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Numerical optimization procedure of TN LCD design process

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The main aim of this work is a presentation of the significance of the numerical optimization procedure for the TN liquid crystal display design process. The assumptions for calculations of such optical parameters as contrast ratio and luminance are presented. The way of measurements of optical parameters (refractive indices and absorption coefficients) for such the display elements as glass, conductive layer, polarizers, etc., which makes it possible to apply these results directly in the computer program worked out by the author, is described. The calculated results of the contrast ratio and luminance for TN transmissive and reflective display are presented. The optimization procedures for negative mode, and for transmissive and reflective type of the display were performed in an independent way.

Keywords: TN displays, numerical optimization procedure, contrast ratio.

1. Introduction

Nowadays, the development of liquid crystal displays (LCDs) reached a very high level. Many ideas can be practically realized but they need a fulfilment of given user requirements. For this aim, different electro-optical effects can be used. Taking it into account a number and kinds of optical elements used to design liquid crystal displays, such a procedure may be very complex, expensive, and time-consuming. For this reason, a numerical program to calculate LCD's optical parameters could be very useful. Such a program should allow to calculate optical parameters of LCD for real conditions of a display operation. So, real properties of the used display's elements, real illuminating light and observation conditions should be taken into account. The computer program worked out by the authors [1–6] makes it possible to calculate the values of contrast ratio, luminance and colour co-ordinates for a TN display with any spectral characteristics of polarizers, glass, antireflective, conductive, and liquid crystal layers (also with a dichroic dye). The calculations can be done for different tilt and twist angles and for any arrangement between a director in LC layer and polarizers axes. Additionally, this program takes into account human eye sensitivity and spectral characteristic of a light source.

There are two program modules, for transmissive display and for reflective one. In the transmissive display, influence of both light sources, i.e., external and internal ones are taken into account.

The physical base of our computer program is the geometry approximation method (GOA) [7–11] modified by the author. This modification provides such results as contrast ratio and luminance of the display that are very close to the values obtained from experiments. It takes into account multilayers structure of a display and the light multiple-reflections phenomena occurring inside it. The results can be obtained without any physical restrictions because the calculations are done in an elementary way for the infinite thin layers of a display. In our earlier paper [1] we have performed an experimental verification of the calculated spectral characteristics for a given LC mixture and we have obtained a very high conformity between the theoretical and experimental results.

The worked out computer program can facilitate the initial choice of the elements for construction of a given display. The designation of all LC display elements (e.g. glass, antireflective and conductive layers, liquid crystal layer, polarizers, ect.) often requires to do many practical tests. Unfortunately, in practice, these tests do not guarantee that all possible cases have been analysed. Moreover, as we wrote earlier, the measurement procedures are very expensive and time-consuming. Additionally, these procedures require to accumulate a lot of different materials, such as polarizers, liquid crystals, glass, etc. For example, if we want to describe the influence of the polarizers on the display contrast ratio value, we should measure the contrast ratio of the samples with the polarizing films, which have different polarization coefficients (e.g., from 0.9 to 0.9999) with a proper density step. Additionally, these measurements should be done for these polarizers and for different glass, conductive layers, liquid crystal layers, etc.

A number of the necessary measurements and the designed display samples often makes such an optimization method expensive and very time-consuming. Therefore, working out the theoretical calculations method of the LCD's optical parameters one can make the optimization

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procedure faster and cheaper. In many cases, it is the only possible solution. In this paper, we would like to show an example of such an optimization procedure done for negative mode of a transmissive and reflective TN LCDs. This mode has been chosen because it is very interesting from practical application point of view because it makes possible to obtain colour visualization by a simple method, e.g., by application of the colour filters.

2. Measurement method of display elements

The important elements of the worked out computer program and optimization procedure is a proper determination of optical parameters of the elements used to display design. The procedures of the element measurement should be easy but they should take into account such physical effects as multiple reflections and interference phenomena. The below described procedures were assumed to determine optical parameters of display elements.

2.1. Polarizing films

The calculation method should comprise a proper measurement procedure of the display elements. The polarization coefficient (denoted by WP) of the used polarizing films, applied in the computer program, is generally defined as

$$WP = \frac{I'' - I^{+}}{I'' + I^{+}} 100\% \tag{1}$$

where I'' and I^{+} denote the light intensity for linearly polarized light along to the polarizer axis and perpendicularly to it, respectively. The light intensity is measured after its passing through the films.

The way of measurements of the polarization coefficient is different for transmissive and reflective films. Analysing the light passing through the two parallel and crossed transmissive polarizers, one can notice that this coefficient described by Eq. (1) can be written as

$$WP_T = \frac{T_p(\parallel) - T_p(+)}{T_p(\parallel) + T_p(+)}, \tag{2}$$

where $T_p(\parallel)$ and $T_p(+)$ denote the transmission measured for two parallel and crossed polarizers, respectively. In this case, the reflection phenomena do not influence the value of the obtained polarizing coefficient.

For reflective films, the situation is more complicated. Analysing the light reflected from the reflective polarizer, Eq. (1), the following equation can be used

$$WP_R = \frac{R_p^r(\parallel) - R_p^r(+)}{R_p^r(\parallel) + R_p^r(+) + A}, \tag{3}$$

where $R_p^r(\parallel)$ and $R_p^r(+)$ denote the reflection coefficient of a single reflective polarizer and for linearly polarized light along the polarizer axis and perpendicularly to it, respectively. A describes the reflections coefficient of the both polarization states of the light from a boundary of a reflective polarizing film and external centre. For this case, the following polarization coefficient (denoted by WWP) were applied

$$\text{for transmissive film} \quad WWP_T = \frac{T_p(\parallel) - T_p(+)}{T_p(\parallel) + T_p(+)}, \tag{4}$$

$$\text{for reflective film} \quad WWP_R = \frac{R_p^r(\parallel) - R_p^r(+)}{R_p^r(\parallel) + R_p^r(+)}. \tag{5}$$

The parameters presented above depend only on absorption properties of the films and can be used to compare the polarizing properties for transmissive and reflective films and to obtain characteristics of the display optical parameters as a function of the only one value of the polarizing coefficient. As one can see, $WP_T = WWP_T$ and can be obtained by simple measurements of $T_p(\parallel)$ and $T_p(+)$. For reflective film, the parameters, WWP_R can be obtained also in a simple way by measurements of $R_p^r(\parallel)$ and $R_p^r(+)$ values. The completed polarization state of reflected light for the given external centre is always calculated from the following equation

$$WP_R = WWP_R \frac{B}{B - A \cdot WWP_R}, \tag{6}$$

where $B = R_p^r(\parallel) - R_p^r(+)$ and A denotes the reflection coefficient for non-polarized light and it depends on refractive indices of polarizing film and the given external centre.

2.2. Liquid crystal layer

The dichroic properties of the LC layer with a dye have been express as $d[\alpha(\parallel) - \alpha(+)]$, where d denotes the layer thickness, $\alpha(\parallel)$ and $\alpha(+)$ denote the absorption coefficient of the planar layer for the light passing through the layer and, linearly polarized parallel to the layer, director and perpendicularly to it, respectively. The measurements of $\alpha(\parallel)$ and $\alpha(+)$ values are very simple. For example, it may be done by using two-beam spectrophotometer where, in the first beam, the sample with a pure liquid crystal is placed, whereas in the second beam there is the sample with a liquid crystal doped by a dye. The necessary conditions are the same thickness of both samples and the same alignment of molecules in both LC layers.

2.3. ITO layer

The description of the light propagating through ITO layer is very significant to obtain the proper value of the display transmission. ITO layer is characterized by a complex value of the refractive index (so $\hat{n}_{ITO} = n_{ITO} - i\alpha_{ITO}$) and for this reason the phase shifts occur for reflected and transmitted light. In addition, the multiple-beam interference phenomena occur. To solve this problem, we propose to make the measurement of spectral transmission of in a system as glass with the conductive layer. One can see [1] that this transmission can be described as

$$\frac{A(B+\alpha_{ITO}^2)e^{-\alpha_{ITO}d_{ITO}}}{C+\alpha_{ITO}^2(D+\alpha_{ITO}^2)}\left\{1+e^{-2\alpha_{ITO}d_{ITO}}\left[\frac{(E+\alpha_{ITO}^2)(F+\alpha_{ITO}^2)}{(C+\alpha_{ITO}^2)(D+\alpha_{ITO}^2)}+\right]^2+2e^{-\alpha_{ITO}d_{ITO}}\frac{(E+\alpha_{ITO}^2)(F+\alpha_{ITO}^2)}{(C+\alpha_{ITO}^2)(D+\alpha_{ITO}^2)}\cos\gamma\right\} \quad (7)$$

$$-T_{ITOm}=0$$

where

$$A=\left[\frac{32\pi n_g}{\lambda(n_g+1)}\right]^2,\quad B=\left[\frac{4\pi n_{ITO}}{\lambda}\right]^2,$$

$$C=\left[\frac{4\pi(n_{ITO}+n_g)}{\lambda}\right]^2,\quad D=\left[\frac{4\pi(n_{ITO}+1)}{\lambda}\right]^2,\quad (8)$$

$$E=\left[\frac{4\pi(n_{ITO}-n_g)}{\lambda}\right]^2,\quad F=\left[\frac{4\pi(n_{ITO}-1)}{\lambda}\right]^2,$$

and

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

In the equations presented above, n_g denotes the refractive index of glass, n_{ITO} and α_{ITO} denote the real and imaginary part of the refractive indices of a conductive layer, respectively, d_{ITO} denotes a thickness of the conductive layer, T_{ITOm} is the light transmission value measured for the system of glass and the conductive layer.

The solution of Eq. (7) gives the values of n_{ITO} and α_{ITO} for n_g and d_{ITO} which can be obtained by using standard measurement methods.

3. Assumption of calculation conditions

Due to many parameters which affect the values of a display contrast ratio and luminance, in this work we have opted to carry out the calculations for the following parameters of the display's elements such as glass, conductive and antireflective layers, LC layer and for the given external conditions:

- glass with the 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) – float sodium glass (no absorption),
- conductive layer with the refractive index equal to 1.832 (no dispersion phenomena) – ITO layer. Layer thickness is equal to 25 nm, the isotropic absorption coefficient has been assumed according to Fig. 1,
- liquid crystal layer with a thickness of 6 µm is used. The director profiles used in calculations for both states, switch-ON and switch-OFF ones, are presented in Fig. 2,
- interference antireflective layer for a wavelength of 550 nm,
- day human eye sensitivity,
- spectral light sources – D_{65} type for reflective display and for external light in transmissive display, *A* type for internal light in transmissive display,
- a value of *Δnd* (*d* is the layer thickness, *Δn* is the birefringence of the liquid crystal) is equal to 0.48 (first transmission minimum regime).

The assumption presented above fulfils the requirements for alphanumerical or graphical black and white displays working under the standard conditions and illuminated by typical light sources.

The complete display system analysed in our calculations is presented in Fig. 3.

The calculations has been limited to the choice of polarizers and LC layer dichroic properties without disper-

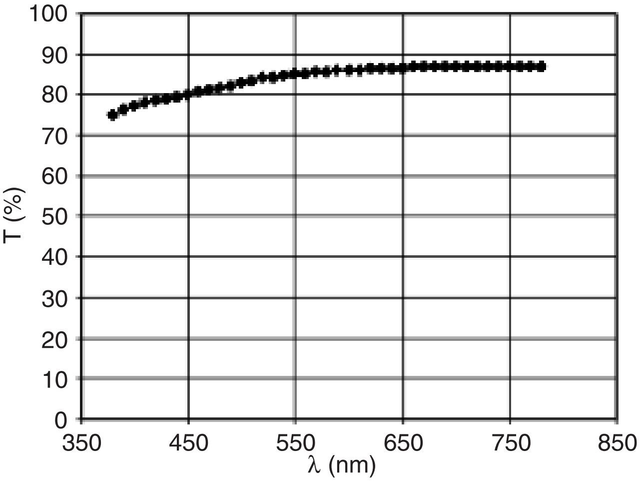


Fig. 1. Transmission of the system: glass with the conductive layer (ITO).

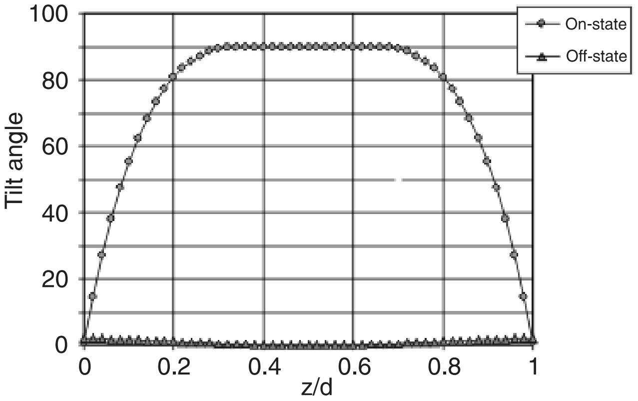


Fig. 2. Function of the director profile for ON and OFF-state assumed in the calculations.

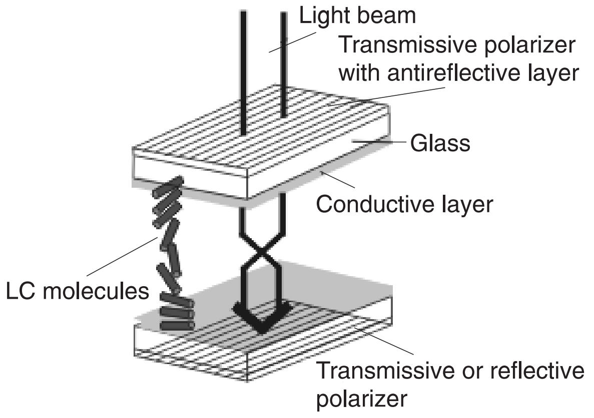


Fig. 3. Schema of the TN liquid crystal display.

sion phenomena because these display elements have the most interesting influence on the display optical parameters. The choice of properties of other elements does not essentially influence the shape of the display transmission characteristic, but increases or decreases the transmission values. The internal polarizer parameters used in the calculations, on both display plates, had the same values ($WWP_T = WWP_R = WWP$). These parameters and dichroic properties of the LC layer ($d[\alpha(\|)-\alpha(+)]$) are shown in Tables 1 and 2.

Table 1. Polarization coefficient of the films assumed in the calculations.

$T_p(\|)$ or $T_p^r(\|)$ (%)	$T_p(+)$ or $T_p^r(+)$ (%)	WWP_T or WWP_R
70	0.0000001	1.00000
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

Table 2. Dichroic properties of the liquid crystal layer assumed in the calculations.

$T_\|$ (%)	$\alpha(\|)$ (1/μm)	T_+ (%)	$\alpha(+)$ (1/μm)	$d[\alpha(\|) - \alpha(+1)]$
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

4. Calculation results

Based on the assumption presented above, the calculation process for both modes of the LC display, reflective and transmissive ones was carried out. It must be underlined that all calculations have been done for negative type of a display.

The results as the value of the display contrast ratio (CR) of the reflective display are presented in Fig. 4 and for transmissive display in Fig. 5. The characteristics for transmissive display have been done for different levels of the external light intensity $I_{external}$ (in comparison with external light intensity) because the external light influences very strongly the contrast ratio value of such a display. Certainly, similar calculations can be done for a positive type of LC display, without antireflective layer and for the second minimum of the layer transmission defined by the expression Δnd in any time using our computer program. In addition, such calculations can be done for any set of the display elements. In this work, we present the contrast ratio of the TN LC display constructed with standard elements as the function of the LC layer dichroic properties and polarizers with different polarization coefficients for the following reasons:

- this function was the most interesting for us because we have the possibilities of the synthesis of different LC mixtures in the Chemical Group of our university,

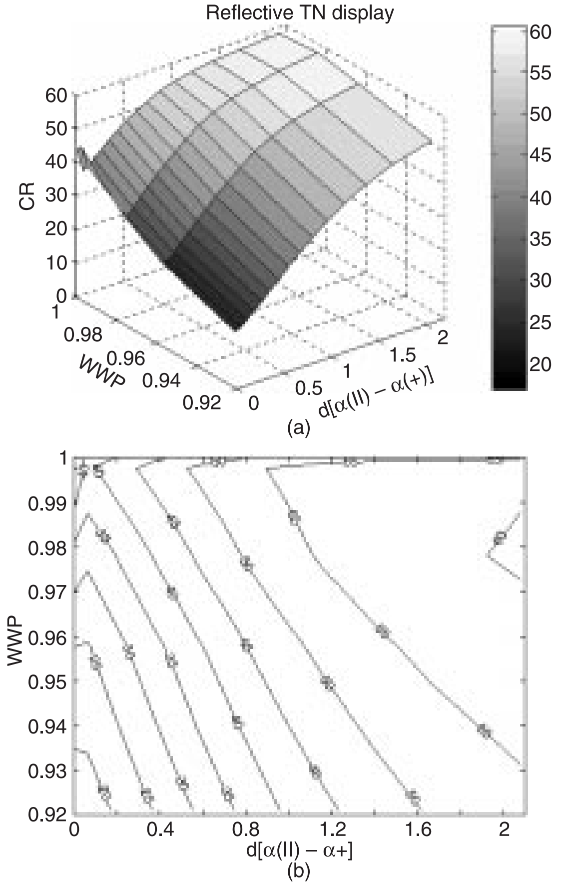
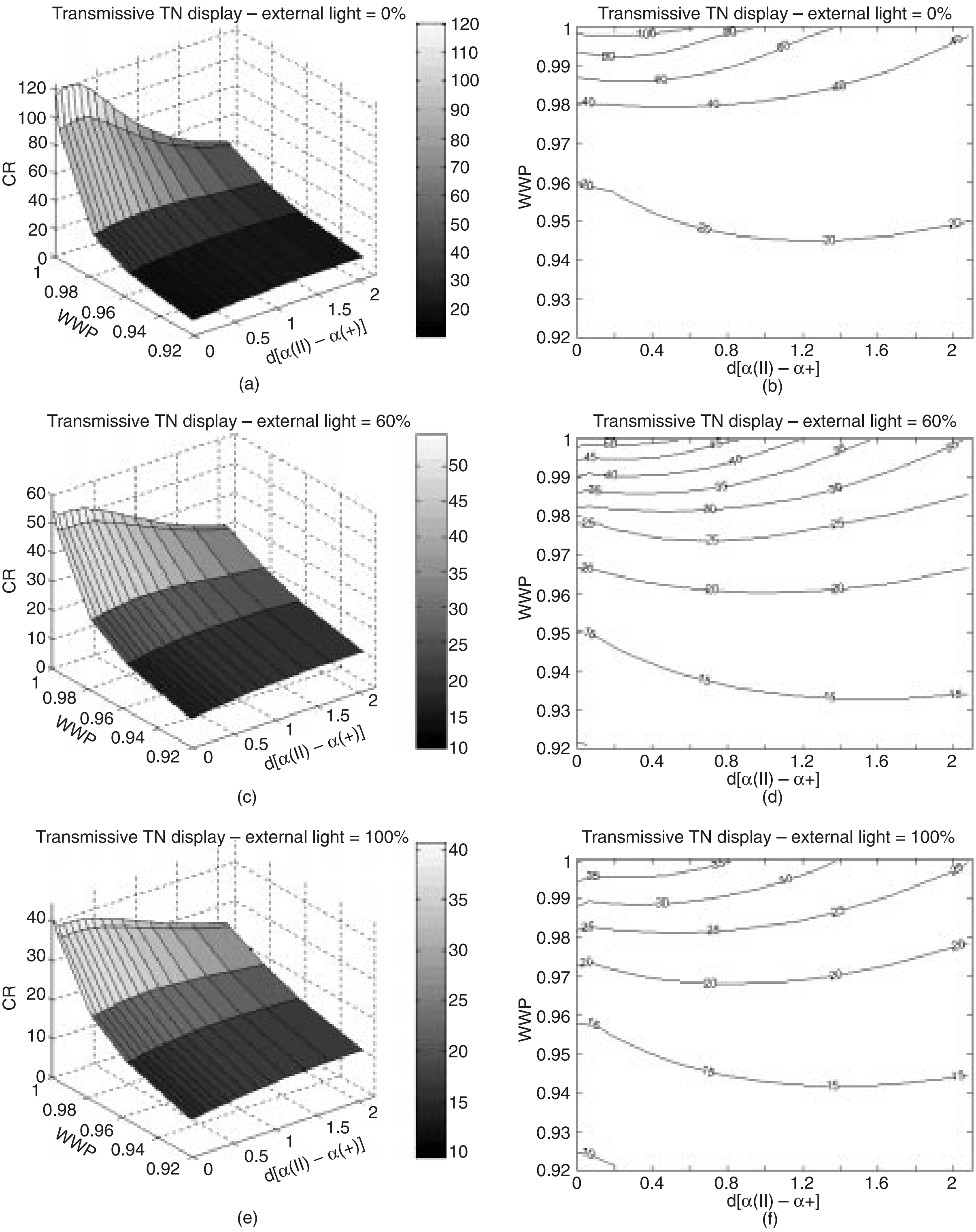


Fig. 4. Contrast ratio for the reflective TN LCD obtained from the calculations: completed function (a), cross section (b).

- the aim of this work is to present the possibilities of numerical calculations of display optical parameters and to show usefulness of such a method.

In Fig. 6, the contrast ratio for transmissive display as a function of polarization coefficient of the used films and external light intensity for liquid crystal layer without dye are presented. This characteristic shows directly the significant influence of external light on the display contrast ratio. The contrast ratio changes from 1:120 for no external light to 1:40 for the intensity of external light equal to 100% of the internal light intensity.

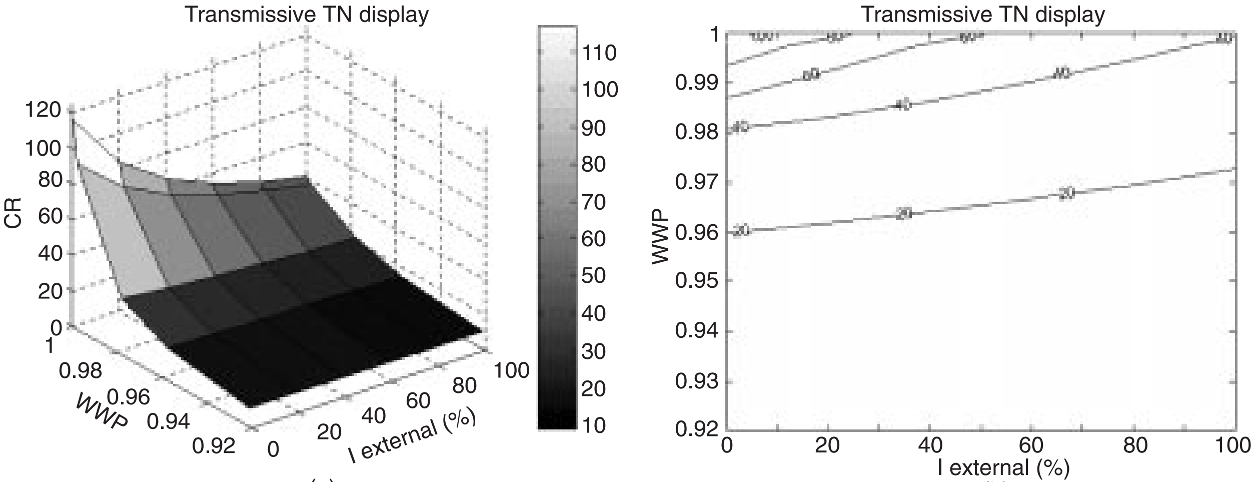


(a) (b)

(c) (d)

(e) (f)

Fig. 5. Contrast ratio for the transmissive TN LCD obtained from the calculations. The rows present the completed function (left hand side) and cross section (right hand side) for given value of the external light intensity.



(a) (b)

Fig. 6. Contrast ratio values for transmissive TN LCD as a function of the external light intensity. There is liquid crystal layer without a dye.

5. Discussion

The obtained results presented in Fig. 4 and Fig. 5 show the influence of the liquid crystal mixture dichroic parameters and polarization coefficients of the used polarizers on the static optical parameters. It should be emphasized that these characteristics are very similar to the measured characteristics presented in our previous paper [1]. It means that the results obtained using our computer program are very compatible with the experimental ones.

One can observe that correct choice of a combination of the dichroic dye into the LC mixture and polarizers is very important to obtain optimal contrast ratio value. For analysis of the negative mode of the reflective TN display constructed from typical materials (glass, conductive layer, etc.) one has to use the polarizers with proper polarizing coefficients to obtain high contrast ratio. Generally speaking, depending on the chosen transmission minimum (first or second one) and the possibility of using the antireflection layer and other display elements, this choice of the combination of the polarizers and dichroic dye should be different.

In the analysed case, to obtain the reflective display with high contrast ratio the *WWP* coefficient of the polarizers should have a value of about 0.98 and simultaneously a dichroic dye characterized by $d[\alpha(\|) - \alpha(+)]$ from the range 1.0–2.0 should be applied. It should be pointed out that the application of a dye may decrease the brightness of the display. Therefore, the final choice of the combination of the polarizers and the dye needs to take into account these phenomena. It depends on user requirements. For transmissive display to obtain the highest value of CR, the polarizers with *WWP* from 0.98 to 0.999 and dichroic dye characterized by $d[\alpha(\|) - \alpha(+)]$ equal to about 0.25 should be used. In this case, we must remember that the higher values of *WWP* cause decrease in brightness of the transmissive display. Similarly to the previous case the final choice must be preceded by an analysis of the display brightness and user requirements.

6. Conclusions

The presented results show that the optimization procedure is significant for the display design process and provides initial determination of optical parameters of the display elements necessary to fulfil the given requirements.

Such an analysis should be done for a determined display and it would be different for different display elements. In this work, we wanted to present and underline the usefulness of this method and show the fact that it can give us the detailed information on the parameters of the LC layer and polarizers which have to be applied to obtain the highest contrast ratio of the display. Without such an analysis carried out for a given type of the display and available display elements, the choice of optimal point of the work would be very difficult. Additionally, only experimental testes would not guarantee that the best configuration of the display elements has been chosen.

Acknowledgments

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