Birefringent color generation by TN LC cells

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Abstract: *We study potentials of liquid-crystal devices (LCD) for birefringent color generation. The considered devices consist of a layer of a twisted nematic liquid-crystal (TN LC) that together with several retardation films is sandwiched between a pair of polarizers. Black & Red, Black & Green and Black & Blue devices for direct and wide angle viewing are considered.*

Keywords: TNLCD; birefringent color generation; optimization.

Introduction

A stack of birefringent plates composed in a certain way and placed between a pair of polarizers is widely used in optics for synthesis of optical filters [1-6] as well as in display technology for color generation [7-10]. Several techniques for finding parameters of the plates in the stack with required optical characteristics have been introduced earlier [1-4]. Since the solving of this optimization problem in the general case is a quite complicate procedure, the proposed techniques operate with the plates having optical retardation divided by a certain value (e.g. dΔn, 2dΔn, 3dΔn…) or involve some symmetrical orientations of the plates. As a result, the obtained solutions include relatively a large number of the retardation plates and cannot be claimed as optimal ones. Moreover, these techniques are not adapted for LCD where at least two working states are necessary to take into account. LC displays with birefringent color generation and tunable optical filters reported earlier [1-8] have relatively complicated structures that include either several LC layers or many birefringent plates.

Recently we have studied birefringent color generation by reflective and transreflective direct viewing ferroelectric LCD [10]. Our technique is based on an algorithm for numerical solving inverse problems. In this paper, we are going to apply the similar method for investigation possibilities of TN LC cells coupled with a restricted amount of retardation films for birefringent color generation. Two cases will be considered: 1) direct viewing TN LCD at normal observation and 2) TN LCD with wide viewing characteristics. We will focus on devices that have two working states: field off and field on, when a strong electrical field is applied. The first state in our calculations is characterized by a planar texture whereas the other one has a homeotropic texture. All calculation will be done on the example of Black & Red, Black & Green and Black & Blue TN LCD. We restrict ourselves by a case when the polarizers are ideal, and LC cell is filled by LC material MLC-6809-000 from Merk (dΔn=0.1295) twisted by 90 degrees. We assume that TN LCD is illuminated by a light source spectrum of which is close to the standard illuminant of E type.

The structure of the TN LCD to be considered is shown in Fig.1.

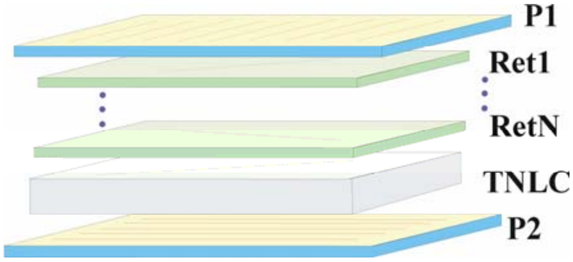

Figure 1. Structure of the considered TN LCD: the layer of TN LC and a set of retardation plates (Ret1,…RetN) are sandwiched between a pair of polarizers (P1,P2)

Direct viewing TN LCD

Optical performance of a direct viewing LCD is defined by brightness and color gamma in each state. In order to build a criterion for an optimization task included simultaneously there parameters, we use the color coordinates of RGB space [11]

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \int \begin{bmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{bmatrix} L(\lambda)T(\lambda)d\lambda\,, \qquad (1)$$

where $r(\lambda)$, $g(\lambda)$, $b(\lambda)$ are the spectral tristimulus values[11], $L(\lambda)$ is the spectrum distribution of the illuminated light, $T(\lambda)$ is the transmittance of a TN LCD. Relative values of the RGB coordinates characterize the color; whereas the absolute values are proportional to the brightness. Evidently, the color gamma and brightness of such a device is defined by the function $T(\lambda)$ that depends on orientation of the polarizers, on orientations and retardations of the LC layer and retardation plates.

After normalization of RGB coordinates in Eq. (1) on $L(\lambda)$ and transmittance of a pair of parallel polarizers, values of the coordinates are changed between 0 and 1. When a LCD is illuminated by light source with white color, a state having white color and maximal brightness of the device is characterized by the coordinates $\begin{bmatrix}1\\1\\1\end{bmatrix}$, whereas the black state has $\begin{bmatrix}0\\0\\0\end{bmatrix}$.

Lets a device that we wish to obtain has one state with color coordinates R_1^d, G_1^d, B_1^d and the other state with coordinates R_2^d, G_2^d, B_2^d, In this case, the calculated coordinates R_1, G_1, B_1 for the first state must tend to R_1^d, G_1^d, B_1^d and the calculated coordinates R_2, G_2, B_2 for the second state must tend to R_2^d, G_2^d, B_2^d:

$$\begin{bmatrix}R_1\\G_1\\B_1\end{bmatrix} \to \begin{bmatrix}R_1^d\\G_1^d\\B_1^d\end{bmatrix}, \quad \begin{bmatrix}R_2\\G_2\\B_2\end{bmatrix} \to \begin{bmatrix}R_2^d\\G_2^d\\B_2^d\end{bmatrix} \qquad (2)$$

To operate with a scalar value during optimization, we build a positive defined function:

$$f = \sum_{i=1,2} \sum_{J=R,G,B} \left(J_i - J_i^d\right)^2, \qquad (3)$$

where the index i corresponds to off and on states, J_i and J_i^d are the calculated and desired color coordinates, respectively. This function reaches its global minimum (zero in the ideal case) when the calculated coordinates as close to the desired ones as possible.

The standard calculus methods [12] for a function minimization cannot be applied here in the usual way, because of the necessity to set the coordinates of a start point closely to the global minimum. To find the global minimum, we used a procedure having in a loop a minimization function with randomized coordinates of the start points. Such procedure enables us to obtain a set of the local minima. Among of the local minima, the lowest value is chosen. As a variable, we also set a parameter that described the wavelength dispersion of the retardation plates. The point is that companies specialized in the retardation films can produce retarders with a preset wavelength dispersion. The retardation in our calculations is defined as

$$\Gamma = \Gamma_o\left(1 + A/\lambda^2\right), \qquad (4)$$

where Γ_o is an initial value, A is a parameter.

Appling the mathematics mentioned above and using the Jones matrix technique [13] for deriving the transmission $T(\lambda)$, we find optimal parameters for Black & Red, Black & Green and Black & Blue TN LCD.

Results of the solutions of the optimization task (Eq.3) are presented in Table 1. Orientations of the polarizers described by the angles α, β and the retardation plates described by the angles γ_1, γ_2 are counted off the orientation of the input director of the LC. The thickness of the LC layer is denoted as d_{TN}. The values obtained for the function f describe differences between the calculated and desired characteristics.

The calculated spectra for configurations of the TN LCD presented in Table 1 are shown in Fig. 2-4.

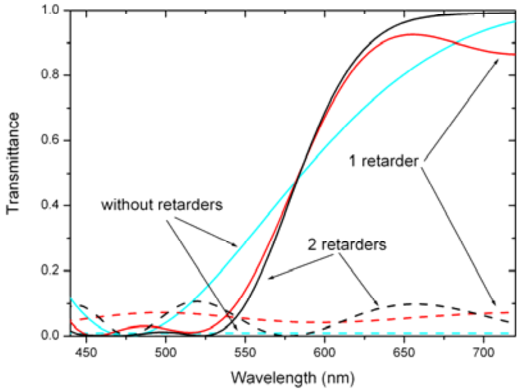

Figure 2. Spectral transmittances of Black & Red TN LCD.

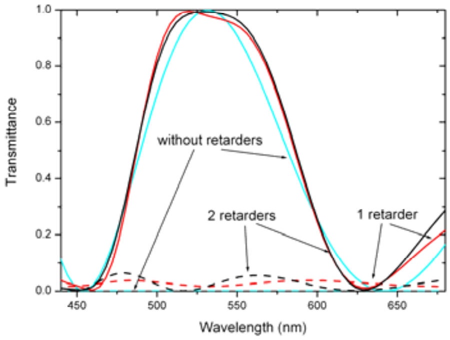

Figure 3. Spectral transmittances of Black & Green TN LCD.

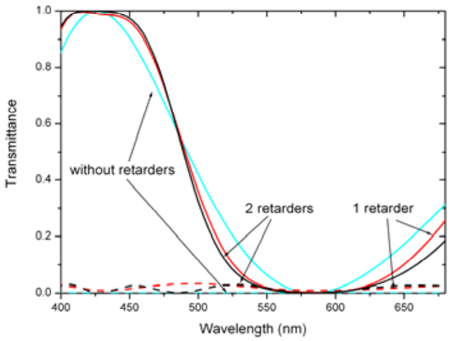

Figure 4. Spectral transmittances of Black & Blue TN LCD.

The color coordinates in CIE1931 diagram of the bright states are shown in Fig.5. The index near the letter corresponded to color (R,G,B) is the number of the retardation plates.

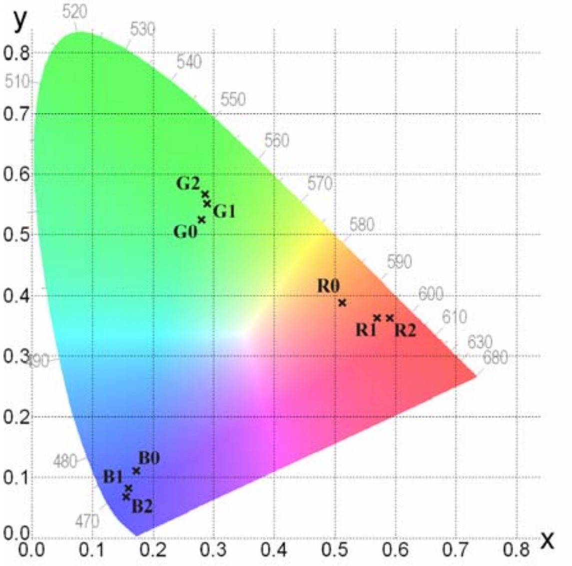

Figure 5. Coordinates of the bright states of the considered TN LCD in CIE1931 diagram.

From the obtained results it is possible to conclude that one or two retardation plates are sufficient, to obtain a TN LCD with reasonably good color and high brightness in the bright state, where as the other state is dark.

We believe that similar results can be obtained for any specific LC material.

Chromatic TN LCD with wide viewing angles

In comparison with the optimization task for direct viewing TN LCDs, finding optimal parameters for a display with wide viewing characteristics is a more complicated task. In addition to high brightness in the bright state and low brightness in the dark state as well as a desirable color gamma, it is necessary to have a good uniformity of visual characteristics for different observed directions.

Criteria for color gamma and brightness in the optimization task are the same as in the case of the direct viewing TN LCD (Eqs. 1-3). To obtain uniformity of the viewing characteristic, we introduced the following minimization function:

$$f_v = \int_0^{2\pi}\int_0^{\pi/3} A(\theta,\varphi)\sum_{i=1,2}\sum_{J=R,G,B}\left(J_i(\theta,\varphi)-J_i^d(\theta,\varphi)\right)^2 d\theta d\varphi , \qquad (5)$$

where $A(\theta,\varphi)$ is a weighting function, θ,φ are azimuth and polar angles, respectively.

In solving this optimization task, we considered TN LCD that has only one retardation plate. The obtained results are summarized in table 2. The transmittance $T(\lambda)$ has been calculated by the extended Jones matrix method [13]. Arias of the change of the color coordinates for observation under polar angles 20°, 40° and 60° are shown in the CIE1931 diagram in Fig. 6.

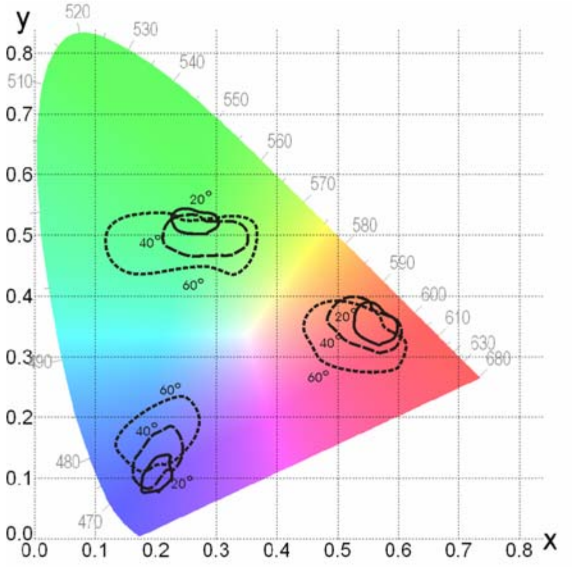

Figure 6. Coordinates of the bright states of Black & Red, Black & Green and Black & Blue in CIE1931 diagram.

As we can see from the diagram, the displays possess quite good color gamma for different angles of the observations. This fact enable us to conclude that a TN LCD with birefringent color generation can be used as a chromatic display with wide viewing angles instead TN LCDs included absorbent filters.

Conclusions

We studied potentials of TN LCD for birefringent color generation. The considered devices consist of a layer of twisted nematic liquid-crystal (TN LC) that together with several retardation films are sandwiched between a pair of polarizers. By solving inverse problem, we found optimal parameters for Black & Red, Black & Green and Black & Blue devices for direct and wide angle viewing. The demonstrated approach for solving the optimization task and the obtained results can be useful for design of various optoelectronics devices (displays, filters, modulators, etc.)

Acknowledgements

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Table 1. Optimal results for direct view chromatic TN LCD

LCD	**Black & Red**			**Black & Green**			**Black & Blue**		
Number of retarders	0	1	2	0	1	2	0	1	2
d_{TN} (μm)	5.21	5.19	5.23	12.08	12.03	11.96	6.35	6.34	6.34
α (°)	47.7	150.1	132.5	134.2	52.0	42.6	135.7	41.0	46.7
β (°)	132.3	48.4	45.3	45.7	134.7	133.2	44.3	136.5	134.6
A	-	-0.021	0.098	-	0.037	0.002	-	0.046	0.079
Γ_1 (μm)	-	1.9	0.64	-	1.88	1.16	-	1.04	0.67
γ_1 (°)	-	136.5	44.2	-	42.8	134.2	-	139.0	135.5
Γ_2 (μm)	-	-	1.34	-	-	1.46	-	-	1.29
γ_2 (°)	-	-	142.6	-	-	36.4	-	-	50.9
R_1	0.01	0.04	0.03	0.00	0.03	0.02	0.00	0.01	0.010.02
G_1	0.01	0.06	0.05	0.00	0.02	0.03	0.00	0.02	0.01
B_1	0.01	0.06	0.05	0.00	0.03	0.03	0.00	0.02	
R_2	0.78	0.97	0.95	0.01	0.01	0.02	0,02	0,01	0.010.01
G_2	0.23	0.19	0.10	0.89	0.95	0.97	0.08	0.03	0.99
B_2	0.05	0.08	0.02	0.15	0.09	0.07	0.94	0.99	
f	0.1035	0.0298	0.0183	0.0326	0.0133	0.0091	0.0105	0.0019	0.0007

Table 2. Optimal results for wide viewing chromatic TN LCD

LCD	**Black & Red**	**Black & Green**	**Black & Blue**
d_{TN} (μm)	5.22	12.21	6.37
α (°)	149.3	51.8	41.3
β (°)	47.9	135.4	135.8
A	-0.021	0.036	0.044
Γ_1 (μm)	1.88	1.85	1.05
γ_1 (°)	135.7	42.4	139.3