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Characterization of edge effects in twisted nematic liquid crystal displays

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Abstract. We present a model to more accurately describe the optical properties of a twisted nematic liquid crystal display (LCD). In particular, we study the optical properties of molecules near either edge of the LCD that are unable to twist and tilt under the application of an external electric field. The properties of these layers can be deduced from the intensity transmittances measured using different configurations of the external linear polarizers. The agreement between the theoretical and the experimental transmittances is excellent, thus enabling the prediction of the actual modulation for any configuration of the polarizers. © *2000 Society of Photo-Optical Instrumentation Engineers.* [S0091-3286(00)01412-4]

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1 Introduction

Twisted nematic liquid crystal displays (LCDs) are electro-optic devices used as display elements in videoprojectors. During the last 15 yrs they have been widely used as spatial light modulators (SLMs) for image processors, optical correlators,[1,2] and programmable optical elements.

These devices usually produce a coupled amplitude and phase modulation of transmitted light as a function of applied voltage.[3] However, different applications require different operating characteristics for optimum performance. Phase-only modulation is usually most desirable when displaying diffractive optical elements. To display input images in an optical image processing setup, however, an amplitude-only modulation is better. In optical pattern recognition, the performance of the correlator depends on the type of encoding used in the matched spatial filter. This encoding also depends on the modulation capabilities[4] of the LCD. A study of the optimal operating curve for an SLM was carried out by Juday et al.[5] The operating curve of the SLM can be modified by changing the optical elements on either side of the LCD. For example, phase-only operation can be obtained by generating and detecting elliptically polarized eigenvectors of the display.[6] For these applications, however, the LCD parameters must be measured as a function of applied voltage.

It would be extremely useful to develop a model whereby the amplitude and phase properties of the LCD can be accurately predicted as a function of applied voltage. Two parameters govern the modulation produced by the display: the twist angle and the birefringence of the liquid crystal. When a voltage is applied to the LCD, the liquid crystal molecules tilt toward the electric field direction and cause both amplitude and phase modulation.

Berreman proposed a physical model to describe the properties of the LCD molecules based on the physical properties of the material.[7,8] He showed from elastic theory that the twist angle is not a linear function of the depth in the LCD, and this dependence varies with the applied voltage. In addition, he showed that the tilt angle of the molecules is not constant, and consequently the birefringence is not a constant along the transmission axis of the LCD.

Taber et al.[9] studied the transmittance of a liquid crystal light valve (LCLV). They used Jones matrices by considering the LCLV as a stack of uniaxial birefringent layers, but used analytical models for the variations of the twist angle and birefringence described by Berreman. The transmittance is obtained by numerical integration assuming a two-parameter fit. However, these parameters are difficult to measure experimentally and it is difficult to predict the transmittance for any configuration of the polarizers.

Lu and Saleh presented another approach based on the Jones matrix formalism for polarization devices.[10] They regarded the LCD as a stack of uniaxial birefringent layers, each one slightly twisted with respect to the previous one. When a voltage is applied to the LCD, the effective birefringence changes because of the tilt of the liquid crystal (LC) molecules. In their model, two assumptions were used to obtain an analytical Jones matrix: (1) the twist angle is a linear function of the depth of LC layers and (2) the effective birefringence is constant for every layer. When a voltage is applied to the LCD these two assumptions may fail because the LC molecules located close to the surfaces of the display cannot tilt the same way those in the center do. Hence, the model of Lu and Saleh is only a good approximation of the display.

Coy et al.[11] proposed a better approximation to this nonlinear behavior of the twist angle and the effective birefringence. They regarded the LC layers that do not tilt as two fixed wave plates coated to the surfaces of the display. With this approximation, they could obtain better fits between the experimental modulation curves and the theoretical ones.

In this paper, we modify the model proposed by Coy et al. to more closely approximate the behavior of these parameters shown by Berreman. In our model, the thickness of the two fixed wave plates increases as the applied voltage increases. We show experimental techniques to measure the birefringence of the fixed wave plates and the effective birefringence of the LCD as a function of applied voltage. Using these measured values, we can predict the actual transmittance for any configuration of the input and output polarizers. We observe that the experimental results are in excellent agreement with the predictions.

In Sec. 2 we review the different models for the LCD based on the Jones matrix formalism. In Sec. 3 we discuss the procedure used to measure the birefringence as a function of the voltage for both the layers at the entrance and exit of the modulator [given by $\delta(V)$] and the bulk part of the LCD [given by $\beta(V)$]. The results obtained for the magnitudes of $\beta(V)$ and $\delta(V)$ are presented in Sec. 4. We discuss the sizes of the birefringence and the layer birefringence. With these measurements, we show in Sec. 5 that the transmittance of the LCD can be predicted for another configuration of the polarizers. In all cases, the proposed model gives excellent agreement with experimental measurements.

2 Jones Matrix Theory

Lu and Saleh[10] introduced a Jones matrix for a twisted LCD as the product of a rotation matrix and a LC matrix as

$$\mathbf{M}_{\mathrm{LCD}}(\alpha,\beta)=\exp(-i\beta)\mathbf{R}(-\alpha)\mathbf{M}(\alpha,\beta). \tag{1}$$

Here $\mathbf{R}(\theta)$ is the 2×2 rotation matrix given by

$$\mathbf{R}(\theta)=\begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix}, \tag{2}$$

and the matrix $\mathbf{M}(\alpha,\beta)$ is given by

$$\mathbf{M}(\alpha,\beta)=\begin{bmatrix}X-iY & Z\\ -Z & X+iY\end{bmatrix}. \tag{3}$$

Here $X=\cos(\gamma)$, $Y=\beta\sin(\gamma)/\gamma$, $Z=\alpha\sin(\gamma)/\gamma$, and $\gamma^2=\alpha^2+\beta^2$. The birefringence is defined as $\beta=\pi d\Delta n/\lambda$, where d is the thickness of the display, λ is the incident wavelength, Δn is the difference between the extraordinary (n_e) and the ordinary (n_o) indices of refraction for the LC molecules, and α is the twist angle of the molecules. Under an applied voltage, the LC molecules tilt toward the direction of the propagation and the effective birefringence of the LC changes. They defined a new parameter $\beta(V)$ given by $\beta(V)=\pi d\Delta n(V)/\lambda$, where now $\Delta n(V)$ decreases as the applied voltage increases. Consequently, the same matrix $\mathbf{M}_{\mathrm{LCD}}$ given in Eq. (1) describes the LCD simply by replacing β with $\beta(V)$. We define β_{off} as the value $\beta(V)$ for the off state when $V=0$.

In general, the LC director at the input surface is not oriented parallel to the laboratory frame and the matrix $\mathbf{M}_{\mathrm{LCD}}$ must be transformed by a rotation. Consequently, three parameters are of interest to determine the Jones matrix of the LCD: the twist angle (α), the birefringence for the off state (β_{off}), and the orientation of the director at the input surface of the display (ψ_D). In previous work, Soutar and Lu[12] and Davis et al.[13] measured these parameters using a method based on the simultaneous rotation of input and output polarizers when they are either parallel or perpendicular.

As mentioned before, when a voltage is applied to the LCD, the twist and tilt angles are affected and the assumptions of the Lu and Saleh model may fail. Coy et al.[11] modified the LCD model by assuming the LC molecules close to the surfaces do not tilt. Consequently these molecules act as two wave plates coated to these surfaces. Each wave plate has its extraordinary axis oriented parallel to the LC director on the corresponding surface. Using this model, the matrix $\mathbf{M}'_{\mathrm{LCD}}$ represents the Jones matrix for the LCD and is given by the next matrix product

$$\mathbf{M}'_{\mathrm{LCD}}(\alpha,\beta,\delta)=[\mathbf{R}(-\alpha)\cdot\mathbf{W}_0(2\delta)\cdot\mathbf{R}(+\alpha)]\cdot\mathbf{M}_{\mathrm{LCD}}(\alpha,\beta)\cdot\mathbf{W}_0(2\delta). \tag{4}$$

Here, the matrix $\mathbf{M}_{\mathrm{LCD}}$ is the same matrix of Eq. (1) and $W_0(2\delta)$ is the Jones matrix for a wave plate that introduces a total phase shift 2δ and is written as

$$\mathbf{W}_0(2\delta)=\begin{bmatrix}\exp(-i\delta) & 0\\ 0 & \exp(i\delta)\end{bmatrix}. \tag{5}$$

As discussed, our model assumes that the thickness of the two wave plates changes with voltage. Consequently the phase shift for the wave plate varies with voltage as $\delta(V)$ and is equal to 0 when the device is in the off state. The parameter $\delta(V)$ is defined as $\delta(V)=\pi d(V)\Delta n/\lambda$, where $d(V)$ is the voltage-dependent thickness of each of the two wave plates coated to the surfaces of the SLM and

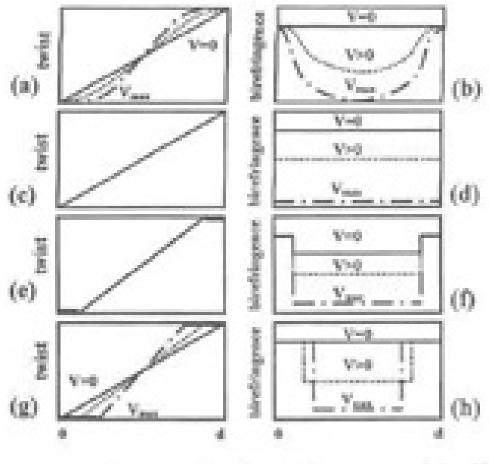

Fig. 1 Sketch of the behavior of the twist angle and the birefringence as a function of the depth in the modulator: (a) and (b) Berreman model, (c) and (d) Lu and Saleh model, (e) and (f) Coy et al. model, and (g) and (h) our model.

Δn and λ have been defined earlier. The total birefringence β_{tot} of the SLM is divided into three parts as $\beta(V)_{\text{tot}} = \delta(V) + \beta(V) + \delta(V)$.

The matrix $\mathbf{M}'_{\text{LCD}}(\alpha,\beta,\delta)$ in Eq. (4) can be simplified as

$$\mathbf{M}'_{\text{LCD}}(\alpha,\beta,\delta) = \exp[-i(\beta+2\delta)]\mathbf{R}(-\alpha) \cdot \begin{bmatrix} X'-iY' & Z \\ -Z & X'+iY' \end{bmatrix}, \tag{6}$$

where we define new parameters X' and Y' as

$$X' = X\cos 2\delta - Y\sin 2\delta, \tag{7a}$$

$$Y' = X\sin 2\delta + Y\cos 2\delta. \tag{7b}$$

Note that the parameter Z is independent of the wave plate phase shift while both X' and Y' are modified.

Next we compare and contrast the various models. Figures 1(a) and 1(b) show the twist and tilt of the LC molecules as a function of position from the input surface ($z=0$) to the output surface ($z=d$) according to the original model by Berreman for different voltages. The Lu and Saleh model assumed a simplified model where the twist angle remains a linear function of z while the tilt angle decreases as a function of applied voltage as shown in Figs. 1(c) and 1(d). Coy et al. proposed a more realistic approximation by adding two layers onto each surface where the molecules do not tilt. Each layer is oriented with its extraordinary axis parallel to the LC director at the respective surface. The region between these two plates is treated exactly as in the Lu and Saleh model, as shown in Figs. 1(e) and 1(f). In this paper, we modify this model a step further by assuming that the widths (and hence the birefringences) of these layers increase as the applied voltage increases, as shown in Figs. 1(g) and 1(h). Consequently we divide the LC layer into two wave plate layers, each having a birefringence of $\delta(V)$, and a central twisted region having a twist of α and a birefringence of $\beta(V)$.

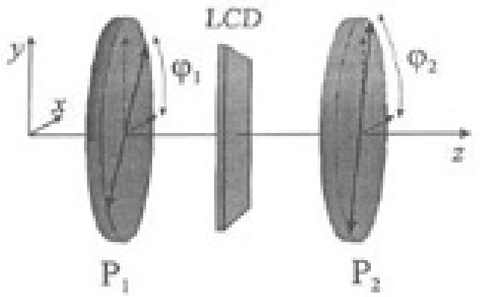

Fig. 2 LCD inserted between input (P_1) and output (P_2) polarizers: φ_1 and φ_2 are the angles for the transmission axes of P_1 and P_2, respectively, with the x laboratory axis, which is selected parallel to the orientation of the LC director.

Therefore, we have two voltage dependent parameters $\beta(V)$ and $\delta(V)$. We first describe an experimental technique for measuring these two parameters as a function of applied voltage. We then show that we can characterize the SLM and predict its behavior for other configurations of the polarizers.

3 Procedures for Measuring $\beta(V)$ and $\delta(V)$

To measure the voltage-dependent parameters $\beta(V)$ and $\delta(V)$, we place the LCD between two linear polarizers, with angles φ_1 and φ_2 with respect to the LCD director at the input surface of the LCD (Fig. 2).

The normalized transmission of the system can be calculated using the Jones matrix that describes the display, resulting in

$$T = [X'\cos(\varphi_1-\varphi_2+\alpha) + Z\sin(\varphi_1-\varphi_2+\alpha)]^2 + [Y'\cos(\varphi_1+\varphi_2-\alpha)]^2. \tag{8}$$

We use previously discussed techniques[12–14] to measure the orientation of the director axis angle at the entrance face Ψ_D, the twist angle α, and the value of the birefringence when the LC cell is in the off state, β_{off}.

In Table 1 we show experimental results obtained from a Sony LCX012BL twisted nematic LCD extracted from a Sony videoprojector model VPL-V500. To eliminate ambiguities in these values, experimental measurements were made with four different wavelengths (633 nm from an He-Ne laser, and 514, 488, and 458 nm from an Ar laser). We note that the birefringence increases as the wavelength decreases. These experimental techniques have been well documented and are not repeated.

Table 1 Physical parameters values for the LCD.

Twist angle (deg)	−92
Director axis angle (deg)	+46
β_{off} (633 nm)	141
β_{off} (514 nm)	185
β_{off} (488 nm)	199
β_{off} (458 nm)	220

To find the values of $\beta(V)$ and $\delta(V)$, we use three different experimental configurations to obtain experimental transmission curves that will be fitted using Eq. (8). The first configuration is equivalent to the one proposed by Zhisheng et al.[15] The input linearly polarized light is oriented parallel to the director axis at the input surface and the output polarizer selects the component parallel to the director at the output surface. Consequently, the polarizers are set at the configurations ($\varphi_1=0$, $\varphi_2=\alpha$). To have normalized values of intensity transmission, the complementary configuration is also measured, i.e., ($\varphi_1=0$, $\varphi_2=\alpha+90$). For this last configuration, the normalized intensity transmission is given by

$$T_{(0,\alpha+90)}=Z^2=\frac{\alpha^2}{\gamma^2}\sin^2\gamma. \tag{9}$$

In analyzing the data, we divide the data for one configuration by the sum of the data for the two configurations. This enabled us to eliminate intensity fluctuations due to interference and diffractive effects.[16]

Note that the transmission for this orientation is insensitive to the layers that do not tilt [the value of $\delta(V)$ does not affect the transmission]. Consequently, this equation can be used to fit the values of $\beta(V)$. However, the accuracy of this technique decreases when the argument of the sinc function increases.

The second configuration we select is ($\varphi_1=+45$, $\varphi_2=\alpha+45$) and its complementary ($\varphi_1=+45$, $\varphi_2=\alpha-45$). Applying Eq. (8) to the configuration ($\varphi_1=45$, $\varphi_2=\alpha-45$), the normalized intensity transmitted by the system is given by

$$\begin{aligned}T_{(45,\alpha-45)}&=1-X'^2\\&=1-\left(\cos\gamma\cos 2\delta-\frac{\beta}{\gamma}\sin\gamma\sin 2\delta\right)^2.\end{aligned} \tag{10}$$

This configuration has two advantages compared with the ($\varphi_1=0$, $\varphi_2=\alpha+90$) configuration. First this configuration is more sensitive to the values of $\beta(V)$ than the previous case. In addition, it is strongly affected by the wave plate $\delta(V)$, enabling the measurement of this parameter.

We can obtain greater experimental accuracy by using additional configurations. In particular, we have chosen a third configuration as ($\varphi_1=+22.5$, $\varphi_2=\alpha+22.5$) and its complementary ($\varphi_1=+22.5$, $\varphi_2=\alpha+112.5$). For this latter experimental configuration, the normalized intensity transmitted by the system is given by

$$T_{(22.5,\alpha+112.5)}=Z^2+Y'^2/2. \tag{11}$$

For maximum accuracy, we made measurements for these three experimental configurations at the same four wavelengths, as discussed. In our fit of the experimental data, we look for the set of values of $\beta(V)$ and $\delta(V)$ that minimize the square of the difference between the experimental data and the theoretically calculated values. In addition, we used the wavelength dependence of the off-state birefringence to scale the values of $\beta(V)$ and $\delta(V)$ for the different wavelengths. We found that this technique produced the best results compared with other schemes where we tried separately fitting each of the intensity curves for different wavelengths.

To use this normalization, we used the values of β_{off} for the different wavelengths (in Table 1) to obtain normalization ratios for both $\beta(V)$ and $\delta(V)$ as function of voltage for the different wavelengths. To obtain these normalization ratios, we have measured β_{off} at the different wavelengths for 9 Sony displays. Our experimental ratios for the 9 SLMs are 1.3, 1.4, and 1.56, respectively, for the 514-, 488-, and 458-nm wavelengths compared with the 633-nm wavelength.

Once these ratios are determined, we used Solver module of the Microsoft-Excel program to obtain the best values for $\beta(V)$ and $\delta(V)$ as function of voltage for the different wavelengths. The Solver module contains an algorithm that, by use of an iterative procedure, assigns values to β and δ in the theoretical expression until the calculated theoretical value converges to the experimental value.

4 Experimental Results for the Values of $\beta(V)$ and $\delta(V)$

All the experiments were conducted with the brightness and contrast controls of the videoprojector at 50 and 100, respectively. The maximum value of these controls is 100. We have measured the intensity at intervals of every 10 gray levels. The gray level we send to the display is a magnitude that is related with the voltage. For the Sony VPL-V500 videoprojector electronics, the voltage decreases monotonically when the gray level increases.

In Fig. 3, we show the experimental data obtained for the Sony LCD with the three configurations and for the four wavelengths. The horizontal axis shows the gray level that is sent to the display. The last data point corresponds to the measurement made with the LCD in the off state ($V=0$).

In Fig. 3(a) the experimental data are shown for the ($\varphi_1=0$, $\varphi_2=\alpha+90$) configuration. As stated before, this data is insensitive to the existence of the border effect and shows the characteristic sinc behavior. In Figs. 3(b) and 3(c), we show the measurements for the ($\varphi_1=45$, $\varphi_2=\alpha-45$) and the ($\varphi_1=22.5$, $\varphi_2=\alpha+112.5$) configurations, respectively. The effects of the border layers are evident in Fig. 3(b). If $\delta=0$, then Eq. (10) would revert to a simple $\sin^2$ behavior. However, the border layer affects the minimum near a gray level of 200.

As stated, we used the Solver routine to simultaneously fit the data for the three configurations and the four wavelengths. The experimental values for $\beta(V)$ are shown for the four wavelengths in Fig. 4(a). In each case, the values increase monotonically with gray level. For a gray level of zero, the birefringence is zero and indicates that the LC molecules are tilted at 90 deg. The birefringence saturates for gray levels above 230. This indicates that the molecules are not tilted and exhibit the maximum birefringence. As expected, the values of $\beta(V)$ also increase as the wavelength decreases at a given gray level.

The experimental values of $\delta(V)$ are shown in Fig. 4(b). At lower voltage levels (higher gray levels) δ is nearly zero for the off state point and increases to a maximum of about

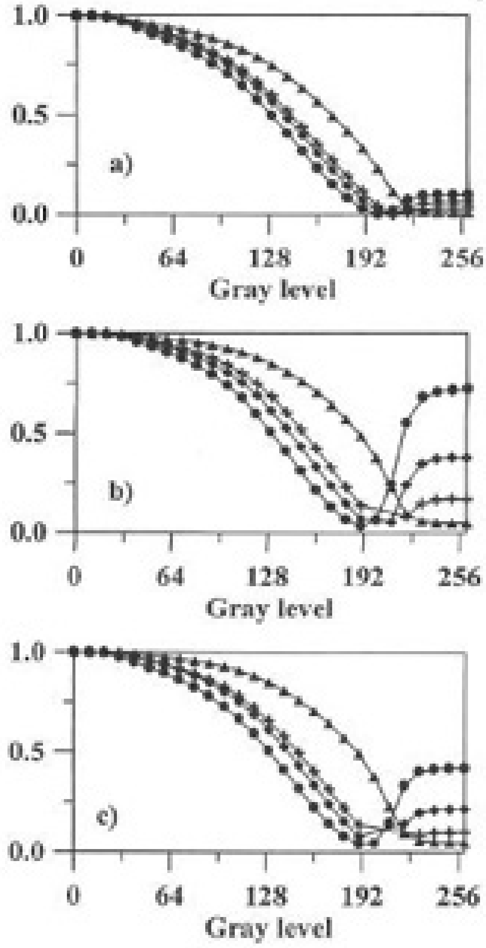

Fig. 3 Intensity transmittance versus the gray level for different configurations of the polarizers (a) 0, $\alpha+90$; (b) 45, $\alpha-45$; (c) 22.5, $\alpha+112.5$, and different wavelengths (▲) 633 nm, (+) 514 nm, (♦) 488 nm, and (●) 458 nm.

20 deg for the shortest wavelength. Similar results were found for other Sony LCDs.

5 Prediction of Modulation Curves

A complete knowledge of $\beta(V)$ and $\delta(V)$ enables the prediction of the transmission curves using any other experimental configuration. In particular, we show the theoretical curve versus the experimental data measured for a different configuration as ($\varphi_1=0$, $\varphi_2=\alpha+45$). Figure 5 shows the results for the Sony display at the 458-nm wavelength [where the values for $\beta(V)$ and $\delta(V)$ are greatest]. The experimental data are shown as the diamonds. The three lines show theoretical curves using the various models. The Lu and Saleh model shows the poorest agreement. In the case of the Coy et al. model, the best fit to the experimental data was obtained using a constant value $\delta=12.9$ deg. The agreement is improved, but is still not very good. Clearly, the prediction made by our generalized model is indistinguishable from the experimental data.

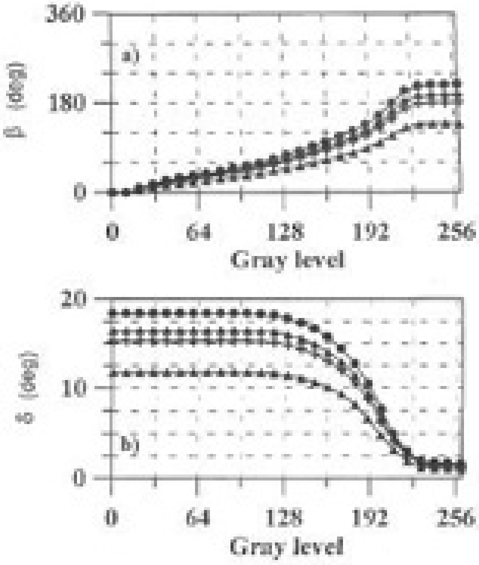

Fig. 4 Measured parameters as a function of voltage for different wavelengths: (▲) 633, (+) 514, (♦) 488, and (●) 458 nm for (a) values of $\beta(V)$ and (b) values of $\delta(V)$.

6 Conclusions

We developed a generalized model to predict the optical performance of twisted nematic LCDs. Our model includes the molecules near either edge of the LCD that are unable to twist and tilt under application of an external electric field. We show a technique to experimentally measure the birefringence and the retardation of the border molecules as functions of voltage. Once we know these values as a function of voltage, we can predict the modulation curve for any experimental configuration of the polarizers. Experimental results show excellent agreement with the model.

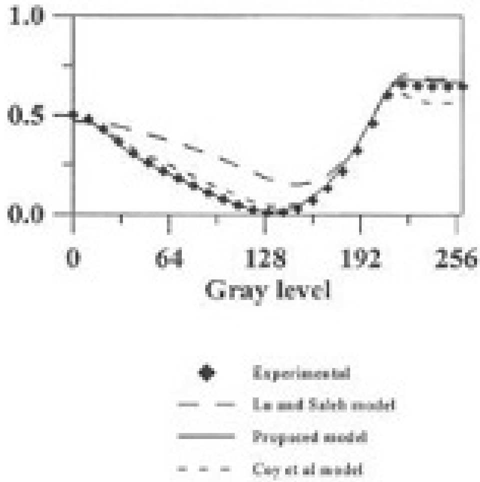

Fig. 5 Comparison between experimental transmission values (♦) for the configuration (0, $\alpha+45$) with the different models for a wavelength of 458 nm.

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May 3, 2001

Dr. Juan Campos
Univ. Autonoma de Barcelona
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E-08193 Bellaterra
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RE: OE 200314 **Revised**, "Quantitative prediction of the modulation behavior of twisted nematic liquid crystal displays based on a simple physical model"

Dear Dr. Campos,

I am pleased to accept your revised manuscript for publication in *Optical Engineering*.

Please direct any future correspondence to the Managing Editor at SPIE in Bellingham, WA. The Managing Editor will contact you once your paper has been assigned to an issue for publication.

If you have not already done so, please send a short biography and a photograph of each author to the Managing Editor. Also, if possible, please send an electronic version of your manuscript and figures. The text must be in MS Word, WordPerfect, LaTeX, or REVTeX, and the figures must be in Postscript, EPS, or TIFF to be usable for composition. Files may be sent on disk(s), as e-mail attachments, or via FTP.

Final manuscripts must be typed double-spaced on only one side of the page, and they must <u>not</u> be in two-column format. Figures should appear at the end of the manuscript, with one figure per page. A separate figure caption list should be included. If your final manuscript does not meet these requirements, please send a reformatted version to the Managing Editor as soon as possible so that publication will not be delayed.

Thank you for submitting your work to *Optical Engineering*.

Sincerely,

Don O'Shea

Donald C. O'Shea
Editor

cc: Chris Engebo, Managing Editor (chrise@spie.org)