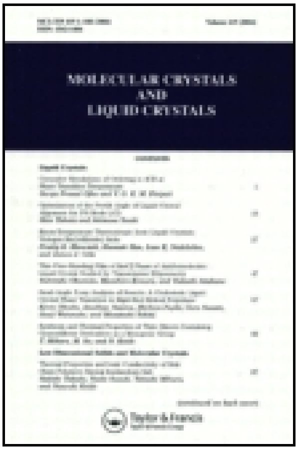

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MULTI-PARAMETERS OPTIMIZATION PROCEDURE OF THE CONTRAST RATIO IN TN TWO-POLARIZER REFLECTIVE DISPLAY

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The aim of our work has been to work out the multi-parameters procedure for the contrast ratio optimization process in a TN reflective display. This procedure has been worked out especially for application in the computer program worked by authors earlier. Using this computer program the multi-parameters optimization procedure for reflective TN two-polarizers display has been done. The difference of optical parameters obtained for real director profile and simplified one has been shown. The close relationships between the properties of individual display elements and the display optical parameters, especially contrast ratio value have been presented.

Keywords: dye-doped display; numerical optimization; reflective TN display

1. INTRODUCTION

The contrast ratio is very important optical parameters for every display, especially for reflective liquid crystal display, because it is passive display with external illuminating. The legibility of a such display depends on the value of the contrast ratio, mainly. Our aim has been to obtain the close relationships between the properties of the display elements and the contrast ratio value. To this end, the computer program to calculate the reflective TN display contrast ratio for the quasi-real work conditions has been worked out [1]. This computer program takes advantage of the modified GOA (Geometry Optics Approximation) method [1–11] and makes possible to calculate the contrast ratio of the LC display for different illuminating source, sensitivity of a human eye, used polarizing films, dichroic

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properties of the LC layer, antireflective and conductive layers, glass ect. Additionally, these calculation takes into account the interference phenomena into the display, the both modes of the display: positive and negative ones and the real director profile into the layer. All calculations have been done for the light beam perpendicular to the display surface. Generally, this method is based on the numerical calculations of the light intensity done for the light beam after a passing through the infinitely thin layers. Obtained results from one layer could be use as an initial data to calculate for the next layer. For any point into the display the light intensity can be described as:

$$I = A^2 + B^2 + C^2 + D^2 \tag{1}$$

where the coefficients A, B, C and D have been obtained from the following formulas:

$$\begin{aligned}
A^n &= \sqrt{e^{-\alpha_{eff}\cdot\delta z}} \cdot \begin{bmatrix} \left(A^{n-1}\cdot\cos\delta\Theta + C^{n-1}\cdot\sin\delta\Theta\right)\cdot\cos\delta_e^{+} \\ +\left(B^{n-1}\cdot\cos\delta\Theta + D^{n-1}\cdot\sin\delta\Theta\right)\cdot\sin\delta_e \end{bmatrix} \\
B^n &= \sqrt{e^{-\alpha_{eff}\cdot\delta z}} \cdot \begin{bmatrix} -\left(A^{n-1}\cdot\cos\delta\Theta + C^{n-1}\cdot\sin\delta\Theta\right)\cdot\sin\delta_e^{+} \\ +\left(B^{n-1}\cdot\cos\delta\Theta + D^{n-1}\cdot\sin\delta\Theta\right)\cdot\cos\delta_e \end{bmatrix} \\
C^n &= \sqrt{e^{-\alpha_{+}\cdot\delta z}} \cdot \begin{bmatrix} \left(-A^{n-1}\cdot\sin\delta\Theta + C^{n-1}\cdot\cos\delta\Theta\right)\cdot\cos\delta_o - \\ +\left(B^{n-1}\cdot\sin\delta\Theta - D^{n-1}\cdot\cos\delta\Theta\right)\cdot\sin\delta_o \end{bmatrix} \\
D^n &= \sqrt{e^{-\alpha_{+}\cdot\delta z}} \cdot \begin{bmatrix} \left(A^{n-1}\cdot\sin\delta\Theta - C^{n-1}\cdot\cos\delta\Theta\right)\cdot\sin\delta_o - \\ +\left(B^{n-1}\cdot\sin\delta\Theta - D^{n-1}\cdot\cos\delta\Theta\right)\cdot\cos\delta_o \end{bmatrix}
\end{aligned} \tag{2}$$

where an upper index denotes number of infinite thin *LC* layer (thickness $\delta z \to 0$). δ_o represents phase shifts occurring after passing a distance δz in LC medium ($\delta_e = \frac{2\pi n_{eff}\delta z}{\lambda}$ *and* $\delta_o = \frac{2\pi n_o \delta z}{\lambda}$). n_{eff} and α_{eff} denote the effective refractive index of LC and effective absorption coefficient, respectively. Its amount to:

$$\begin{aligned}
n_{eff} &= n_e \cdot n_o \cdot \sqrt{\frac{1 + tg^2\Theta_s}{n_o^2 + n_e^2 \cdot tg^2\Theta_s}} \\
\alpha_{eff} &= \alpha_{||} \cdot \alpha_{+} \cdot \sqrt{\frac{1 + tg\Theta_s}{\alpha_{+}^2 + \alpha_{||}^2 \cdot tg^2\Theta_s}}
\end{aligned} \tag{3}$$

(Θ_s – tilt angle accorded to the director profile curve in the liquid crystal layer)

The coefficients $\alpha_{||}$ and α_{+} denote the absorption indices for the linearly polarized light along the layer director and perpendicularly to it, respectively.

There is the same method used for to calculate for on- and off-state of the display. The difference between these states it is only the different director profile curve into the LC layer.

Finally, the contrast ratio value of the display has been calculate from the below expression [13,14]:

$$CR(\Delta nd) = \frac{\int_{380}^{780} H(\lambda) \cdot V(\lambda) \cdot T_{ON}(\Delta n, d, \lambda) d}{\int_{380}^{780} H(\lambda) \cdot V(\lambda) \cdot T_{OFF}(\Delta n, d, \lambda) d} \tag{4}$$

where:
$H(\lambda)$ – spectral characteristic of the light source;
$H(\lambda)$ – human eye sensitivity,
$T_{ON}(\Delta n, d, \lambda), T_{OFF}(\Delta n, d, \lambda)$ – display transmission in on-state and off-state, respectively.

The measurements of the display elements optical parameters which will be used in the calculations should be done in the close given way. These methods have been detailed described by authors earlier [1,8,–11] and will not presented in this work again.

2. PROPERTIES OF THE DISPLAY ELEMENTS USED IN THE MULTI-PARAMETERS OPTIMIZATION PROCEDURE

The standard reflective TN display working in negative mode has been analyzed in our work. The schema of studied set-up of the display has been presented in Figure 1.

Our analysis has been conducted for the both transmission minimum: first and second ones. The influence of the polarizing films properties and dichroic properties of the liquid crystal layer on the contrast ratio of such a display has been considered. The following standard properties of the other display elements have been assumed:

a) glass with the refractive index equal 1,52 (no dispersion phenomena, no absorption);
b) conductive layer with the refractive index equal 1,8 (no dispersion phenomena). The transmission of the system: conductive layer and glass has been presented in Figure 1. Layer thickness has been equal 25 nm, the isotropic absorption coefficient has been assumed;
c) liquid crystal layer with thickness 6 μm has been used. The director profiles used in calculations for real situation and for simplified state have been presented in Figure 2. The simplified state means the constant tilt angle into LC layer equal 0° and 90° to the display surface for off- and on-state respectively;

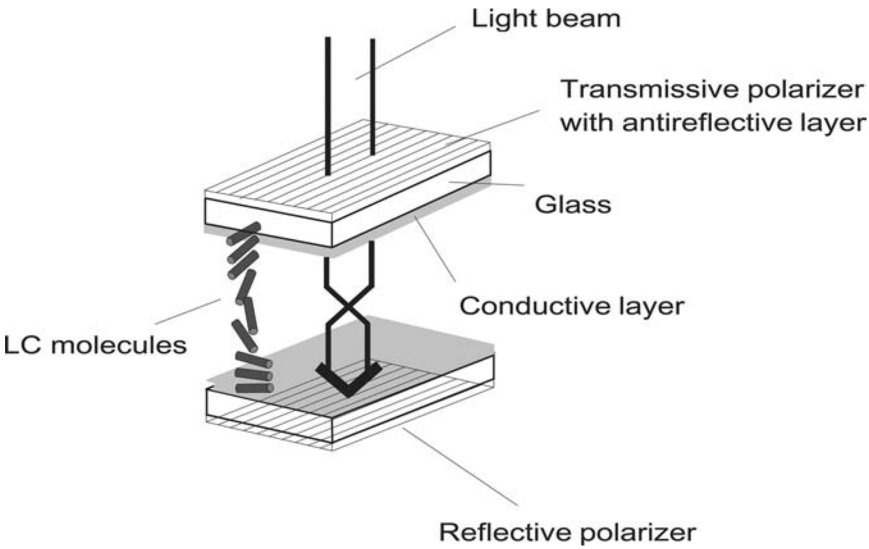

FIGURE 1 Schema of the studied set-up of the reflective TN display assumed in our analysis. The off-state has been presented. In on-state the reorientation of the LC molecules to homeotropic structure enables light beam to return back.

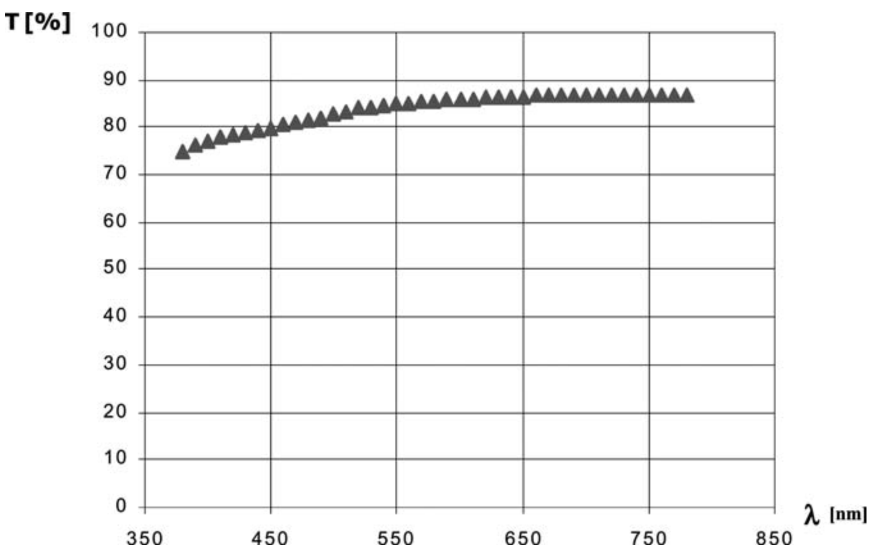

FIGURE 2 The transmission of the system: glass with the conductive layer assumed in our calculations.

d) antireflective layer with thickness 112 nm and refractive index equal 1,244 has been take into account. It is interference layer;
e) display has been illuminated by external light source D65 type (as Sun).

The polarization coefficients (denote by WWP) of the polarizing films used in calculations have been obtained from the following definitions:
– for transmissive films

$$WWP = \frac{T_p(||) - T_p(+)}{T_p(||) + T_p(+)} \tag{5}$$

– for reflective films

$$WWP = \frac{T_p^r(||) - T_p^r(+)}{T_p^r(||) + T_p^r(+)} \tag{6}$$

where $T_p(||)$ and $T_p(+)$ denote the transmission coefficient of a single polarizer for the linearly polarized light according to the polarizer axis and perpendicularly to it, respectively. $T_p^r(||)$ and $T_p^r(+)$ denote the reflection coefficient of a single polarizer and for linearly polarized light according to the polarizer axis and perpendicularly to it, respectively. These expressions presented above can be obtained from the general definitions of the polarization coefficient [13,14]:

$$WWP = \frac{I^{||} - I^{+}}{I^{||} + I^{+}} \cdot 100\% \tag{7}$$

where $I^{||}$ and I^{+} denote a light intensity after propagation through the single polarizer, with linear polarization according to polarizing axis of the film and perpendicularly to it, respectively. After rejection the reflective light beam from the measured results for reflective film the expression (6) denotes polarizing possibilities of the film interior.

This calculation method of WWP has made possible to describe the both types of the polarizers: reflective and the transmissive ones in the same way with the help of the same external light polarizing properties of the films. These parameters defined by expressions (5) and (6) depend on the absorption coefficients of the polarizers, only.

The dichroic properties of the LC layer have been defined as the expression $d(\alpha_{||} - \alpha_{+})$ where d denotes the layer thickness and the $\alpha_{||}$ and α_{+} denote the absorption coefficient of the planar LC layer for the light passing through the layer and linearly polarized according to the layer director and perpendicularly to it, respectively. In the earlier work [14] we have shown that the contrast ratio of the TN reflective display working in negative mode has depend on the value of this expression only, but has not depend on the absolute values of the d, $\alpha_{||}$ and α_{+}.

The following values of WWP coefficient (Table 1) and expression $d(\alpha_{||} - \alpha_{+})$ (Table 2) have been used in our calculations.

3. RESULTS OF THE MULTI-PARAMETERS OPTIMIZATION PROCEDURE

The calculation for the all combination of the prolarizing films and dichroic layer from the Tables 1 and 2 have been done. These calculations have been done for the simplified and real director profiles from Figure 3. The results of the obtained contrast ratio as a function of polarizing coefficient of used films and dichroic LC layer properties have been presented in Figure 4.

These conducted calculations have made possible to select the optimal work point of the display, which has depend on the display work conditions. The reflective display should have the contrast ratio higher then 1:6 for clear visualisation. For the intense illumination this contrast ratio value should be higher then 1:15. Seeing the figure presented above one can observe that for real TN reflective display:

- contrast ratio has the highest values for no dichroic LC layer in the case of a lack antireflective layer. It can gain the values about 1:6, 1:7 (higher for the first minimum). The most important has been the fact, that the highest contrast ratio has been obtained for the polarizing film lower that 0,96 (for second minimum) and for a range (0,96–0,95) for the first minimum. For the other value of polarizing coefficient the contrast ratio value can decrease to 80% of maximum value, even. The highest value of the contrast ratio obtained in this case has been equal about 1:7,2 for first minimum and 1:5,7 for second one;
- in the case when the antireflective layer is used the situation is more interesting. The two interesting area of the obtained functions have been

TABLE 1 Polarization Coefficients of Polarizers Used in the Calculations

No	WWP
1	0,9998
2	0,9977
3	0,9780
4	0,9577
5	0,9212

TABLE 2 Dichroic Properties of the Liquid Crystal Layers Used in the Calculations

No	$d(\alpha_{\parallel} - \alpha_{+})$	No	$d(\alpha_{\parallel} - \alpha_{+})$	No	$d(\alpha_{\parallel} - \alpha_{+})$
1	0,0642	6	0,4698	11	1,1628
2	0,1332	7	0,5754	12	1,3860
3	0,2076	8	0,6930	13	1,6740
4	0,2874	9	0,8268	14	2,0796
5	0,3744	10	0,9810		

observed, the same ones for the both transmission minimum. The first one: for no dichroic LC layer the highest contrast ratio has been obtained for the polarizing films with polarization coefficient from the range (0,98– 0,99), the second one for the films with WWP equal from 0,945 to 0,98 and the dichroic layer with the value of $d(\alpha_{\parallel} - \alpha_{+})$ higher than 2,0, simultaneous. Additionally, the value of the contrast ratio for second area has been higher about 30% than in the first one (for first minimum) and about 5% for second minimum. When the antireflective layer is used the value of the contrast ratio for the first transmission minimum has been higher about 40% than for second minimum. The highest value which can obtain has been equal about 1:60 for first minimum and about 1:38 for second one.

Additional information from the conducted optimization procedure have been the qualification of the influence of the director profile on the CR

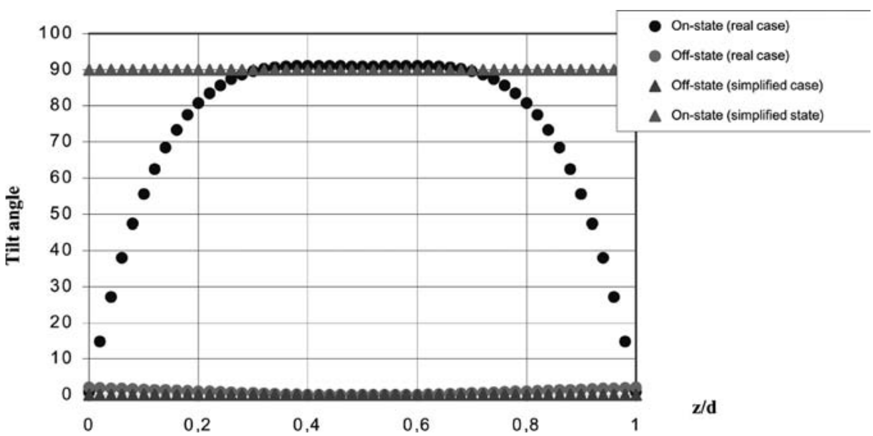

FIGURE 3 The simplified and real director profile into the LC layer assumed in our calculations.

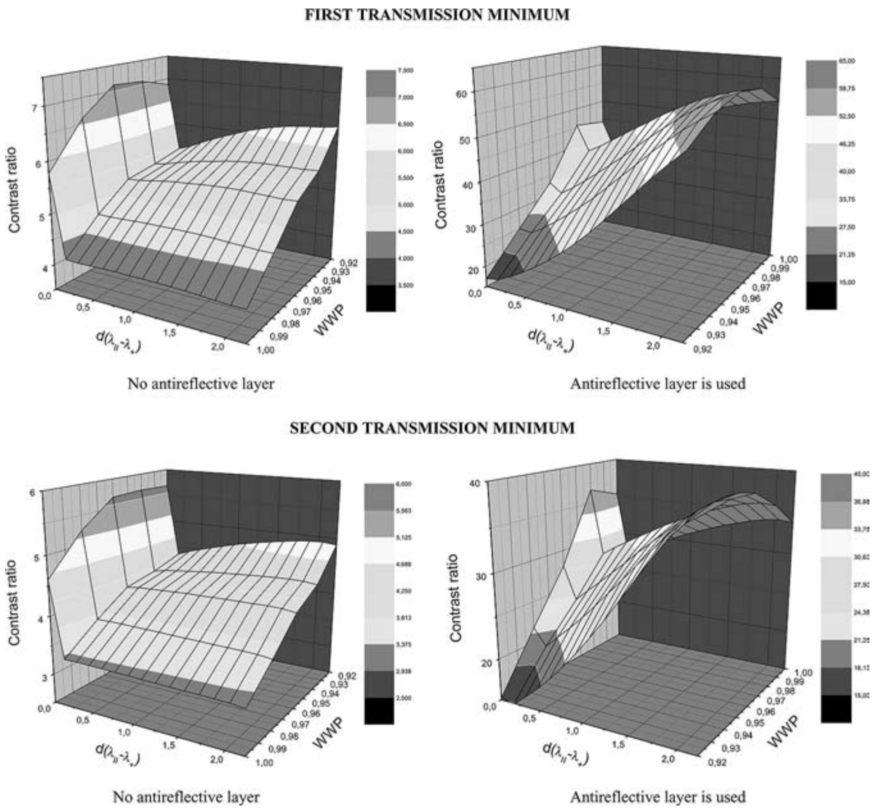

FIGURE 4 The contrast ratio of the TN reflective display working in negative mode as a function of used element properties: polarizing films and dichroic layer. The both transmission minimum: the first and second ones have been presented.

values. The results for the analysed display type have been presented in Figure 5. One can observe that this impact has been higher for using antireflective layer. It is motivated by the reflection effect. The reflected beam masks the significance of the LC layer properties. These difference has not been considerable, yet and its amounts about 2% (as an absolute difference between the $CR_{ideal}CR_{real}$ relation for the antireflective layer and for a lack of it) for the both minimum. The changes of the CR value caused by the used director profile curve in analysed display has been equal about 0–7% for first minimum and 3–11% for second one. It has been caused by the higher optical anisotropy in the second minimum. The higher value of the expression $d(\alpha_{\|} - \alpha_{+})$ (higher dichroic properties of the layer) has caused higher value of the relation $CR_{ideal}CR_{real}$ (higher changes of the

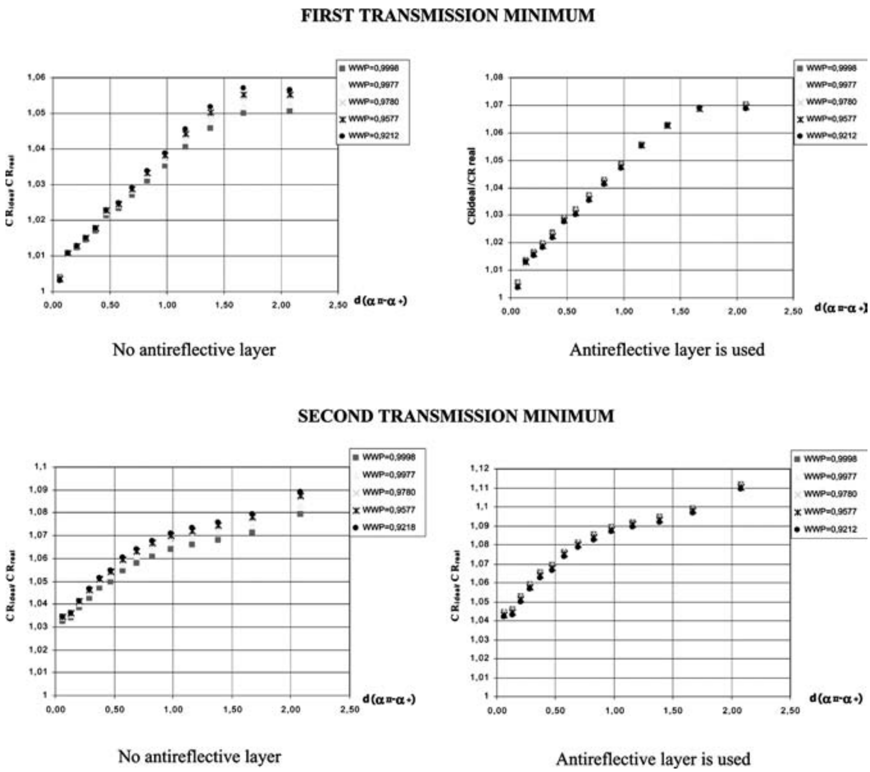

FIGURE 5 The relation between the contrast ratio CR for simplified director profile (CR_{ideal}) and for real one (CR_{real}). The negative mode of reflective TN display has been analysed. The results for the both minimum: the first and second ones have been presented.

contrast ratio). The increase of layer dichroic properties modifies the light transmission in ON-state stronger for higher value of the $d(\alpha_{\parallel} - \alpha_{+})$

4. CONCLUSIONS AND DISCUSSION

The shown optimization procedure can be done for any mode and for any type of the display. It makes possible to obtain the close information about the properties of the display elements which should be apply to obtain the highest values of the contrast ratio. These results presented above have been the example, but the presentation of the all obtained results has not been possible in one work. However, the following conclusions can be formulated:

- the optimization procedure for any display type and for any application of it should be done to obtain the best optical parameters;
- right conducted procedure makes possible to obtain the display contrast ratio higher about 30–40% (for presented mode of the display) by application of the dichroic dye;
- right choice of the polarizing films is very important and it should be done for given display elements, chosen display type and work mode;
- the close relationships between the properties of the chosen display element properties and contrast ratio can be obtained;

This worked out procedure makes possible to conduct the display construction process easily, chipper and more proper. In joint with the calculation method for light beam not-perpendicularly to the display surface (it is working out in this time by authors) should make possible to conduct complete optimization procedure for any LC display with nematic layer and for any applications of it.

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