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ПОВЫШЕНИЕ КОНТРАСТА ОТРАЖАТЕЛЬНЫХ ЖИДКОКРИСТАЛЛИЧЕСКИХ ДИСПЛЕЕВ НА ОСНОВЕ НЕМАТИКОВ

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Предложен метод численного расчета оптических характеристик отражательных жидкокристаллических дисплеев (ЖКД), на основе которого проведена их оптимизация. Результаты получены для таких элементов ЖКД, как поляризационные пленки, дихроичные слои жидких кристаллов, противоотражающие и проводящие слои, стеклянные подложки и т.д. Определена зависимость контраста отражательного ЖКД на основе твист-эффекта от свойств составляющих его элементов.

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THE CONTRAST RATIO IN A REFLECTIVE LIQUID CRYSTAL DISPLAY WITH A NEMATIC PHASE

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The way of the numerical calculations of the optical parameters for a reflective LCD is presented. Basing on these calculations the optimization procedure for such a display had been carried out. The results have been obtained for different properties of the display elements such as the polarizing films and dichroic liquid crystals layer. It have been done for given antireflective layer, conductive layer, glass etc. As the result the characteristics of the contrast ratio of the reflective twisted nematic display as a function of the properties of the different display elements are presented.

1. Introduction

The reflective mode of liquid crystal display (RM LCD) makes it possible to use an external light and from this reason the power consumption of such a display can be not high. Therefore this mode is still rival in comparison with other display types. It applies also to the new display types, e.g. organic light emitting diode (OLED). Additionally, the technology of RM LCD is good known and worked out. The most serious problem with such a display is the value of the contrast ratio and luminance in bright state and its angle characteristics. However, the proper choice of the display elements such as polarizers, liquid crystal mixtures, glass, conductive, antireflective and other layers can makes it possible to obtain very high contrast and brightness of this display.

The described display can work in positive or negative mode. In our work the second one is analyzed. This choice has been done because in this mode the color visualization can be obtain in very simple method (e.g. by a filter application). It should be underlined that in this mode the influence of the liquid crystal layer on the display optical parameters is especially high. It makes it possible to carry out the optimization procedure by means of a selection of the display elements with proper parameters.

The practical accomplishment such a procedure is very complicated because it requires to do many experiments. Additionally, we have to have the very large set of all display elements. Therefore the computer program for the calculations of a display optical parameters can be very useful. This program have to calculate these parameters very correctly. Very correctly means in this case that the obtained results will be accorded to the results from the experiments [1, 2]. It causes that in this program the following condition and phenomena should be take into account [1–6]: light reflections from all phase boundaries; light interferences into the display; human eye sensitivity; real spectral characteristics of light sources; light absorption of all display elements; real state of an illuminating light polarization.

Additionally, the measurement methods of the display elements should be worked out in this way to assure possibility to use directly these experimental results in the numerical program. Therefore these measurement methods of e.g. polarizer (transmissive and reflective one), conductive layer, glass and liquid crystal layer have been also worked out.

2. Parameters of the display elements used in the calculations

The display construction established in our calculations is presented in Fig. 1.

For proper describing and calculation process of this display the following parameters have been determined for the wavelengths from all visible range.

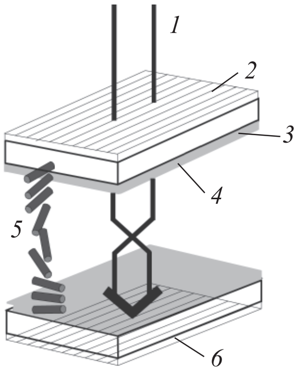

Fig. 1. The system of a reflective display analyzed in our work. *1* – light beam, *2* – transmissive polarizer with antireflective layer, *3* – glass, *4* – conductive layer, *5* – LC molecules, *6* – reflective polarizer.

2.1. Polarizing films

For describing of the polarizing properties of used film a polarization coefficient should be determined. This parameters is denoted in this work as WWP and is generally defined as [7, 8]:

$$\text{WWP} = \frac{I^{\|} - I^{+}}{I^{\|} + I^{+}} 100\%, \qquad (1)$$

where $I^{\|}$ and I^{+} denote a light intensity after a passing through the single film (or a reflection from a film) linearly polarized parallel or perpendicular to the film polarization axis, respectively.

This coefficient should be obtained for transmissive and reflective film in different way. For transmissive one it is relatively simple situation. In this case the polarization coefficient do not depend on external center and can be obtained from the measurements done for two parallel and crossed polarizers. One can easily show that the coefficient described by equation (1) can be described also as [6]:

$$\text{WWP}^{t} = \frac{T_p(\|) - T_p(+)}{T_p(\|) + T_p(+)} = \sqrt{\frac{T_{pm}^{\|} - T_{pm}^{+}}{T_{pm}^{\|} + T_{pm}^{+}}}, \qquad (2)$$

where $T_p(\|)$ and $T_p(+)$ denote the transmission coefficient through a single polarizing film for a light linearly polarized parallel and perpendicular to the polarizer axis, respectively. $T_{pm}^{\|}$ and T_{pm}^{+} denote the transmission coefficient measured for two parallel or crossed polarizers, respectively.

As one can see, it is very simple to determine a polarization coefficient WWP^t for a transmissive film. Two measurement processes should be done: the first one for two parallel films, the second one: for crossed ones. For reflective films the situation is more complicated. On the one hand in this case the polarization coefficient should describe the absorption properties of a film adequate to the transmissive film. On the other hand for reflective polarizer the light passes through the film twice. Additionally, the reflection phenomena from an external boundary gives the not polarized light which adds to the measurements. From this reason the measurement method for a reflective film should be different. For proper determination the polarization coefficient of a reflective polarizer the linearly polarized light should be used. Two experiments should be done: the first one for a light linearly polarized according to the polarizer axis and the second one: for perpendicular to it. Such the measurements permit to describe the polarization coefficient as [6]:

$$\text{WWP}^{r} = \frac{T_p^{r^{\|}} - T_p^{r^{+}}}{T_p^{r^{\|}} + T_p^{r^{+}}} \qquad (3)$$

where $T_p^{r^{\|}}$ and $T_p^{r^{+}}$ denote the measured reflection coefficient for the single polarizer and for a light linearly polarized according to the polarizer axis and perpendicularly to it, respectively.

One can prove that this coefficient (3) can be described also as [6]:

$$\text{WWP}^{r} = \frac{T_p^{r}(\|) - T_p^{r}(+)}{T_p^{r}(\|) + T_p^{r}(+) + A}, \qquad (4)$$

where $A = \dfrac{R_{pec}}{\left(1 - R_{pec}\right)^2}$ and it describes the reflections from a boundary of a reflective polarizing film and external centre (*p–ec*). $T_p^r(\|)$ and $T_p^r(+)$ denote the transmission of the light linearly polarized according to the polarizer axis and perpendicular to it, respectively for a twice passing through the film.

As one can see the polarization coefficient for reflective film obtained from measurements is not universal coefficient because it depends on an external centre. For a making it possible to compare the polarizing properties of the transmissive and reflective films the following definition of a polarizing coefficient WWP^r for a reflective polarizer used in computer program has been proposed:

$$\text{WWP}^{r} = \frac{T_p^{r}(\|) - T_p^{r}(+)}{T_p^{r}(\|) + T_p^{r}(+)}. \qquad (5)$$

The equation (5) describes the polarizing properties of a reflective film which depends only on it's absorption. It is the same situation as for the transmissive films. Knowing an external centre and refractive index of a film the proper transmission coefficients $T_p^r(\|)$ and $T_p^r(+)$ can be obtained from the measured values of $T_p^{r^{\|}}$ and $T_p^{r^{+}}$. From the second hand establishing in a computer simulation given value of a coefficient WWP^r (so given values of $T_p^r(\|)$ and $T_p^r(+)$, too) the values of $T_p^{r^{\|}}$ and $T_p^{r^{+}}$ measured for given external centre can be determined.

2.2. Liquid crystal layer

For a liquid crystal (LC) layer the values of the refractive indices (ordinary and extraordinary one) have to be determined. It can be done e.g. by known wedge measurement method [6]. Additionally, the LC layer can have also the dichroic properties. In this case the absorption coefficients ($\alpha_{\parallel}$ – for light polarization parallel to a long LC molecule axis and α_{+} – for light polarization perpendicular to it) should be properly determined. With this end one should be done the comparative measurements for LC layer with and without a dichroic dye and for linearly polarized light for these two direction: parallel and perpendicular to a LC molecule long axis (layer director). It is important to do these experiments for planar structure of a layer and for the cells with the same thickness. Obtaining the transmission values for these layers one can determine the absorption coefficient as [7]:

$$\alpha_{\parallel} = -\frac{\ln T_{\parallel}}{d} \text{ and } \alpha_{+} = -\frac{\ln T_{+}}{d}, \qquad (6)$$

where $T_{\parallel}$ and T_{+} denote the difference between transmission values for dichroic and not dye-doped LC layers measured for a light linearly polarized according to the planar LC layer director and perpendicular to it, respectively. d denotes a thickness of LC layer.

2.3. Conductive layer and glass

The next problem it is a proper determining of the properties of a system: conductive layer and glass. First, the refractive indices of these elements and a thickness of a conductive layer should be determine. It can be done by standard methods. Additionally, the absorption coefficient of a conductive layer should be measured. It can be done from a spectral measurements of the transmission of the system: glass with a conductive layer. For this case an equation for a light passing through an analyzed system can be described as [1, 3, 6]:

$$\frac{A\left(B+\alpha_{\mathrm{ITO}}^2\right)e^{-\alpha_{\mathrm{ITO}}d_{\mathrm{ITO}}}}{\left(C+\alpha_{\mathrm{ITO}}^2\right)\left(D+\alpha_{\mathrm{ITO}}^2\right)}\left\{\begin{array}{l} 1+e^{-2\alpha_{\mathrm{ITO}}d_{\mathrm{ITO}}}\left[\dfrac{\left(E+\alpha_{\mathrm{ITO}}^2\right)\left(F+\alpha_{\mathrm{ITO}}^2\right)}{\left(C+\alpha_{\mathrm{ITO}}^2\right)\left(D+\alpha_{\mathrm{ITO}}^2\right)}\right]^2+ \\ +2e^{-\alpha_{\mathrm{ITO}}d_{\mathrm{ITO}}}\dfrac{\left(E+\alpha_{\mathrm{ITO}}^2\right)\left(F+\alpha_{\mathrm{ITO}}^2\right)}{\left(C+\alpha_{\mathrm{ITO}}^2\right)\left(D+\alpha_{\mathrm{ITO}}^2\right)}\cos\gamma \end{array}\right\}-T_{\mathrm{ITO}m}=0, \qquad (7)$$

where

$$A=\left[\frac{32\pi n_g}{\lambda\left(n_g+1\right)}\right]^2,\; B=\left[\frac{4\pi n_{\mathrm{ITO}}}{\lambda}\right]^2,\; C=\left[\frac{4\pi\left(n_{\mathrm{ITO}}+n_g\right)}{\lambda}\right]^2,$$
$$D=\left[\frac{4\pi\left(n_{\mathrm{ITO}}+1\right)}{\lambda}\right]^2,\; E=\left[\frac{4\pi\left(n_{\mathrm{ITO}}-n_g\right)}{\lambda}\right]^2,\; F=\left[\frac{4\pi\left(n_{\mathrm{ITO}}-1\right)}{\lambda}\right]^2, \qquad (8)$$

and

$$\gamma=\mathrm{arctg}\left(\frac{-8\pi\alpha_{\mathrm{ITO}}}{\left(\lambda n_{\mathrm{ITO}}\right)^2+4\pi\alpha_{\mathrm{ITO}}^2-\lambda^2}\right)+\mathrm{arctg}\left(\frac{-8\pi\alpha_{\mathrm{ITO}}n_g}{\left(\lambda n_{\mathrm{ITO}}\right)^2+4\pi\alpha_{\mathrm{ITO}}^2-\lambda^2 n_g}\right)-\frac{4\pi n_{\mathrm{ITO}}d_{\mathrm{ITO}}}{\lambda}, \qquad (9)$$

n_{ITO} and n_g detote the refractive indices of a conductive layer and glass, respectively; d_{ITO} denotes a thickness of a conductive layer; $T_{\mathrm{ITO}m}$ is a measured light transmission through the system glass and a conductive layer.

The absorption coefficient of a conductive layer can be obtained from equation (7) by numerical method, e.g. "falsi" method. In our computer program this "falsi" method is used.

3. The calculation assumptions

The example of an optimization procedure for a reflective twisted nematic (TN) display working in negative mode is presented in this work. Because is many different parameters which influence on the display contrast ratio the following general assumptions have been done:

Table 1

$T_p(\parallel)$ or $T_p^r(\parallel)$, %	$T_p(+)$ or $T_p^r(+)$, %	WWP or WWP^r
70	0.0000001	1
75	0.001	0,99997
80	0.01	0.99975
85	0.1	0.99765
90	1	0.97802
92.5	2	0.95767
97.5	4	0.92118

a) display is illuminated by D_{65} light source;

b) light reflections from all phase boundaries and light interference phenomena into a display is taken into account;

c) polarizers on the both display plates characterizes the same value of the polarization coefficient WWP. It means that WWP^t = WWP^r;

d) thickness of a conductive layer is equal 25 nm and a liquid crystal layer 6 μm;

e) refractive indices are the following value (dispersion phenomena is not taken into account): for glass – 1.54, for conductive layer – 1.82, for both polarizers – 1.52;

f) transmission value of the system glass with conductive layer is equal 85% (no dispersion);

g) day human eye sensitivity is assumed;

h) tilt angle is equal 2°, twist angle is equal 90°;

i) first transmission minimum for negative mode is analyzed;

j) antireflective layer on the display front plate is used. This layer is fitted into a wavelength 550 nm.

The following parameters of the display elements can be change: a polarization coefficient of used films and dichroic properties of a liquid crystal layer. These elements have been change because its have the greatest influence on the display contrast ratio. For analyze one has assumed the following values of these parameters:

a) polarization coefficients of the films are given in Table 1.

b) dichroic properties of a liquid crystal layer are given in Table 2.

The contrast ratio (CR) value is obtained from the following expression [1]:

$$\mathrm{CR}(\Delta nd) = \frac{\int_{380}^{780} H(\lambda)V(\lambda)R_{\mathrm{ON}}(\Delta n, d, \lambda)d\lambda}{\int_{380}^{780} H(\lambda)V(\lambda)R_{\mathrm{OFF}}(\Delta n, d, \lambda)d\lambda}, \quad (10)$$

where $H(\lambda)$ – spectral characteristic of the light source; $V(\lambda)$ – human eye sensitivity, $R_{\mathrm{ON}}(\Delta n, d, \lambda)$, $R_{\mathrm{OFF}}(\Delta n, d, \lambda)$ display reflectance for on- and off-state, respectively.

Table 2

$T_\parallel$, %	$\alpha_\parallel$, 1/μm	T_+, %	α_+, 1/μm	$(\alpha_\parallel - \alpha_+)d$
100	0.0000	100	0.0000	0.0000
75	0.0479	80	0.0372	0.0642
65	0.0718	80	0.0372	0.2076
55	0.0996	80	0.0372	0.3744
45	0.1331	80	0.0372	0.5754
35	0.1750	80	0.0372	0.8286
25	0.2310	80	0.0372	1.1628
15	0.3162	80	0.0372	1.6740
5	0.4993	80	0.0372	2.7726

Note: Thickness of a layer d is equal 6 μm.

4. The calculation results

Basing on the assumptions presented above in chapter 3 the calculations of the contrast ratio for RM LCD working in a negative mode have been done. These carried out calculations can be used to the choice of an optimal work point of a display. The obtained function of a display contrast ratio has been done for first transmission minimum but in our case this minimum has not been defined by constant Δnd value (Δn – birefrigrance, d – thickness of LC layer). Generally it is known that the first minimum for a TN structure is defined by value $\Delta nd = 0.48$. This assumption is correct only for ideally linearly polarized light and not dichroic LC layer. Therefore it is proper only for not real work conditions of a display. To prove this thesis the calculations for a LC layer in RM LCD (without the reflections, interference phenomena etc. and other display elements) have been done for different polarization coefficients of the used films. The results are presented in Fig. 2. As one can see just for very low value of a transmission $T_p^r(+)$ equal about 0.000001% (so for high value of a coefficient WWP equal near 1) one can observe a deforma-

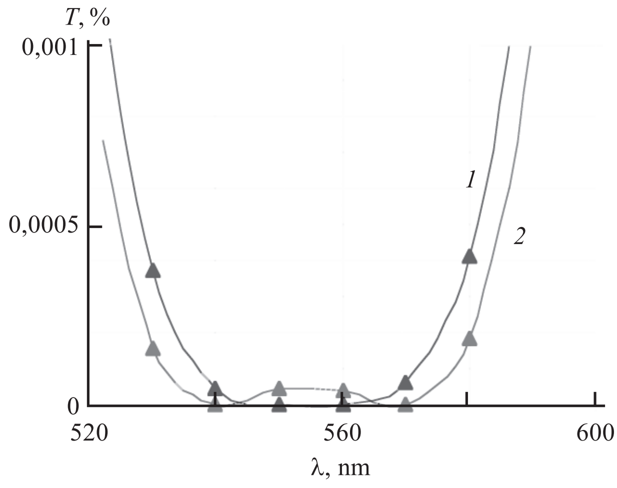

Fig. 2. Transmission for switch-OFF (dark) state of a display for LC layer in RM LCD. $T(+)$ denote a transmission $T_p^r(+)$. $T(+) = 10^{-9}$ (*1*), 10^{-6}% (*2*).

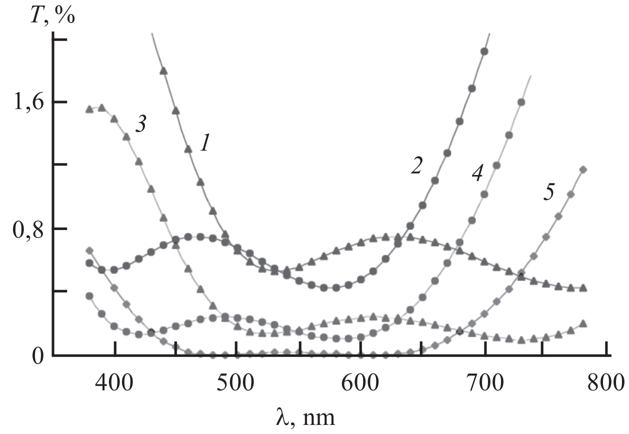

Fig. 3. Transmissions of a LC layer in RM LCD for chosen polarizing films. In a description values of Δ*nd* are presented. For these characteristics the maximum of contrast ratio is obtained. WWP = 0.97 (0.545) (*1*), 0.97 (0.405) (*2*), 0.99 (0.530) (*3*), 0.99 (0.530) (*4*), 0.999 (0.470) (*5*).

tion of a function $T_p^{r'}(+) = f(\lambda)$. There are not only one minimum of this function (contrary to ideal linearly light polarization) but two minimum points are observed for different wavelengths.

In Fig. 3 these transmissions for the different values of WWP are presented. These characteristics were done for the points of the maximum contrast ratio values.

As one can see in Fig. 2 and 3 a function of a transmission and contrast ratio is not simple one even for only LC layer. In Fig. 4 the contrast ratio calculated for LC layer is presented. One can see that for very high value of WWP this function has one maximum, yet. When WWP decreases second maximum of a contrast ratio is created. Additionally, a location of a CR maximum is shifted to lower values of Δ*nd*.

The reflective mode of LCD needs to use the bright polarizers because in other case the luminance in ON-state has very low value. That's way a location of CR maximum should be determine in detail. Additionally, for a real liquid crystal display (taking into account the assumptions described in chapter 3) a function of CR is individual deformed for each kind of used polarizers. It is presented in Fig. 5. As one can see these functions have two maximum points even for very high-polarization films. In this case the shift of a maximum point location can be observed. Therefore, the characteristics of Δ*nd* values for the different polarizers have been done. Its are presented in Fig. 6. These characteristics present the proper values of Δ*nd* (for only LC layer and for LC display) to assure the maximum value of CR.

Analyzing the results presented above one can see that the shift of Δ*nd* value is very high and can not be pass over. In Fig. 7 these shifts (from standard value of Δ*nd* = 0.48) are shown. Presented results make it possible to do the proper choice of the combination of LC mixture (Δ*n*) and cell thickness (*d*) for used polarizing

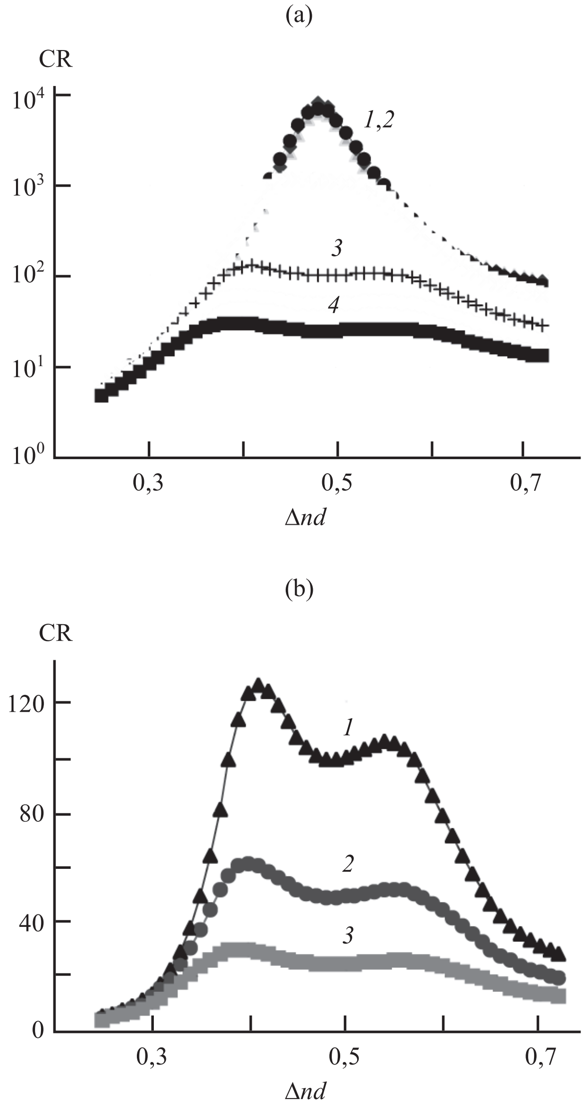

Fig. 4. The contrast ratio for a LC layer in RM LCD. a – for all used polarizers; WWP = 1 (*1*), 0.99975 (*2*), 0.97802 (*3*), 0.92118 (*4*). b – for bright polarizers; WWP = 0.97802 (*1*), 0.95767 (*2*), 0.92118 (*3*).

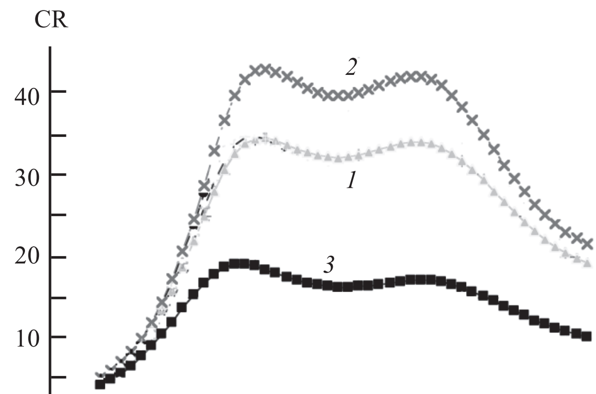

Fig. 5. The contrast ratio for a real RM LCD. Two maximum points can be observed. WWP = 1 (*1*), 0.99765 (*2*), 0.92118 (*3*).

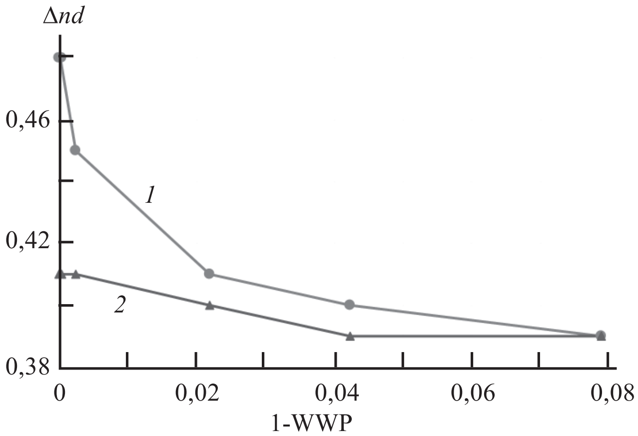

Fig. 6. The proper values of Δnd for RM LC layer (*1*) and LCD (*2*) to obtain the maximum of the contrast ratio.

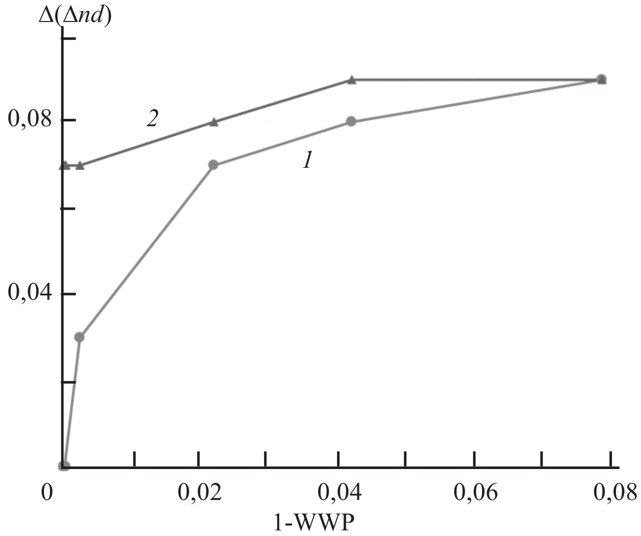

Fig. 7. The shift of Δnd value for LC layer (*1*) and RM LCD (*2*).

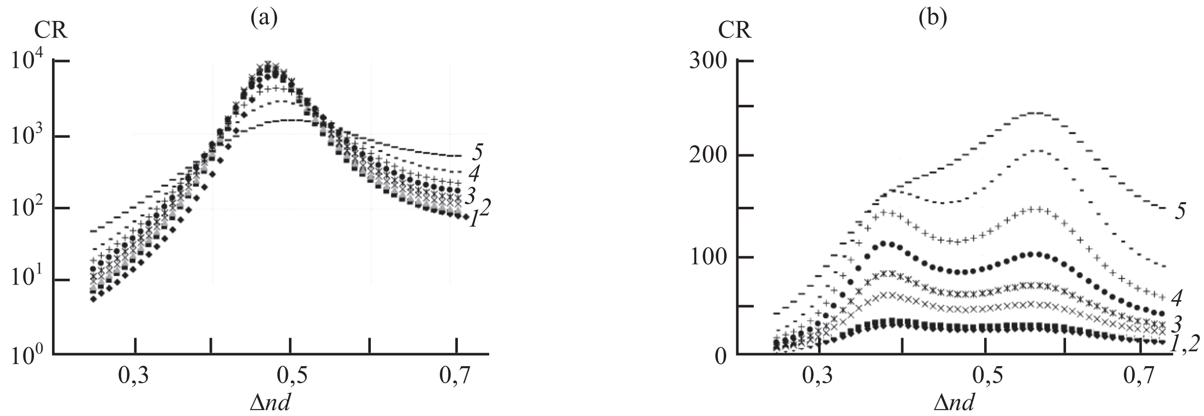

Fig. 8. The examples of CR characteristics for given polarizers and different dichroic properties of a layer for LC layer. WWP = 0.99975 (a), 0.97802 (b). $(\alpha_{\parallel} - \alpha_{+})d = 0$ (*1*), 0.2076 (*2*), 0.5754 (*3*), 1.1628 (*4*), 2.7726 (*5*).

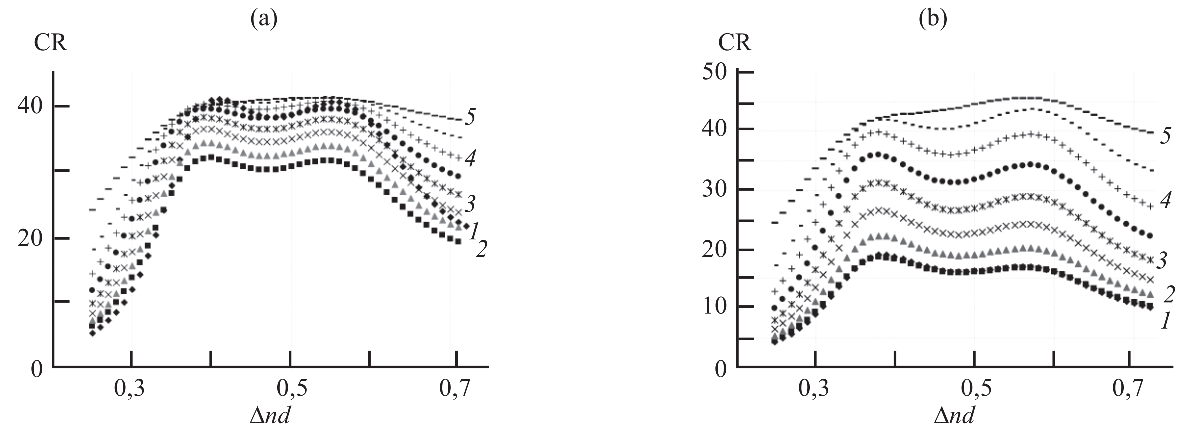

Fig. 9. The examples of CR characteristics for given polarizers and different dichroic properties of a layer for LC display. WWP = 0.99975 (a), 0.97802 (b). $(\alpha_{\parallel} - \alpha_{+})d = 0$ (*1*), 0.2076 (*2*), 0.5754 (*3*), 1.1628 (*4*), 2.7726 (*5*).

films. However it is not complete information about RM LCD display because the dichroic properties of a layer is not taken into account. The application of a dichroic dye into LC layer can cause the additional changes in CR characteristics. The dichroic dye works as an additional polarizer into this layer. The examples of the contrast ratio characteristics for given polarizing films and LC layer dichroic properties are presented in Fig. 8 (LC layer) and Fig. 9 (LC display).

The results presented in Fig. 8 and Fig. 9 shown that the point of the maximum contrast ratio value for RM LC layer and display shifts to the higher value of Δnd

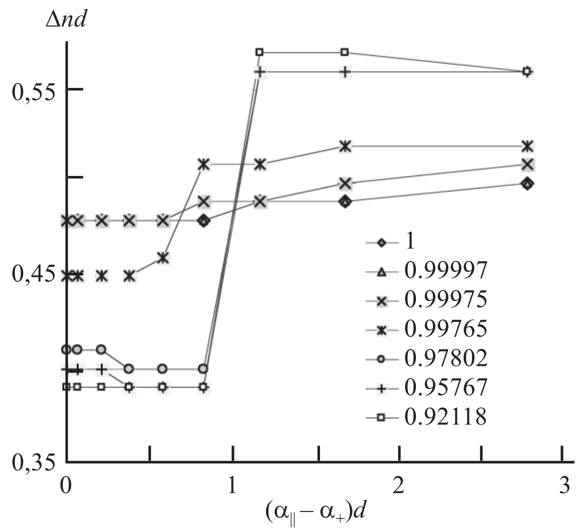

Fig. 10. The values of Δnd for maximum contrast ratio and for different polarizing films. These results have been obtained for LC layer.

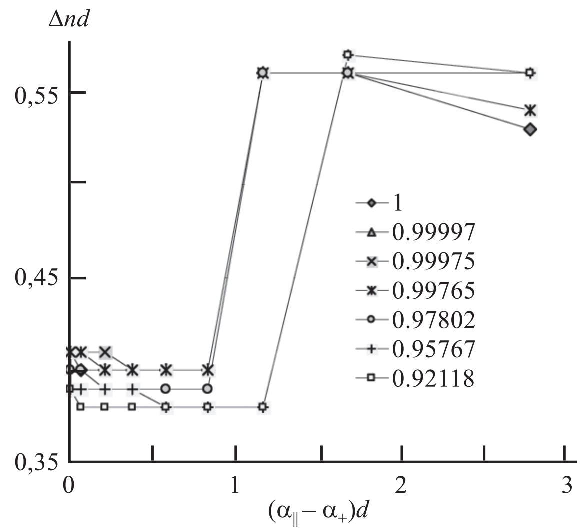

Fig. 11. The values of Δnd for maximum contrast ratio and for different polarizing films. These results have been obtained for LC display according to the assumptions presented in chapter 3.

value when the dichroic properties of a layer increases. Additionally, in this case it is not a simple shift. One can observe a quicker growth of the second maximum in comparison to the first one. Therefore it should be expected a sudden change a location of CR maximum point. The calculated values of Δnd at the points of the maximum contrast ratio for LC layer and LC display are presented in Fig. 10 and Fig. 11, respectively.

The results presented in Fig. 11 can be appreciated as a final information about optical matching needed to obtain the maximum contrast ratio in RM LCD. As one can see this matching should be different for different polarizing films and additionally it should be strongly modified for using dichroic dye into a LC layer. After a determining the optical matching point for RM LCD one can do the complete optimization procedure for such a display. The calculations have been done for assumptions presented in chapter 3. As a results CR have been obtained as a function of the polarizing films and dichroic properties of used LC layer. These results are presented in Fig. 12.

As one can see in Fig. 12 the proper combinations of a polarizer and dichroic dye can be chosen for given applications. The several maximum values of a CR are observed. Depending on a display brightness necessary for a given application the proper work point can be chosen from this characteristic. It should be underlined that this characteristic is done for the matching points shown in Fig. 11. It is interesting how this characteristic will seem for standard value of Δnd (0.48). It is presented in Fig. 13.

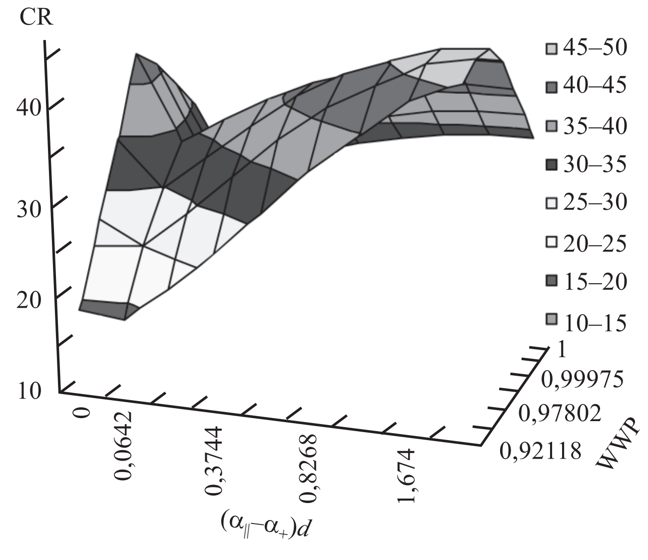

Fig. 12. The maximum values of a contrast ratio for RM LCD constructed according to the assumptions described in chapter 3.

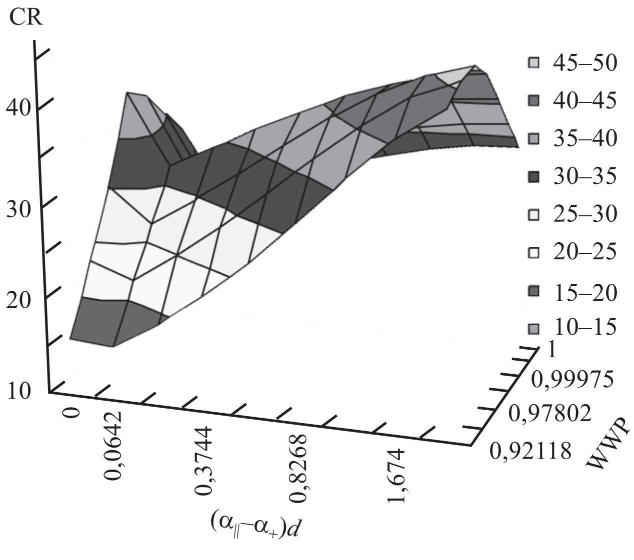

Fig. 13. The contrast ratio of RM LCD done for Δnd = 0.48.

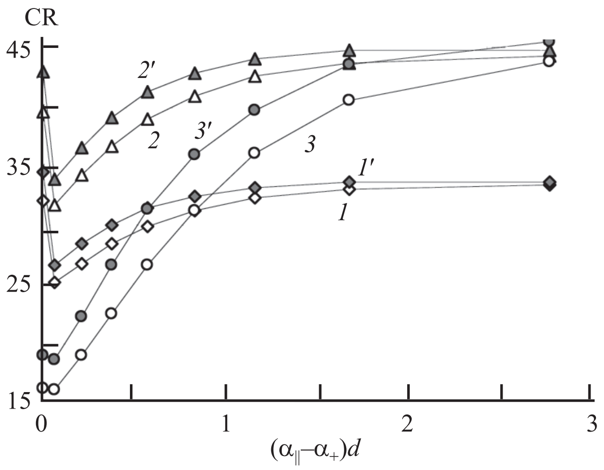

Fig. 14. The comparison of the CR values done for values of $\Delta nd = 0.48$ and for the matching points. *1* – WWP = 1, $\Delta nd = 0.48$; *1′* – WWP = 1, Δnd = max; *2* = 0.99765, 0.48; *2′* – 0.99765, max; *3* – 0.92118, 0.48; *3′* – 0.92118, max.

The presented in Fig. 12 and 13 results shown that these both functions are very similar but the values of CR obtained for the matching points are higher. Therefore one can affirm that the optical matching do not influence on the proper choice of a RM LCD work point but can make it possible to obtain higher values of a display contrast ratio.

The comparison of these both functions for chosen polarizing films are shown in Fig. 14.

As one can see the differences between CR values obtained for these both states is high. In the some cases it can be equal even about 15–20%. Additionally, the results presented in Fig. 14. shown when the choice of the matching point is necessary.

5. Conclusions

In presented work the close characteristic of the contrast ratio values have been obtained for Reflective Mode of a TN LCD. It is very useful tool for a display constructor. This characteristic has been obtained for given assumptions but it can be done for each other. Additionally, the influence of a proper matching point on the CR values has been shown. Simultaneously, the values of Δnd in the matching points for reflective LC layer and RM LCD have been close determined. The influence of the dichroic dye and a kind of used polarizers on a shift of this point has been presented. The significance of a proper choice of Δnd in RM LCD has been determined. The restrictions of the CR values in a real RM LCD can be appointed from presented results of this work.

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