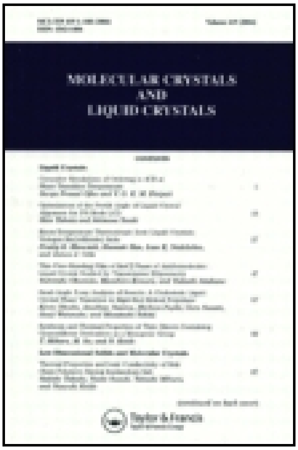

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

# Reflective Liquid Crystal Display using a Non-Twist Quarter-Wave Cell

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Version of record first published: 24 Sep 2006

To cite this article: Tae-Hoon Yoon, Gi-Dong Lee & Jae Chang Kim (2001): Reflective Liquid Crystal Display using a Non-Twist Quarter-Wave Cell, Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals, 364:1, 479-490

To link to this article: http://dx.doi.org/10.1080/10587250108025018

*Mol. Cryst. and Liq. Cryst.*, 2001, Vol. 364, pp. 479-490
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# Reflective Liquid Crystal Display using a Non-Twist Quarter-Wave Cell

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We propose an optical configuration for a high-contrast reflective liquid crystal display that can be applied to most of non-twist display modes. By fabricating a homogeneous cell with the proposed configuration, we demonstrated high contrast ratio of 50:1 and fast response time of 12 ms without using a wide-band film.

*Keywords:* liquid crystal display; reflective display; non-twist cell; ingle polarizer mode; quarter-wave cell; Mueller matrix

## 1. INTRODUCTION

Recently, the role of reflective liquid crystal displays (LCDs) is becoming more and more important because of their low power consumption and lightweight. Especially, the single polarizer mode, which can provide the high brightness, is considered as a suitable structure for reflective LCDs[1-4]. However, contrast of single polarizer LCDs is lower than that of double-polarizer LCDs because of the light leakage in the dark state. To overcome this disadvantage in a reflective cell, we need to make the reflected light polarized linearly over the entire visible spectra by using a wide-band quarter-wave film[3].

In this paper, we propose an optical configuration for single polarizer reflective LCDs using non-twist quarter-wave LC cells. We found that the proposed configuration provides a bright display with high contrast without using a wide-band film. It can be applied not only

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to horizontal switching modes such as in-plane switching (IPS) cells[5], ferroelectric LC (FLC) cells[6], and anti-ferroelectiric LC (AFLC) cells[7], but also vertical switching modes such as homogeneously aligned cells, vertically aligned (VA) cells[8], π-cells[9], and hybrid aligned cells.

## 2. SINGLE POLARIZER REFLECTIVE LCD

Figure 1 shows the optical principle of a single polarizer reflective LCD. It is composed of a polarizer, a metallic reflector and retardation layers between them. The dark state can be obtained by the double pass through a quarter-wave layer. The linearly polarized light passed through the polarizer will be changed to the circularly polarized light as it passes through the layer with a quarter-wave retardation. The polarization of the reflected light changes to 90°-rotated linearly polarization by propagating backward through the quarter-wave retardation layer. The final polarization of the reflected light is perpendicular to the transmission axis of the polarizer, so that the polarizer will block the reflected light. As a result, we could achieve the dark state. However, it does not mean that we can obtain the perfect dark state, since this condition can be satisfied only at a single design frequency. Therefore, we have to find optical configurations of retardation layers that satisfy the above optical condition for the perfect dark state over the entire visible wavelength range.

For the bright state, the total retardation must be a multiple of a half-wave. Then, the polarization of the reflected light double-passed through the retardation layers is the same as the input polarization,

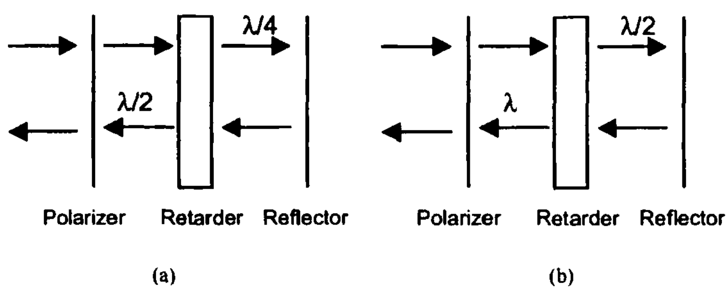


FIGURE 1. A single polarizer reflective LCD. (a) in the dark state, (b) in the bright state.

so that the final polarization is coincident with the transmission axis of the polarizer. As a result, we could achieve the bright state. If polarization dispersion over the entire visible wavelength range is small, we can expect high brightness.

## 3. CONFIGURATION FOR THE DARK STATE

A non-twist quarter-wave LC cell that consists of a non-twist quarter-wave LC layer, a reflector, and a polarizer may be used as a reflective display. If we align the non-twist LC layer homogeneously along the transmission axis of the polarizer or vertically, there will be no change in the polarization by the double pass through the cell. The reflected light will pass through the polarizer again, so that we can achieve the bright state. If we align the quarter-wave LC layer homogeneously along an angle 45° with respect to the transmission axis of the polarizer, the polarization will be rotated by 90° by the double pass through the cell. Then, the polarizer will block the reflected light, so that we achieve the dark state. However, a quarter-wave LC layer alone could not provide the completely dark state over the entire visible wavelength ranges because of the wavelength-dependent phase retardation, which may result in poor contrast. In order to achieve the completely dark state over the entire visible wavelength ranges, we propose a configuration with a half-wave retardation film inserted between the LC layer and the polarizer, as shown in Fig. 2. To search for the optimum device configurations, we calculated the reflectance in the dark and bright state as a function of optical parameters, such as the retardation of the cell $d\Delta n$, and the angle of the LC director $\theta_L$ with or without an applied electric field, and the optic axis $\theta_F$ of the retardation film. We assumed that the transmission axis of polarizer chosen as the reference angle is oriented along the $x$-axis.

With the proposed configuration, the bright state can be achieved by aligning the non-twist quarter-wave LC layer vertically or by aligning LC molecules horizontally in parallel with the optic axis of the half-wave film. Only the $x$-polarized component of the incident light will pass through the polarizer. The polarization will be rotated by an angle $2\theta_F$ by propagating through the half-wave film. There will be no change in the polarization by the double pass through a vertically aligned LC layer or a LC layer aligned homogeneously in parallel with the optic axis $\theta_F$ of the half-wave film. After the double pass through the LC layer, the reflected light polarized at an angle $2\theta_F$ will be rotated by $-2\theta_F$ by propagating backward through the half-wave film. Finally, the reflected light will be polarized again along the $x$ direction,

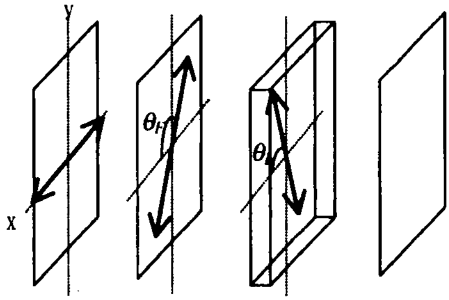


FIGURE 2. Optical configuration of a reflective non-twist quarter-wave LC cell with a half-wave film.

which will pass through the polarizer. Thus, we achieve the bright state. The cell as a whole may be regarded as a half-wave retarder. As a result, the cell can provide the very bright state over the entire visible wavelength spectra in a reflective display.

The dark state can be achieved as follows: The polarization will be rotated by an angle $2\theta_F$ by propagating through the half-wave film whose optic axis is oriented at an angle $\theta_F$. Then, the polarization will be changed to the circular polarization by propagating through a homogeneously aligned quarter-wave LC layer. Then, the reflected light with circular polarization will experience additional retardation of a quarter wave. The polarization will be rotated by $-2(2\theta_F - \theta_L)$ by the double pass through a quarter-wave LC layer aligned homogeneously at an angle $\theta_L$. The reflected light is polarized at an angle $2\theta_F - 2(2\theta_F - \theta_L) = -2\theta_F + 2\theta_L$. After the double pass through the LC layer, the polarization of the reflected light will be rotated by $2((-2\theta_F + 2\theta_L) - \theta_F) = 2(-3\theta_F + 2\theta_L)$ by propagating once more through the half-wave film whose optic axis is oriented at an angle $\theta_F$. Finally, the reflected light will be polarized at an angle $(2\theta_F - 2\theta_L) + 2(-3\theta_F + 2\theta_L) = -4\theta_F + 2\theta_L$. If the angle of the output polarization is equal to ±90°, or

$$\theta_L = 2\theta_F \pm 45°. \quad (1)$$

the polarizer will block the reflected light. By choosing $\theta_F$ and $\theta_L$ appropriately, we can achieve the completely dark state over the entire visible wavelength spectra.

## 4. CONDITION FOR HIGH-CONTRAST OPERATION

Now, for the wide-band operation of the device, we find the optimum angles of the optic axis of the half-wave film $\theta_F$ and that of the LC layer $\theta_L$ by using the Mueller matrix[10]. The Mueller matrix of a rotated birefringent layer is given by

$$M(\theta, \beta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta + \cos\beta \sin^2 2\theta & (1-\cos\beta)\sin 2\theta \cos 2\theta & \sin\beta \sin 2\theta \\ 0 & (1-\cos\beta)\sin 2\theta \cos 2\theta & \sin^2 2\theta + \cos\beta \cos^2 2\theta & -\sin\beta \cos 2\theta \\ 0 & -\sin\beta \sin 2\theta & \sin\beta \cos 2\theta & \cos\beta \end{pmatrix} \quad (2)$$

where $\theta$ is the angle of the optic axis of a birefringent layer and $\beta$ is its phase retardation. To change the incident $x$-polarized light to the circularly polarized light by passing through the LC cell, the Stokes vectors of polarization must satisfy the following condition,

$$S_o = M(\theta_L, \beta_L)\, M(\theta_F, \beta_F)\, S_i, \quad (3)$$

where $M(\theta_L, \beta_L)$ and $M(\theta_F, \beta_F)$ are Mueller matrices of the LC layer and the retardation film, respectively. $\beta_L$ and $\beta_F$ are the retardations of the LC layer and the film, respectively. $S_o = (1\ 0\ 0\ \pm 1)^T$ and $S_i = (1\ 1\ 0\ 0)^T$ are Stokes vectors of the circularly polarized light at the reflector surface and the linearly polarized input, respectively. For retardation of $\beta_L = \pi/2$ and $\beta_F = \pi$, we get

$$\sin(4\theta_F - 2\theta_L) = \pm 1, \text{ or } 4\theta_F - 2\theta_L = \pm 90°, \quad (4)$$

by solving Eq. (3), which is the same as Eq. (1). If a cell satisfies this condition, the cell will change the linear polarization to the circular polarization at a certain frequency $f_o$.

Now we need like to find the condition under which a linearly polarized input light can be changed to the circularly polarized light over the entire visible wavelengths by propagating through the cell.

If we change the frequency by $\Delta f$, the retardation will change by a factor $\delta = \Delta f / f_o$. For the frequency $f = f_o + \Delta f = f_o(1 + \delta)$, the retardations of the half-wave film and the quarter-wave LC layer are, $\beta_L = \pi(1 + \delta)/2$ and $\beta_F = \pi(1 + \delta)$, respectively. Here we assume that the wavelength dependence of the retardation of the film and that of the LC layer are the same. By substituting $\beta_L = \pi(1 + \delta)/2$ and $\beta_F = \pi(1 + \delta)$

into Eq. (3), the output Stokes vector $S_o$ can be written as

$$S_o = \begin{pmatrix} 1 \\ \cos 2\theta_L \cos(4\theta_F - 2\theta_L) + \delta \sin 2\theta_L (2\sin 2\theta_F + \sin(4\theta_F - 2\theta_L)) \\ \sin 2\theta_L \cos(4\theta_F - 2\theta_L) - \delta \cos 2\theta_L (2\sin 2\theta_F + \sin(4\theta_F - 2\theta_L)) \\ \pm 1 \end{pmatrix} \quad (5)$$

Since Eq. (3) cannot be solved easily for an arbitrary $\delta$, we solved it only for a small $\delta$. We used the approximation

$$\cos(\beta + \delta) \approx \cos\beta - \delta \sin\beta, \quad \sin(\beta + \delta) \approx \sin\beta + \delta \cos\beta$$

for $\delta << 1$. By inserting Eq. (4), Eq. (5) can rewritten as

$$S_o = \begin{pmatrix} 1 \\ \delta \sin 2\theta_L (2\sin 2\theta_F \pm 1) \\ -\delta \cos 2\theta_L (2\sin 2\theta_F \pm 1) \\ \pm 1 \end{pmatrix} \quad (6)$$

By equating Eq. (6) with $(1\ 0\ 0\ \pm 1)^T$, we obtain

$$\sin(2\theta_F) = \pm 1/2, \text{ or } \theta_F = \pm 15°, \quad (7)$$

By substituting Eq. (7) into Eq. (4), we get $\theta_L = \pm 75°$. Under the condition $\theta_F = \pm 15°$ and $\theta_L = \pm 75°$, the linearly polarized light will change to the circularly polarized light at frequencies $f \neq f_0$ as well. After the double pass through the cell, the polarization will again be linearly polarized, but rotated by 90°. It will be blocked by the polarizer, so that we achieve the completely dark state over the entire visible wavelengths in a reflective cell. If we consider the difference in wavelength dependence of retardation between the LC layer and the film, the optimum angles might be slightly different from the above value. As shown in Fig. 3, the condition $\theta_F = \pm 15°$ and $\theta_L = \pm 75°$ provides very low reflectance over the entire visible wavelength ranges.

A non-twisted quarter-wave LC cell can be realized in most of switching modes in the NB mode or in the NW mode. For the normally black mode of the proposed configuration, a quarter-wave LC layer can be aligned homogeneously along an angle $\theta_L = \pm 75°$ by the rubbing process with a half-wave film aligned along an angle $\theta_F = \pm 15°$. For horizontal-switching cells, such as an IPS mode cell, a FLC cell, and an

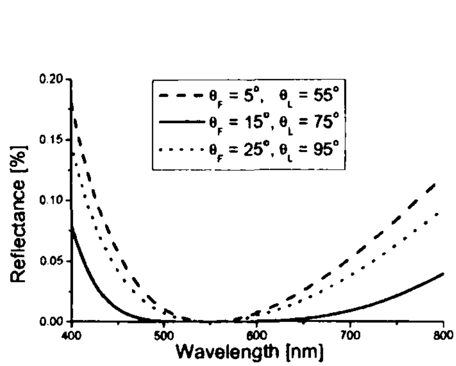


FIGURE 3. Calculated reflection spectra of the dark states with $\theta_L$ as a parameter. ($\theta_F = \theta_L/2$ - 22.5°)

AFLC cell, the LC layer can be rotated to the angle $\theta_L$ = ±30° by applying appropriate electric fields in order to achieve the bright state. The bright state of vertical switching cells, such as a homogeneously aligned nematic cell, a π–cell, and a hybrid-aligned cell, can be achieved by applying vertical electric field to the cells.

For the NW mode, we exchange the optical configurations in the dark state with that in the bright state. In the horizontal switching mode, the bright state can be obtained by aligning a LC layer horizontally along an angle $\theta_L$ = ±30°. In order to achieve the dark state, LC layers can be rotated to the angle $\theta_L$ = ±75° by applying appropriate electric fields to these horizontally switching cells. In the vertical switching mode, VA mode cells can be used for the normally white mode. VA mode cells rubbed along the angle $\theta_L$ = ±75° can be switched to the homogeneous alignment along the rubbing direction by applying vertical electric fields in order to achieve the dark state.

Fortunately, a half-wave retardation film can be located on top of the LC layer, so that the parallax problem does not occur. On the contrary, due to the small retardation of the LC layer, we might have difficulty in manufacturing process. Table 1 shows the summary of optical configurations of the applicable switching modes.

## 5. CONFIGURATION FOR THE BRIGHT STATE

Wide-band property in a reflective LC cell can be obtained by making the output polarization over the entire visible wavelength range very close to the polarization at the optical design wavelength (for example: 550 nm). Whether the LC layer is switched horizontally or

TABLE 1. Summary of optical configurations for quarter-wave LC cells.

| Mode | | Horizontal Switching | | Vertical Switching | | Bistable Switching | |
|---|---|---|---|---|---|---|---|
| | | Dark | Bright | Dark | Bright | Dark | Bright |
| LC layer | Alignment | Homogeneous | | Homogeneous | Homeotropic | 180°-Twisted | |
| | O.A. (α) | ± 75° | ± 30° | ± 75° | - | ± 75° | - |
| | Twist | 0° | 0° | 0° | 0° | 0° | 360° |
| O.A. of λ /2 film (β) | | ± 15° | | | | | |
| Applicable mode | | IPS, FFS, FLCD, AFLCD, etc | | π-cell, VA cell, etc | | BTN LCD | |

vertically affects the reflection spectra in the bright state. In order to investigate the effect of the switching mode on the bright state in the proposed configuration, we plotted polarization paths on the Poincare sphere[10].

Path 1 in Fig. 4 shows the polarization path on the Poincare sphere of the bright state in a vertical-switching LC cell. P1 represents the transmission axis of the polarizer and P2 represents the optic axis of the half-wave film. The bright state is determined only by the half-wave film aligned along an angle of 15°, since the polarization is not changed by a vertically-aligned LC layer. The polarization of the incident light will rotate along the path 1 during the double pass through the cell. Then, the output polarization at a single design wavelength (generally 550 nm) is in parallel with the transmission axis of the polarizer precisely. Then, on the Poincare sphere, the output light is located at the same point as the input light. In the figure, '◇'represents the polarization at a longer wavelength and '◆' represents the polarization at a shorter wavelength. As shown in Fig. 4, phase dispersion is small because the locus of the path 1 is relatively short. It will result in a relatively high reflectance.

Figure 5 shows the polarization path on the Poincare sphere of the bright state in a horizontal-switching LC cell. P2 represents the optic axis of the half-wave film and P3 represents that of the quarter-wave LC layer. The solid line on the path 1 shows the phase dispersion when the incident light propagates through the half-wave film. Then, by the double pass through the quarter-wave LC layer, the polarization is rotated by 180° through a circle centered at a point P3. Therefore, polarization positions at longer wavelengths and shorter wavelengths will be exchanged, as shown in Fig. 5. Path 3 is the rotation path at a

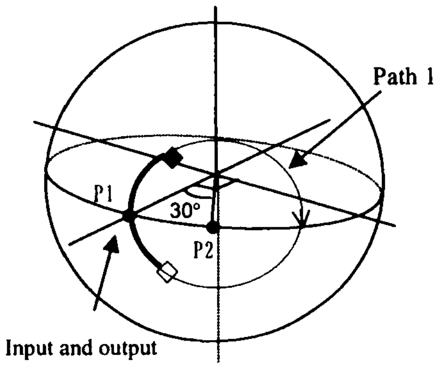


FIGURE 4. Poincare sphere representation of the polarization path for the bright state in a vertical-switching cell.

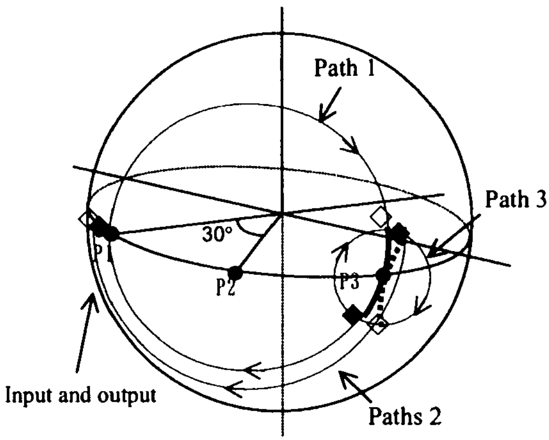


FIGURE 5. Poincare sphere representation of the polarization path for the bright state in a horizontal-switching cell.

longer or shorter wavelength. The thick dotted line in Fig. 5 shows rotated polarization distribution. Finally, by passing through the half-wave film again, the polarization of the reflected light will rotate along the paths 2. Here, polarization dispersion of the output light is decreased significantly as shown in Fig. 5 because the polarization path difference between the longer wavelength and the shorter wavelength is compensated by 180° polarization rotation due to the quarter-wave LC layer. As a result, this optical configuration in the bright state plays the role of a wide-band wave retarder, so that we can expect very high reflectance.

We calculated their reflection spectra in the bright state by using the 2×2 Jones matrix method. Figure 6 shows the calculated reflectance in the bright state of the proposed 2-kinds of optical configurations compared with other optimized single-polarizer reflective LCDs. The solid line represents reflection spectra in the bright state of a horizontally-switched cell. The dashed line represents reflection spectra of a vertically-switched cell. The dash-dotted line represents the reflection spectra of the bright state in a TN cell (twist angle: 80°, $d\Delta n$: 0.26 μm, angle of the input director: 18°) with a wide-band λ/4 film[11] and the dotted line represents that in a non-twist λ/4 cell with a wide-band λ/4 film, respectively. Figure 6 shows us that the proposed configuration could provide the same level of brightness and display color in the bright state as other modes that use a wide-band film. Especially, a horizontal-switching cell provides the highest reflectance.

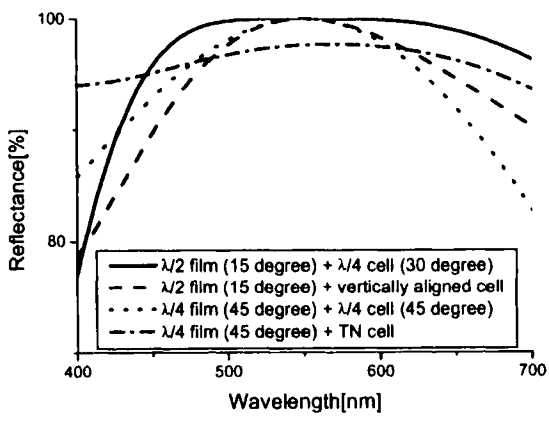


FIGURE 6. Calculated reflection spectra of the bright states in single polarizer reflective LCD modes.

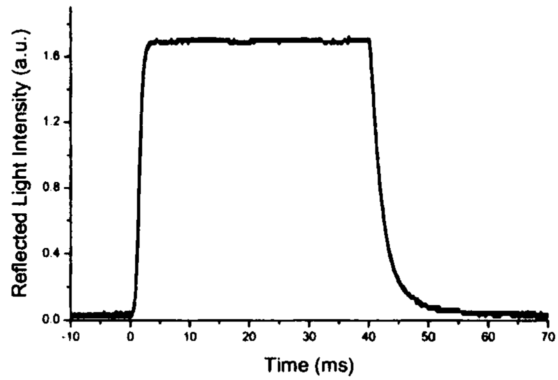


FIGURE 7. Measured optical switching characteristics of a quarter-wave homogeneous LC cell.

## 6. EXPERIMENTAL RESULTS

In order to check the feasibility of the proposed configuration, we fabricated a quarter-wave homogeneous LC(ZLI-4119 from Merck). cell with the cell gap d = 2.28 μm. Figure 7 shows the measured optical switching characteristics of a fabricated LC cell when a 5-volt rectangular pulse is applied to the cell. We achieved very high contrast ratio of 50:1 and response time (= rise time + fall time) of 12 ms. By fabricating many kinds of single-polarizer reflective cells proposed in previous works, we found that the proposed configuration provides the highest contrast ratio.

## 7. CONCLUSION

We proposed an optical configuration for a high-contrast reflective liquid crystal display, which provides a bright display with the high contrast ratio of 50:1 without using a wide-band film. Especially, we can achieve the highest brightness in a horizontal-switching cell.

Acknowledgements

This work was supported by the University Research Program of Ministry of Information and Communication.

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