Global characterization of nematic liquid crystal display Sony LCX038ARA with applied electric field in the modulation amplitude-coupled regime

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Abstract. In this work, we showed experimental and theoretical results of the characterization of a spatial light modulator based in a nematic liquid crystal display Sony model LCX038ARA with electric field excitation. The parameters: effective molecular twist and equivalent retardation are determinated using the retarder-rotor technique in the amplitude-coupled regime.

Keywords. SLM, LCD, Amplitude-coupled Regime of Modulation, Retarder-rotor Technique, Nematic phase SLM.

1. Introduction
One of the main applications of Liquid Crystal Display (LCD) devices is in Spatial Light Modulators (SLMs) [1-2]. Most SLMs are in nematic phase and are known as Twisted Nematic Liquid Crystal Displays (TN-LCDs). TN-LCDs produce amplitude-coupled modulation depending on the applied voltage [3].

To characterize the complete behavior of a TN-LCD is necessary to know the magnitude and sign of the manufacture parameters of the LCD with applied electric field between their pixelated electrodes, like the effective molecular twist and the equivalent retardation [4]. In this work, we show the experimental calibration of a transmission LCD Sony LCX038ARA for the previous cited parameters. Both parameters are found using the retarder-rotor technique. This technique is a combination of the Soutar-Lu method for a null voltage applied to LCD and their Stokes parameters [5-6]. In addition, we analyze the experimental results obtained previously for the molecular twist angle ($\varphi$), the angle of the molecular axis ($\Psi_D$), and birefringence ($\beta$) when a null voltage is applied [7].

2. Methodology
To calibration of a TN-LCD under applied voltage, we found the total twist angle ($\varphi$), the angle of molecular axis at the entrance face ($\Psi_D$), and the maximum birefringence ($\beta$), without applied voltage used the Soutar-Lu method [7]. The Soutar-Lu model uses the Jones matrix analysis when the TN-LCD is sandwiched between two polarizers with the purpose of find the parameters above mentioned it using the transmitted intensity curves for the crossed polarizers and parallel polarizers.
After finding these parameters, we proceed to characterize the TN-LCD by the retarder-rotor technique. This method considers that the TN-LCD behaves as a polarization system formed by a retarder followed by a rotor, through an applied voltage. The retardation effect is added on an arbitrary phase state \([8]\). Both \(\varphi_{eq}\) and \(\delta_{eq}\) in equation (1) take different values depending on the magnitude of the voltage applied to TN-LCD. External voltage on the TN-LCD is accomplished by transforming the gray levels to 0-255 scale potential differences through the photoelectric effect, for the case of an 8 bits converter. At each gray level \(g\) corresponds a voltage \(V\) and the relationship between the two values is usually linear \([5]\). \(\varphi_{eq}\) and \(\delta_{eq}\) are estimated using circularly polarized light. The LCD in terms of retardation and rotor is written as \([6,8]\):

\[
\mathbf{M}_{TN-LCD} = \exp(-i\beta)\mathbf{R}(\varphi_{eq})\mathbf{W}P\left(2\delta_{eq}, \frac{\varphi_{eq} + \delta_{eq}}{2}\right),
\]

where \(\beta\) and \(\varphi\) are the birefringence and molecular twist respectively, when the TN-LCD has a zero voltage applied. While \(\delta_{eq}\) is the equivalent retardation and \(\varphi_{eq}\) is the effective twist for each potential difference. Then, the electromagnetic wave at the output of the TN-LCD has a electric field amplitude \(E_{out}\) that can be written by the following equation \([6,8]\):

\[
E_{out} = \exp(-i\beta)\mathbf{R}(\varphi_{eq})\mathbf{W}P\left(2\delta_{eq}, \frac{\varphi_{eq} + \delta_{eq}}{2}\right)E_{in}.
\]

with \(E_{in}\), the incoming polarized electric field, typically circular polarized; \(\exp(-i\beta)\) is the inherent retardation of the birefringent material, \(\mathbf{R}(\varphi_{eq})\) is a rotor operator or twist and \(\mathbf{W}P(2\delta_{eq}, (\varphi_{eq} + \delta_{eq})/2)\) is the retardation operator that describes the state of polarization due to the external voltage applied. Cartesian components of the electric field \(E_{out}\) lead to find mathematical expressions for Stokes parameters of the light transmitted through the TN-LCD given by \([6,8]\):

\[
\begin{align*}
S_0 &= 1, \\
S_1 &= \sin(\varphi - \varphi_{eq}) \sin 2\delta_{eq}, \\
S_2 &= -\cos(\varphi - \varphi_{eq}) \sin 2\delta_{eq}, \\
S_3 &= \cos 2\delta_{eq}.
\end{align*}
\]

According to equation (6) we can infer that it is possible to find the equivalent retardation (\(\delta_{eq}\)) using the \(S_3\) parameter. While, the \(S_1/S_2\) ratio could lead to determine the equivalent twist (\(\varphi_{eq}\)), both when an external voltage is applied to the TN-LCD \([6,8]\):

\[
\begin{align*}
\delta_{eq} &= \frac{1}{2} \arccos(S_3) \\
\varphi_{eq} &= \varphi + \arctan\left(\frac{S_1}{S_2}\right).
\end{align*}
\]

3. Results

The table 1 shows the experimental results obtained for the total twist angle (\(\varphi\)), the angle of molecular axis at the entrance face (\(\Psi_D\)) and maximum birefringence (\(\beta\)) of the TN-LCD with null applied voltage.
Table 1. Measured parameters for the TN-LCD without applied voltage.

| Parameter                  | Value      |
|----------------------------|------------|
| Twist angle (ψ)           | +93.8°     |
| Angle of the molecular axis (Ψ_D) | -14.9°     |
| Birefringence (β)         | 2.126 rad  |

After finding the initial parameters of the TN-LCD, we proceed to find the experimental values of ϕ_eq and δ_eq using the schematic setup shown in Fig. 1. The light source is a He-Ne laser (L) model R30990 from Newport™ operating at 632.8 [nm] with 5 [mW] of power and random polarization. In order to eliminate high spatial frequencies like noise from the emerging light beam, we have used the objective (O) and pinhole (PH) to spatial filter the laser beam. Subsequently the emerged beam is collimated using the lens L1. The choice of lens L1 was made taking into account the selected spatial filter and searching a full illumination of the TN-LCD active area. The LCD is sandwiched between a polarizer (P) and an analyzer (A). Finally, the output beam converges at the image focal plane of lens L2 with the purpose to obtain efficient intensity measurements of the output beam using the power-meter (PM). Setup includes two quarter wave plates (QWP or λ/4). The first quarter wave plate (QWP1) is placed in front of TN-LCD to generate the required circular polarization state. While the second one (QWP2) is placed after the TN-LCD for S_3 measurement parameter (see equation 6). Thus ϕ_eq and δ_eq both are experimentally obtained from the Stokes parameters following a method analogous to described in previous section, for a series of 26 images of gray levels ranging from g = 0 to g = 255 in steps of 10 displayed on the TN-LCD [9].

Figure 1. Schema of Experimental setup for measuring ϕ_eq and δ_eq using circularly polarized light to illuminate the TN-LCD.

The left side of Fig. 2 shows the experimental results for S_1, S_2 and S_3 and for each gray level g applied to the TN-LCD model LCX038ARA. From the experimental curve shown on the left of Fig.2 and equations (7) and (8) are found the values of ϕ_eq and δ_eq. The right side of same figure shown the experimental values of ϕ_eq and δ_eq. In this figure we can see that the experimental values for effective twist shows abrupt jumps for the first seven measured gray levels. This behavior can be explained by the corresponding uncertainty of ϕ_eq, given by [10]:

$$\sigma_{\psi_{eq}} = \frac{1}{S_1^2 + S_2^2} \sqrt{S_2^2 \sigma_1^2 + S_1^2 \sigma_2^2}$$

(9)

where σ_1 and σ_2 are estimates uncertainties for S_1 and S_2 Stokes parameters. According to equation (9), the uncertainty of ϕ_eq will grow unlimited when S_1 and S_2 tend to zero or are very small, as seen for the first gray levels of experimental plot shown on the left side of the Fig. 2. For this reason, the accurate determination of ϕ_eq for the first gray levels requires another method. The value
of $\phi_{eq}$ for the first gray levels can be found if the TN-LCD is illuminated with linear polarized light in the direction of the horizontal axis of the crystal reference system itself, and consequently the corresponding normalized intensity is written as [6]:

$$T = \left(\frac{E_x}{E_y}\right)\left(\frac{E'_x}{E'_y}\right) = \cos^2\delta_{eq}\cos^2\left(\xi + \phi_{eq}\right) + \sin^2\delta_{eq}\cos^2\left(\xi - \phi_{eq}\right).$$  \tag{10}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image}
\caption{Experimental results for the Stokes parameters $S_1$, $S_2$ and $S_3$ with circular polarized light throughout of TN-LCD in terms of the gray level $g$ deployed (left side). Experimental results for the values $\phi_{eq}$ and $\delta_{eq}$ (right side).}
\end{figure}

where $\xi$ is the angle between the transmission axis of the analyzer and the molecular director axis in front of the TN-LCD. From equation (10) is possible to determine the value of $\phi_{eq}$ and $\delta_{eq}$ by a nonlinear fit of the experimental values of $T(\xi)$. The left side of Fig. 3 shows the experimental results for transmission TN-LCD at zero gray level together with the plot obtained for nonlinear fitting. From this curve we infer the value of effective twist and equivalent delay, given by $\phi_{eq} = 12.000^\circ$ and $\delta_{eq} = 16.036^\circ$, respectively. Following an analog procedure, we obtained the values of $\phi_{eq}$ and $\delta_{eq}$ for other six remaining gray levels.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image}
\caption{Experimental results (blue points) and nonlinear fitting (red curve) to find $\phi_{eq}$ and $\delta_{eq}$ at the zero gray level (left side). Adjusted experimental results for $\delta_{eq}$ and $\phi_{eq}$ versus gray level applied to TN-LCD (right side).}
\end{figure}

Finally, the right side of Fig. 3 shows the experimental data for equivalent retardation (blue plot) and effective twist (black plot) in function of gray level displayed onto TN-LCD (external applied...
voltage). From these data, we can see that the TN-LCD has a higher performance as rotor than as retarder, i.e. our TN-LCD Sony LCX038ARA has a tendency global to rotate the polarization state of the incident beam that it includes an additional phase value on the incident light.

4. Conclusions
The retarder-rotor technique combined with Stokes parameters could be used for characterize any TN-LCD when an external potential difference is applied. Parameters characterizing the equivalent system (δ_eq and φ_eq) for each gray level were experimentally measured. Both δ_eq as φ_eq are estimated from measurements of the Stokes parameters using incoming circularly polarized light to the TN-LCD. Comparing the obtained results of the transmitted light of the TN-LCD when a linear polarized wave and a circular polarized electromagnetic wave is used, we have found that the values for φ_eq and δ_eq are very similar. However, it is worth noting that the scheme of lighting the TN-LCD to find the effective twist and equivalent retardation when an external potential difference is applied is very tedious regarding the method of Stokes parameters.

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