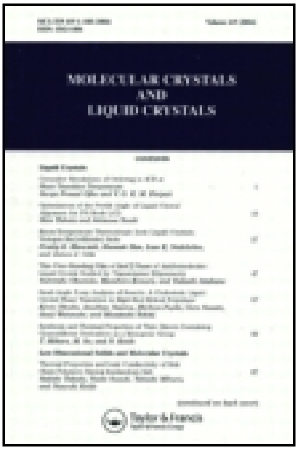

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Optical Parameters of an Optimized TN Display for Large-Area Application

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Version of record first published: 24 Sep 2006

Mol. Cryst. and Liq. Cryst., 2001, Vol. 367, pp. 849-863
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Optical Parameters of an Optimized TN Display for Large-Area Application

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The aim of the present paper is to show the optical parameters of liquid crystals display (LCD) for large-area applications. The mathematical and numerical model of light propagation through the display is given. The experimental verification of theoretical results has been done. The contrast ratio vs. polarization coefficient and dichroic property of the LC layer has been obtained.

Keywords: large-area systems; optimization of optical parameters; numerical modelling

INTRODUCTION

Large-size LC displays are applied widely in construction of advertising and information posters. A big advantage about them is a possibility to construct modular boards of any dimensions. Small power-consumption and a passive regime of their operation are another very important factors. TN displays technology and a wide variety of liquid crystalline materials used in it seem to be one of the most prospective for large-size displaying. Requirements imposed for a large-area display are listed in Table 1.

Asterisked parameter "luminance in on-state" is related to passive displays first of all, working in negative mode (light symbols on the dark background).

TABLE 1 **Requirements for large-area display[1,2]**

Requirements groups	Parameter	Typical requirements
general	effective contrast ratio CR_{obs}	higher than 1:25
	good angle of view	higher than 40°
	switching times	shorter than 250 ms
	temperature regime of operation	-30°C - +70°C
	luminance in on-state	higher than 30%
	life	>10000h
	colour	possibility of displaying coloured images
special	mobility	transportable
	durability	resistant to typical atmospheric emissions
	power	batteries, possibility of working in rooms with inefficient air-conditioning
	wider temperature regimes	-35°C - +80°C

Optimization of optical properties of a large-size TN display is a problem to be solved. TN effect in the negative mode (only this mode makes it possible to get coloured imagery) does not give satisfactory values of contrast ratio and luminance of light state in the same time. Additionally in reflection state contrast ratios are low (commonly lower then 1:15). An optimization oriented towards improving the above mentioned relation between optical contrast ratio and luminance of light state of negative TN mode is presented and discussed in this paper.

THEORITICAL ASSUMPTION

To optimize TN display we have applied GOA[3,4,5,6,7,8,9,10] (Geometrical Optics Approximation) method, enriched with the following elements:

- taking into account the whole visible range, human eye's sensitivity and the source of light spectral characteristics;
- inclusion of refractive indexes dispersion of glass plates, conductive layers and polarizers;

- taking into account dispersion of absorption characteristics of polarizers and conductive layers;
- discussion of light interference;
- modelling for two independent light sources (external and internal)considering TN layer as a linearly dichroic medium.

The GOA method is put in the following coordinates (Fig. 1).

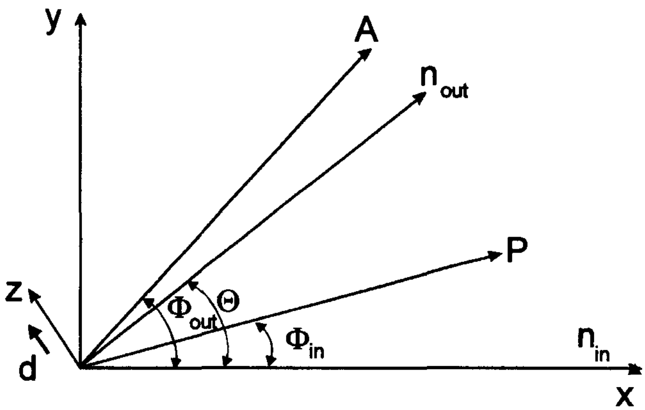

FIGURE 1 Coordinates system for analysis of light transmission through a layer of twisted LC nematics.

An initial point for our calculations was introduction of another x'y' coordinates system connected with an inicatrix axis of layer's refractive indexes projection on a plane parallel to it's boundary. At the border of the layer from the input polarizer's side the system x'y' overlaps with the xy system. Transmission coefficients for electric field intensity of electromagnetic (light) wave oriented in parallel and perpendicularly to the polarizer's axis can be calculated using the system of equations:

$$\tfrac{1}{2}\cdot\left(1-R_{pp}\right)^{2}\cdot\left[T_{p}^{2}(||)+T_{p}^{2}(+)\right]=T_{pm}^{||} \quad (1)$$

$$T_{p}(||)\cdot T_{p}(+)\cdot\left(1-R_{pp}\right)^{2}=T_{pm}^{+} \quad (2)$$

where R_{pp} is refraction index at the polarizer's foil and the air boundary:

$$R_{pp}=\left(\frac{1-n_{p}}{1+n_{p}}\right)^{2} \quad (3)$$

and $T_p(\|)$ and $T_p(+)$ are transmission coefficients for light polarized linearly in parallel and perpendicularly to polarizer's axes, respectively, while $T_{pm}^{\|}$ and T_{pm}^{+} are experimentally obtained transmission coefficients for two polarizing films oriented in parallel and perpendicularly with regard to the polarizing axes. n_p is the refractive index of polarizer.

Using this method we are able to get spectral transmission characteristics for the whole visual wavelength using a simple spectrophotometric analysis.

When the vector $\vec{E}$ of electric field intensity of the projecting light is given as $E = A \cdot e^{i\cdot(\omega t - K\cdot z_0)}$ where:

ω - periodicity (frequency) of the light's wave;

K - light's wave vector in the air;

z_o - optical distance covered by the wave along z axis (Fig. 1) and z_o=0;

at standarized amplitude value A=1 then in the LC layer we obtain (along the parallel and perpendicular orientation of the polarizer, respectively) the following value of E:

$$E^p_{\|} = t_{in} \cdot \sqrt{\frac{1}{2} T^p(\|) \cdot e^{-\alpha_{ITO} \cdot d_{ITO}}} \cdot e^{i\cdot(\omega t - \phi_{in})} \tag{4}$$

$$E^p_{+} = t_{in} \cdot \sqrt{\frac{1}{2} T^p(+) \cdot e^{-\alpha_{ITO} \cdot d_{ITO}}} \cdot e^{i\cdot(\omega t - \phi_{in})} \tag{5}$$

where index p characterizes the light state after passing through "input layers" i.e. a polarizer and other display's layers located between the source of light and the LC and before crossing the conductive layer-LC border, then t_{in} is the value of vector's E amplitude transmission through the input layers' border, ϕ_{in} is the phase shift value resulting from covering the thickness of the input layers ($\phi_{in} = \sum_i K_i \cdot z_i$ where K_i is wave vector in medium i and z_i is thickness of the medium i). d_{ITO} is thickness of the conductive layer and a_{ITO} – its absorption coefficient. Those vectors should be considered separately, because they have different phase properties in the case of scattered light, in other words – we are not in position to determine their values explicitly.

The values of vectors (4) and (5) at any point of LC describe precisely polarization of the light penetrating a display. Further description of the path of the light across the transducer will be done for the real part of the E-vector with a coordinate system x'y' rotating according to the changes director's n of the LC layer. It is indispensable for simplifying

of vector E mathematical form determining it's amplitude at any point while passing through indefinite number of LC layers.
If the thickness of LC layer is δz and director's angle of rotation δΘ, the intensity E in x'y' coordinates will take the form[11]:

$$E^0(x') = E^0(x)\cdot\cos\delta\Theta + E^0(y)\cdot\sin\delta\Theta \tag{6}$$
$$E^0(y') = -E^0(x)\cdot\sin\delta\Theta + E^0(y)\cdot\cos\delta\Theta \tag{7}$$

and after passing the LC layer, under assumption $\delta\Theta \to 0$ and due to difference between ordinary and extraordinary rays' velocities:

$$E^1(x') = \left(E^0(x)\cdot\cos\delta\Theta + E^0(y)\cdot\sin\delta\Theta\right)\cdot\cos(\omega t - \delta_e) \tag{8}$$
$$E^1(y') = \left(-E^0(x)\cdot\sin\delta\Theta + E^0(y)\cdot\cos\delta\Theta\right)\cdot\cos(\omega t - \delta_o) \tag{9}$$

and at the same time:

$$E^1(x') = Ampx'\cdot\cos(\omega t + \delta_w) \tag{10}$$
$$E^1(y') = \pm Ampy'\cdot\cos\left(\omega t + 90^0 + \delta_w\right) \tag{11}$$

where Ampx' and Ampy' are amplitudes of vector E in x' and y' direction, δ_e and δ_0 represent phase shift due to covering δz distance in LC for extraordinary and ordinary rays and can be define as follows: $\delta_e = \frac{2\pi n_{eff}\delta z}{\lambda}$ *and* $\delta_o = \frac{2\pi n_o \delta z}{\lambda}$, δ_w is phase shift resulting from coordinate system's rotation, index 1 is put for intensity of the vectors after passing the first layer.
Analysing vectors (8)-(11) and taking into account dichroic properties of the layer we get the following representation of amplitudes' values in consecutive points of a TN layer:

$$A^n = \sqrt{e^{-\alpha_{\parallel}\cdot\delta z}}\cdot\begin{bmatrix}\left(A^{n-1}\cdot\cos\delta\Theta + C^{n-1}\cdot\sin\delta\Theta\right)\cdot\cos\delta_e + \\ +\left(B^{n-1}\cdot\cos\delta\Theta + D^{n-1}\cdot\sin\delta\Theta\right)\cdot\sin\delta_e\end{bmatrix} \tag{12}$$

$$B^n = \sqrt{e^{-\alpha_{\parallel}\cdot\delta z}}\cdot\begin{bmatrix}-\left(A^{n-1}\cdot\cos\delta\Theta + C^{n-1}\cdot\sin\delta\Theta\right)\cdot\sin\delta_e + \\ +\left(B^{n-1}\cdot\cos\delta\Theta + D^{n-1}\cdot\sin\delta\Theta\right)\cdot\cos\delta_e\end{bmatrix} \tag{13}$$

$$C^n = \sqrt{e^{-\alpha_{\perp}\cdot\delta z}}\cdot\begin{bmatrix}\left(-A^{n-1}\cdot\sin\delta\Theta + C^{n-1}\cdot\cos\delta\Theta\right)\cdot\cos\delta_o - \\ +\left(B^{n-1}\cdot\sin\delta\Theta - D^{n-1}\cdot\cos\delta\Theta\right)\cdot\sin\delta_o\end{bmatrix} \tag{14}$$

$$D^n = \sqrt{e^{-\alpha_{\perp}\cdot\delta z}}\cdot\begin{bmatrix}\left(A^{n-1}\cdot\sin\delta\Theta - C^{n-1}\cdot\cos\delta\Theta\right)\cdot\sin\delta_o - \\ +\left(B^{n-1}\cdot\sin\delta\Theta - D^{n-1}\cdot\cos\delta\Theta\right)\cdot\cos\delta_o\end{bmatrix} \tag{15}$$

where absorption coefficient $\alpha_{\parallel}$ and α_{+} express absorptions of a dichroic layer for the light polaryzed linearly alongside n projection (in other words – also the indicatrix of refractive indexes) on x'y' plane – as well as in perpendicular direction. For a dye of p-type this means that $\alpha_{\parallel}$ in absorption coefficient alongside the long axes of ellipsoid of absorption coefficient projected on x'y' plane, while for a n-type dye this represent perpendicular direction. The same can be said about the α_{+} coefficient.

These create a possibility to determine polarization of the light at any point of a layer in x'y' coordinates dividing it into particular sublayers. Consequently, we are able to determine qualitatively vectors before and after passing the analyzer. Application of the Fresnel formula creates a possibility of settling the shape of vectors reflected from each phase borders and transpose them towards an observer.

The presented configuration of vector E penetrating a layer as a recurrence formula seems to be very simple to put to numerical analysis. Basing on mathematical analysis of the problem there has been made a programme for modelling an operation of a LC display (e.g. TN) named NAOP LCD (Numerical Analysis of Optical Parameters of LCD). The course of light beams discussed while determining optimum parameters a reflective TN display is presented in Fig. 2.

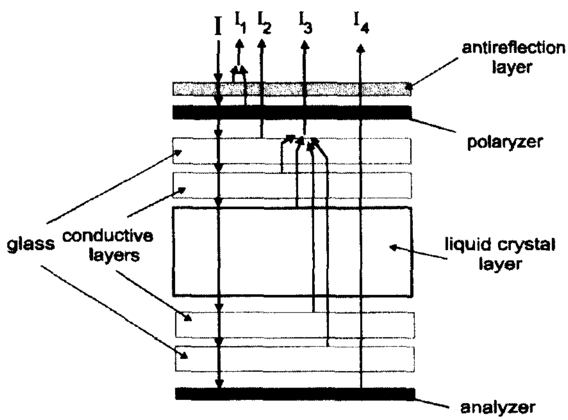

FIGURE 2 Path of a beam of light in reflection display. For the reflected beams (I_1 – I_4) reaching on observer one should take into account the values of transmission through individual phase boundaries while the way back.

This approach made it possible to carry out a numerical optimization of TN display operation in negative mode and reflection system. To determine the value of luminance L and contrast ratio CR there have been employed the following formulae[12]:

$$L(\Delta nd)=\frac{\int_{380}^{780} H(\lambda)\cdot V(\lambda)\cdot T(\Delta n,d,\lambda)d\lambda}{\int_{380}^{780} H(\lambda)\cdot V(\lambda)d\lambda} \quad \text{and} \quad CR=\frac{L_{ON}}{L_{OFF}} \qquad (16)$$

where H(λ) is a spectral distribution function of the incident light and V(λ) - the curve of spectral sensitivity of a human eye.

NUMERICAL OPTIMIZATION

Within the framework of a reflective TN display there has been analyzed an influence of polarizer films' qualities, then the light reflection from phase boundaries as well as dichroic properties of a TN layer with regard to the values of contrast ratio and coefficient luminance for light state of operation. There has been shown, that CR values in TN, reflective system depend only on the value of a layer dichroism given by formula: $d(\lambda_{\|}-\lambda_{+})=3S\lambda_{o}cd$ (where d - thickness of a layer, $\lambda_{\|}$, λ_{+}, and λ_{o} - absorption coefficients for extraordinary, ordinary rays and for an isotropic layer, respectively, S - order parameter for directions characterized by transmissions of a dye in a layer, c – weight concentration of a day in LC) as well as a polarizing coefficient value of the employed films.

As one can see in Fig. 3 there appear some optimum positions of $CR=f(3S\lambda_{o}cd)$ function, location of witch shift towards higher values of it's argument, while polarization coefficient of the film decreases. Recognisable is the fact, that within the range of the second transmission minimum advisable is to employ layers of higher dichroism to increase CR ratio.

Similarly, decrease in polarizability of the film may be recompensed by a dye application, to maintain a given level of CR, However, the presented scheme shows an ideal situation, i.e. there are not taken into account any reflections from phase boundaries as well as interference phenomena. It is well know fact, that elimination of the former as well as the latter factors is crucial. Fig. 4 shown a role of antireflective layer positioned on the frontal side of reflection display. In this simulation polarizers with flat spectrum and having absorption coefficient listed in

Table 2 have been used. Properties of the ITO layer and sodium glass are typical.

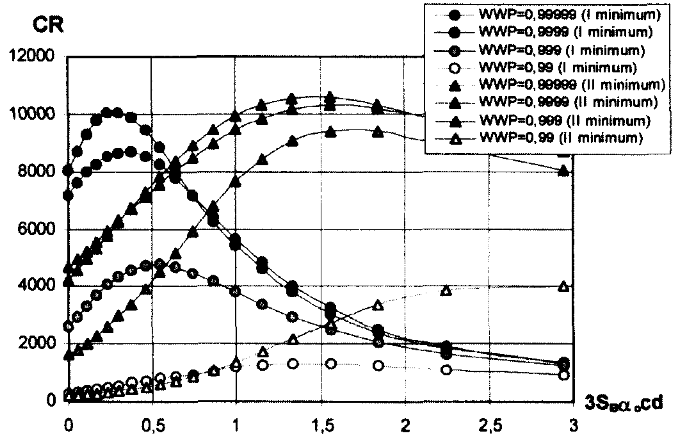

FIGURE 3 Dependence CR ratio for TN layer operating in negative mode and in reflective system on dichroic properties of LC. Singular curves represent a variety of polarization coefficients of applied films for both I and II minimum of transmission.

TABLE 2 Properties of polarizers applied in simulation of optical characteristics of TN display

Nr	Transmission T(II) [%]	Transmission T(+) [%]	Polarization coefficient PC [%]
1	100	0,0001	99,9998
2	80	0,01	99,975
3	85	0,1	99,765
4	90	1	97,802
5	92,5	2	95,767
6	97,5	4	92,118

a)

b)

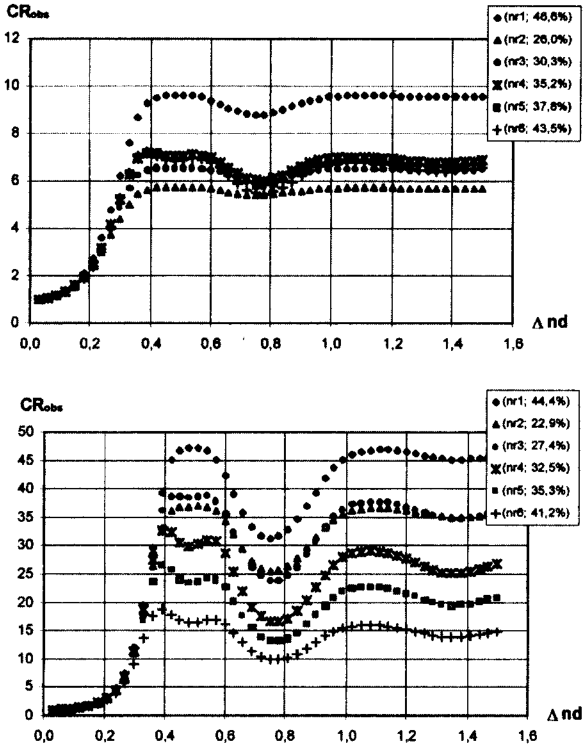

FIGURE 4 Contrast ratio CR_{obs} observed by a user for a TN display working in reflection mode under real conditions.
a) lack of an antireflective layer;
b) antireflective interference layer of 550nm has been applied.

Fig. 4 shows clearly the negative influence of harmful reflection from phase borders and necessity of their elimination. To take fill advantage of positive properties of dichroic layer maximum limitation of these reflections is required. As it appears from Fig. 3 there is a direct link between dichroic properties of a layer and contrast ratio of employed polarizers. Consequently, there exists a possibility to determine correlation between luminance of the light mode of a display and contrast ratio CR for an "only" birefringence layer and a dichroic one.
To get so an optimization of polarizers choice should be carried out. Review of catalogues of obtainable allows to draw a conclusion, that in general terms there are two types of polarizers: so called standard polarizers with ordering of a dye in the film at the level of 0,88-0,9 and

high contrast ones at the level of 0,92-0,94. Assuming these values of order we can determine mutual relations of contrast ratio and luminance of light state for a TN layer having both dichroic and nondichroic properties. Thus, we can determine explicitly an influence of applied dye suspended in the bulk of LC on optical properties of a LC display. Those relations are presented in Fig. 5.

a)

b)

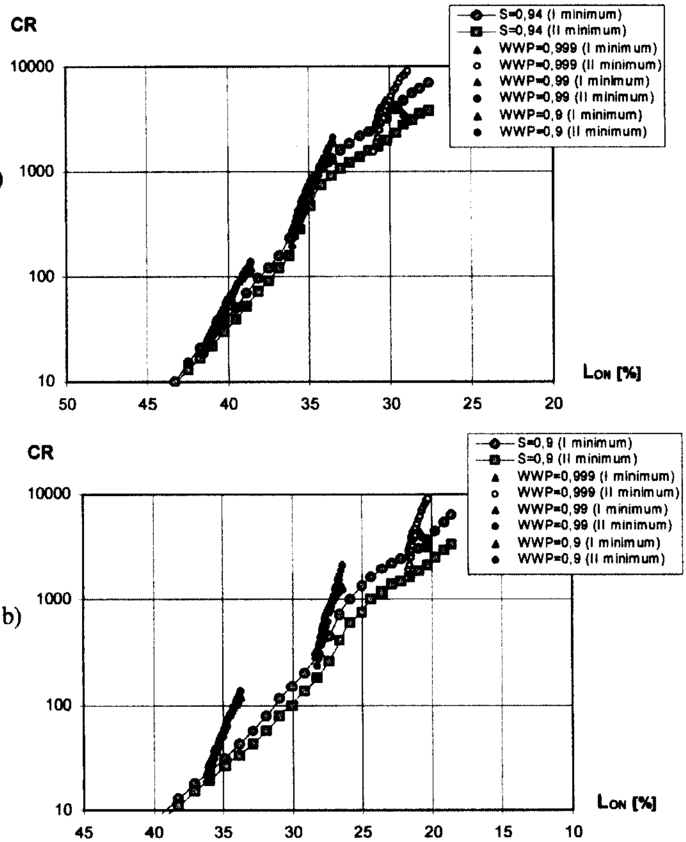

FIGURE 5 Dependence of contrast ratio CR on luminance L_{ON} of light state for TN layer operating in negative mode and in reflective system at I and II minimum of transmission for:

a) polarizers of high contrast type (S=0,94);
b) polarizers of standard type (S=0,9).

Extra curves represent contrast ratio coefficient and luminance of light state when chosen polarizers containing black dichroic dye (S=0,8) were applied.

The results presented above enable us to determine an approach to improve optical properties of a layer by a proper choice of polarizing films and black dichroic dye admixture. In reflective system there are the following regularities. For films of "high contrast" type obtaining a luminance value L_{ON}>30% is possible for PC (polarization coefficient) c.a. 0,9992. Black dichroic dye enables substantial increase of contrast ratio, especially within the range of the second minimum of transmission for any possible value of PC. There is, however, some range of PC values (0,99-0,994) where only at the second minimum black dichroic dye improves optical parameters of a layer than a change in PC. Within the range of first minimum changes caused by dye admixture and film properties are approximately the same.
For system employing standard polarizers the upper limit of PC value (under condition L_{ON}>30%) reaches 0,97. Let us notice, that in this very case using a black dichroic dye results in considerable improvement of mutual relation between CR and luminance of light state of a layer for all the range of coefficient PC.

EXPERIMENTAL VERIFICATION OF RESULTS

Black dichroic dye (mixture of commercially obtainable dyes KD-8, KD-9, KD-10 and KD-184 which we got from NIOPIK Company, Moscow[13]) and LC mixture W-1173 prepared by scientific team led by Prof. Dąbrowski, Institute of Chemistry, MUT have been investigated. This composition is fully miscible and is designed for working within the 2nd minimum of transmission. LC cells has been made applying technology worked out in Liquid and Solid Crystals Department, MUT, based on spacer of 6μm. Additionally there has been used LC compositions by MERCK Ltd.: MLC-13200-100, MLC-6657-100 and MLC-6694-000. Compositions MLC-13200-100 and MLC-6694-000 are designed for operating within the 1st minimum (layer thickness approximately 6 μm), while composition MLC-6657-100 within 2nd minimum.
Dye's miscibility in LC in working compositions amounts to 2,5% for basic mixture W-1173 (at 20°C) and 1% for all substances delivered by MERCK Ltd.. Measurement cells were constructed using sodium glass

made using “float” method, covered with conductive ITO layer. Spacer’s thickness 6 μm. Polarizers THN-42 type were employed.
Two-beam BECKMAN spectrophotometer, model UV5270 has been used to determine optical parameters of LC cells. This apparatus made it possible for us to determine layer’s absorption, luminance, CR and chromatic coordinates at room temperature according to the requirements discussed earlier in this paper.
The specification of obtained experimental data for different dye concentration (Table 3) as well as data given by simulation numerical method are compared in Table 4.

TABLE 3 Measurement cells to determine optical parameters

Cell nr	Basic composition	Dye concentration [weight %]	Cell thickness [μm]	Δnd at 22°C
1E	W-1173	0,00	5,84	1,2206
2E	W-1173	1,03	5,82	1,2164
3E	W-1173	1,74	5,85	1,2227
4E	W-1173	2,46	5,84	1,2206
5E	MLC-6657-100	0,00	5,90	1,0128
6E	MLC-6657-100	0,52	5,92	1,0094
7E	MLC-6657-100	1,05	5,94	1,0060
8E	MLC-6694-000	0,00	5,84	0,4917
9E	MLC-6694-000	0,52	5,84	0,4917
10E	MLC-6694-000	1,04	5,86	0,4934
11E	MLC-13200-100	0,00	5,75	0,5057
12E	MLC-13200-100	0,55	5,77	0,5072
13E	MLC-13200-100	1,04	5,74	0,5045

TABLE 4 Results of calculations and experimental measurements of chosen optical parameters

Cells nr	Luminance in off-state L_{OFF} [%]		Luminance in on-state L_{ON} [%]		Effective contrast ratio CR_{obs}		Relative difference [%]		
	Calcul.	Measu.	Calcul.	Measu.	Calcul.	Measu.	L_{OFF}	L_{ON}	CR_{obs}
1E	2,390	2,393	33,68	33,01	14,1	13,8	0,2	2,0	2,2
2E	1,747	1,756	30,40	30,02	17,4	17,1	0,5	1,3	1,8
3E	1,408	1,418	28,45	28,08	20,2	19,8	0,7	1,3	2,0
4E	1,216	1,218	26,63	26,16	21,9	21,5	0,2	1,8	1,9
5E	2,618	2,598	33,68	33,00	12,9	12,7	0,7	2,1	1,6
6E	2,198	2,185	31,78	31,02	14,5	14,2	0,6	2,5	2,1
7E	1,874	1,864	29,94	29,45	16,0	15,8	0,5	1,7	1,3
8E	2,087	2,093	33,68	33,28	16,1	15,9	0,3	1,2	1,3
9E	1,761	1,742	32,18	31,70	18,3	18,2	1,1	1,5	0,5
10E	1,560	1,556	30,72	30,34	19,7	19,5	0,3	1,2	1,0
11E	2,092	2,081	33,68	33,51	16,1	16,1	0,5	0,5	0,0
12E	1,750	1,761	32,14	31,87	18,4	18,1	0,6	0,8	1,7
13E	1,564	1,564	30,83	30,02	19,7	19,2	0,0	2,7	2,6

The obtained results of contrast ratio and luminance measurements enable us to draw a conclusion, that the theory presented in this paper, concerning light propagation through a LC display has been verified experimentally with good results. Additionally, there is a possibility to make numerical simulation of operation of LC display under conditions different from those of spectrophotometer (outer illumination, change from transmission to reflection mode, application of an antireflection layer, glass parameters change as well as conductive layer, use of different types polarizers ect.) using numerical NAOP LCD programme.

CONCLUSIONS

The numerical modelling of LC display's operation we have made using NAOP LCD programme enable us to make on analysis of:

1. Influence of transparency and polarizability of polarizing films on contrast ratio of TN layer.
2. Finding of universal relations of contrast ratio TN layer with dichroic properties of LC.
3. Correlation of polarizer's qualities and values of dichroism to determine mutual dependencies of contrast ratio and luminance of light state of TN layer working in negative mode.
4. Getting information about quantitative and qualitative influence of each component of LC display on the value of effective contrast ratio while operating in real conditions.

The results we have obtained using computer modelling as well as experimental results lead us to formulation the following conclusions:

1. There exists a possibility of improving optical parameters of TN layer by means of black dichroic dye.
2. It is possible to determine changes of contrast ratio CR for a TN layer in relation to percentage of black dichroic dye at a given point of optical matching for any value of LC layer's thickness.
3. Relation between luminance of light in the light state of negative mode of TN layer and contrast ratio for different combinations of polarizing films and dichroic properties of used LC is possible to determine in explicit way.
4. To take advantage of TN layer dichroism there is necessary to use (in real constructions) antireflection layers as well as proper matching of conductive layer.
5. Numerical modelling we're carried out is a good approximation of operation LC display in real conditions for negative mode. This supports correctness of the model we're assumed for performing credible simulations.
6. Changes in contrast ratio are much higher in the range of 2nd transmission minimum than in the 1st minimum. In real constructions they can range from several per cent (for high values of polarization coefficient of used films) up to more then 50% for transparent polarizers.

The investigations we're made supported the idea, that there is possible to improve optical parameters of TN displays and their application as large-area displays, even for special purposes.
There have been determined an approach to changing optical properties of a display according to technological requirements (construction of a

display, properties of components). It shows, that this relatively simple effect supported technologically can be applied in construction of large-area displays.

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