Efficient polarization converter for projection displays

W. C. Yip, H. C. Huang, and H. S. Kwok

In the waveguiding limit, a twisted nematic liquid crystal cell behaves as an achromatic polarization rotator. We propose and demonstrate the application of such a polarization rotator to convert unpolarized light into linearly polarized light with almost 100% efficiency. This polarization converter has a 2:1 aspect ratio, which is close to the 16:9 ratio for modern televisions. It can be used therefore in a projection display with polarization-dependent light valves such as a liquid crystal light valve. Both transmittive and reflective light valves can be used. The temperature dependence of the achromatic polarization rotator is also studied. © 1997 Optical Society of America

Key words: Twisted nematic liquid crystal, projection displays, achromatic polarization rotator.

1. Introduction

Many projection displays are based on the manipulation of light polarization in a liquid crystal (LC) light valve.[1–4] However, all light sources produce mostly unpolarized light. Hence the effective control and conversion of unpolarized light into polarized light is an important concern for projection displays. Many optical systems have been proposed to achieve a high level of conversion of unpolarized to polarized light, including the use of cholesteric LC cells,[5–7] combinations of standard polarizing beam splitter (PBS) cubes,[8–11] and specially designed PBS.[12] A cholesteric LC-based system that recycles the unwanted polarization was demonstrated recently with nearly 88% efficiency.[7] However, this kind of polarizer is difficult to work with in the projection mode.

Most systems that involve a combination of PBS cubes require elaborate optical alignment. Some require quarter-wave plates for polarization rotation and are therefore not achromatic. We propose a polarization converter based on tandem PBS's and an achromatic polarization rotator. The geometry is quite simple, and elaborate alignment is not required. The achromatic polarization rotator is based on a twisted nematic (TN) LC cell operating in the waveguiding mode. Very high polarization conversion efficiency of nearly 90% and an aspect ratio of approximately 16:9 can be obtained without further optical manipulation with cylindrical lenses. This system can be used in projection displays with either reflective or transmittive light valves. Also, the thermal stability of such achromatic polarization rotators is studied in anticipation of practical applications where high-intensity light is used.

2. Design of Polarization Converter

The basic design of the polarization converter in the reflective mode and the transmittive mode, respectively, is shown in Figs. 1 and 2. It consists of two tandem PBS's with an achromatic polarization rotator between them. As shown in the figures, the s-polarized component is first reflected out and impinges on either the reflective or transmittive light valve. The transmitted p-polarized wave from the first PBS is rotated 90° by a TN LC cell and becomes s-polarized. As a result, it will be reflected by the second PBS. The total of light reflected from both PBS's will be s-polarized as shown. The light that emerges from this polarization converter has an aspect ratio of 2:1, which is very close to the 16:9 standard for high-definition television and is used in most modern TV systems.

This polarization converter in principle has a 100% utilization of the input unpolarized light. In the reflective mode shown in Fig. 1, the light valve rotates the polarization of the incoming light by 90° so that the reflected light can be transmitted by the polarization converter. One example is an electrically

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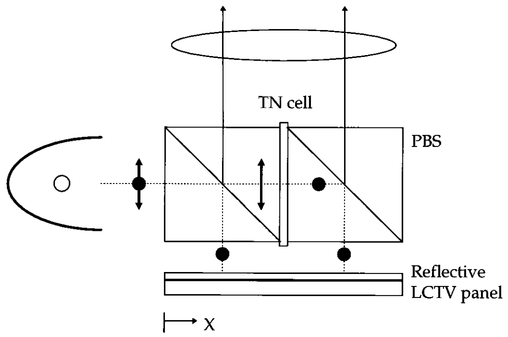

Fig. 1. Reflective projection system with the polarization converter.

controlled birefringence (ECB) LCD.[1] Other examples are the reflective TN ECB,[2] the mixed-mode TN cell (MTN),[3] and the optically compensated bend (OCB) mode.[4] After its transmission through the polarization converter, an image can subsequently be formed on a projection screen with an imaging lens. The case for a transmittive light valve is shown in Fig. 2. In this mode another polarizer has to be used at the output of the LC panel to modulate the polarized light. In most cases, the LC panel can simply be a TN cell.

There are two important considerations for the application of this polarization converter in a practical projection system. First, the presence of a gap between the two adjacent PBS's can potentially produce a nonuniform illumination on the light valve. We show that if the LC cell is kept thin and a slightly diverging light beam is used, this gap can be effectively filled. The most important point is that the gap does not appear on the image plane of the imaging lens. Thus it will not be imaged on the screen. This situation is very much like that of the reflecting mirror of a Cassegrainian telescope. It should not affect the quality of the image. Second, the polarization rotator in between the two PBS's should be achromatic and temperature insensitive. We discuss below that this requirement can be satisfied effectively by a 90° TN LC cell. Alternatively, an achromatic half-wave retardation film[13] can be used in place of the TN cell. However, if one is concerned about high-contrast ratio and wide-acceptance angle, the TN cell is the better choice.

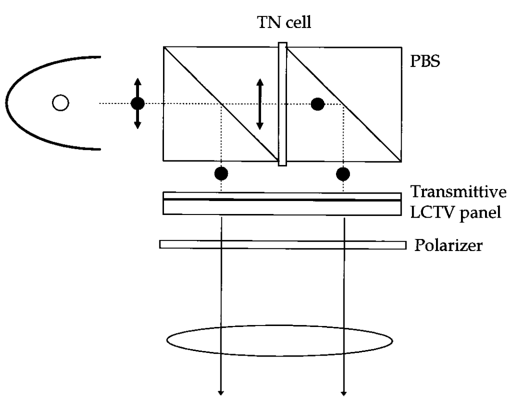

Fig. 2. Transmittive projection display system with the polarization converter.

3. Achromatic Polarization Rotator

A. Optical Transmission

It is well known that in the adiabatic or waveguiding limit,[2] a 90° TN LCD rotates the polarization of the input light by 90°. For practical purposes, the waveguiding limit cannot be reached, and one has to work in one of the Mauguin minima.[14] As a result, there is some slight wavelength dispersion in the polarization rotation.

The theory of light transmission through a TN LCD has been discussed thoroughly in many texts.[14,15] For TN LC, the eigenmode solutions are in general elliptically polarized.[14] If the product of the cell thickness d and the LC birefringence Δn is much larger than the wavelength λ,

$$d\Delta n \gg \lambda, \tag{1}$$

the eigenmodes become linearly polarized waves. This is the waveguiding limit.

Assuming the polarization axes of the front and the rear polarizers are parallel to the input and the output LC directors, respectively, the transmittance of normal incident light is given by the Gooch and Tarry formula[2]:

$$T = \frac{1}{1 + u^2} (u^2 + \cos^2 \varphi \sqrt{1 + u^2}), \tag{2}$$

where

$$u = \frac{\pi}{\varphi} \frac{\Delta n d}{\lambda},$$

and φ is the twist angle. If the twist angle is 90° and the front and rear polarizer axes are parallel, Eq. (1) reduces to

$$T = \frac{1}{1 + u^2} \sin^2 \frac{\pi}{2} (1 + u^2)^{1/2}. \tag{3}$$

Thus as u approaches infinity in the waveguiding limit, T becomes zero, implying that the output is perpendicularly polarized to the output polarizer, i.e., rotated by 90°. At the Mauguin minima, $T = 0$ for some special values of u. The output is also effectively rotated by 90°. In fact, however, the output consists of two elliptically polarized waves that interfere to form a linearly polarized wave that is perpendicular to the output polarizer. It is verified that in the second Mauguin minimum, the variation of the output over the entire visible spectrum is <5%.[2] Hence it is safe to regard the TN LC cell as an achromatic polarization rotator even if $d\Delta n$ is not too large.

Table 1. Specifications of 90° TN LC Cell

Physical Parameter	TN Cell
Clearing temperature T_c	82.2 °C
Melting temperature T_m	−10 °C
Ordinary refractive index n_o	1.524
Birefringence Δn	0.258
Cell gap d	9 μm
Slide glass dimension	40 mm × 22 mm × 0.15 mm
Viscosity η (22 °C)	66 mPa × s

B. Thermal Dependence

Above the clearing temperature T_c a nematic LC behaves as an isotropic liquid. Below T_c the long axis of the LC molecule tends to align with neighboring molecules to minimize the total energy, and the nematic phase is observed. The approximate order parameter for this alignment is given by[14]

$$S \cong \left(1 - \frac{0.98T}{T_c}\right)^{0.22}, \tag{4}$$

where T is the temperature. When the temperature varies, the birefringence can be expressed as[15]

$$\Delta n = g(T)\,\frac{\lambda^2\lambda^{*2}}{\lambda^2 - \lambda^{*2}}, \tag{5}$$

where λ^* is the mean resonance wavelength of the LC. The function $g(T)$ can be shown by[16]

$$g(T) = \frac{1}{\varepsilon_0}\,\frac{\delta K}{n_e + n_o}\,S, \tag{6}$$

where δK is the molecular anisotropy. Because for most commonly used LC the variation of refractive indices is similar,[17,18] an empirical approximation to fit the temperature dependence can be assumed as

$$g(T) \cong g_0 \exp\left[\frac{-(T - T_0)}{T_c}\right] S, \tag{7}$$

where T_0 is the room temperature and g_0 is a normalization constant to be determined. Therefore from Eqs. (4), (5), and (7), the birefringence can be written as

$$\Delta n \cong g_0\,\frac{\lambda^2\lambda^{*2}}{\lambda^2 - \lambda^{*2}} \exp\left[\frac{-(T - T_0)}{T_c}\right]\left(1 - \frac{0.98T}{T_c}\right)^{0.22}. \tag{8}$$

We use this formula to fit the experimental data on the temperature dependence of Δn.

4. Experimental Results

A very thin 90°-twisted LC cell was fabricated, and the specifications are given in Table 1. Clay-Adams glass slides of 0.15-mm thickness were used. The glass plates were cleaned and rinsed with detergent and deionized water at 50 °C. After dehydration baking, the glass was spin coated with polyimide. Cured polyimide was then rubbed and dispersed with spacers. An empty cell was formed after epoxy was applied along the perimeter. The compression of the cell was critical because the slide glass could be broken easily. The last process was LC filling in a vacuum chamber with Roche TN-403. No chiral dopant was introduced so that the depression of T_c could be avoided.[19]

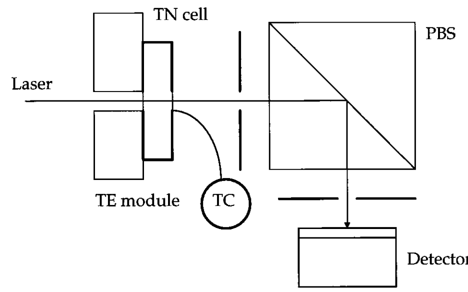

Fig. 3. Experimental setup to measure the thermal dependence of TN LC.

The thermal sensitivity of this LC cell was characterized with the setup shown in Fig. 3. The laser beam was s polarized relative to the PBS. If the polarization rotator worked perfectly, no light should have been detected. This setup was therefore a sensitive measure of the quality of the TN cell. The LC cell was placed in contact with a thermoelectric module to vary its temperature. We made a good thermal contact by wrapping the cell with aluminum foil and applying a thermal conductive compound. A thermocouple was located adjacent to where the laser beam transversed the cell, and the variation of transmittance was recorded by the detector. The polarization direction of a laser beam was aligned parallel to the input LC director based on null detection.

The measured transmittance *versus* temperature for red (632.8 nm), green (514 nm), and blue (457.9 nm) lights was plotted as shown in Figs. 4, 5, and 6, respectively. Simulation results from Eqs. (3) and (8) were shown as solid lines. For TN-403, $\lambda^* = 246$ nm and $g_0 = 4.6793$ were obtained for the calculation.[15] The theoretical fits agree with the experimental data up to approximately 0.75 T_c, beyond which the measured transmittance fluctuated more

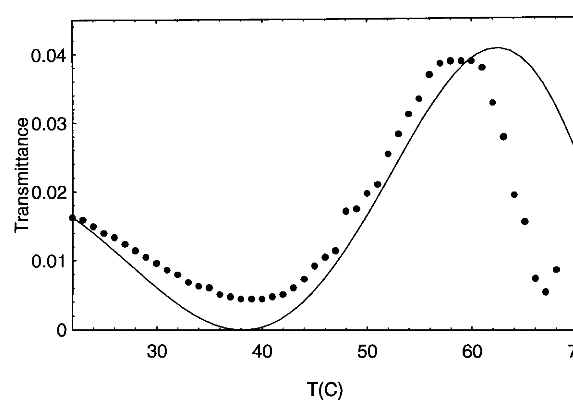

Fig. 4. Transmittance of the TN cell *versus* temperature at λ = 632.8 nm.

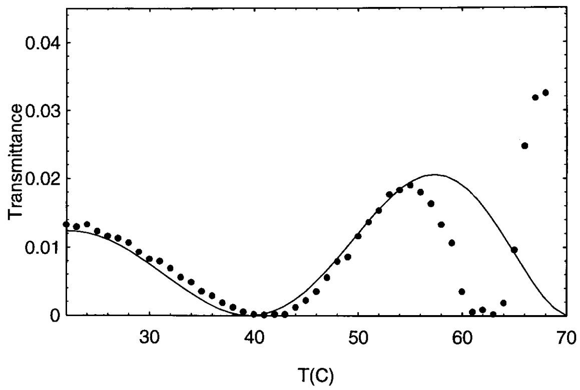

Fig. 5. Transmittance of TN cell versus temperature at λ = 514 nm.

rapidly and deviated from the theoretical curves. In general, the leakage of light is 1% in the 35 °C temperature region. This is the expected operating temperature of the polarization converter. This amounts to a 1% variation of the output of the second PBS in the polarization converter and is quite acceptable.

To measure the light uniformity at the output plane of the polarization converter, we scanned the light intensity along the horizontal distance x, as shown in Fig. 1. The detector was covered with a 0.24-mm-wide slit, and faced normal to the PBS surface. The detector plane was 30 mm from the PBS surface. The achromaticity range of the PBS in this experiment was from 400 to 700 nm. A commercial lamp system that consisted of a Xenon lamp with an arc gap of 0.9×2.7 mm, a four-element condenser, and a liquid filter (water) was used so that parallel rays with <10 mm deviation could be maintained over a 200-mm illuminated distance.

As expected, when the input light is well collimated, a sharp dip in the middle of the light intensity profile was observed. It is shown as the curve with the squares in Fig. 7. The light level dropped to nearly 20%. Actually, this dip was not caused by the TN cell but by the limited clear aperture of the PBS because the overall thickness of the TN cell was far

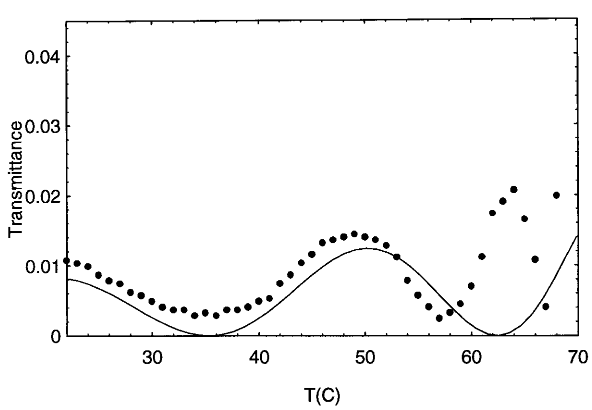

Fig. 6. Transmittance of TN cell versus temperature at λ = 457.9 nm.

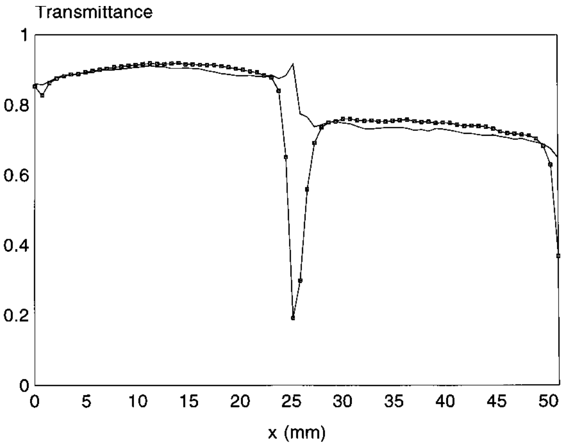

Fig. 7. Transmission profile of the polarization converter with collimated light (curve with square) and a 5° diverging light source (solid curve).

less than the width of the dip. However, if we made the input beam slightly divergent by placing a negative lens in front of the first PBS, the dip disappeared, as shown by the solid curve in Fig. 7. For the particular measurement in Fig. 7, a −500-mm lens was used, and the divergence of the light beam was approximately 5°. It can also be observed from Fig. 7 that the light intensity from the second PBS was lower than that of the first PBS. The difference in transmittance for $x < 25$ mm and $x > 25$ mm was about 16%. This is caused by absorption/scattering/reflection loss through the TN LC cell. The light intensity is also slightly higher in the midsection, reflecting the nonuniformity of the input beam intensity profile.

Figure 8 shows the measured output profile at three different wavelengths, 650.5, 530, and 450.5 nm (R, G, B). We obtained these outputs by filtering white light with a 10-nm-bandwidth interference filter. There is an almost 10% variation in transmittance between the red and the blue lights, caused by

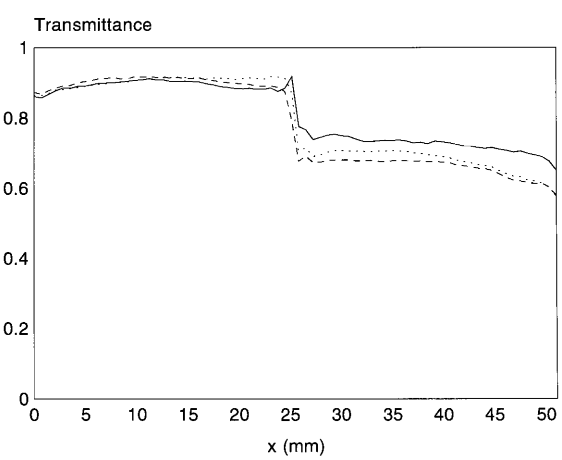

Fig. 8. Transmission profile of the polarization converter for three different wavelengths: solid curve, 650.5 nm; dotted curve, 530 nm; dashed curve, 450.5 nm.

the limited bandwidth and the small acceptance angle of the PBS. Actually, for most commercial PBS's, extinction ratios $>1000:1$ in a 300-nm bandwidth about a central wavelength of 550 nm are typical. However, when the incident angle is greater than $\pm 2.5°$, the contrast of the optical system will roll off gradually.[20–21]

It can thus be seen that the polarization converter worked basically as designed. The most important drawback is that there is a left–right imbalance in intensity owing to Fresnel reflection loss. Antireflection coatings applied to the LC cell glass surfaces should bring this difference to an acceptable value. A PBS with a larger acceptance angle and a wider operating spectral range should also help. Finally, it should be mentioned that measurements shown in Figs. 7 and 8 were taken with the cell at 37 °C.

5. Conclusion

We demonstrate an optical system for the efficient use of unpolarized light in a projection system. This system is particularly useful for a 16:9 reflective projection display. The output image has this 16:9 aspect ratio without a sacrifice of a large portion of the input light or the use of fancy cylindrical imaging lenses. It works with an ordinary light source with cylindrical symmetry.

We have also studied an achromatic polarization rotator with nematic LC and its temperature dependence. The temperature dependence is quite acceptable below 0.75 T_c. We have also shown that the temperature dependence can be modeled quite well with conventional theories of nematic LC. However, as the temperature increases beyond approximately 0.75 T_c, the transmittance with undoped nematic LC fluctuates rapidly. For practical purposes, the light leakage is $<1\%$.

This polarization converter has, in principle, 100% efficiency. In practice, 88% transmittance was achieved without elaborate antireflection coatings. We believe that this optical design has good application potential for both reflective and transmittive projection display systems.

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