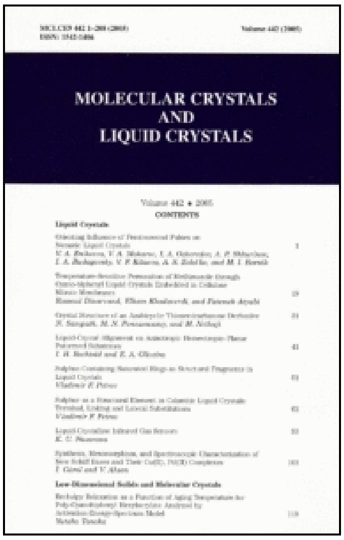

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Influence of Liquid Crystal Texture on Optical Parameters of Transmissive LCD Working Under High External Lighting

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Influence of Liquid Crystal Texture on Optical Parameters of Transmissive LCD Working Under High External Lighting

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The problem with using of transmissive liquid crystal displays under high external (sunlight) illumination conditions is widely well known for many years [1,2]. Especially, it can be seen in case of angle characteristics of luminance or contrast ratio. This problem can be partially solved, for example, by using antireflective layers, proper choosing of polarizers and texture of liquid crystal layer. In this work the influence of liquid crystal layer texture on angle characteristics of luminance and contrast ratio of the display operating under high external illumination is analyzed. To do it, transmissive liquid crystal displays with TN [3] and IPS [4] effects were chosen. The analysis was done using computer program [5,6] offering determination of optical parameters of a display for any observation angle and any optical parameters of the display elements, taking into account the interference phenomena occurring in a display, different direction of ordinary and extraordinary wave-vectors, dispersion phenomena of refractive indices, absorption coefficients of the display layers, etc. These calculations were done for TN and IPS conditions, different polarizers, external light intensity and for negative display mode. The results have shown in detail the influence of chosen texture of LC layer on angle characteristics of optical parameters of a display working under high external illumination conditions.

Keywords Contrast ratio; high external lighting; in-plane switching; luminance; twisted nematic

1. Introduction

The liquid crystal (LC) displays take advantages of different effects occurring in the liquid crystal thin layer. Majority of them are based on an influence of the external electric field on molecular director. The product of influence of an electric field and cell surface on liquid crystal molecules leads to formation of the organized structure, so-called texture. In the displays using the nematic liquid crystals, the most popular effects base on twisted liquid crystal layers, especially the TN (twisted nematic) effect, where the twist angle between cell walls in off-state equals 90°. After the application of electric field the texture of a layer changes from twisted to homeotropic one

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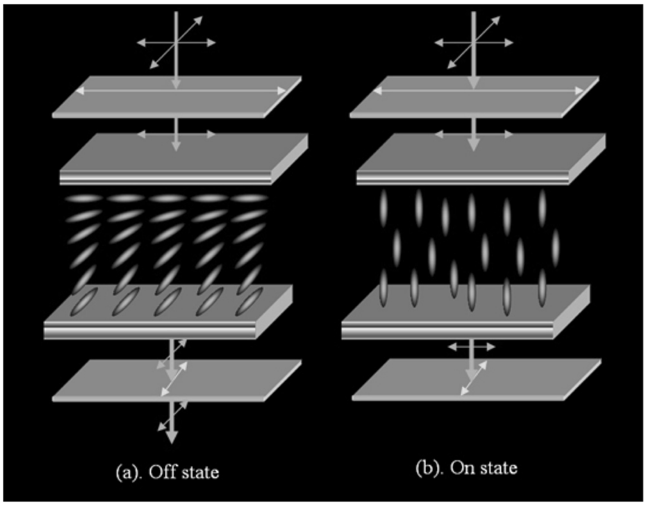


Figure 1. The operating principle of TN display. Normally white (NW) mode is presented. (Picture from website www.personal.kent.edu)

(see Fig. 1). The twisted texture rotates the polarization plane of light passing through the LC layer, while homeotropic structure does not, so we can modulate the light intensity by using two polarizers placed on the both surfaces of a LC layer. Depending on the angle of the mutual arrangement of polarizer and analyzer axes we can obtain in the off-state white or dark image. Such modes of TN display are called: normally white (NW) and normally black (NB), respectively.

TN effect is well known and widely described. Additionally its technology is not difficult and is used for tens of years. Unfortunately, despite TN effect is sufficient for standard visualization applications, the displays using this effect have several essential disadvantages, which causes that its applications in not standard conditions, for example under high external illumination, is not workable. The main disadvantages of TN display are as follows: high dependence of luminance and contrast ratio on observation angle, not sufficient values of obtained contrast ratio, not symmetric distribution of contrast ratio as a function of observation angle, etc. Especially, it concerns TV or computer screens, because in that case NB mode should be applied. This display mode does not make it possible to obtain the contrast ratio higher than about 1:150 (for ideal polarizers, whole visible range of light and taking into account sensitivity function of human eye), because the optical matching in off-state (twisted texture) can be achieved only for one wavelength perfectly. Therefore for these applications, to obtain the displays with high contrast ratio and wide and symmetric angle characteristics, new effects (display modes) had to be worked out [7–10].

One of promising effect seems to be In-Plane Switching mode (IPS), which principles are presented in Figure 2. This mode can create only negative images, but it is very good for TV and computer screen applications. The main advantage of this mode is the fact that in the dark state (off-state) we have non-twisted structure and the director is parallel to the polarizer axis (perpendicular to the analyzer axis), so the polarization of a light passing through the display does not change during this process. Therefore, dark state is determined mainly by properties of the used

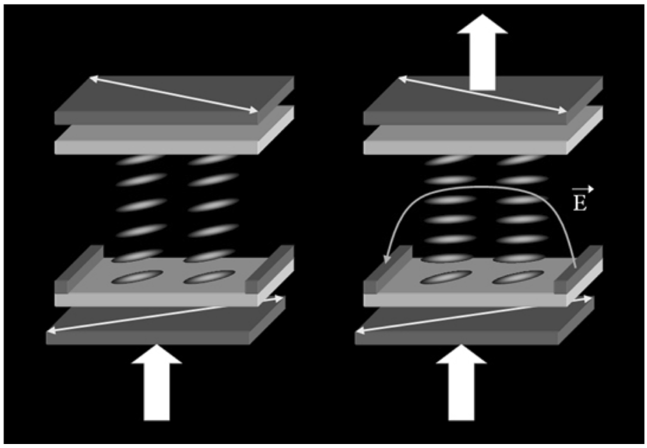


Figure 2. The operating principle of IPS display. (Picture from website www.personal.kent.edu)

polarizing films. It allows to obtain considerably higher values of contrast ratio than in TN display. Additionally, the angle distribution of luminance and contrast is wider and more symmetrical that in TN effect.

In this work such angle characteristics of transmissive NB TN and IPS displays working under high illumination are presented and compared.

2. Short Information About the Mathematical Model of a Light Propagation Through the Display Used in Our Work

To determine the transmission characteristics of light passing through a LC display the Maxwell equations for generally dichroic medium (1) were used, and are presented below.

$$\begin{array}{l} 1)\ rot\overrightarrow{H} - \frac{\delta \overrightarrow{D}}{\delta t} = 0 \\ 2)\ rot\overrightarrow{E} + \frac{\delta \overrightarrow{B}}{\delta t} = 0 \\ 3)\ div\overrightarrow{D} = 0 \\ 4)\ div\overrightarrow{B} = 0 \end{array} \quad \text{and} \quad \begin{array}{l} \overrightarrow{D} = \varepsilon_o \hat{\varepsilon} \overrightarrow{E} \\ \overrightarrow{B} = \mu_o \mu \overrightarrow{H} \end{array} \quad \text{where } \hat{\varepsilon} = \begin{bmatrix} \varepsilon_o & 0 & 0 \\ 0 & \varepsilon_o & 0 \\ 0 & 0 & \varepsilon_e \end{bmatrix} \qquad (1)$$

$\hat{\varepsilon}$ denotes dielectric tensor of a medium, $\overrightarrow{B}$ and $\overrightarrow{H}$ describe the magnetic filed, $\overrightarrow{D}$ and $\overrightarrow{E}$ describe electric field, ε_o and ε_e denote the principal dielectric constants measured for directions perpendicular and parallel to the optical axis of a medium. Generally ε_o and ε_e have a complex form.

The equations in shape (1) can be used to describe different kinds of media: anisotropic, isotropic with absorption and only isotropic one. It is very convenient, because using these equations in one form allows all layers composing LC display to be described. After describing these equations for every layer of an analyzed display (using the optical properties of each one such as refractive index/indices in complex form and orientations of optical axis and also initial conditions defined by an angle of incidence of a light) the ordinary wavevector $\overrightarrow{k_o}$ and extraordinary one $\overrightarrow{k_e}$ of light for each display layer can be obtained as (2):

$$\overrightarrow{k_o} = \begin{bmatrix} \beta\cos\alpha\cos\phi\cos\Theta + \beta\sin\alpha\sin\phi\cos\Theta - k_{oz}\sin\Theta \\ -\beta\cos\alpha\sin\phi + \beta\sin\alpha\cos\phi \\ \beta\cos\alpha\cos\phi\sin\Theta + \beta\sin\alpha\sin\phi\sin\Theta + k_{oz}\cos\Theta \end{bmatrix}$$
$$\overrightarrow{k_e} = \begin{bmatrix} \beta\cos\alpha\cos\phi\cos\Theta + \beta\sin\alpha\sin\phi\cos\Theta - k_{ez}\sin\Theta \\ -\beta\cos\alpha\sin\phi + \beta\sin\alpha\cos\phi \\ \beta\cos\alpha\cos\phi\sin\Theta + \beta\sin\alpha\sin\phi\sin\Theta + k_{ez}\cos\Theta \end{bmatrix} \tag{2}$$

$\beta = (\omega/c)\, n_i \sin\Theta_i$, n_i denotes refractive index of an external medium, Θ_i is an angle of incidence of a light, and:

$$k_{oz} = \pm\sqrt{\frac{\omega^2}{c^2}n_o^2 - \beta^2} \qquad k_{ez} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{2a}$$

where:

$$A = n_o^2\sin^2\Theta + n_e^2\cos^2\Theta$$
$$B = \beta\sin 2\Theta\cos(\alpha - \phi)(n_e^2 - n_o^2)$$
$$C = \beta^2\cos^2(\alpha - \phi)(n_o^2\cos^2\Theta + n_e^2\sin^2\Theta) + \beta^2\sin^2(\phi - \alpha)n_o^2 - \frac{\omega^2 n_e^2 n_o^2}{c^2}$$

n_o and n_e denote the ordinary and extraordinary refractive index of analyzed layer, α is the rotation angle of incidence surface of a light and laboratory coordinate system, ϕ and Θ are the angles of the mutual relations between optical axis of a given layer and laboratory coordinate system.

Additionally, the unit vectors of an electric field ($\overrightarrow{o}$ – for ordinary wave and $\overrightarrow{e}$ for extraordinary one) in each layers can be determined as (3):

$$\overrightarrow{o} = \left[\frac{-k_y}{\sqrt{k_x^2 + k_y^2}}, \frac{k_x}{\sqrt{k_x^2 + k_y^2}}, 0\right] \text{ and}$$
$$\overrightarrow{e} = \left[\frac{k_x}{M\left(\frac{\omega^2 n_o^2}{c^2} - k^2\right)}, \frac{k_y}{M\left(\frac{\omega^2 n_o^2}{c^2} - k^2\right)}, \frac{k_z}{M\left(\frac{\omega^2 n_e^2}{c^2} - k^2\right)}\right] \tag{3}$$

where:

$$M = \sqrt{\frac{k_x^2 + k_y^2}{\left(\frac{\omega^2 n_o^2}{c^2} - k^2\right)^2} + \frac{k_z^2}{\left(\frac{\omega^2 n_e^2}{c^2} - k^2\right)^2}}.$$

It should be underlined that the Eq. (2a) give two solutions, which describe two possible directions of light propagation through a given layer for fixed external conditions defined by the angles of light incidence. Therefore, after this part of calculations the Maxwell equations for each phase boundary occurring in a LC display can be formulated in unambiguous way. Solving these equations described for electric and magnetic fields of a light passing through the boundary gives the transmission and reflection coefficients. And again, these coefficients for the both possible directions of propagating light are calculated in one procedure. The obtained coefficients have a following shortened form (4):

$$T = \begin{bmatrix} t_{oo} & t_{eo} \\ t_{oe} & t_{ee} \end{bmatrix} \quad \text{and} \quad R = \begin{bmatrix} r_{oo} & r_{eo} \\ r_{oe} & r_{ee} \end{bmatrix} \tag{4}$$

t_{ab} and r_{ab} denote the transmission and reflection coefficients, respectively. The acronym *ab* describes the transformation of *a-type* wave to *b-type* wave is represented by this coefficient and *o* denotes ordinary wave, *e* – extraordinary one.

Because the wavevectors can have a complex form, the matrices T and R generally include the complex expressions, but have very useful form for computer processing. Using these coefficients calculated for all boundaries occurring in an analyzed display:

- the first: the transmission and reflection coefficients for each layer of a display,
- the second: the general transmission and reflection coefficients for a display as a whole,

can be obtained.

The proposed by us method of constructing of these coefficients is schematically presented in Figure 3.

The acronyms $T_{(n)}$, $T'_{(n)}$, $R_{(n)}$, $R'_{(n)}$, $T_{(N)}$, $T'_{(N)}$, $R_{(N)}$, $R'_{(N)}$, $T_{(N+1)}$, $T'_{(N+1)}$, $R_{(N+1)}$ and $R'_{(N+1)}$ describe:

$T_{(n)}$ – transmission of a layer no. n for +z direction of a wave propagation,
$T'_{(n)}$ – transmission of a layer no. n for −z direction of a wave propagation,
$R_{(n)}$ – reflection of a layer no. n for +z direction of a wave propagation,
$R'_{(n)}$ – reflection of a layer no. n for −z direction of a wave propagation,
$T_{(N)}$ – transmission of a system of layers from no. 1 to no. N for +z direction of a wave propagation,
$T'_{(N)}$ – transmission of a system of layers from no. 1 to no. N for −z direction of a wave propagation,
$R_{(N)}$ – reflection of a system of layers from no. 1 to no. N for +z direction of a wave propagation,
$R'_{(N)}$ – reflection of a system of layers from no. 1 to no. N for −z direction of a wave propagation,
$T_{(N+1)}$ – transmission of a system of layers from no. 1 to no. N + 1 for +z direction of a wave propagation,
$T'_{(N+1)}$ – transmission of a system of layers from no. 1 to no. N + 1 for −z direction of a wave propagation,
$R_{(N+1)}$ – reflection of a system of layers from no. 1 to no. N + 1 for +z direction of a wave propagation,
$R'_{(N+1)}$ – reflection of a system of layers from no. 1 to no. N + 1 for −z direction of a wave propagation.

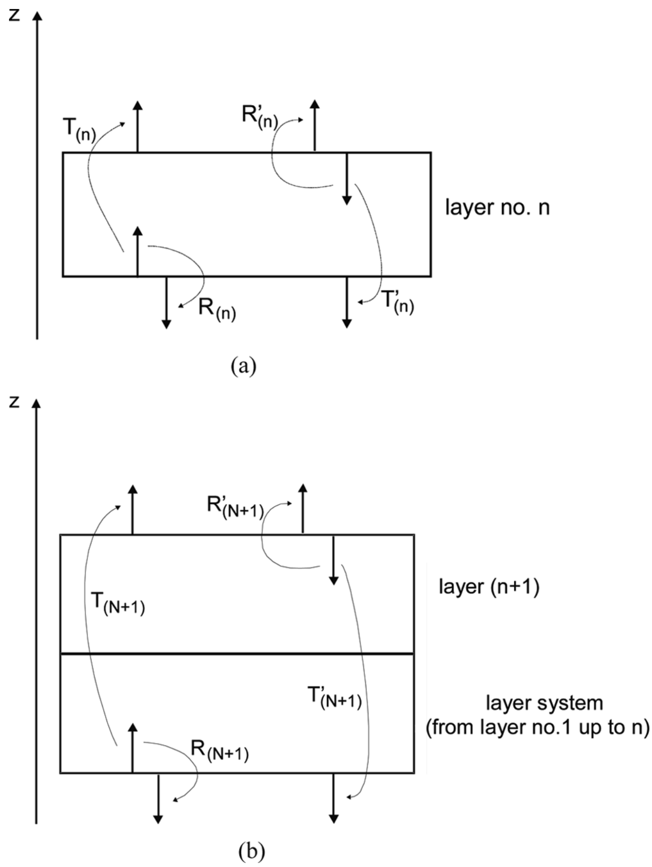


Figure 3. The schema of determining of transmission and reflection coefficients: (a) for a single layer and (b) for a display as a whole.

It is worth to underline that the coefficients describing a particular layer obtained using the presented method, include the information about multi interference effects occurring in this layer. The coefficients obtained for system of the layers include additionally the information about an interference phenomena occurring in the whole system – all combinations are taken into account. To describe these interference phenomena properly, time cohesion coefficients of a light are used. These coefficients are obtained basing on spectral characteristics – for transmissive display – of the both illuminating sources: external and internal ones, using the Fourier transformations.

The process of calculation the transmission and reflection coefficients for a system of the layers is very easy for computer processing, because the next coefficients obtained during this process are connected by very simple relations (5):

$$T_{(N+1)} = \sum_{m=1}^{\infty}[T_{(n+1)}(R'_{(N)}R_{(n+1)})^{m-1}T_{(N)}] = \begin{bmatrix} T_{oo}^{(N+1)} & T_{eo}^{(N+1)} \\ T_{oe}^{(N+1)} & T_{ee}^{(N+1)} \end{bmatrix}$$
$$T'_{(N+1)} = \sum_{m=1}^{\infty}[T'_{(N)}(R_{(n+1)}R'_{(N)})^{m-1}T'_{(n+1)}] = \begin{bmatrix} T'^{(N+1)}_{oo} & T'^{(N+1)}_{eo} \\ T'^{(N+1)}_{oe} & T'^{(N+1)}_{ee} \end{bmatrix} \tag{5}$$

$$R_{(N+1)} = R_{(N)} + \sum_{m=2}^{\infty}[T'_{(N)}(R_{(n+1)}R'_{(N)})^{m-2}R_{(n+1)}T_{(N)}] = \begin{bmatrix} R_{oo}^{(N+1)} & R_{eo}^{(N+1)} \\ R_{oe}^{(N+1)} & R_{ee}^{(N+1)} \end{bmatrix}$$

$$R'_{(N+1)} = R'_{(n+1)} + \sum_{m=2}^{\infty}[T_{(n+1)}(R'_{N}R_{(n+1)})^{m-2}R'_{(N)}T'_{(n+1)}] = \begin{bmatrix} R_{oo}^{\prime(N+1)} & R_{eo}^{\prime(N+1)} \\ R_{oe}^{\prime(N+1)} & R_{ee}^{\prime(N+1)} \end{bmatrix}$$

As one can see, starting from layer no. 1 in $k-1$ steps (k – number of the layers in an analyzed display) the transmission and reflection coefficients of a display as a whole can be calculated using the equations presented above.

The full descriptions of this mathematical theory of light propagation is published in our earlier papers [5,6].

3. Assumptions of the Angle Characteristics Calculations

To calculate the angle characteristics of luminance and contrast ratio the computer program, written in our Institute, was used. This program relies on mathematical model of light propagation through the display described above. This mathematical model makes it possible to obtain the transmission and reflection coefficients of a display taking into account:

- interference phenomena occurring in a display taking into account all layers;
- absorption coefficient of each layer and dispersion of it;
- dispersion of refractive indices of the layers;
- any angle of a light propagation;
- real direction of ordinary and extraordinary waves propagation and real direction of polarization of its (no small birefringence approximation);
- any director profile function in a LC layer.

The calculation can be performed for any wavelength, and in the same time the transmission and reflection coefficients are calculated for given observation angle. It is very convenient, because luminance of a display as a sum of luminance from external and internal light sources can be obtained in one calculation process.

In our calculation of luminance and contrast ratio of NB TN and IPS displays the following properties of a display elements were assumed:

- float sodium glass with refractive index equal to 1.5267 (435 nm), 1.5224 (486 nm), 1.5187 (546 nm), 1.5178 (587 nm) and 1.5143 (656 nm) and thickness of 0.7 mm;
- ITO conductive layer with refractive index equal to 1.8320 and thickness of 25 nm;
- liquid crystal layer with thickness of 6 μm;
- Δnd equal to 0.48 and 0.3 for NB TN and IPS, respectively;
- internal light source is A type, external one D_{65} type;
- interference antireflective layer on the front surface of a display (the same for NB TN and IPS) is matched to 550 nm;
- polarizer and analyzer with thickness of 0.25 mm and the same optical properties (presented in Table 1);
- profile function was obtained using variational method (using minimum of total free energy) [11] for weak anchoring of liquid crystal on both side of cell.

Table 1. The main properties of the polarizing films used in the calculations

No.	PC	T(II)	T(+)	k_o	k_e
1	0.9999	0.8	0.000040	0.00003907	0.00293344
2	0.999	0.8	0.000400	0.00003907	0.02934757
3	0.995	0.8	0.002005	0.00003907	0.14703207
4	0.99	0.8	0.004020	0.00003907	0.29480299

where:

PC – polarization coefficient of a film;

T(II) and T(+) denote the transmission coefficients of a light, linearly polarized parallel and perpendicular to the polarization axis of a film, respectively. These transmissions are determined for the "virtual" situation, where the refractive index of a film equal to 1. In the other words, such constructed coefficients include the information only about absorption of a film. It is very useful, because such coefficients can be applied in calculations in the same way independent from properties of external medium (glass, air, antireflective layer etc.);

k_o and k_e are the imaginary part of refractive indices for ordinary and extraordinary wave, respectively.

The calculations were performed for visible range of light (400 nm–750 nm), using daily human eye sensitivity function.

4. Obtained Results

As a result the cross section functions of a luminance of the both states (OFF and ON) as well as contrast ratio were obtained. These functions were calculated for azimuth angle equal to 0 deg (according to the polarizer axis) and 90 deg (perpendicular to it). In Figures 4 and 5 the most interesting results (cross section of contrast ratio) are presented, calculated for NB TN and IPS display, respectively. These calculations were done for the situation of high external lighting, e.g., the intensity of external light was equal from 100% to 300% of intensity of internal light source.

As one can see in the figures presented above, ISP mode has a better angle characteristics of contrast ratio that NB TN one. First of all, one can see in Figure 4 that for NB TN effect the maximum value of contrast ratio possible to obtain under high external lighting is lower than 1:120 and is achieved only for very narrow observation angle. Additionally, one can observe high asymmetrical distribution of contrast ratio (left-right and up-down), especially for polarizing films with low polarization coefficient. The difference between the values of contrast ratio for the same azimuth angle can achieve even 20%. It should be noticed here, that visible angle very fast decreases when the external intensity light increases. For example, for contrast ratio equal to 1:20, the observation angle decreases from about 50 deg (for external intensity equal to 100% of internal one) to about 38 deg for external intensity equals 300%. In IPS mode contrast ratio can reach much higher values. It is even more that 1:400 for intensity of external light equals 100% of intensity of internal illumination. But even for very high external lighting (300%) contrast ratio (for polar angle equal 0 deg) equals about 1:140. It is more that maximum possible value in NB TN mode. Additionally, one can see in Figure 5 the angle distribution of

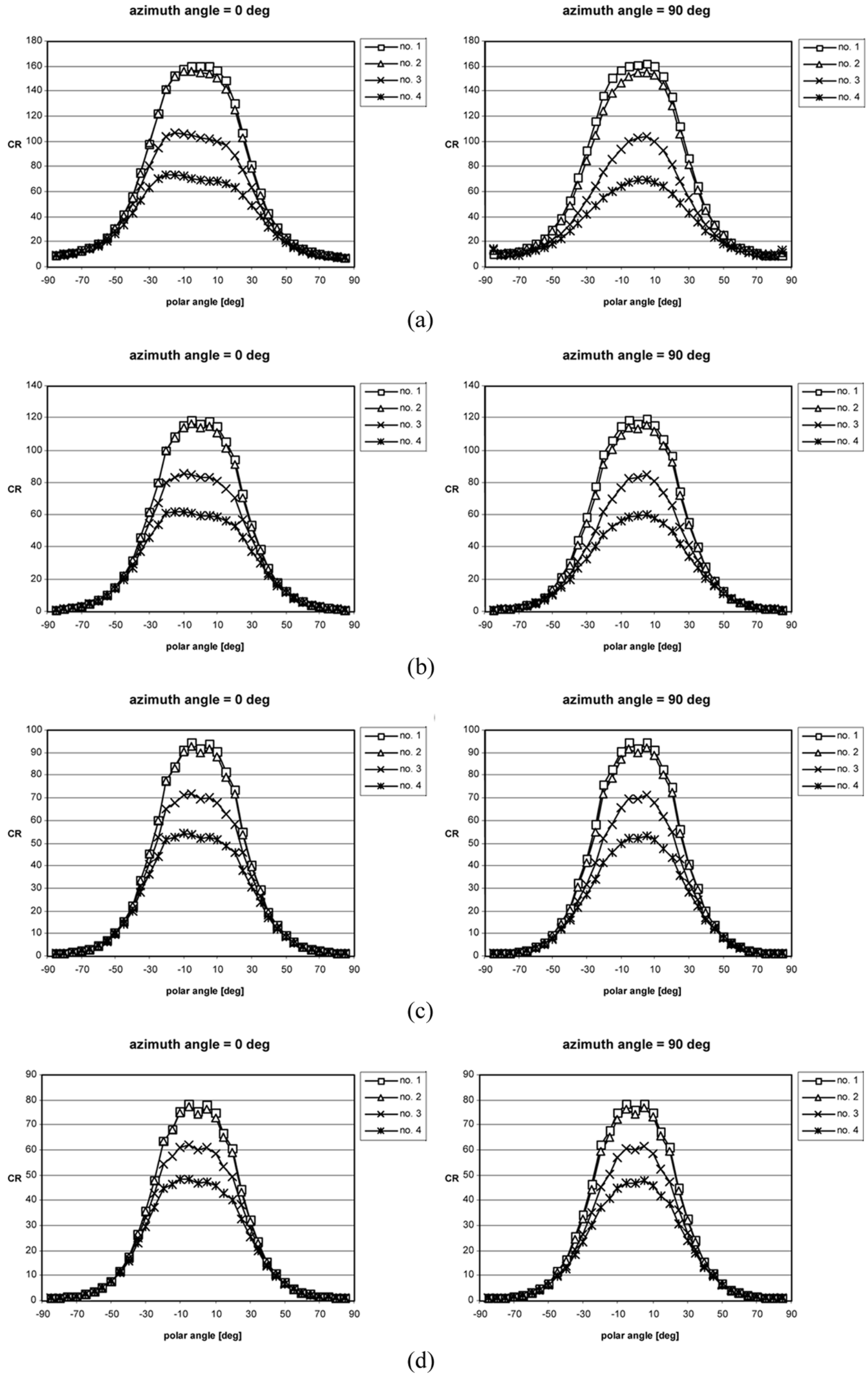
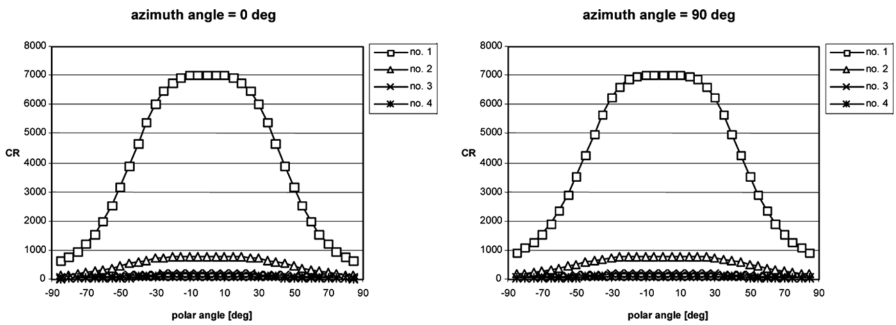
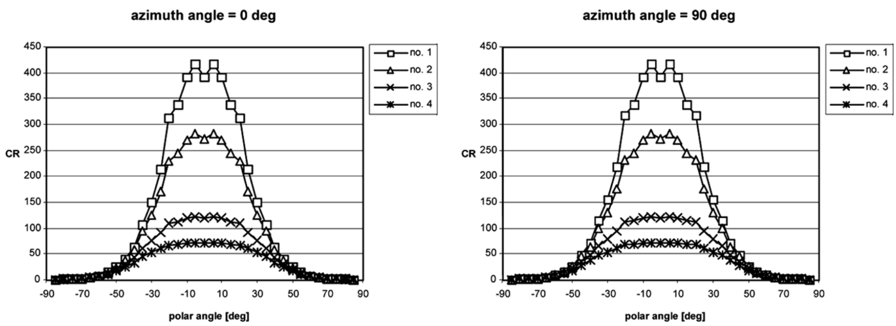


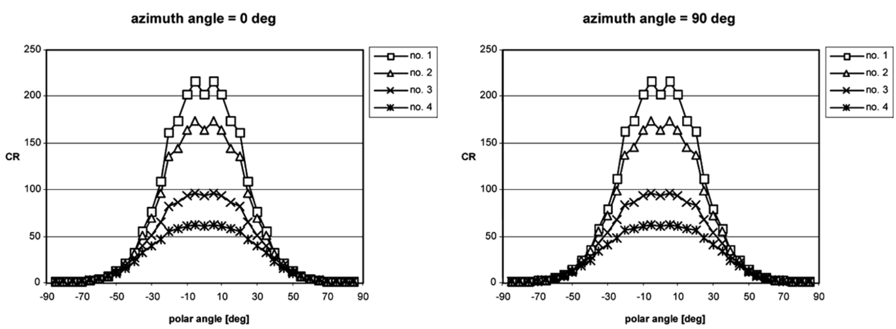
Figure 4. Cross-section of contrast ratio of NB TN transmissive display; (a) – no external light, (b) – external light intensity equals 100% of external one, (c) – external light intensity equals 200% of external one, (d) – external light intensity equals 300% of external one.



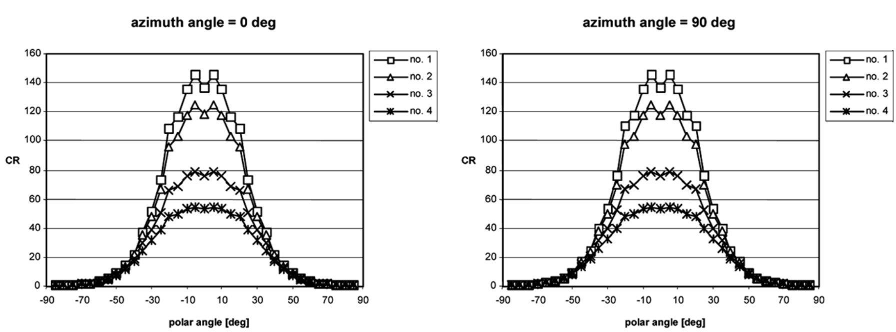
(a)



(b)

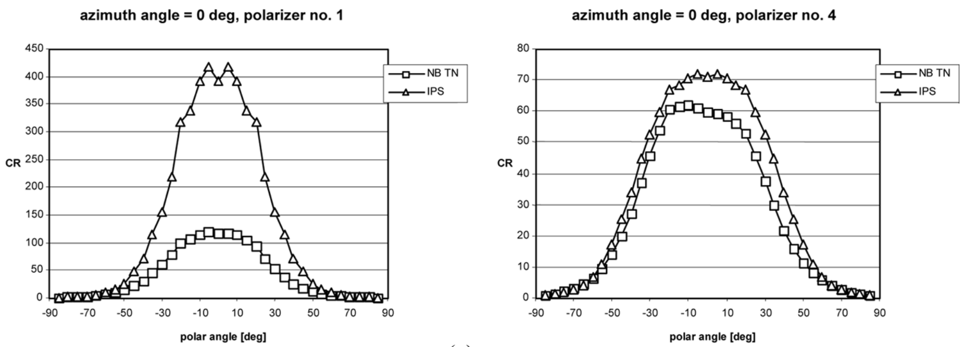


(c)

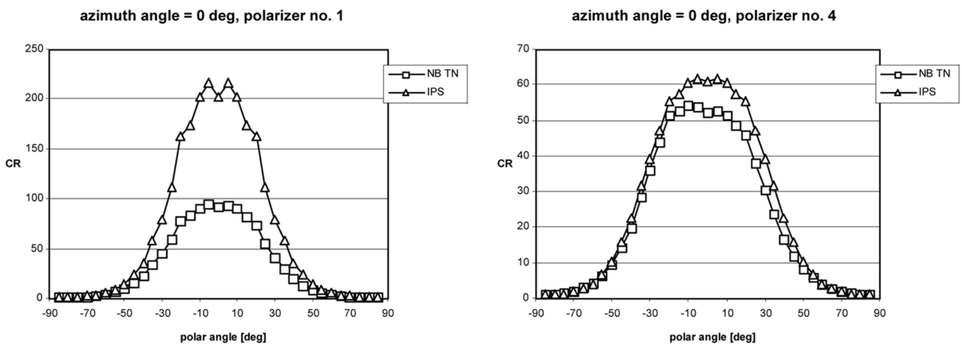


(d)

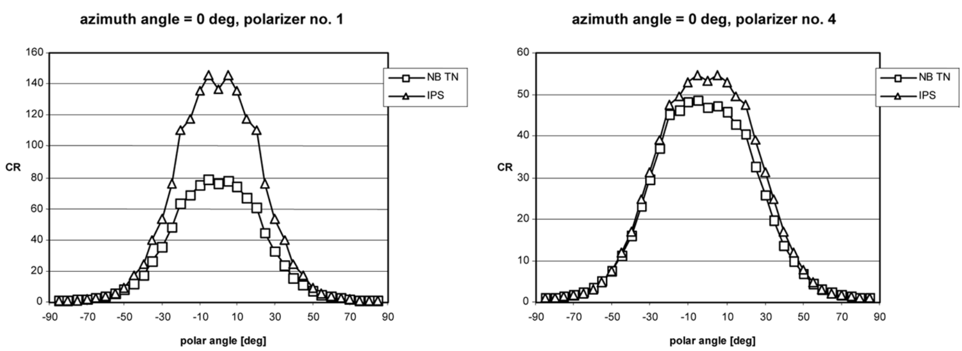
Figure 5. Cross-section of contrast ratio of IPS transmissive display; (a) – no external light, (b) – external light intensity equals 100% of external one, (c) – external light intensity equals 200% of external one, (D) – external light intensity equals 300% of external one.



(a)



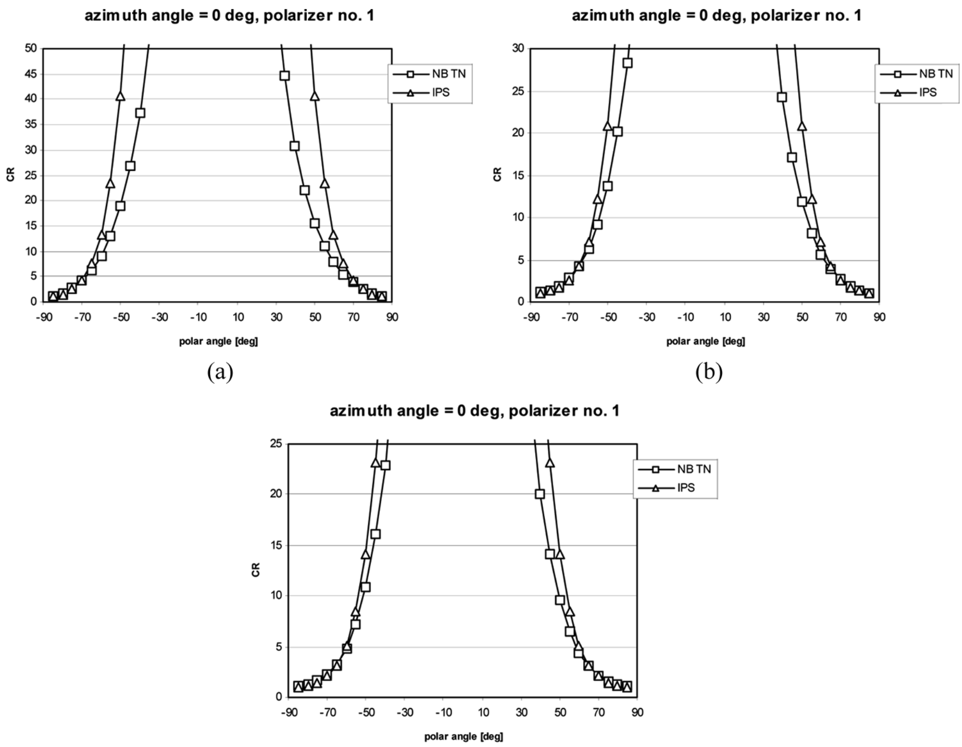
(b)



(c)

Figure 6. Comparison of cross-sections of contrast ratio of NB TN and IPS transmissive displays for polarizers nos. 1 and no. 4; (a) – external light intensity equals 100% of external one, (b) – external light intensity equals 200% of external one, (c) – external light intensity equals 300% of external one.

contrast ratio is very symmetrical in all directions and for all polarizers. Additionally the viewing angle is wider (for the same values of contrast ratio) than for NB TN mode. For value of contrast ratio equals 1:20 it is 55 deg (for external intensity light equals 100% of internal one) and 41 deg (for 300%). The improvement (increase) of viewing angle is especially shown for the bright polarizing films (see polarizer no. 4 in Fig. 6), but for polarizers with high polarization coefficient this angle is also wider (see Fig. 7).



(a) (b) (c)

Figure 7. Increasing of view angle in IPS in comparison with NB TN LCD for polarizer no. 1; (a) – external light intensity equals 100% of external one, (b) – external light intensity equals 200% of external one, (c) – external light intensity equals 300% of external one.

5. Conclusions

The results obtained by us in this work show the influence of the display mode (NB TN or ISP) on angle distribution of contrast ratio for different polarising films. It should be underlined, that in our calculations all elements of a display, despite optical matching (e.g., birefringence of liquid crystal) and profile function of director, are identical in the both cases (thickness, refractive indices, mutual arrangement etc.). Therefore obtained results can be treated as good comparison between optical parameters (in this case contrast ratio) possible to obtain using NB TN and IPS modes. It should be underlined in this place that our results show the difference between angle characteristics of NB TN and IPS effects in the case when high external illuminating occurs. Therefore, its can be usefulness in the case of analyze of LC displays applied in the special conditions, for example sunlight illuminated places.

Acknowledgments

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