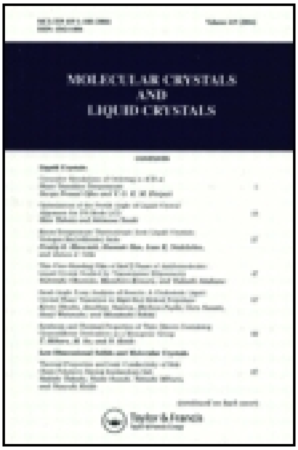

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Determination of LCD Electro-Optical Parameters Using Mathematical Model to Obtain Optimized Device Operating Under High External Illumination

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Liquid Crystal Displays (LCDs) are widely used as visualization devices, also in special places and conditions such as: plane cockpits, "outdoor" advertisement and information boards, mobile devices, etc. Such applied displays – in relation to standard displays, widely available on the market, should meet special requirements for image quality, such as very high contrast ratio and luminance, wide viewing angle, faithfulness of colour visualization, etc. Additionally, for "outdoor" applications, all these parameters should be ensured in high external (sun) illumination conditions. Because an analysis of display parameters based only on experimental results is very difficult, expensive, and long-lasting, a mathematical model of light propagation through the LCD and, based on it, a computer program were worked out. This mathematical model offers determination of optical parameters of a display for any observation angle, any optical parameters of display elements, and any display structure, taking into account the interference phenomena occurring in a display, different directions of ordinary and extraordinary wavevectors and polarization vector, dispersion phenomena of refractive indices and absorption coefficient of the display layers, etc. It should be underlined, that our model takes into account temporal coherence of light and can be used to determine the transmission and reflection coefficients at the same time. Thus, it possible to analyse displays working in transmissive and reflective modes. This paper presents basis assumptions of this mathematical model and our computer program. Additionally, hypothetical results obtained from this program for a display operating under high external illumination are given.

Keywords: electro-optical parameters; liquid crystal display; mathematical and computer optimization procedure

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1. INTRODUCTION

Nowadays, Liquid Crystal Displays are widely used for visualization applications, starting from small numerical devices to a large-area TV and a computer display. Unfortunately, even though their parameters such as contrast ratio, luminance and quality of colour visualization are high enough for standard applications, they are not adequate for special conditions. The example of such special conditions analyzed in our work is a situation, when an LC display must be used under high external illumination or/and it is observed at a very wide range of angles. The first situation occurs, e.g., in glass cockpits of planes, mobile devices, and for "out-door" information and advertisement boards. Additionally, for "out-door" large-area applications (advertisement and information boards) a display image should have high parameters for very wide observation angles. As regards the luminance or contrast ratio, these parameters depend on external illumination and observation angle, but this dependence is lower than for colour visualization. In other words, the optimization procedure should take into account not only angle characteristics of luminance and contrast ratio but also should give the exact information about quality of colour imaging as a function of an observation angle. Such information can be colour-coordinates (for example CIE1931 or CIE1976), which in connection with a luminance value in unambiguous way determine quality of colour visualization. Therefore, to determine optimal construction of a display operating in special conditions, the very exact spectral characteristics of transmitted and reflected light are needed, because small differences in the spectral characteristics can strongly affect colour visualization, stronger than they affect luminance. Because of it, our aim is to construct a proper mathematical model to determine spectral characteristics of light passing through the LC display, which makes it possible to obtain these characteristics for the conditions close to real ones.

2. BASIC AIMS OF CARRIED OUT STUDIES

As it was mentioned in the previous section, our aim was to construct a mathematical model of light propagation through the LC display. Using this model, the spectral characteristics of light after its passing through a display can be obtained. Such characteristics are needed to calculate the basic optical properties of a display such as: luminance, contrast ratio, and colour coordinates according to Eqs. (1), (2) and (3) [1,2].

$$\text{Luminance}: L = \frac{\int_{380}^{780} H(\lambda) \cdot S(\lambda) \cdot T(DisPar, \lambda) d\lambda}{\int_{380}^{780} H(\lambda) \cdot S(\lambda) d\lambda} \tag{1}$$

$$\begin{aligned} \text{Contrast ratio: } CR &= \frac{L_{BRIGHT}}{L_{DARK}} \\ &= \frac{\int_{380}^{780} H(\lambda) \cdot S(\lambda) \cdot T_{BRIGHT}(DisPar, \lambda) d\lambda}{\int_{380}^{780} H(\lambda) \cdot S(\lambda) \cdot T_{DARK}(DisPar, \lambda) d\lambda} \end{aligned} \tag{2}$$

Colour coordinates, e.g., CIE1931: $x = X/M$; $y = Y/M$ where: $X + Y + Z = M$ and:

$$\begin{aligned} X &= \int_{380}^{780} T(DisPar, \lambda) \cdot S(\lambda) \cdot \overline{X}(\lambda) d\lambda \\ Y &= \int_{380}^{780} T(DisPar, \lambda) \cdot S(\lambda) \cdot \overline{Y}(\lambda) d\lambda \\ Z &= \int_{380}^{780} T(DisPar, \lambda) \cdot S(\lambda) \cdot \overline{Z}(\lambda) d\lambda \end{aligned} \tag{3}$$

DisPar – denotes display optical parameters (optical properties of a display as a whole).

BRIGHT and *DARK* denotes bright and dark state of a display, respectively.

H(λ) and *S(λ)* denote human eye sensitivity function and spectral characteristic of a light source, respectively.

$\overline{X}(\lambda), \overline{Y}(\lambda), \overline{Z}(\lambda)$ – denote colour matching functions.

The parameters described by Eqs. (1–3) depend on work conditions, such as a type of the used light source and observation conditions (day, night). These parameters can describe quality of visualization in unambiguous way but they can be obtained only if a display transmission function is known. This function depends on many display parameters (*DisPar*) such as: local profile function in a liquid crystal layer determined by driving voltage, complex refractive indices of all display layers, quantity and mutual arrangement of the layers. Additionally, this function also depends on a type of a light source, because a light transmission coefficient is different for each wavelength and the coherence time of a light influences the interference efficiency. It should be underlined, that in the final optical parameters of a display working in a transmission mode both light sources should be considered: external and internal ones. Therefore, for this case the luminance, contrast ratio and colour coordinates should be calculated according to Eqs. (1–3), but twice for two "transmission" functions: for the light transmitted through a display and for the light reflected from it. These two functions have to be obtained for the same display work conditions, despite light sources which are different for these both phenomena – transmission and reflection ones. To determine final optical parameters, the normalizing procedure is needed. For example, luminance in this case can be determined as:

$$L = \frac{\int_{380}^{780} H(\lambda) \cdot [S_1(\lambda) \cdot T_1(DisPar, \lambda) + k \cdot \overline{S}_2(\lambda) \cdot T_2(DisPar, \lambda)] d\lambda}{\int_{380}^{780} H(\lambda) \cdot [S_1(\lambda) + k \cdot \overline{S}_2(\lambda)] d\lambda} \tag{4}$$

where:

$$\overline{S}_2(\lambda) = S_2(\lambda) \cdot \frac{\int_{380}^{780} S_1(\lambda) d\lambda}{\int_{380}^{780} S_2(\lambda) d\lambda}$$

Normalizing coefficient k is the ratio of light intensity of a source no. 2 to a source no. 1.

$S_1(\lambda)$ denotes the spectral characteristic of light sources: external or internal one.

$\overline{S}_2(\lambda)$ is the normalized spectral characteristic of a light source no. 2 in relation to a source no. 1.

T_1 ($DisPar$, λ) and T_2 ($DisPar$, λ) denote the "transmission" coefficients of a display for transmitted and reflected light.

Other optical parameters (contrast ratio and colour coordinates) can be calculated in a similar way. The problem described above does not appear when a reflective mode is analyzed. A crucial problem which must be solved is a mathematical theory of light passing through the display, which takes into account as many phenomena occurring during this process as possible. The currently available calculation methods include the simplifications and limitations and can be used only for standard applied displays. Because our investigations concern the displays used for special applications, the theory of light passing through the display should include such phenomena as:

- spectral characteristics of a light source/sources,
- dispersion of refractive indices of all layers and their complex form,
- complex form of wavevectors and real directions of ordinary and extraordinary wave in anisotropic or dichroic layers,
- multi-interference phenomena occurring in the display, including temporal coherence of the used light source.

The mathematical model considering the presented above phenomena offers calculations for any spectral characteristics of a light source and any observation angle. Additionally, it should give the information about the transmission for the both directions of display lighting. It is needed to determine the optical parameters for transmissive display.

In our previous paper [3,4], such a model worked out at our Institute was presented. It is very important to underline, that to properly describe the interference phenomena, coherence time of light was used. It was obtained using the Fourier transformation of a spectral characteristic of the illuminating source.

3. COMPUTER PROGRAM TO CALCULATE OPTICAL PARAMETERS OF AN LC DISPLAY

Due to the mathematical theory of light propagation through the layers system, e.g., LC display, developed at our Institute, it was possible to construct the computer program for precise calculations of optical parameters such as luminance, contrast ratio, and colour coordinates of a display working under real conditions. Because the mathematical theory includes many phenomena occurring inside the display, such a program can be very useful to determine optical parameters of particular display layers, to obtain desirable parameters of a display as a whole. It is especially important for special operation conditions, e.g., high external illumination. In this situation, optical properties of the display elements strongly influence the final display parameters. So, the calculations should be done under the conditions close to real ones what ensures our program.

This program, called by us, Computer Support of Optimization Process (CSOP) can calculate:

- spectral characteristics of light transmitted and reflected from the display
- luminance and colour coordinates of a display,
- polarization of light transmitted and reflected from a display,

for any incident light (spectral characteristic and polarization) and any illuminating angle. Basing on these possibilities, the modules to calculate static, dynamic and angle characteristics of a TN display were worked out, basing on the known electrooptical distortion model [2].

4. HYPOTHETICAL RESULTS OBTAINED FROM CSOP PROGRAM

Using CSOP program, short hypothetical analysis of the influence of external illumination level on a contrast ratio of a standard TN transmissive display was carried out. The following properties of the display layers were assumed:

- glass – refractive indices (no absorption) equal to **1.5267** (wavelength = 435 nm), **1.5224** (486 nm), **1.5187** (546 nm), **1.5178** (587 nm) and **1.5143** (656 nm) – sodium glass with a thickness equal to **500 μm**;
- conductive layer – refractive index (no absorption and dispersion) equal to **1.832** – ITO layer with a thickness equal to **25 nm**;
- liquid crystal layer – thickness equal to **6 μm**. Standard OFF and ON profile functions. 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);
- antireflective layer – interference one matched to a wavelength of **550 nm**;
- polarizers – set-up of the films, which part is presented in Table 1 (no dispersion phenomena).

$T_p(II)$ and $T_p(+)$ denote transmission coefficients of two parallel and crossed polarizers, respectively.

PC means polarization coefficient of a single polarizer.

For the presented calculations, the following assumptions were used:

- human eye sensitivity – daily type,
- external light source – D_{65} type,
- internal light source – A type,

TABLE 1 Polarizing Films Used in Hypothetical Calculations

T_p(II) [%]	T_p(+) [%]	*PC*
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

- observation angle equal to 0 deg (normal direction),
- ratio of external source intensity to internal one: 10%, 25%, 50%, 75%, 100%, 150%, and 200%.

The obtained results are shown in Figures 1, 2, and 3.

The results presented in these figures show the influence of external illumination on the contrast ratio and the luminance of a bright state in TN transmissive display. They were obtained for a given polarizer set-up and given properties of the particular display layers. The obtained results show how the chosen layer system can be applied to construct a display for application under high illumination. As one can see in Figure 1, a value of the contrast ratio strongly depends on the polarization coefficient of the used films and level of external light. The dependence of CR on a polarization coefficient (PC) is lower for high illumination, but the absolute values of a contrast ratio decrease very fast when the external light intensity grows. On the other hand, luminance of bright state fast increases with growing intensity of the external light (see Fig. 2). Therefore, to choose the optimal point of work, the values of contrast ratio and bright state luminance needed for given application should be analysed. In Figure 3, the detailed graphs of the contrast ratio and bright state luminance obtained for the external light intensity equal to 10% and 200% of the internal

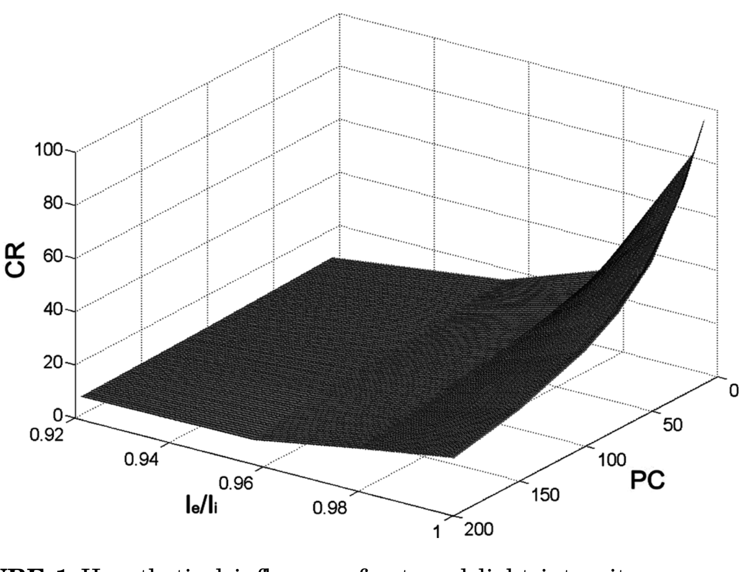

FIGURE 1 Hypothetical influence of external light intensity on a contrast ratio of a given TN display.

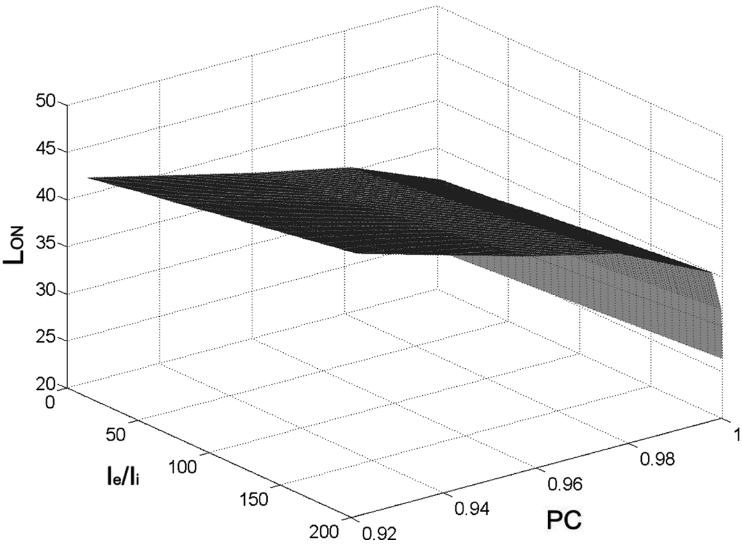

FIGURE 2 Hypothetical influence of external light intensity on luminance of bright state of a given TN display.

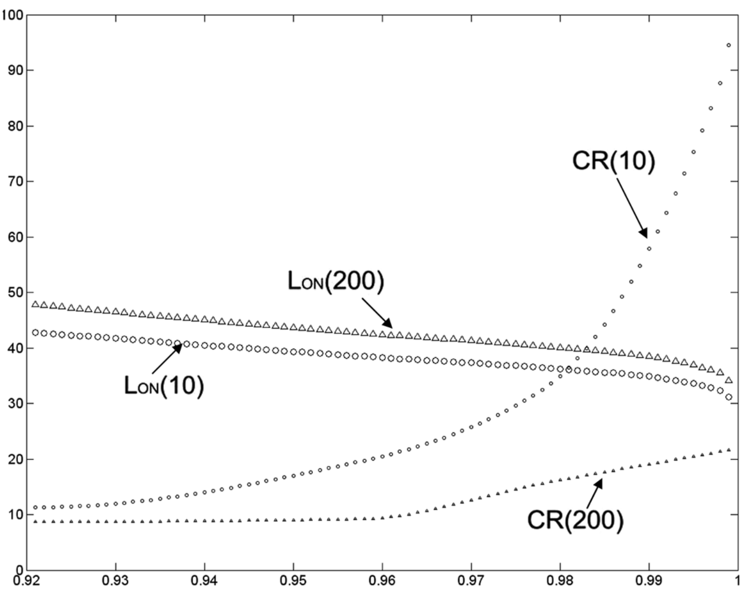

FIGURE 3 Contrast ratio and luminance of bright state for the intensity of an external light equal to 10% (CR(10) and $L_{ON}(10)$) and 200% (CR(200) and $L_{ON}(200)$) of internal light intensity, respectively.

light were presented. As one can see, in the case of low illuminating, the contrast ratio decreases very fast (about 4 times), when the polarization coefficient of the used films decreases from 0.99997 to about 0.97. At the same time, the luminance increases only of about 20%. For the value of the polarization coefficients under 0.97, the contrast ratio decreases slowly, but the fall of CR is still higher than the luminance growth.

Under high illumination, the contrast ratio decreases only 2 times when the polarizing coefficient of the films changes from 0.99997 to 0.97. Additionally, the luminance value is higher than under low illuminating and also increases when the PC of a film decreases. For the bright polarizers (polarization coefficient lower than $\sim$0.96), the very interesting phenomenon is observed. The luminance increases, but the value of a contrast ratio is nearly constant. Therefore, to construct a very bright display operating under high illumination (using the analyzed in this work set-up of the display layers), the polarizers with a polarization coefficient equal to about 0.92–0.93 should be applied. If the value of a contrast ratio is very important, the polarizers with PC from a range (0.96–0.995) should be used. The chose of a defined value depends on acceptable value of luminance, because it decreases when the polarization coefficient of the films increases. The polarizers with a polarization coefficient higher than $\sim$0.995 should not be applied in a TN transmissive display working under high illumination, because in this case a contrast ratio increases slowly (about 6%), but luminance decreases faster (about 15%). It is different situation than for low external illumination. In this case, the growth of a polarizing coefficient from 0.995 to 0.999 causes that a contrast ratio increases of about 33% and at the same time the luminance decreases of only about 13%.

5. CONCLUSIONS

The mathematical model of light propagation through the liquid crystal display worked out at our Institute in connection with a computer program can be a very useful tool for determining the optical parameters of a display. Additionally, such a tool can be used to carry out very complicated optimization procedures. Especially important is the fact, that this model takes into account many phenomena occurring during a light propagation process and it does not include simplifications. Therefore, it can be used for calculation or optimization procedures, not only for standard applications of the LC displays but also for special ones (in this case, the simplified methods give calculations similar to our calculations). In the last case, even insignificant changes of optical properties of the display elements strongly influence the display parameters, especially colour coordinates and angle characteristics. In this paper, the influence of a polarization coefficient of the used films on a contrast ratio and luminance in bright state in TN transmissive display was determined for high external illumination.

REFERENCES

[1] Bahadur, B. (1992). *Liquid Crystals Applications and Uses*, World Scientific.
[2] Yeh, P. & Gu, C. (1999). *Optics of Liquid Crystal Displays*, John Wiley and Sons: New York.
[3] Zieliński, J. & Olifierczuk, M. (2007). *Proceedings of Conference on Liquid Crystals 2005*, 341.
[4] Zieliński, J. & Olifierczuk, M. (2006). *MCLC*, *454*, 395[797].