# New method of designing LCD with optimal optical properties

*S. T. Tang and H. S. Kwok*
**Centre for Display Research, Hong Kong University of Science and Technology, Clear Water Bay, HONG KONG**

## Abstract

**Mueller calculus is employed to find the conditions that govern linear polarization preservation and the linear to circular polarization transformation in a general twisted nematic LC cell. The results are applied to the design of both transmittive and reflective twisted nematic LCDs. New optimized optical modes are reported. This method provides a clear physical interpretation of all LCD modes.**

## Introduction

We have previously introduced the 2D-parameter space for the optical design of general twisted nematic LCDs based on the 2x2 Jones matrix[1]. Here we introduce another approach based on the 4x4 Mueller matrix for optimizing the optical properties of LCDs. This method has the advantage that polarization change of the light after passing through the twisted nematic layer can be seen very clearly. A parameter space can be generated which shows the relationship between all LCD modes, published and unpublished. We applied this new parameter space to the design of optical display modes including HTN, STN, RTN and RSTN etc. It is discovered that many of the announced display modes are indeed not optimized and can be further improved.

## Theory

The Mueller matrix representation of a generally twisted nematic layer[2] can be written as

$$M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & A & B & C \\ 0 & D & E & F \\ 0 & G & H & K \end{pmatrix}$$

where the matrix elements have been given before[2]. For any linearly polarized light input, the output Stokes vector is given by

$$S = \begin{pmatrix} 1 \\ A\cos 2\alpha + B\sin 2\alpha \\ D\cos 2\alpha + E\sin 2\alpha \\ G\cos 2\alpha + H\sin 2\alpha \end{pmatrix}$$

where $\alpha$ is the input polarizer angle. S is in general elliptically polarized. Under special conditions, S will be linearly or circularly polarized. These are the conditions for optimal transmittive or reflective displays.

### 1. Linear polarization output (LP)

A linearly polarized output requires that $S_3 = G\cos 2\alpha + H\sin 2\alpha = 0$. There are two solutions.

<u>*Solution I (LP1):*</u>

$$\delta^2 + \phi^2 = (N\pi)^2 \qquad \text{and} \qquad \gamma = \phi + \alpha \quad (1)$$

where $\delta$ is the retardation of the LC cell, $\phi$ is the twist angle, N is an integer and $\gamma$ is the corresponding output polarization angle.

<u>*Solution II (LP2):*</u>

$$\frac{\phi}{\sqrt{\delta^2+\phi^2}}\tan\sqrt{\delta^2+\phi^2} = \tan 2\alpha$$

and

$$\gamma = \phi - \alpha \qquad (2)$$

ISSN0099-0966X/99/3001-0180-$1.00 + .00 (c) 1999 SID

## 2. Circular polarization output (CP)

In order to have a circular polarized light output, we have $S_1 = S_2 = 0$ and $S_3 = \pm 1$. Since M is unitary, thus $S_3 = \pm 1$ implies that K = 0 and $\tan 2\alpha = H / G$. This leads to the solutions for the twist angle and retardation of the cell to be:

$$\frac{\delta^2}{\delta^2+\phi^2}\sin^2\sqrt{\phi^2+\delta^2}=\frac{1}{2} \qquad \text{and}$$

$$\tan 2\alpha = \frac{-\sqrt{\delta^2+\phi^2}}{\phi}\cot\sqrt{\delta^2+\phi^2} \qquad (3)$$

## Applications to LCD optical mode design

Figure 1 shows the new parameter space showing the locus of LP1, LP2 and CP solutions. These lines represent all the possible operating modes of the twisted nematic LCD. In general, transmittive displays involve linear polarization preservation modes (LP1 and LP2) and single polarizer reflective displays involve linear to circular polarization transformation modes (CP).

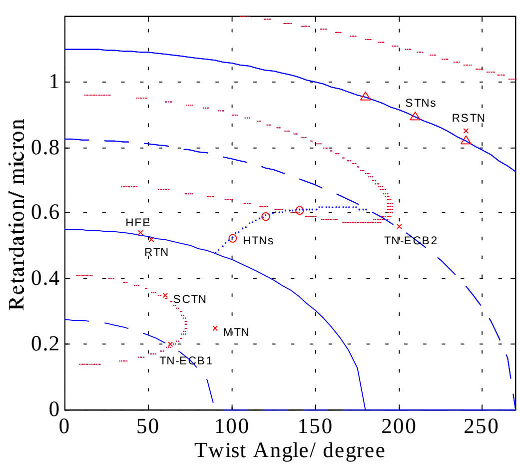


**Figure 1.** _ solid lines represent the LP1 solutions; -- dash lines represent the LP2 solutions when $\alpha = 45^o$; …dotted curves are the CP solutions. It can be seen that all transmittive or reflective general twisted nematic modes lie on one of these curves. Triangles ($\Delta$) are STNs and circles (o) are HTNs.

## 1. Transmittive displays

*Case I. LP1 to LP2 switching*

Assuming that the non-select state is a LP1 state and the select state is a LP2 state. Thus we have $\gamma^{ns} = \phi + \alpha$ and $\gamma^{s} = \phi - \alpha$. Since the polarizers should be perpendicular to each other in order to have a maximum contrast, we therefore have $\alpha = \pm 45^o$. This is actually typical for STN displays. The $d\Delta n$ values calculated according to equation (1) with $\lambda = 0.55$ µm are:

| Twist Angle | $180^o$ | $210^o$ | $240^o$ |
|---|---|---|---|
| Retardation / µm | 0.953 | 0.893 | 0.820 |

*Case II. LP2 to homeotropic switching*

A non-select LP2 state gives $\gamma^{ns} = \phi - \alpha$, and a selected homeotropic state requires $\gamma^{s} = \alpha \pm 90^o$. Thus we have $\alpha = ( \phi \pm 90^o ) / 2$. Typical examples are HTN displays,

| Twist Angle | $100^o$ | $120^o$ | $140^o$ |
|---|---|---|---|
| Input Polarizer Angle | $5^o$ | $15^o$ | $25^o$ |
| Retardation / µm | 0.527 | 0.591 | 0.612 |

Retardation values are calculated by using equation (2) with $\lambda = 0.55$µm. TN display is seen as a special case with $\phi = 90^o$ and $\alpha = 0^o$.

## 2. Reflective Displays

*Case I. CP to homeotropic switching*

These are normally dark modes. The TN-ECB[3] modes are typical examples with $\alpha = 0^o$. The MTN[4] mode is not exact, the SCTN[5] is exact, however other optimized modes can also be found nearby. Below is a table of design parameters for comparison. Upper row shows the original parameters and the lower row shows the optimized parameters. (See also figure 2 and 3.)

| MTN | | | SCTN | | |
|---|---|---|---|---|---|
| $d\Delta n$/µm | $\phi$ | $\alpha$ | $d\Delta n$/µm | $\phi$ | $\alpha$ |
| 0.25 | $90^o$ | $20^o$ | 0.35 | $60^o$ | $30^o$ |
| ***0.26*** | ***$72^o$*** | ***$15.6^o$*** | ***0.30*** | ***$70^o$*** | ***$22.8^o$*** |

ISSN0099-0966X/99/3001-0180-$1.00 + .00 (c) 1999 SID

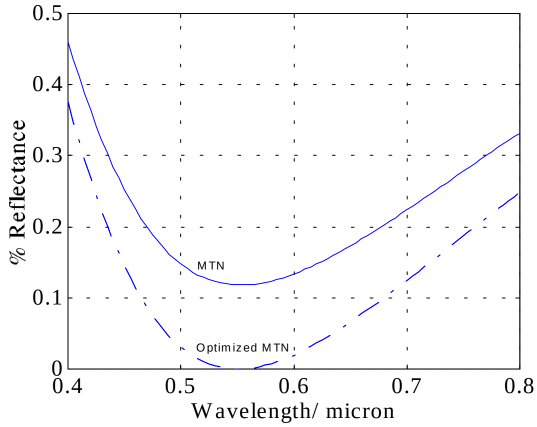


**Figure 2.** _ solid line is the original MTN reflectance Vs wavelength curve; -.- dashed line is the optimized mode using the present calculations.

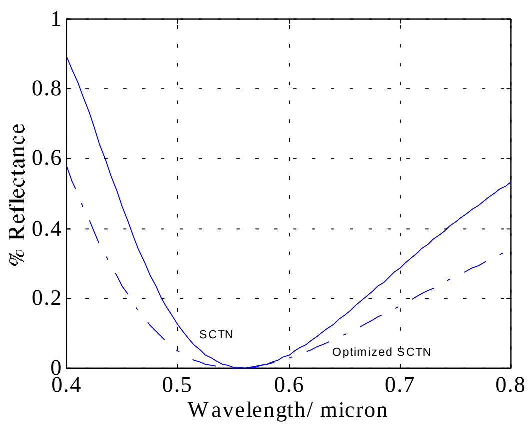


**Figure 3.** _ solid line is the original SCTN reflectance vs wavelength curve; -.- dashed line is the optimized one using the present calculations.

*Case II. LP1 to CP switching*

These are normally white modes. Examples are the HFE[6], RTN[7] and RSTN[8] displays. The normal states are fairly close to LP1 modes. An optimized version is listed below. Upper row shows the original parameters and the lower row shows the optimized parameters.

| HFE | | RTN | | RSTN | |
|---|---|---|---|---|---|
| dΔn/μm | φ | dΔn/μm | φ | dΔn/μm | φ |
| 0.54 | $45^o$ | 0.52 | $52^o$ | 0.85 | 240 |
| ***0.533*** | ***45°*** | ***0.527*** | ***52°*** | ***0.82*** | ***240*** |

## Conclusions

We have successfully derived the required conditions for linear polarization preservation and linear to circular polarization transformation of a twisted nematic layer by using the Mueller matrix. This method is straightforward with amenable to clear physical interpretations. It can serve as a guideline for all general twisted nematic displays design. When combined with the 2x2 Jones matrix generated parameter space, all LCD modes can be displayed congenially. Improved designs of some published reflective LCDs are also given to demonstrate the power of this method.

## References

[1] H.S. Kwok, J. Appl. Phys., 80 (7), 1 Oct 1996, p3687-3693.

[2] S.T.Tang and H.S.Kwok, SID '98 Digest p552-555.

[3] T. Sonehara and O. Okumura, Japan display '89 p192-195.

[4] S.T. Wu and C.S Wu, Appl. Phys. Lett. 68 (11), 11 March 1996, p1455-1457.

[5] K.H. Yang, Euro-display '96, p449.

[6] A. R. Kmetz, Proc. SID 21, 63 (1980).

[7] F.H. Yu, J. Chen, S.T. Tang and H.S. Kwok, J. Appl. Phys. 82 (11), 1 Dec 1997, P5287-5294

[8] J. Chen, F.H. Yu, H.C. Huang and H.S. Kwok, Jpn. J. Appl. Phys. Vol. 37 (1998) Pt.1, No.1, p217-223.

ISSN0099-0966X/99/3001-0180-$1.00 + .00 (c) 1999 SID