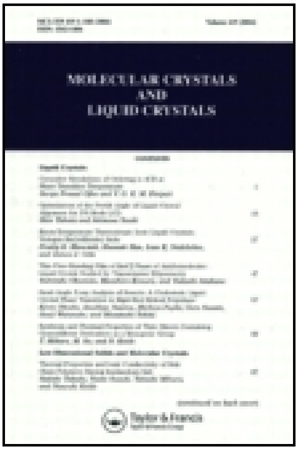

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NUMERICAL OPTIMIZATION OF 2 POLARIZER REFLECTIVE TN DISPLAY

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The analysis of display static optical parameters such as luminance and contrast ratio has been done using the special computer program. The influence of the optical parameters of individual display elements on the parameters of the whole display has been given (especially polarization coefficient of the polarizing films and dichroic properties of liquid crystal layer – "guest-host" effect). The way of the optimization of the reflective TN display has been shown for its different applications. The possibility of an improvement of contrast ratio and brightness for this display has been set.

Keywords: numerical modeling; optical parameters; reflective LCD

INTRODUCTION

The static optical parameters of all display kinds (e.g. Liquid Crystal Displays) such as brightness, contrast ratio and color coordinates determine the possibilities to use these displays for given applications. For this reason it is very important to fix an influence of the individual display elements on the display parameters, as well as to known how calculate these parameters correctly. If we have the correct computational method we would calculate these parameters for different display elements and we would carry out an optimization procedure.

In this work the numerical program [1,2] (worked out by authors) for calculation of the optical LCD parameters has been adopted. This program takes advantage of GOA [3–8] method modified by authors. Using this program the optical parameters such as luminance in on-state, contrast ratio and color coordinates can be calculated for a normal incidence of light.

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The calculation can be done for "quasi-real" display. It means, that the real spectral characteristics of the display elements, such as glass, conductive layer, liquid crystal layer, polarizer, analyzer etc. have been taken into account, moreover the light interference, absorption, reflection from phase boundaries, spectral characteristic of human eye sensitivity and spectral characteristic of a real illuminated source have been adopted.

Our calculation method uses the GOA method assumptions and the scheme of a light passing through the reflective display as it is shown on Figure 1.

Finally, the light intensity after passing display can be obtained as:

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

where the coefficients A, B, C and D denote the amplitudes of the light wave in the following light description:

$$E^n(x) = A^n \cdot \sin \omega t + B^n \cdot \cos \omega t \tag{2}$$

$$E^n(y) = C^n \cdot \sin \omega t + D^n \cdot \cos \omega t \tag{3}$$

which are obtained from complex Fresnel formula (for isotropic mediums phase boundaries) and for anisotropic medium (liquid crystal) from the

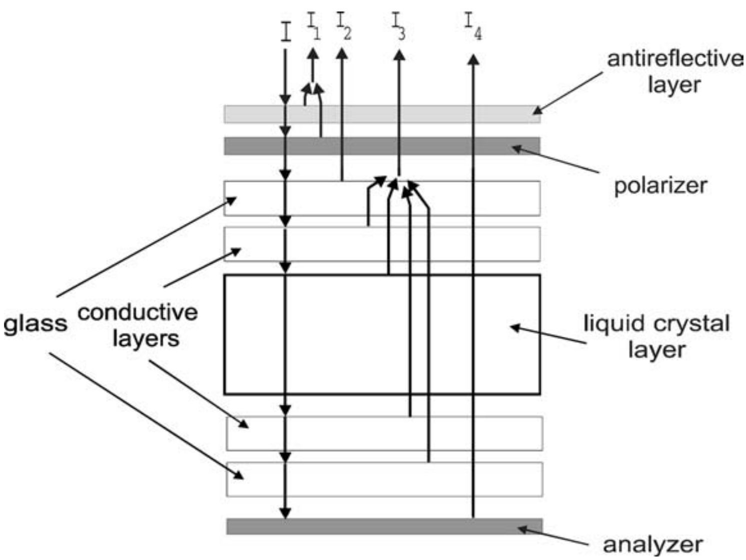

FIGURE 1 The way of light beam through the reflective LC display adopted in the computer program. I – an intensity of illuminating light, I_1, I_2, I_3 and I_4 – the intensities of the light reflected from the appropriate phase boundaries after the interference.

following formulas [1,2]:

$$A^n = \sqrt{e^{-\alpha_\parallel \cdot \delta z}} \cdot \begin{bmatrix} (A^{n-1} \cdot \cos\delta\Theta + C^{n-1} \cdot \sin\delta\Theta) \cdot \cos\delta_e + \\ +(B^{n-1} \cdot \cos\delta\Theta + D^{n-1} \cdot \sin\delta\Theta) \cdot \sin\delta_e \end{bmatrix} \tag{4}$$

$$B^n = \sqrt{e^{-\alpha_\parallel \cdot \delta z}} \cdot \begin{bmatrix} -(A^{n-1} \cdot \cos\delta\Theta + C^{n-1} \cdot \sin\delta\Theta) \cdot \sin\delta_e + \\ +(B^{n-1} \cdot \cos\delta\Theta + D^{n-1} \cdot \sin\delta\Theta) \cdot \cos\delta_e \end{bmatrix} \tag{5}$$

$$C^n = \sqrt{e^{-\alpha_+ \cdot \delta z}} \cdot \begin{bmatrix} (-A^{n-1} \cdot \sin\delta\Theta + C^{n-1} \cdot \cos\delta\Theta) \cdot \cos\delta_o - \\ +(B^{n-1} \cdot \sin\delta\Theta - D^{n-1} \cdot \cos\delta\Theta) \cdot \sin\delta_o \end{bmatrix} \tag{6}$$

$$D^n = \sqrt{e^{-\alpha_+ \cdot \delta z}} \cdot \begin{bmatrix} (A^{n-1} \cdot \sin\delta\Theta - C^{n-1} \cdot \cos\delta\Theta) \cdot \sin\delta_o - \\ +(B^{n-1} \cdot \sin\delta\Theta - D^{n-1} \cdot \cos\delta\Theta) \cdot \cos\delta_o \end{bmatrix} \tag{7}$$

where an upper index denotes number of infinite thin LC layer (thickness $\delta z \to 0$). δ_o represent phase shifts occurring after passing a distance δz in LC medium ($\delta_e = 2\pi n_{eff}\delta z/\lambda$ and $\delta_o = 2\pi n_o \delta z/\lambda$). n_{eff} denotes the effective refractive index of LC and it amounts to:

$$n_{eff} = n_e \cdot n_o \cdot \sqrt{\frac{1 + \mathrm{tg}^2\Theta_s}{n_o^2 + n_e^2 \cdot \mathrm{tg}^2\Theta_s}}\,(\Theta_s - \text{tilt angle}) \tag{8}$$

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

The luminance and the contrast ratio have been calculated from the following formulas [9]:

$$L(\Delta nd) = \frac{\int_{380}^{780} H(\lambda) \cdot V(\lambda) \cdot T(\Delta n, d, \lambda)\mathrm{d}\lambda}{\int_{380}^{780} H(\lambda) \cdot V(\lambda)\mathrm{d}\lambda} \tag{9}$$

$$CR = \frac{\int_{380}^{780} H(\lambda) \cdot V(\lambda) \cdot T_{ON}(\Delta n, d, \lambda)d}{\int_{380}^{780} H(\lambda) \cdot V(\lambda) \cdot T_{OFF}(\Delta n, d, \lambda)d} \tag{10}$$

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

RESULTS AND DISCUSSION

Using computer program described above the calculation of static optical parameters for reflective TN display has been done. The calculation has been done for float glass and for standard ITO layer. The refractive coefficients of glass, polarizer and ITO, as well as the ITO layer absorption coefficient, have been measured experimentally, earlier. These measurements have been carried out by spectrophotometer method. These coefficients have been calculated from Fresnel formulas described for given systems using measured characteristic of their light transmission.

All calculation have been done for A illuminating source and for day-sensitivity of human eye. The light interference phenomena have been taken into account. The polarizing coefficients for polarizer and analyzer have been standardized and defined as [10]:

$$WP = \frac{T(\|) - T(+)}{T(\|) + T(+)} \tag{11}$$

where $T(\|)$ and $T(+)$ denote the light transmission through the single polarizing films (for polarizer it is one way passing through the film and for analyzer it is passing through the polarizing film to a mirror and back) for light polarizing along the polarizing axis and perpendicular to it, respectively. The analyzer mirror has been regarded as an ideal mirror.

The most important problem considered in this work has been a value of contrast ratio in quasi-real reflective TN display. The optical properties of a TN layer are easy to fix, but the properties of the whole display in a real conditions are not, yet. In this paper the results of the calculations of contrast ratio for such quasi-real conditions have been done.

The properties of the polarizing films (polarizing films in polarizer and analyzer) gathered in Table 1 have been adopted for calculations. It is necessary to stress that the transmission coefficients in Table 1 have been given for linearly polarized light. It means that the transmission for the two parallel and crossed polarizers has been equal to (12) and (13), respectively.

$$T_{\|} = \frac{1}{2}\left[T^2(\|) + T^2(+)\right] \tag{12}$$

$$T_{+} = T(\|)T(+) \tag{13}$$

TABLE 1

Transmission $T(\|)$ [%]	Transmission $T(+)$ [%]	Polarization coefficient WP
80	0,01	0,9998
85	0,1	0,9977
90	1	0,9780
93	2	0,9579
95	4	0,9192

The calculations for both display modes, positive and negative ones have been done. Additionally, these calculation have been done for the first and the second transmission minimum. The results have been obtained for different polarization coefficients of polarizer and analyzer and for different levels of liquid crystal layer absorption. A dichroic properties of a LC layer have been adopted. This absorption has had positive character (higher for LC director axis) in a case of positive mode and negative one (higher for direction perpendicularly to LC director axis) in a case of negative mode. The absorption properties of a LC layer have been determined in the expression $(\alpha_{\|} - \alpha_{+})d$, where $\alpha_{\|}$ and α_{+} denote absorption coefficients of a planar layer for a passing through the layer light polarized along the layer director and perpendicularly to it, respectively, d denotes thickness of a LC layer.

The results of the calculations are shown on Fig. 2 and 3.

As one can see, the contrast ratio depends on the both properties of a display: polarizing coefficients of polarizer and analyzer and LC layer

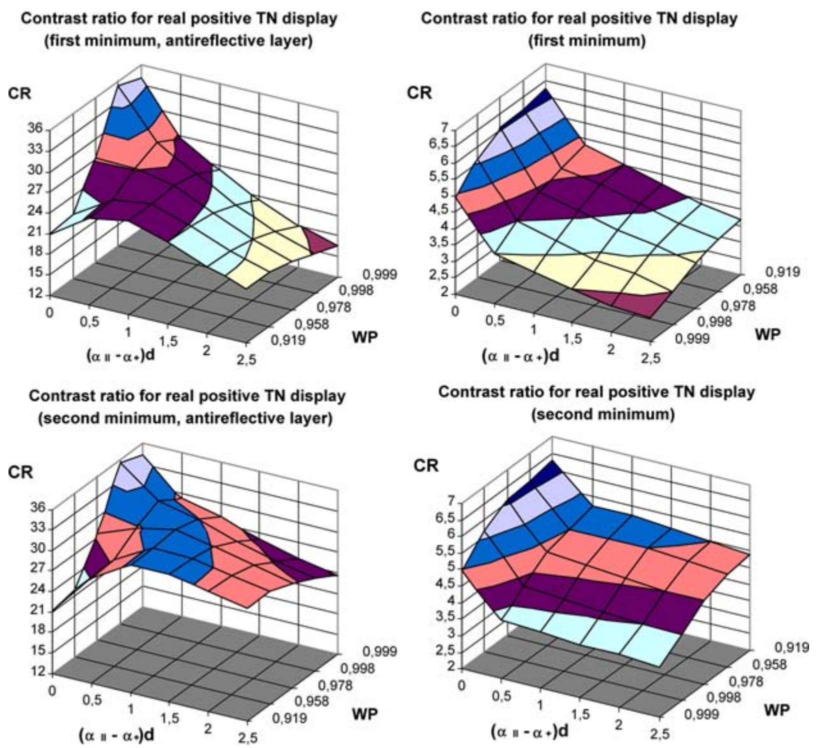

FIGURE 2 The contrast ratio of a reflective TN display (positive mode) as a function of a polarization coefficient of polarizing films and LC layer dichroic properties. (See COLOR PLATE VI)

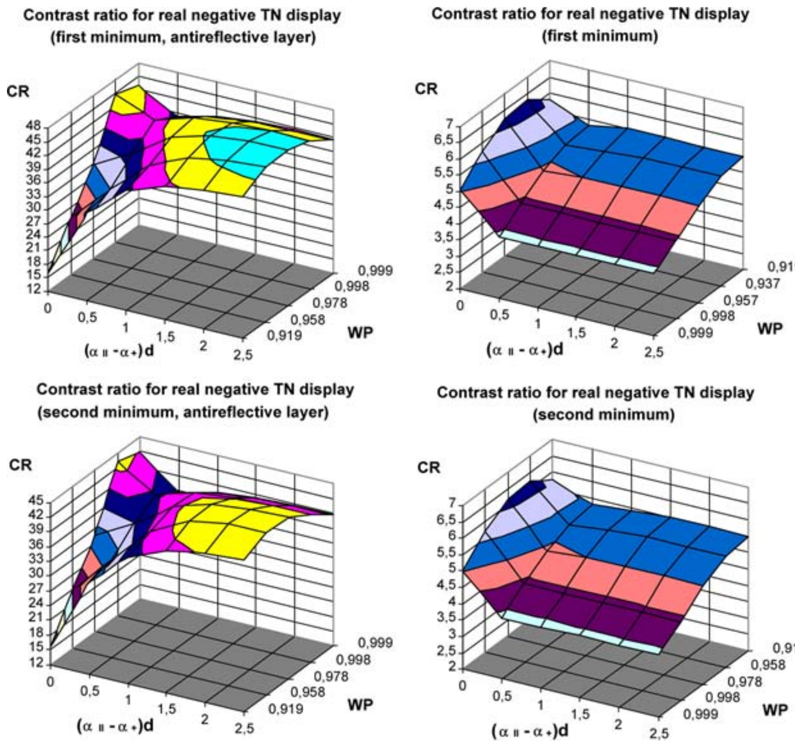

FIGURE 3 The contrast ratio of a reflective TN display (negative mode) as a function of a polarization coefficient of polarizing films and LC layer dichroic properties. (See COLOR PLATE VII)

dichroic properties. The optimum of contrast ratio can be chosen. This choice depends on a display application and it have to take into account a level of display luminance, too. On Figure 4 the luminance of on-state and off-state for the first minimum and an antireflective layer is shown (for both modes of a display: positive and negative).

The performed analysis has proved that the absolute values of the polarizing films transmission, as well as the absolute LC dichroic layer transmission have not influenced the values of the display contrast ratio. Only values of the polarizing coefficients and a value of an expression $(\alpha_{\|} - \alpha_{+})d$ have influenced it. Thus, the graphs no. 2 and 3 are the universal functions (for given ITO layer and glass). The display luminance of the both off- and on-states can depend on the absolute values of these parameters, however. On Fig. 4 the hypothetical display luminance is presented. In this case the light transmission through a planar layer (6 μm thick) has been equal 85% for light polarized along the layer absorption

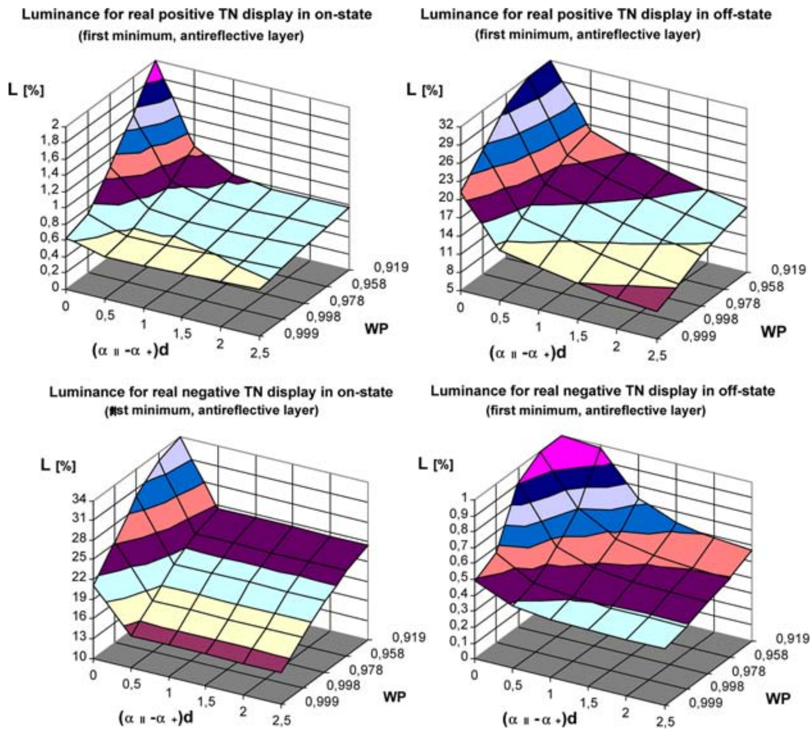

FIGURE 4 The hypothetical luminance of a reflective TN display (positive and negative modes). The first minimum and an antireflective layer have been considered. (See COLOR PLATE VIII)

axis and a proper values delivered from expression $(\alpha_{\|} - \alpha_{+})d$ for perpendicularly polarized light.

The properties of applied materials have to be known when carrying out the analysis of the optical properties of a quasi-real refractive TN display. For standard ITO layer and float glass one can carry out the following optimization procedure, for example:

1. To obtain a positive mode display with very high contrast ratio (luminance is not important).
   If the antireflective layer can be used the polarizers with the polarizing coefficient about 0,998 should be adopted. A dye should not be used. If the antireflective layer can not be used the polarizers should have polarizing coefficient smaller than 0,970.
2. To obtain a positive mode display with very high contrast ratio and as the smallest luminance in on-state.

If the antireflective layer can be to used, the polarizers should have a polarizing coefficient about 0,985 and a dye with $(\alpha_{\parallel} - \alpha_{+})d$ about 0,5 should be adopted, because in this case the contrast ratio decreases about 20% from the maximum value but the luminance of the on-state decreases about 50% from a point of the maximum contrast ratio.

3. To obtain a negative mode display with very high contrast ratio (luminance in not important).
   If the antireflective layer can be used, the polarizers with the polarizing coefficient from 0,990 to 0,960 and a dye with $(\alpha_{\parallel} - \alpha_{+})d$ about 2,0 should be adopted. If the antireflective layer can not be used, the polarizers should have polarizing coefficient about 0,960–0,970. A dye should not be adopted.
4. To obtain a negative mode display with very high contrast ratio and the highest possible luminance in on-state.

If the antireflective layer can be used, the polarizers should have a polarizing coefficient about 0,950–0,960 and a dye with $(\alpha_{\parallel} - \alpha_{+})d$ from 1,5 to 2,5 should be used, because in this case the contrast ratio is the highest and the luminance of on-state decreases about 30% from the maximum, but for the maximum luminance the contrast ratio is smaller about 50% than in this point. If the contrast ratio would be less important the polarizers with the polarizing coefficient about 0,980 and a dye with $(\alpha_{\parallel} - \alpha_{+})d$ about 0,2 should be used. In this case the contrast ratio decreases about 20% from the maximum but the luminance decrease have a value about 80% of the maximum.

CONCLUSIONS

The more optimization procedures for given applications and different optical properties of used material can be done, certainly. In this work we wanted to present possibilities of worked out computer program and to show selected case of a reflective TN display. Presented results show that the choice of the polarizing films and dichroic properties of a LC layer are very important for construction of real reflective TN displays. Interaction between the properties of individual display elements do not influence on display optical parameters in the simple way. Therefore, the numerical optimization procedure is very useful.

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