Accurate color predictability based on a spectral retardance model of a twisted-nematic liquid-crystal display

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A B S T R A C T
In this work we present the application of a simple physical model to accurately predict the broadband spectral transmittance and colorimetric properties of a twisted-nematic liquid crystal display (TNLCD). We spectrally calibrate the retardance parameters to evaluate the spectrum of the light transmitted by a TNLCD sandwiched between two linear polarizers. When the TNLCD is illuminated with a broadband light source, the full spectrum can be predicted as a function of the addressed gray level for any arbitrary orientation of the polarizers. Thus, the color of the transmitted light can be also be estimated with very good accuracy. As an example, a polarizers’ configuration is shown that yields, without using color filters, a relatively large color gamut compared to the standard configuration. Experimental results confirming the validity of such predictions are presented, both on the measured spectral responses as well as on the trajectories at different chromatic diagrams.

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1. Introduction

Nowadays, liquid crystal displays (LCD) are relevant devices in many type of optical applications [1,2]. While their primary application continues to be as image-displaying elements, there are other areas like diffractive optics, polarization optics and adaptive optics, where the possibility to program optical elements onto the LCD opens a widespread number of applications. Therefore, the common twisted-nematic LCDs (TNLCDs) [3] play an important role as spatial light modulators (SLM) and have become the usual devices in research laboratories of those previously mentioned fields.

A proper operation of the TNLCD-SLMs requires a good knowledge of the physical parameters affecting the optical modulation, typically the orientation of the liquid crystal director and the birefringence of the material, i.e., the difference of the ordinary and extraordinary refractive indices. Since this information is not always available in commercial displays, a number of reverse engineering experiments have been proposed in the literature to measure such parameters, prior to selecting the appropriate polarization configuration [4]. In order to avoid ambiguities in the solution of the parameter’s values, these techniques involve measuring the transmission of the LCD in the off-state for various polarization configurations and for various wavelengths [5], or even taking spectral measurements [6–8]. The birefringence of the liquid crystal is wavelength dependent [9], therefore, the optical modulation response of LC displays has a strong chromatic dispersion [10–12].

In order to completely control the LCD transmittance, it is very convenient to have a physical model that enables an accurate prediction of the optical polarization modulation properties as a function of the addressed signal. There are mainly two approaches to this purpose. One of them is based on evaluating different microscopic models which assume a certain behavior of the LC molecules when the voltage is applied [13], whereas macroscopic methods are based on the response of the LCD when the output polarization state is evaluated, and no assumption on the microscopic physical parameters is made [14,15]. Both approaches are able to accurately predict the transmission of the TNLC device. However, the macroscopic approach works only for one specific wavelength used in the device calibration.

For many interesting applications of LC technology, an accurate characterization of the device to control the optical modulation as a function of the wavelength is necessary, especially in those applications that are making use of the phase modulation [16]. This is the case of Fourier transform spectroscopy [17,18], where LC devices offer a new design and unattended monitoring implementations instead of using moving parts components. Also for the pulse shaping of femtosecond lasers [19,20], where different phases are encoded onto different spectral components by means of the LCD. Liquid crystal based spectral filters have been also used in hyperspectral systems [21]. Polarimetric imaging is another example where LC technology is employed to introduce wave retardations instead of turning mechanical devices [22,23]. Polychromatic polarimetry...
requires a precise control of the retardations versus wavelength to properly generate and register any polarization states.

Therefore, the goal of this work is to show that by applying a LC birefringence chromatic dispersion model we can accurately predict the spectrum of the light transmitted by a TNLCD in the complete visible range. This a priori estimation of the wavelength-dependence transmittance of the TNLCD is demonstrated here for different polarization configurations, including the ability to accurately predict many different colors that can be generated by the device. We apply a well-known simplified physical model, which has been successfully exploited to predict the coherent optical modulation properties of various LC-SLMs under monochromatic illumination [13]. This model employs only two retardation parameters that depend on the applied voltage: one corresponds to the phase shift introduced in the central part of the TNLC cell (\(\beta\)), and the other describes the phase shift introduced by the TNLC layers on the cell edges (\(\delta\)). Following Ref. [13], we experimentally calibrate these retardance parameters of a commercial TNLCD for some specific wavelengths, and they are extrapolated to derive retardance values for all wavelengths in the visible range. With these data, this simplified model enables to predict the transmittance in the complete visible spectral range and, therefore, the colorimetric properties of the transmitted light for any arbitrary polarization can be calculated.

Besides predicting the spectrum of the transmitted light, this work is also interesting for color generation and optimization, which is nowadays a key subject due to the powerful industry developed around display technology. LCD monitors have each pixel divided into three subpixels with RGB color filters and each subpixel is individually addressable through appropriate electronics by changing the voltage –3. In addition each subpixel is sandwiched by linear polarizers which are commonly placed crossed. Color LCD-based projection filters [24]. Color reproduction models are then applied based on radiometric scalars for the non-linear opto-electronic transfer functions of the LC cells as a function of the input digit counts of each channel [25]. Here, on the contrary, we concentrate on the color variations generated by the LCD when illuminated with a broadband white spectrum. Although the color variation obtained in this way provides a much-reduced color gamut as compared to standard independently controlled three RGB subpixels, we show that it is possible to achieve a relatively large gamut by selecting an appropriate orientation of the polarizers. The precise color prediction shown in this work demonstrates the accuracy of the LC birefringence chromatic dispersion model, an aspect that can be relevant in a number of other LCD applications as those mentioned before.

The paper is organized as follows. In Section 2 we summarize the simple physical model that is applied to obtain the microscopic LC parameters along the LC cell. Their polarization modulation properties are described by means of the Jones matrix treatment. In Section 3 we show how the colorimetric properties of the light transmitted through the polarizer–TNLC–analyzer system are derived from the developed model. In Section 4 we show experimental results that demonstrate the accuracy in predicting the evolution with the addressed signal of the spectrum and color of the transmitted light for different polarization configurations. Finally, Section 5 contains the conclusions.

2. Microscopic TNLC cell model and its physical parameters

We summarize here the physical model and spectroscopic characterization method [8,13] employed in this work to predict the spectral transmittance and colorimetric properties of the system polarizer–TNLC cell-analyzer. The physical model is simple and was initially proposed in Ref. [13]: it considers that the TNLC cell is characterized by three parameters: 1) the twist angle (\(\alpha\)), which typically has a value \(\alpha = 90^\circ\), 2) the effective retardance (\(\beta_{ef}\)) introduced by the liquid crystal layers in the central region of the cell, which is considered to have a linear twist-angle variation and also a uniform tilt angle which depends on the applied voltage, and 3) the effective retardance (\(\beta_{ef}\)) introduced by the edge (boundary) liquid crystal layers, where the liquid crystal director is unable to tilt. While \(\alpha\) is a constant parameter, the two retardance parameters are voltage sensitive, one (\(\beta_{ef}\)) because the width and the tilt angle at the central region change, and the other (\(\delta_{ef}\)) because the width of the edge layers change. When the display is in the off-state, the retardance parameters adopt the values \(\beta_{ef}=\beta_{max}\) and \(\delta_{ef}=0\). In addition, that is most relevant for this work, \(\beta_{ef}\) and \(\delta_{ef}\) are wavelength dependent, with larger values as \(\lambda\) decreases.

The Jones matrix \(\mathbf{M}_{\text{LCD}}\) describing the LCD is given by [8,13]:

\[
\mathbf{M}_{\text{LCD}}(\alpha, \beta_{ef}, \delta_{ef}) = e^{-i(\beta_{ef}+\delta_{ef})/\lambda} \mathbf{R}(-\alpha) \mathbf{M}(\alpha, \beta_{ef}, \delta_{ef}),
\]

where \(\mathbf{R}(-\alpha)\) is the 2 \(\times\) 2 rotation matrix

\[
\mathbf{R}(-\alpha) = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) \\ \sin(\alpha) & \cos(\alpha) \end{pmatrix}.
\]

and the matrix \(\mathbf{M}(\alpha, \beta_{ef}, \delta_{ef})\) is given by

\[
\mathbf{M}(\alpha, \beta_{ef}, \delta_{ef}) = \begin{pmatrix} A - iB & C \\ -C & A + iB \end{pmatrix}
\]

with

\[
A = \cos(\gamma) \sin(2\delta_{ef}) + \frac{\beta_{ef}}{\lambda^2} \sin(2\delta_{ef}),
\]

\[
B = \cos(\gamma) \sin(2\delta_{ef}) + \frac{\beta_{ef}}{\lambda^2} \sin(2\delta_{ef}),
\]

\[
C = \frac{\sin(\gamma)}{\gamma},
\]

\[
\gamma = \sqrt{\alpha^2 + \beta_{ef}^2}.
\]

Eq. (1) is the Jones matrix describing the device in the reference framework where the LC director at the entrance surface is considered parallel to the horizontal x axis. If the LCD is oriented such that the LC director has an angle \(\Psi_D\) relative to the laboratory frame, Eq. (1) is modified to

\[
\mathbf{M}_{\text{LCD}}(\alpha, \beta_{ef}, \delta_{ef}) = \mathbf{R}(\Psi_D) \mathbf{M}_{\text{LCD}}(\alpha, \beta_{ef}, \delta_{ef}) \mathbf{R}(\Psi_D
\]

We calibrated the physical parameters of our display, a SLM from CRL-Opto, model XGA-3 TN-LCD, with 1074 \(\times\) 768 pixels, by following the procedure explained in detail in Refs. [5,13]. For this calibration, we used four wavelengths: 633 nm, 514 nm, 488 nm and 457 nm. The twist angle, the orientation of the LC director at the entrance surface and the maximum retardance are first obtained for the off-state LC. The input director is oriented at \(\Psi_D = +91^\circ\) with respect to the laboratory reference frame, and the twist angle is \(\alpha = -94^\circ\). Values \(\beta_{max} = 121^\circ, 158^\circ, 171^\circ\) and \(190^\circ\) have been measured in our device for wavelengths \(\lambda = 633, 514, 488\) and 457 nm, respectively. In order to extrapolate the retardance values in the off-state (\(\beta_{max}\)) to the full visible spectral range, we consider that the refractive indices of liquid crystal materials can be usually described by Cauchy type equations [26]. Therefore, retardance values as a function of wavelength can be properly described as

\[
\beta_{max}(\lambda) = \frac{a}{\lambda} + \frac{b}{\lambda^3},
\]
where $a$ and $b$ are constant values that can be used to fit the experimental data points. Fig. 1(a) shows the dependence of the retardance with wavelength for our TNLC device; the circles correspond to the measured values and the solid line is the best data fit, which is obtained with $a = 1.1354 \times 10^4$ rad$\times$nm and $b = 7.7933 \times 10^4$ rad$\times$nm$^2$. The corresponding correlation coefficient is $R^2 = 0.9957$. As expected, the retardance decays as the wavelength increases. This curve fully describes the wavelength dependence of the off-state retardance.

The next step is to calibrate the behavior of the effective retardance parameters ($\beta_{ef}$ and $\delta_{ef}$) as a function of the applied voltage. The voltage applied to each pixel in the display is determined by the gray level ($g$) addressed to the display, which ranges from 0 to 255. Maximum voltage is applied with zero gray level, and the voltage decreases as $g$ increases. The retardance parameters were measured as a function of $g$ as reported earlier [8], for the four specific wavelengths of calibration. The results are presented in Fig. 1(b) and (c). Note the small values of the retardance $\beta_{ef}(\lambda, g)$. Normally those edge layers were simply neglected in previous calibration models. However, they remarkably contribute to accurately describe the LCD modulation and it is relevant to take them into account [13]. Note again that both retardance parameters, $\beta_{ef}(\lambda, g)$ and $\delta_{ef}(\lambda, g)$, increases as the wavelength decreases.

Let us emphasize that by using these results and the calibration procedure explained in Ref. [8] we can obtain the retardance parameter curves for any wavelength (not only for the calibration wavelengths) as a function of the gray level. The basic idea is to consider that the LC chromatic dispersion presented in Fig. 1(a) is maintained when the voltage is applied, and thus the retardance for any arbitrary wavelength ($\lambda$) is related to that for a reference wavelength ($\lambda_r$) through the relations [8]:

$$\beta_{ef}(\lambda, g) = \frac{\beta_{max}(\lambda)}{\beta_{max}(\lambda_r)} \beta_{ef}(\lambda, g),$$

$$\delta_{ef}(\lambda, g) = \frac{\delta_{max}(\lambda)}{\delta_{max}(\lambda_r)} \delta_{ef}(\lambda, g).$$

Such determination of $\beta_{ef}(\lambda, g)$ and $\delta_{ef}(\lambda, g)$ effective retardances leads to a full prediction of the modulation properties as a function of both the wavelength and the voltage since the Jones matrix that defines the TNLCD (Eq. (1)) can be obtained for each value of $\lambda$ and $g$;

Thus, the normalized spectral transmittance, $\tau_{\phi_1\phi_2}(\lambda, g)$, of the TNLCD placed between two linear polarizers with orientations $\phi_1$ and $\phi_2$ measured relative to the liquid crystal director at the input surface of the display, can be calculated using the Jones matrix in Eq. (1), being the result [13]:

$$\tau_{\phi_1\phi_2}(\lambda, g) = |A(\lambda, g)\cos(\phi_1 - \phi_2 + \alpha) + C(\lambda, g)\sin(\phi_1 - \phi_2 + \alpha)|^2 + |B(\lambda, g)\cos(\phi_1 + \phi_2 - \alpha)|^2.$$

Fig. 1. (a) Off-state retardance parameter as a function of the wavelength. Symbols are the experimental values at the calibration wavelengths (633, 514, 488 and 457 nm). Solid line is the potential fit to the data. On-state effective retardances $\beta_{ef}(b)$ and $\delta_{ef}(c)$ as a function of the addressed gray level for the specific calibration wavelengths.

Fig. 2. (a) Picture of the setup. (b) Spectral irradiance $I_o(\lambda)$ in the absence of analyzer.
Since $\beta_{ef}$ and $\delta_{ef}$ depend on $\lambda$ and $g$, so do the LCD Jones matrix elements $A$, $B$ and $C$ defined in Eqs. (4a,b,c). Therefore, for each wavelength and for each value of $g$, the spectral relative transmittance $\tau_{cg}(\lambda, g)$ can be calculated from the functions $\beta_{cg}(\lambda, g)$ and $\delta_{cg}(\lambda, g)$. Note that Eq. (8) depends on the angles $\varphi_1$ and $\varphi_2$. For common TN LCD display applications, the polarizer angles are $\varphi_1 = 0^\circ$ and $\varphi_2 = \alpha$, that corresponds to the standard crossed-configuration since the twist angle $\alpha$ approximates $90^\circ$. Then, $\tau_{cg}(\lambda, g) = A^2(\lambda, g) + B^2(\lambda, g) = 1 - \left( \frac{\alpha}{\gamma} \right)^2 \sin^2(\gamma)$, which corresponds to the classical Gooch–Tarry curve [27]. In the following we apply the TN LCD physical model described by Eq. (8) to provide spectral and colorimetric predictions in other polarization configurations.

3. Colorimetric prediction of the TN LCD transmission

We present in this section the transmission predicted by the above described model when the TN LCD is illuminated with a broadband spectrum from a regular tungsten light source. We apply the Jones matrix in Eq. (1), together with the full voltage–wavelength characterization of the effective retardances shown in Fig. 1, to predict the spectral irradiance, the illuminance and the colorimetric properties of the light transmitted through the system polarizer–LCD analyzer, as a function of the gray level ($g$) addressed to the display.

If the light source illuminating the display has a spectral irradiance $I_0(\lambda)$, and assuming a uniform spectral transmission for the two polarizers, the transmission through the system polarizer–LCD analyzer is characterized by an irradiance function that depends on the gray level and the wavelength as

$$I(\lambda, g) = \tau(\lambda, g) I_0(\lambda).$$

Since the normalized spectral transmittance $\tau(\lambda, g)$ is given by Eq. (8), and depends on the selected polarizers’ angles $\varphi_1$ and $\varphi_2$, so does the spectral irradiance $I(\lambda, g)$. The perceived color generated by the system can be determined by projecting the irradiance function shown in Eq. (8) onto the basis of color matching functions that represent the response of the human visual system to the electromagnetic stimulus of arbitrary spectral content. As defined by the CIE 1931-XYZ standard observer, the tristimulus values of this transmitted light can be calculated as [28,29]

$$X(g) = \int I(\lambda, g) x(\lambda) d\lambda,$$

$$Y(g) = \int I(\lambda, g) y(\lambda) d\lambda,$$

$$Z(g) = \int I(\lambda, g) z(\lambda) d\lambda,$$

where $x(\lambda)$, $y(\lambda)$ and $z(\lambda)$ denote the color matching functions. The corresponding chromaticity coordinates, that represent the color perceived by the eye, are then calculated as a function of the addressed gray level from the normalization of these values as

$$x(g) = \frac{X(g)}{X(g) + Y(g) + Z(g)},$$

$$y(g) = \frac{Y(g)}{X(g) + Y(g) + Z(g)},$$

$$z(g) = \frac{Z(g)}{X(g) + Y(g) + Z(g)}.$$

Therefore, the color variation as a function of $g$ is defined by the trajectory $(x(g), y(g))$ in the CIE $xy$ chromaticity diagram. The photometric characteristics of the transmitted light are fully

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Fig. 3. Theoretical (solid line) and measured (symbols) spectral irradiance $I(\lambda, g)$ for the indicated gray levels and the following polarizer configurations with $\varphi_1 = 0$: (a) standard ($\varphi_2 = \alpha$), (b) $\varphi_2 = \alpha + 30^\circ$, (c) $\varphi_2 = \alpha + 60^\circ$ and (d) $\varphi_2 = \alpha + 90^\circ$. 

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characterized by the illuminance function, \( I_v(g) \), which can be calculated as
\[
I_v(g) = K_n Y_v(g),
\]
where \( K_n = 683 \text{ lm/W} \) denotes the maximum photopic luminous efficiency of the human eye. Our goal here is to employ the physical model presented in Section 2 to predict the colorimetric properties of the light transmitted by the system polarizer–LCD–analyzer as a function of the addressed gray level, by means of the functions \( x(g), y(g), \) and \( I_v(g) \).

It could be also convenient to express the colorimetric changes in the CIELAB color space [28–30], which aspires to perceptual uniformity and it is a color-opponent space. The \( L^*a^*b^* \) components are calculated from the \( x,y,z \) components as
\[
L^*(g) = 116\left(\frac{Y(g)}{Y_n}\right)^{1/3} - 16.
\]

Fig. 4. Illuminance and colorimetric characteristics as a function of the gray level in the configurations with \( \varphi_1 = 0 \): (a) standard (\( \varphi_2 = \alpha \)), (b) \( \varphi_2 = \alpha + 30^\circ \), (c) \( \varphi_2 = \alpha + 60^\circ \) and (d) \( \varphi_2 = \alpha + 90^\circ \).
Fig. 5. Theoretical (solid lines) and measured spectral irradiance for the polarizers’ configuration with φ₁ = 19.5° and φ₂ = −29.5°.

\[ a^* (g) = 500 \left[ f \left( \frac{X(g)}{X_n} \right) - f \left( \frac{Y(g)}{Y_n} \right) \right] \]  
\[ b^* (g) = 200 \left[ f \left( \frac{Y(g)}{Y_n} \right) - f \left( \frac{Z(g)}{Z_n} \right) \right] \]  

where \( f(s) \) is defined as

\[ f(s) = \begin{cases} 
7.778s + \frac{16}{115} & \text{if } s \leq 0.008856 \\
1 & \text{if } s > 0.008856 
\end{cases} \]  

and where the CIE XYZ tristimulus values \( X_n, Y_n, Z_n \) correspond to the selected reference white source.

4. Simulation and experimental results

In order to probe the model’s ability to predict the colorimetric properties of the display, we illuminate the optical system (polarizer-LCD-analyzer) with a collimated beam from a tungsten lamp. Fig. 2(a) shows a picture of the setup. The light transmitted by the system is focused on the back focal plane of a converging lens, where it is captured by a fiber to be analyzed with a calibrated UV-visible spectro-radiometer (Stellar-Net, model EPP-2000). In order to show results comparable with those obtained when a signal is addressed to the LCD, the curve shown in Fig. 2(b) corresponds to the spectral irradiance captured when the analyzer is included in the system and it can be regarded as the function \( I_\lambda (\lambda) \) in Eq. (9). This way we can ignore other effects like the diffraction generated by the pixelated structure of the device, which contribute to generate losses, but do not alter the colorimetric properties of the transmitted light. The spectrum shown in Fig. 2(b) is also selected as the reference white source, having tristimulus values \( X_0 = 20.903, Y_0 = 20.745 \) and \( Z_0 = 5.120 \) W/m², respectively.

First, we evaluate the spectral and colorimetric properties for the standard configuration of the polarizers. Fig. 3 shows both the predictions and the measured data for the spectral irradiance \( f(\lambda,g) \), measured in watt/m² nm, behind the polarizer-LCD-analyzer system, for the standard case, \( \phi_1 = 0, \phi_2 = \alpha \), and for the other three angles of the analyzer: \( \phi_2 = \alpha + 30° \), \( \phi_2 = \alpha + 60° \), and \( \phi_2 = \alpha + 90° \) (similar results were obtained when rotating the first polarizer). For each case, measurements were taken in the range available from the spectrometer (from 200 to 850 nm), although only the range 400 to 700 nm is plotted here. The results in Fig. 3 correspond to the addressed gray levels \( g = 0, 64, 128, 192 \) and 255. The continuous lines represent the predicted spectral irradiance \( f(\lambda,g) \), calculated from Eqs. (8) and (9) using the previously calculated retardance parameters \( \beta_0(\lambda,g) \) and \( \delta_0(\lambda,g) \). Dots indicate the experimental data captured with the spectro-radiometer. The agreement with the predictions is excellent for all of them. Let us note that although our LCD is pixelated, we are using it here like a single-pixel device since the same gray level is addressed to all pixels. As we mentioned in the introduction, the aim of the paper is to show the color produced by a single pixel when the polarization and the spectral properties of the TN LCD are completely controlled.

Fig. 4 shows the photometric and colorimetric results derived from the previous spectra, where each row corresponds to each of the four tested configurations. The first, second and third columns show, respectively, the illuminance \( I_e(g) \) versus the addressed gray level, measured in luxes, the color change represented in the CIE1931 xy chromaticity diagram, and the color change represented in the CIE L*a*b*b diagram. Once again, the continuous line denotes the predictions and dots denote the experimental data. The different addressed gray level are depicted in the two color diagrams using gray level solid dots, where \( g = 0 \) corresponds to a black dot and \( g = 255 \) to a white dot, respectively. The results for the standard configuration (Fig. 4(a)) show a monotonically increasing illuminance versus \( g \), and a minimal color change in the whole change. These results show an excellent prediction of the transmitted light spectral and colorimetric content for all the tested polarization configurations.

Such accurate predictability achieved with the applied model makes it possible to use it to extend the color gamut generated by the system in comparison to the standard cross-polarizers configuration. In that sense, we perform a numerical computation of the spectral modulation properties and we search for orientations of the polarizer-analyzer pair that result in specific colorimetric characteristics. We search for the polarizers’ configuration that yield the largest area enclosed by the trajectory described in the CIExy diagram for the whole range of gray levels addressed to the display. After a numerical computer search, the polarizers’ orientations \( \phi_1 = 19.5° \) and \( \phi_2 = −29.5° \) were obtained. The results are presented in Figs. 5 and 6, where we show the variation in the measured and predicted spectral irradiance (Fig. 5) and the corresponding illuminance and colorimetric
change (Fig. 6). It is interesting to note how the curve in the CIExy chromatic diagram traces almost a complete closed ellipse around the central white point. Once again, the predictions of the model agree very well with the experimental spectral irradiance (Fig. 5) and illuminance (Fig. 6, left).

Finally, the spectral and colorimetric characteristics of the light exiting the optical system are directly visualized with a color camera (Basler, model scA1390-17fc with 1392 × 1040 pixels). For that purpose, a point source is imaged onto the camera viewed through the display. The LCD and the analyzer were placed just in front of the camera’s objective while the polarizer was located right after the display. The validity of these predictions on the spectral response as well as on the color diagram has been probed experimentally.

Such an excellent agreement in the colorimetric aspects between experiment and numerical results is a consequence of the very accurate description of the optical modulation upon applied voltage (addressed gray level) for any wavelength within the visible range. This remarkable prediction capability can be interesting for all types of LCD applications where a controlled modification of an input light spectrum is necessary, such as in pulse shaping applications, colorimetric calibrations, polychromatic polarimetry, etc.

This excellent predictive ability allows for performing computational search of the appropriate polarizers’ configurations to provide a desired spectral response. As an example, in this work we found a configuration which provides a relevant wider range of colors in comparison with the common cross-polarizer configuration. This birefringence-based color generator has a relatively limited color gamut, specially compared to the standard color generation with independently controlled RGB subpixels. However, it is a very simple setup which does not require color filtering and can provide a certain degree of tunability of the chromatic properties. The proposed procedure might be also interesting for the application to other devices, as for instance newer liquid crystal on silicon (LCOs) displays.

5. Conclusions

In this work we applied a previously reported characterization method that allows for fully describing the spectral and voltage dependence of the TNLC cell retardance parameters. As a consequence, we provide a very accurate prediction of its broadband optical modulation, including the broadband spectral transmittance and colorimetric properties of the polarizer–TNLCD–analyzer system as a function of the gray level addressed to the display. The validity of these predictions on the spectral response as well as on the color diagram has been probed experimentally.

References

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