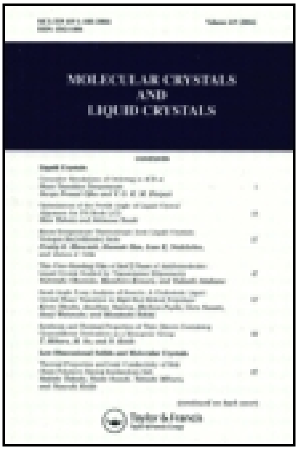

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Optimization of One-Polarizer Reflective LCDs with Phase Compensator

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OPTIMIZATION OF ONE-POLARIZER REFLECTIVE LCDs WITH PHASE COMPENSATOR

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New approach to optimization of reflective LCD, based on "Polarization Transformation Efficiency" (PTE) conception, is presented. This approach is used for optimization of one-polarizer RLCD in RTN mode. We have found the conditions, which enable to realize perfect dark and bright states in RTN-LCDs with a phase compensator between the polarizer and LC cell. We believe that the proposed new method of LCD optimization can be successfully applied for the definition of the new advanced LCD configurations with a high brightness, contrast and duty ratio.

1. INTRODUCTION

The applications of the phase compensators is an effective method to obtain a perfect image in LCD with a sufficient brightness and high contrast [1]. However a proper choice of the phase compensators is rather complicated problem even in case of the computer modeling of the output LCD parameters [1–5]. Our paper demonstrates original approach essentially simplifying the optimization of RLCDs with phase compensators. We consider the black and white (B/W) switching of one polarizer reflective LCD (RLCD) in RTN mode [6,7].

2. POLARIZATION TRANSFORMATION EFFICIENCY

Consider on one-polarizer RLCD with a non-absorbing LC layer (see Fig. 1). On the assumption that bulk reflection in the LC layer is negligible, we can

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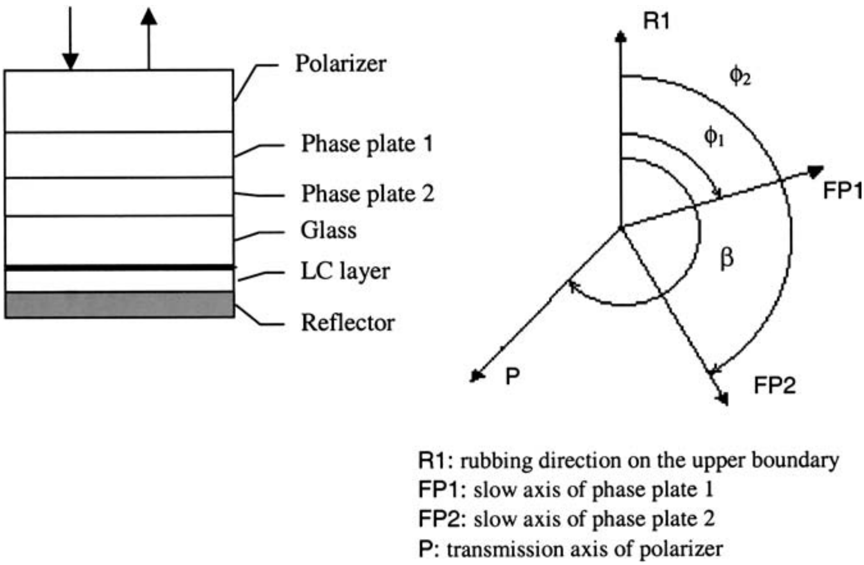

FIGURE 1 RLCD configuration. Definition of the angles ϕ_1, ϕ_2, and β.

describe the optical transformation performed by the layer with a unitary 2×2 matrix T connecting the complex amplitudes of the orthogonal polarized components of the input and output light [8–12]. The evaluation of the matrix T in the approximation of a low LC optical anisotropy can be obtained using the Jones matrix method [8,9]. More accurate estimation can be obtained with the matrix method [10–12] (for the case of normal light incidence the corresponding calculation technique is presented in Section 4 of this paper). In any case the transfer matrix T can be written as $T = c\hat{T}$, where c is complex factor with $|c| = 1$ and $\hat{T}$ is a unitary matrix of the form $\begin{pmatrix} a & b \\ -b^* & a^* \end{pmatrix}$. Let the "dark" and "bright" states of the LC cell correspond to the controlling voltages $\mathrm{U} = \mathrm{U}_1$ and $\mathrm{U} = \mathrm{U}_2$. The minimum reflectance (R) in the "dark" state we may announce as the first optimization criterion, while the second one will be maximum R value in the LCD "bright" state. We may introduce the "Polarization-Transformation Efficiency" (PTE) parameter (Q) as follows:

$$Q = 1 - \left| \mathrm{Re}\left[\tilde{F}_1^{+}\tilde{F}_2\right]_{11} \right|^2, \tag{1}$$

where $\tilde{F}_1$ and $\tilde{F}_2$ are the values of the matrix $\tilde{F}$, corresponding to the voltages U_1 and U_2. The matrix $\tilde{F}$ is defined as follows:

$$\tilde{F} \equiv \hat{T}_R \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} \hat{T}_D,$$

where $\hat{T}_D$ и $\hat{T}_R$ are the transfer matrices $\hat{T}$, which correspond to the direct and return light propagation through the LC layer. The value of Q depends on the parameters of LC layer, voltages U_1 and U_2, the light wavelength and the viewing angle. Using the parameter Q we can easily calculate the RLCD reflectance in the dark and bright states. The maximum achieved reflectance of RLCD with a phase compensator in the "bright" state (the parasitic reflections are not taken into account) in case of the realization of a perfectly "dark" state can be expressed as $R = 2Qt_p{}^2 t_R$, where t_p is the polarizer transmittance for non-polarized incident light at a given viewing angle, t_R is the average reflectance of the mirror at a given direction. The parameter Q has the values between $Q = 0$ and $Q = 1$. If Q is close to 1, both the announced criteria of the optimization are obtained. Otherwise, we are unable to solve the optimization problem. The slight dependence of the parameter Q on the light wavelength and viewing angle means the achromatic switching and wide LCD viewing angles accordingly. Such analysis allows us to estimate, whether the LC layer parameters are optimal without varying the phase compensator parameters that considerably simplifies the procedure.

We shall demonstrate our approach on the concrete example of the LCD optimization. The reflective LCD configuration is shown on Figure 1. All the computer simulations were made using LCD-OPT software [13].

3. RTN RLCD WITH B/W SWITCHING

Active Matrix RLCD, including LCOS RLCD, operating in RTN mode was found to be very promising [6,7]. The typical reflectance spectra of RTN-LCD without phase compensators in $U = U_1$ and $U = U_2$ states are shown in Figure 2, while Figure 3 provides the voltages dependence of the average reflectance. RTN-LCD performance needs to be improved due to a chromatic "dark" state. One can try to correct the color of the "dark" state by inserting the phase retarders between the polarizer and the LC cell (Fig. 1). Figure 4 shows the dependence of the PTE parameter Q_{550} evaluated at $\lambda = 550\,\text{nm}$ for a normal light incidence of the model RTN LCD at $U = U_2$ (in this example voltage $U = U_1 = 0V$ corresponds to the "bright" state of LCD). In the calculations the following parameters of LC layer were used: $K_{11} = 1.32 \cdot 10^{-6}$ dyne, $K_{22} = 6.5 \cdot 10^{-7}$ dyne, $K_{33} = 1.38 \cdot 10^{-6}$ dyne, $\varepsilon_{\parallel} = 8.3$, $\varepsilon_{\perp} = 3.1$; principal refractive indices $n_{\perp} = 1.48$, $n_{\parallel} = 1.58$ at the

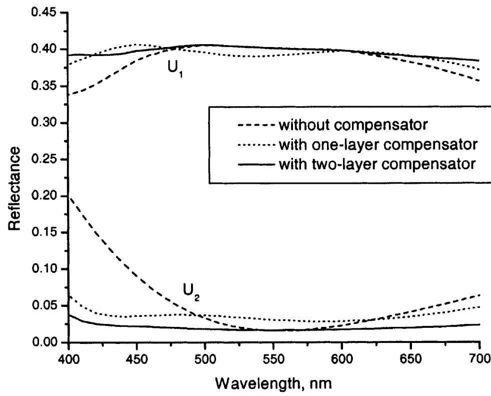

FIGURE 2 Reflectance spectra of RTN-LCDs. The voltages $U_1 = $ oV in the "bright" state. $U_2 = 2.65$V and $U_2 = 2.73$V for the "dark" state without and with compensator respectively. *One-layer compensator:* principal refractive indices $n_\perp = 1.5$, $n_\parallel = 1.58$ at $\lambda = 550$ nm, thickness $L_1 = 4.3\,\mu$m, orientation angle $\phi_1 = 92.8°$ (see Fig. 1), polarizer angle $\beta = 9.5°$. *Two-layer compensator:* $n_\perp = 1.5$, $n_\parallel = 1.58$, $L_1 = 6.07\,\mu$m, $\phi_1 = 86.05°$, $L_2 = 1.66\,\mu$m, $\phi_2 = 2.41°$, $\beta = 2.96°$.

wavelength of 550 nm; twist angle = 52°, pretilt angles = 4°, LC layer thickness d = 5.36 μm. The curve on Figure 4 allows us to determine the region of optimal values of the voltages U_2. It is a region from 2.2 V to 3.3 V, where Q_{550} is close to 1. Figure 4 provides the spectral dependence of the PTE parameter Q for RTN-LCD at various voltages U_2 from this region ($U_1 = 0$ V). As seen from Figure 4. if we choose $U_2 = 2.73$ V, we can obtain an achromatic and highly transparent "bright" state, as the

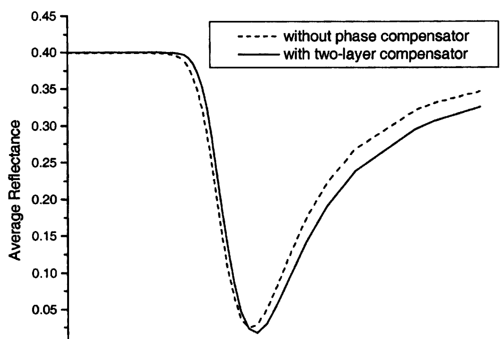

FIGURE 3 Voltage dependence of average reflectance of RTN-LCD.

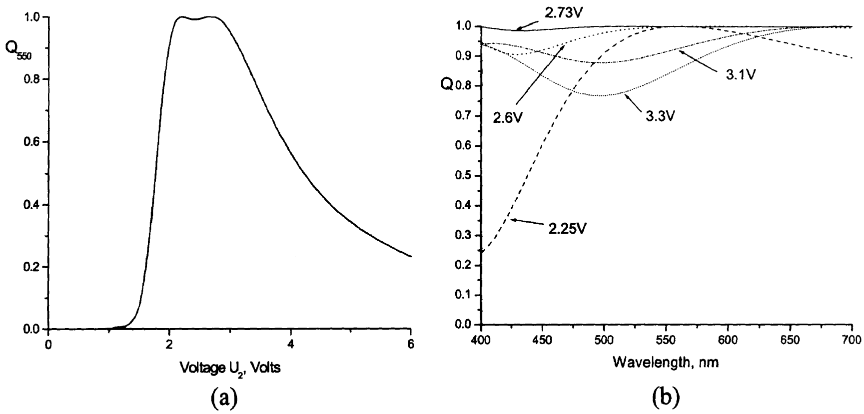

FIGURE 4 (a) Voltage dependence of PTE Q_{550} of LC-layer in RTN LCD. The parameters of the LC layer are given above (see Fig. 2); $U_1 = 0$ V. (b) Wavelength dependence of the PTE parameter Q for RTN-LCD at various voltages $U = U_2$ ($U_1 = 0$ V).

parameter Q is close to 1 within the whole region of the visible spectrum. Indeed, selecting the parameters of the phase compensator to provide the minimum average RLCD reflectance at $U_2 = 2.73$ V, we got the desirable reflectance in the "bright" and the "dark" states (Fig. 2). We applied the compensators consisting of one and two uniaxial plates. Spectral dependence of refractive indices of the phase plates were fixed, while the thickness of the phase plates L_1 and L_2, the orientation angles of these plates ϕ_1 and ϕ_2, and the angle of the polarizer orientation β were varied (Fig. 1). The results of the optimization are shown in Figure 2. The perfect "dark" state can be obtained in case of the two-layer compensator. The spectra shown in Figure 2 were calculated taking into account all parasitic reflections by transfer 8×8 matrix method [14], while AR-layers on the outer boundary of RLCD and around the transparent conductive layer were inserted [15]. The parameters of all the isotropic AR layers were taken from Ref. [15].

4. CALCULATION OF 2×2 TRANSMISSION MATRIX OF LC LAYER

To calculate the 2×2 transmission matrix of LC layer we integrate the differential equation for the transfer operator of 1D-inhomogeneous locally uniaxial medium in the approximation of negligible bulk reflections [12]. This approach provides the higher accuracy of the estimation of the transmission matrix [8,9], as the low LC optical anisotropy is not necessary. Here we present the corresponding calculation technique for the case of normal light incidence.

Matrix $\hat{T}_D$ (see Eq. (1)) can be calculated using the following formulas derived from the mentioned differential equation [12]:

$$\hat{T}_D = R(\vartheta(1))\tilde{t},\ R(\vartheta) = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix},\ \tilde{\mathbf{t}} = \breve{\mathbf{t}}(1)$$

$$\vartheta(\eta) = \int_0^{\eta} f_c(\bar{\eta})\varphi_\eta(\bar{\eta})d\bar{\eta},\ \varphi_\eta \equiv d\varphi/d\eta,$$

$$f_c(\eta) \equiv \frac{1+\frac{1}{2}\gamma(\eta)}{\sqrt{1+\gamma(\eta)}},\quad \gamma(\eta) = \frac{n_e(\eta)}{n_\perp} - 1,\ n_e(\eta) = \frac{n_\| n_\perp}{\sqrt{n_\perp^2 + (n_\|^2 - n_\perp^2)\sin^2\theta(\eta)}}$$

where η is a reduced spatial coordinate along the axis normal to the LC layer boundaries, planes $\eta = 0$ and $\eta = 1$ coincide with these boundaries; $\theta(\eta)$ is a tilt angle of the LC director $\mathbf{n}(\eta)$, $\varphi(\eta)$ is the angle between the rubbing direction on the upper LC layer boundary and the projection of $\mathbf{n}(\eta)$ onto the plane of this boundary; $\mathrm{n}_\|$ and $\mathrm{n}_\perp$ are the principal refractive indices of liquid crystal, $\breve{\mathbf{t}}(\eta)$ is the function satisfying the following equation:

$$\frac{d\breve{\mathbf{t}}(\eta)}{d\eta} = \frac{i\pi d}{\lambda}\Delta\sigma(\eta)\begin{pmatrix} \cos 2\vartheta(\eta) & \sin 2\vartheta(\eta) \\ \sin 2\vartheta(\eta) & -\cos 2\vartheta(\eta) \end{pmatrix}\breve{\mathbf{t}}(\eta),\quad \breve{\mathbf{t}}(0) = \mathbf{U}, \tag{2}$$

$$\Delta\sigma(\eta) \equiv n_e(\eta) - n_\perp$$

$\mathbf{U}$ is the matrix unit, d is the thickness of the LC layer, λ is the wavelength of the incident light in vacuum. To integrate equation (2) the following approximation can be used:

$$\tilde{\mathrm{t}} = \begin{pmatrix} c_1 & c_2 \\ -c_2^* & c_1^* \end{pmatrix} \cong \tilde{\mathrm{t}}_N\tilde{\mathrm{t}}_{N-1}\cdot\ldots\cdot\tilde{\mathrm{t}}_1\tilde{\mathrm{t}}_0, \tag{3}$$

where

$$\tilde{\mathrm{t}}_{\mathrm{j}} = \begin{pmatrix} a_1^{(\mathrm{j})} + ia_2^{(\mathrm{j})} & ia_4^{(\mathrm{j})} \\ ia_4^{(\mathrm{j})} & a_1^{(\mathrm{j})} - ia_2^{(\mathrm{j})} \end{pmatrix},$$

$$a_1^{(\mathrm{j})} = \cos\delta_{\mathrm{j}},\ a_2^{(\mathrm{j})} = \sin\delta_{\mathrm{j}}\cos 2\vartheta_{\mathrm{j}},\ a_4^{(\mathrm{j})} = \sin\delta_{\mathrm{j}}\sin 2\vartheta_{\mathrm{j}},$$

$$\delta_{\mathrm{j}} = \frac{\pi\Delta\sigma(\eta_{\mathrm{j}})\Delta\eta_{\mathrm{j}}d}{\lambda},\ \vartheta \equiv \vartheta(\eta_{\mathrm{j}}),$$

$$\eta_{\mathrm{j}} = \mathrm{j/N}, \quad \mathrm{j} = 0, 1, \ldots, \mathrm{N};$$

$$\Delta\eta_{\mathrm{j}} = \begin{cases} 1/N, & \mathrm{j} = 1, 2, \ldots, N-1, \\ 1/(2N), & \mathrm{j} = 0, \mathrm{N}; \end{cases}$$

$N+1$ is the number of the integration nodes. The values of $\vartheta(\eta)$ in the integration nodes η_{j} can be calculated as follows

$$\vartheta(\eta_0) = 0,\ \vartheta(\eta_{\mathrm{j}}) = \vartheta(\eta_{\mathrm{j}-1}) + \Delta\vartheta_{\mathrm{j}}, \quad \mathrm{j} = 1, 2, \ldots, N,$$

$$\Delta\vartheta_{\mathrm{j}} \cong \frac{1}{2}(f_c(\eta_{\mathrm{j}}) + f_c(\eta_{\mathrm{j}-1}))(\varphi(\eta_{\mathrm{j}}) - \varphi(\eta_{\mathrm{j}-1}))$$

A reasonable good accuracy of the estimation of the matrix $\hat{T}_D$ is usually achieved at $N = 200$. Specific forms of the matrices $\tilde{\mathbf{t}}_{\mathrm{j}}$ allows a simple calculation of the components of matrix $\tilde{\mathbf{t}}$ (see Eq. (3)) with the following recurrent formulas:

$$c_1^{(0)} = a_1^{(0)},\ c_2^{(0)} = a_2^{(0)},\ c_3^{(0)} = 0,\ c_4^{(0)} = a_4^{(0)},$$

$$c_1^{(\mathrm{j})} = a_1^{(\mathrm{j})} c_1^{(\mathrm{j}-1)} - a_2^{(\mathrm{j})} c_2^{(\mathrm{j}-1)} - a_4^{(\mathrm{j})} c_4^{(\mathrm{j}-1)},$$

$$c_2^{(\mathrm{j})} = a_1^{(\mathrm{j})} c_2^{(\mathrm{j}-1)} + a_2^{(\mathrm{j})} c_1^{(\mathrm{j}-1)} - a_4^{(\mathrm{j})} c_3^{(\mathrm{j}-1)},$$

$$c_3^{(\mathrm{j})} = a_1^{(\mathrm{j})} c_3^{(\mathrm{j}-1)} - a_2^{(\mathrm{j})} c_4^{(\mathrm{j}-1)} + a_4^{(\mathrm{j})} c_2^{(\mathrm{j}-1)},$$

$$c_4^{(\mathrm{j})} = a_1^{(\mathrm{j})} c_4^{(\mathrm{j}-1)} + a_2^{(\mathrm{j})} c_3^{(\mathrm{j}-1)} + a_4^{(\mathrm{j})} c_1^{(\mathrm{j}-1)},$$

$$\mathrm{j} = 1, 2, \ldots, N;$$

$$\mathrm{Re}c_1 = c_1^{(N)},\ \mathrm{Im}c_1 = c_2^{(N)},\ \mathrm{Re}c_2 = c_3^{(N)},\ \mathrm{Im}c_2 = c_4^{(N)}.$$

As normal light incidence is considered, matrix $\hat{T}_R$ (see Eq. (1)) can be expressed in terms of the matrix $\hat{T}_D$ components as follows

$$\hat{T}_R = \begin{pmatrix} [\hat{T}_D]_{11} & -[\hat{T}_D]_{21} \\ -[\hat{T}_D]_{12} & [\hat{T}_D]_{22} \end{pmatrix}.$$

5. CONCLUSION

A new approach for optimization of reflective LCD has been presented. Using the parameter called "Polarization Transformation Efficiency", we have optimized one-polarizer RLCD in RTN mode with phase compensators. Insertion of a phase compensator into RTN RLCD enables to realize perfect dark and bright states of the device. We believe that the proposed new method of LCD optimization can be successfully applied for the definition of new advances LCD configurations with a high brightness, contrast and duty ratio.

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