC and a mesogenic bifunctional monomer is filled into the cell. The cell is then
placed under UV light to photopolymerize the monomers in such a way that LC molecules domains are fixed in proper position by polymer networks like the one obtained in Fig. 5.1 by applying voltage. The difference from the active PLWG fabrication, however, is that polymer networks are created that can orient LC molecules as shown in Fig. 5.1 (b), without applying voltage [9, 25, 53, 54]. The LEDs are installed along the edge of the plate. The unpolarized light produced by the LCDs is coupled into the LWGP. The incident light can be considered to consist of two orthogonal linearly-polarized components: one component with polarization in the $x$-$z$ plane (the LC plane) and the other component with polarization in the $y$ direction (perpendicular to the LC plane). Incident light with polarization in the $y$ direction (Ray 2, Fig. 5.1(b)) encounters the same refractive index (the ordinary refractive index $n$ of the LC) in different domains and thus would not be scattered. When the light hits the interface of the PLWG with a large incident angle (defined with respect to the normal of the PLWG), it is bounced between the two air-substrate interfaces of the PLWG due to total internal reflection and thus propagates through the PLWG. Incident light with polarization in the $x$-$z$ plane (Ray 1, figure 5-1 (b)) encounters the refractive index [2]:

$$n_{\text{eff}} = n_e n_o / \sqrt{n_e^2 \sin^2 \alpha + n_o^2 \cos^2 \alpha}, \quad \text{6-1}$$

where $\alpha$ is the angle between the LC director and the polarization of the light. Because the orientation of the LC is different in different domains, the encountered refractive index
also differs from domain to domain; therefore, the light becomes scattered. When the scattered light hits the interface of the PLWG with a small incident angle, it is refracted out of the plate, so the light coming out of the PLWG is linearly polarized in the \(x\) direction. Unscattered light with polarization in the \(y\) direction can be reflected backward with its polarization rotated to the \(xz\) plane when it hits the combination of a quarter-wave plate and a reflector at the other edge of the plate. On its way back, it will be scattered and come out of the PLWG with polarization in the \(x\) direction.

6.3 Experiment and results

In our experiment, a mixture was created from 92.9\% weight nematic LC BL038 (from Merck), 6.9\% bifunctional monomer HCM-009 (from HCCH, China) and 0.2\% photoinitiator BME (from Polyscience). The mixture had a positive dielectric anisotropy \((\Delta \varepsilon > 0)\) and was filled into a cell consisting of two parallel glass substrates with transparent ITO electrodes. On top of the ITO, a layer of polyimide was spin coated, baked and rubbed to create the homogeneous alignment layer for the LC. The cell thickness was controlled by 10 \(\mu\)m spacers. The cell was placed under UV light with an intensity of 1.3 mW/(cm\(^2\)) to polymerize the monomers.

Before the polymerization, the mixture of the LC and monomer was homogeneously aligned in the \(x\) direction as shown in Fig. 6.1(a). The monomers were photopolymerized by UV irradiation in two steps. In the first step, no voltage was applied
and the cell was irradiated by UV light for 2 min to polymerize some of the monomers. The polymer network formed was aligned parallel to the cell substrate in the rubbing direction, as shown in Fig. 6.1(b), and tended to keep the LC in the homogeneous state [9, 25, 53, 54]. In the second step, 20 V was applied across the cell, and the LC in the regions where there were no polymer networks was tilted toward the z direction. Because the randomly located polymer network formed in the first step had an aligning effect, the LC oriented in different directions on the x-z plane in different domains; thus, the material switched to a poly-domain structure as shown in Fig 6.1(c). The cell was irradiated further to polymerize the remaining unpolymerized monomers. The polymer networks formed in this step were along the tilted LC directions and thus stabilized the poly-domain structure. After the polymerization, the applied voltage was removed and the LC remained in the poly-domain state as shown in fig. 6.1(d). SEM studies showed that the domain size was comparable to the wavelength of visible light.

The film made from the above process was used as a polarizing LWGP. Three LEDs were installed on the edge of the film, perpendicular to the rubbing direction. The light was then coupled into the PLWG. The unpolarized incident light could be considered as two linearly polarized components: one component with polarization in the x-z plane (the LC plane) and the other component with polarization in the y direction (perpendicular to the LC plane). Incident light with polarization in the y direction (Ray 2 in Fig. 6.1(d)) encounters the same refractive index (the ordinary refractive index of the LC) in different domains and thus is not scattered. When the light hits the interface of the PLWG with a large incident angle (defined with respect to the normal of the PLWG), it is bounced
between the two interfaces of the PLWG due to total internal reflection and thus propagated through the PLWG. Incident light with polarization in the $x$-$z$ plane (Ray 1 in Fig. 6.1(d)) instead encounters different refractive indices in different domains and thus becomes scattered with a deflected propagation direction. When the scattered light hits the interface of the PLWG at a small incident angle, it becomes refracted out of the plate. Thus, the light coming out of the PLWG is linearly polarized in the $x$ direction. Unscattered light with polarization in the $y$ direction can be reflected backwards with its polarization rotated to the $xz$ plane when it hits the combination of a quarter-wave plate and a reflector at the other end of the plate. On its way back, it will be scattered and comes out of the PLWG with polarization in the $x$ direction.

![Figure 6.1 Schematic diagrams showing how the permanent polarizing light waveguide plate is made.](image)

(a) homogeneous state before polymerization, (b) first step of polymerization without applied voltage, (c) second step of polymerization with applied voltage, (d) multi-domain state after polymerization.
We constructed a 4x4 cm² PLWG and characterized its polarization dependence of scattering. In the experiment, an unpolarized laser beam was shined on the PLWG normal to its surface. A polarizer and then a photo-detector were placed directly behind the PLWG as shown by the inset in Fig. 6.2. The collection angle of the detector was set to 4°. The polarizer was rotated to check the polarization of the light after the PLWG. The scattering of the plate was almost the same with and without applied voltage (20 V), which indicated that the LC was fixed in the poly-domain state by the polymer network. When the polarizer angle was set to 0°, the transmission axis of the polarizer was perpendicular to the x-z plane and the transmittance was about 70% (normalized to the
detected light intensity when the PLWG was removed). The transmittance decreased when the polarizer was rotated, reaching a minimum (~0%) when the polarizer angle was 90° (where the polarization of the incident light was parallel to the rubbing direction). For the component of light with polarization perpendicular to the LC plane, the encountered refractive index was the ordinary refractive of the LC, independent of the orientation of the LC in the $xz$ plane, and therefore it passed through the PLWG. When the polarizer angle was 0°, the transmittance of this component was detected, so the transmittance was therefore high with any light loss mainly due to reflection from the interfaces. For the component with the polarization parallel to the $xz$ plane, the encountered refractive index varied from domain to domain, depending on the orientation of the LC in the $xz$ plane, and therefore it was scattered away from the original propagation direction. When the polarizer angle was 90°, the transmittance of this component was detected and was found to be low. This result indicates that the unscattered light was linearly polarized in the direction perpendicular to the LC plane.

We then studied the optical properties of the polarizing PLWG with an edgelight. In this experiment, three white LED were installed, evenly distributed, along the edge (parallel to the rubbing) of the PLWG. The light was coupled into the PLWG. When light propagated through the PLWG, some light was scattered out of the plate. A polarizer and a photo-detector were placed on top of the PLWG as shown by the inset in Fig. 6.3. The scattered light intensity was measured as the polarizer was rotated and the results are shown in Fig. 6.3. The measurement was taken at a position 0.5 cm away from the LED edgelight. In the figure, arbitrary units were used because the measured intensity depended
on the area of the plate and the collection angle of the detector, and we did not have the equipment to measure the absolute light efficiency. When the polarizer angle was 0° (perpendicular to the LC plane), the scattered light intensity was at a minimum of 27 units. As the polarizer was rotated, the scattered light intensity increased. When the polarizer angle was 90° (parallel to the LC plane), the scattered light intensity was at a maximum of 71 units. This indicated that the light scattered out of the plate was partially polarized. The contrast ratio between the maximum and minimum intensities was 71: 27 =2.6: 1.

The intensity of the light that scattered out of the PLWG also depended on the distance from the LED edgelight. The scattered light intensity was measured at various positions along the central line on top of the PLWG and the result is shown in Fig. 6.4. At a position near the edge, the light was mainly from the central LED (the other two LEDs did not contribute much), so the scattered light intensity was low. As the distance was increased, the light intensity first increased. It peaked at a position 3 cm from the edge. When the distance was increased beyond that, the scattered light intensity decreased. As the light propagated through the waveguide plate, its intensity became weaker because more and more light became scattered out. When the polarizer was parallel to the LC plane, the detected intensity of the light scattered out of the plate was always higher than that when the polarizer was perpendicular to the LC plane.
In LCDs, the intensity of the light coming out of the waveguide plate should ideally be uniform. The results from Fig. 6.4 show, however, that the intensity was not uniform. The problem can be solved by two approaches. The first approach is to install more LEDs along the edge. The second approach is to control the UV light intensity spatially during the polymerization of the monomers, as the scattering of the material depends on the UV intensity during the polymerization process, and thus compensates for the spatial dependence of the light intensity coming out of the plate.

Figure 6.3 Scattered light intensity as a function of the polarizer angle of the polarizing PLWG when edgelit.
We also fabricated a 4x4 in² stable polarizing PLWG and photographed it under various polarization and edgelighting conditions. A linear sheet polarizer was placed on top of the PLWG and a LED light was installed along its edge. Figure 6.5(a) shows a photograph of the result when the edgelight was turned off and the transmission axis of the polarizer was perpendicular to the alignment layer rubbing direction. The scattered ambient light (polarized parallel to the rubbing) was absorbed by the polarizer; the PLWG appeared transparent and, thus, the scene behind it could be clearly seen. Figure 6.5(b) shows a photograph of the result when the transmission axis of the polarizer was parallel to the alignment layer rubbing direction. The scattered ambient light was not absorbed by the polarizer; the PLWG appeared milky and the scene behind it was not visible. Figure 6.5 (c) shows a photograph of the result when the edgelight was turned on and the

**Figure 6.4** Scattered light intensity as a function of the distance from the edgelight. //: polarizer parallel to rubbing, ⊥: polarizer perpendicular to rubbing.
transmission axis of the polarizer was perpendicular to the alignment layer rubbing direction. The scattered light from the edgelight (polarized parallel to the rubbing) was absorbed by the polarizer; the PLWG still appeared transparent and thus the scene behind it could be seen. Lastly, Fig. 6.5(d) shows a photograph of the result when the transmission axis of the polarizer was parallel to the alignment layer rubbing direction. The scattered light from the edgelight was not absorbed by the polarizer; the PLWG appeared white and the scene behind it was not visible.

![Photographs of the passive PLWG.](image)

**Figure 6.5 Photographs of the passive PLWG.** (a) edgelight off and polarizer perpendicular to the rubbing. (b) edgelight off and polarizer parallel to the rubbing. (c) edgelight on and polarizer perpendicular to the rubbing. (d) edgelight on and polarizer parallel to rubbing direction
light waveguide plate made from a polymer-stabilized nematic LC film which we call a passive PLWG [58]. It selectively scatters light: light with polarization in one direction is scattered out of the plate and light with polarization in the orthogonal direction continues to propagate through the plate. The waveguide plate thus converts the unpolarized light produced by the edgelight into linearly polarized light by selective scattering.

In the second part of this chapter, the optimization of the polarizing waveguide to achieve a high contrast ratio was reported. We also reported on the angular intensity profile of the light scattered out of the PLWG and the effect of the plate structure.

6.5 Experiments and results

We carried out a systematic study of the polarizing PLWG with an aim to optimize its performance. One key parameter is the degree of polarization of light coming out of the plate. Because the LC was not perfectly confined to the \(xz\) plane and the refractive indices of the LC and polymer network were not exactly matched, some light with polarization in the \(y\) direction also scattered out of the plate. After trials of many combinations of different LCs and monomers, we identified a combination of the LC MAT11-575 and the bifunctional mesogenic monomer RM257 (both from Merck) that minimized the scattering of the light with polarization in the direction perpendicular to the LC plane. A small amount of photo-initiator was also added into the mixture. The concentration of the monomer was 13 wt\%. The cell thickness was controlled by 10 \(\mu\)m spherical spacers. The size of the cell was 2 in x 2 in. The cell was irradiated by UV light for 2:30 minutes in a
homogeneous state without applied voltage and then for 30 minutes with 50 V, 1 kHz applied.

We first tested the polarization dependence of the scattering properties of the plate. Green laser light was incident normally on the plate as shown in the inset of Fig. 6.6. A polarizer was placed in front of the plate and a detector with 4° collection angle was placed behind the plate. The transmittance was measured as the polarizer was rotated. The result is shown in Figure 6.6 where the polarizer angle was defined with respect to the alignment layer rubbing direction. When the applied voltage during the measurement was 0 V, the scattering of the plate was very weak and thus the transmittance was high. When the polarizer angle was 90°, there was no scattering and the transmittance was also very high.

When the polarizer angle was 0°, however, the transmittance decreased slightly, indicating the plate was weakly scattering. When 80 V, 1 kHz was applied, the plate became strongly scattering. When the polarizer angle was 90°, the scattering became weak, but the transmittance was still high. When the polarizer angle was 0°, the transmittance became low, which indicated that the plate was strongly scattering.
The polarization dependence of the scattering behavior of the plate when it was edgelit was measured. Three LEDs (evenly distributed) were installed along the edge of the plate perpendicular to the alignment layer rubbing direction. In order to check the polarization state of the light coming out of the plate, a polarizer was placed in front of the photo detector as shown by the inset in Fig. 6.7. The detector was placed very close to the plate and the intensity of the light was measured. When the polarizer was rotated, the scattered light intensity varied, which indicated that the transmitted light was partially polarized. When the polarizer was aligned parallel to the alignment layer rubbing direction (0°), the intensity was higher than that when the polarizer was aligned perpendicular to the rubbing direction (90°). When no voltage was applied across the plate, the intensity was low. The contrast ratio between the intensities of the light with polarization parallel and
perpendicular to the rubbing direction was 5:1. When 80 V was applied, the material became more scattering and the intensity of the light coming out of the plate was tripled; the contrast ratio also increased to 9:1.

![Diagram](image)

**Figure 6.7 The polarization state of the light scattered out of the PLWG from top**

The intensity of the light coming out of the plate also depended on the position relative to the edge where the LEDs were installed and the result is shown in Fig. 6.8. The main cause for the intensity change was the intensity of the propagating light vary with position. There were two factors that variation of the intensity of the propagating light. The first
factor was that the LEDs were point light sources. The second factor was that as the light propagated through the material, more and more light was scattered out of the plate.

![Graph](image)

**Figure 6.8** PLWG light scattered out to position with respect to the edgelith

The angular intensity profile of the light scattered out of the plate was measured, and the result is shown in Fig. 6.9. The intensity peaked at the plate normal direction. Therefore, the plate also has the function of collimation films.
Figure 6.9 The angular intensity profile of the light scattered out of the PLWG

In the PLWG, light was scattered out of both sides of the plate. Only light coming out of the top side (toward the LC panel) was utilized. We tried various methods to recycle the light coming out of the bottom side by putting different light reflectors. We measured the intensity of the light coming out of the top side. The measurement setup is shown in Fig. 6.10 and the result is shown in Fig. 6.11. In the measurement, no voltage was applied. When a black tape was placed beneath the plate, although the contrast ratio was high, the light coming out of the bottom side was absorbed, so this structure was not particularly useful. When an isotropic scattering plate was used, the intensity increased, but the
contrast ratio decreased. When a mirror was used, the intensity increased and the contrast remained around 4.5:1. When a reflective polarizer was used, the best result was achieved: both the intensity and the contrast ratio were high; however, because reflective polarizers are expensive, the structure with the mirror is the more practical solution.

Figure 6.10 Set-up for measuring the light scattering out from both sides
6.6 Discussion

The contrast ratio between the intensities of the two components of light coming out of the PLWG with the two orthogonal polarizations is about 5:1. Partially polarized light can be changed into completely polarized light by placing a linear polarizer on top of the PLWG. Assuming the polarizer is perfect, when a regular LWGP was used, the light efficiency of LCD was 50%. When the polarizing PLWG with contrast ratio of 5:1 was used, the light efficiency increased to $5/(5+1)= 83\%$; therefore, the polarizing PLWG still can significantly improve the light efficiency of edgelight LCDs.

Figure 6.11. Scattered light intensity profiles from using different light recycling plate as the PLWG background in opposite side of measurement
We developed a novel polarizing light waveguide (PLWG) plate that can convert unpolarized light into linearly polarized light by selective scattering. It can significantly increase the light efficiency of edgelit LC displays and thus prolong the battery life of hand-held devices.

Another important property of the PLWG is the angular profile of the intensity of the light coming off the plate. Our preliminary studies showed that the outcoming light peaked at the normal direction of the plate and was independent of the position on the plate.

In summary, we developed a stable polarizing light waveguide plate for edgelit LC displays. It selectively scatters light without applied voltage. It can convert unpolarized light into polarized light and thus significantly improve the light efficiency of current LC displays.
REFERENCES


