Optical characteristics of a guest–host reflective liquid-crystal display with a phase compensator but no polarizing sheet and with positive image contrast

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Computer modelling has been used to study the design of a guest–host reflective liquid-crystal display with a phase compensator, operating at the nematic–cholesteric transition. It is shown that, by choosing the parameters of the phase plate and the step of the helix of the chiral additive, it is possible to simultaneously obtain high reflectance and image contrast and also a moderate degree of multiplexing.

INTRODUCTION

The guest–host effect is one of the most widely used electrooptic effects for creating information-display devices based on liquid crystals (LCs).[1,2] These displays have the advantage that they are simple to fabricate and have good ergonomic characteristics, such as high image contrast and large viewing angles. At the same time, guest–host devices have the disadvantage that displays with a high contrast have low transmittance or reflectance when polarizers are used (less than 20% for transmissive designs) or low contrast (less than 2:1) with high transmittance or reflectance for displays having no polarizing sheets. Moreover, a substantial drawback of these displays is low information capacity, caused by low values of the degree of multiplexing of such devices (less than 32:1).

For transmissive designs of guest–host displays, it is possible to increase the transmittance while simultaneously increasing the image contrast by means of twisted LC structures with a twist angle of $\Phi_T = 90°$ by using a phase compensator,[3,4] located between the polarizing sheet and the cell with the LC. However, if one considers the most widely used reflective design for such an LC device, the reflectance of such an display does not exceed 15% on the whole, and this substantially narrows the region in which these devices can be used. As is well known,[1,2] modern reflective information-display systems based on various electrooptic effects in LCs must satisfy the following requirements:

- The reflectance must be at least 20%.
- The image contrast must be at least 4:1 for both black-and-white and color images.
- The degree of multiplexing must be at least 32:1.

Designs for guest–host reflective displays without a polarizing sheet are currently known that use the STN structure and a film-type phase compensator to increase the image contrast and to achieve acceptable values of the degree of multiplexing.[5,6] Such devices use standard LC structures with positive dielectric anisotropy and a twist angle of the LCs in the range 240°–250°. These display systems satisfy all the technical requirements enumerated above and imposed on modern information-display devices. However, at the same time, such systems produce a negative image, and this is a drawback in certain types of displays.[1,2] Because of this, we have studied the optical characteristics of a guest–host reflective LC display based on an LC with negative dielectric anisotropy and with a chiral additive, with a phase plate but no polarizing sheet. The optimum design has been found for a guest–host reflective LC display with no polarizing sheet that satisfies the requirements imposed on high-information-content information-display devices and gives a positive image.

DESIGN AND OPERATING PRINCIPLE OF THE LC DISPLAY

This type of LC display is an LC cell behind which are successively a film-type phase compensator and a reflector. It is proposed to use the nematic–cholesteric transition in an LC with negative dielectric anisotropy and a chiral additive in this guest–host reflective display, along with a dye having positive dichroism. In the OFF state, the LC has a homeotropic initial orientation and the minimum light absorption, since the dye that is used possesses positive dichroism. When a voltage is applied to the control electrodes of the LC cell, the molecules of the LC in the cell change their inclination, and the LC structure as a whole acquires a twisted structure because of the chiral additive. The light absorption is maximized in this state.

A guest–host cell in the state with maximum absorption is a polarizer with a small degree of polarization, and, since an ordinary phase compensator is an analog of a homogeneous planar layer of LCs, a system consisting of the guest–host cell, an ordinary phase compensator, and a mirror is equivalent to the design of a reflective LC display based on a supertwisted LC structure. In this case, the polarizer is a controllable guest–host cell, and the phase plate creates the necessary phase relationship for obtaining a contrast image. The operating principle of this LC display can be explained as follows: In the OFF state, when no voltage is applied to the control electrodes of the guest–host LC cell, the natural light transmitted through the LC layer remains unpolarized, since the LC layer with dye in this case is an isotropic medium. When a control voltage is applied to the electrodes of the cell, the LC structure becomes twisted with a twist angle determined by the chiral additive,[1,2] and the LC layer with dye operates as a polarizer with a small degree of polarization. The type of polarization of the light transmitted through the guest–host cell in this case depends on what orientation of the LC is used in the working cell in the ON state. In general, the light will have partial elliptical polarization. Subsequently, the light, after passing through the phase plate, being reflected from the mirror, and passing through the phase plate, acquires a definite phase increment. By adjusting this phase increment by the appropriate choice of the thickness of the phase plate, it is possible to achieve total absorption or total transmission of light through the guest–host cell on the reverse ray path. Thus, the thickness of the phase plate must be chosen so that the reflection of the device is minimal in the ON state. This allows optical switching between the ON state (with minimum reflection) and the OFF state (with maximum reflection).

We should point out that it is more convenient to use such a device in the colored operating regime, when the switching between the two working states goes from a strongly colored state to an uncolored or weakly colored state. When this is done, the color switching between the ON and OFF states is determined by the transmission spectrum of the dichroic dye used in the guest–host cell. The phase plate serves to minimize the reflection of the display for the OFF state. We should point out that the device can also be based on a black-and-white dye. The image contrast is small in this case, since it is impossible to select a phase compensator that would simultaneously provide the necessary phase relationships for the red and blue regions of the spectrum. For this reason, this design should mainly be used for displays that are based on switching between an uncolored state and a strongly colored state.

OPTICAL CHARACTERISTICS OF A REFLECTIVE GUEST–HOST REFLECTIVE LC DISPLAY WITH NO POLARIZING SHEET

We used the following relationships to unambiguously describe the optical characteristics of a guest–host LC display:[2]

- For a black-and-white dye, the reflection R_{on} averaged over the spectrum for the ON state, when the voltage on the control electrodes of the LC cell substantially exceeds the threshold voltage,

  $$R_{\text{on}}=\left(\int_{390\text{nm}}^{720\text{nm}} R_{\text{on}}(\lambda)\overline{y(\lambda)}\,d\lambda\right)\Bigg/\left(\int_{390\text{nm}}^{720\text{nm}}\overline{y(\lambda)}\,d\lambda\right), \quad \text{(a)}$$

  where $R_{\text{on}}(\lambda)$ is the reflectance spectrum of the display in the ON state, and $y(\lambda)$ is the visibility curve of the human eye, taking into account the emission spectrum of a D_{65} source.
- For a black-and-white dye, the reflection R_{off} averaged over the spectrum for the OFF state, corresponding to a control voltage on the electrodes of the LC cell close to the threshold voltage,

  $$R_{\text{off}}=\left(\int_{390\text{nm}}^{720\text{nm}} R_{\text{off}}(\lambda)\overline{y(\lambda)}\,d\lambda\right)\Bigg/\left(\int_{390\text{nm}}^{720\text{nm}}\overline{y(\lambda)}\,d\lambda\right), \quad \text{(b)}$$

  where $R_{\text{off}}(\lambda)$ is the reflectance spectrum of the display in the OFF state.
- For a black-and-white dye, the contrast averaged over the spectrum,

  $$\text{Contrast}=R_{\text{off}}/R_{\text{on}} \quad \text{(c)}$$

The degree of multiplexing, determined in the standard way,

$$N=\frac{(U_{\text{on}}^2+U_{\text{off}}^2)^2}{(U_{\text{on}}^2-U_{\text{off}}^2)^2}, \quad \text{(d)}$$

where U_{on} and U_{off} are the control voltages corresponding to the states of the display with reflectances R_{on} and R_{off}.

If a dichroic dye that has a single absorption band in the red, blue, green, or any other region of the visible spectrum is used as a guest, then, instead averaging the reflectances R_{on} and R_{off} and the Contrast over the spectrum, we use $R_{\text{on}}(\lambda_{\max})$, $R_{\text{off}}(\lambda_{\max})$, and Contrast($\lambda_{\max}$) to describe the characteristics of the display, computed for the wavelength $\lambda_{\max}$ of the maximum absorption of the colored dichroic dye. This is done because the reflectances and the contrast averaged over the spectrum in the case of blue and red dyes will not strongly differ for dyes with different dichroic ratios. It should be pointed out here that, for a colored dye, a large difference in $R_{\text{on}}(\lambda_{\max})$ and $R_{\text{off}}(\lambda_{\max})$ (i.e., a large contrast at the wavelength of the maximum absorption of the dye) will denote a larger difference in saturation of the color of the dye, but the dominant wavelength will be constant in this case. Thus, the use of reflectance and contrast values computed or measured at the wavelength of the maximum absorption of the dye is completely justified and gives an unambiguous description of the optical characteristics of the display.

It should be pointed out that, when a colored dye is used, the refractive indices of the orienting and electrode layers, as well as their thicknesses, will be chosen so that the reflection from these elements of the display will be minimized, while the reflection from the outer glass surface of the display can be reduced to a minimum by using antireflective optics. Thus, all the stray reflections from all possible interfaces in the LC display, which reduce the image contrast, can be minimized for a colored guest–host reflective display. We therefore neglected them in the calculations.

The characteristics of the proposed LC device were studied by computer modelling, using the MOUSE-LCD software package.[7] The tilt angle of the LC molecules on the substrates of the cell in the initial orientation was considered to be 90° and identical over the entire thickness of the LC cell

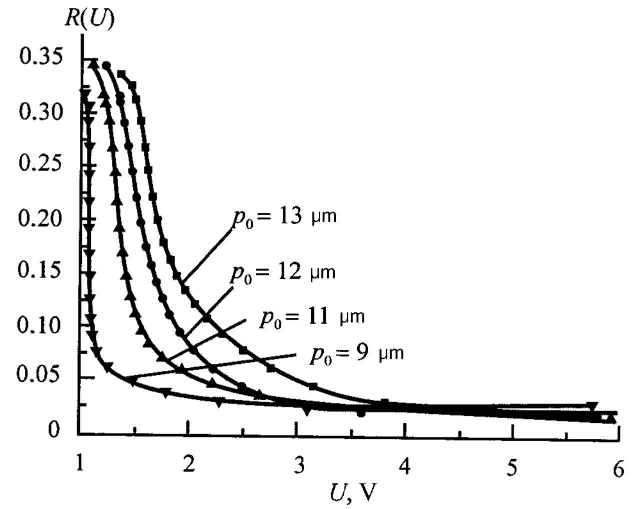

FIG. 1. Reflectance calculated at the wavelength of the absorption maximum of the dye vs control voltage for various values of the step p_0 of the helix of the chiral additive. See text for further explanation.

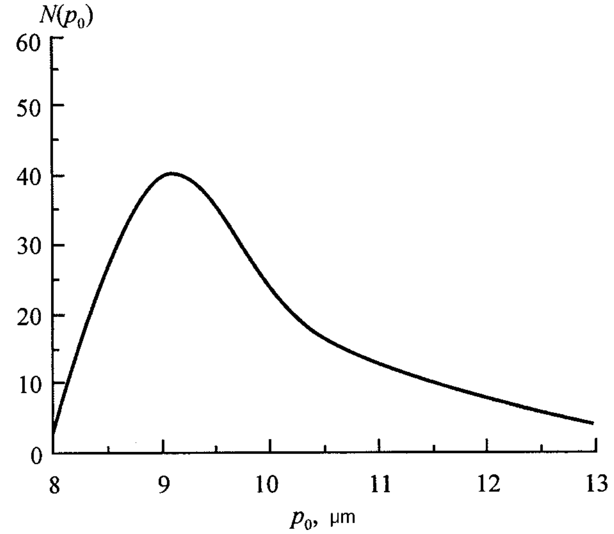

FIG. 2. Degree of multiplexing of a reflective guest–host LC display with a phase compensator and no polarizing sheet vs the step of the helix of the chiral additive. See text for further explanation.

(homeotropic initial orientation). The twist angle of the LC structure in the ON state was varied by choosing the step of the helix of the chiral additive. We chose KD-10 dye for the calculations, which has a high dichroic ratio (maximum absorption at $\lambda = 650$ nm).[8] The dispersion of the refractive-index anisotropy of the phase plate whose parameters were used in the calculations was $\Delta n(\lambda = 0.42\ \mu\text{m}) = 0.00343$, $\Delta n(\lambda = 0.5\ \mu\text{m}) = 0.0032$, $\Delta n(\lambda = 0.61\ \mu\text{m}) = 0.003$. We chose ZLI-5800-100 as the model LC material,[9] but we assumed in the calculations that this LC has negative dielectric anisotropy.

As our calculations showed, an LC with such values of the elasticity coefficients is chosen because the volt–contrast response is not steep enough for other ratios of the elasticity constants, and it is impossible to reach the required values of the degree of multiplexing. It can thus be concluded that, to reach acceptable multiplexing levels in guest–host reflective devices with a phase compensator based on the nematic–cholesteric transition, LC materials are needed with a ratio of the elastic constants and a dielectric anisotropy the same as for high-information-content STN displays. We should point out that the sign of the dielectric anisotropy must be negative in such an LC material.

Figure 1 shows how the reflectance of the display averaged over the spectrum depends on the control voltage for a guest–host reflective LC display with a phase compensator but no polarizing sheet for various values of the step p_0 of the chiral additive. The step of the helix of the chiral additive determines the twist angle of the LC structure in the ON state; therefore, by varying p_0, we in fact change the twist angle of the LC in the excited state. As can be seen from this figure, the reflectance of the display for the OFF state is independent of p_0, since this state is determined only by the boundary conditions and is independent of the chiral additive. In the ON state, when the working voltage exceeds the threshold value by a factor of ten, the reflection of the display is also identical for various values of p_0. This is explained by the presence of the phase compensator, the variation of whose thickness and of the orientation angle of whose optical axis makes it possible to minimize the reflection of the display in this state. The maximum attainable image contrast then equals 22:1, while the reflectance of the display in the OFF state reaches 35%.

If the working voltage is low, while the initial structure of the LC was already deformed and a twist has appeared in it, the image contrast for such a voltage strongly depends on the step of the helix of the chiral additive. It should be noted that decreasing the step of the helix of the chiral additive is equivalent to increasing the twist angle of the LC structure when a control voltage is applied to the electrodes of the cell, and therefore the step of the helix affects the slope of the dependence of the reflectance of the display on the control voltage. This is shown in Fig. 2, which presents the dependence of the degree N of multiplexing of the display on the step of the helix of the chiral additive, with the degree of multiplexing being computed for the ON and OFF states, for which the image contrast was no less than 4:1. As can be seen from this figure, the $N(p_0)$ dependence has a pronounced maximum, whose presence is associated with the features of the deformation behavior of the LC in an electric field for different values of the step of the helix of the chiral additive.[1] Similar behavior of the $N(p_0)$ dependence is observed for reflective LC displays with a phase compensator but no polarizing sheet that use LCs with positive dielectric anisotropy.[5,6]

If the $R(U)$ dependences for displays in which LCs are used with positive and negative dielectric anisotropies are compared, the following conclusion can be drawn: The two types of displays have the same maximum attainable image contrast, but different values of the degree of multiplexing N and reflectance $R_{\max}$ in the light state. A display containing LCs with positive dielectric anisotropy has high values of the degree of multiplexing (up to 200:1) with a contrast of at least 5:1, but moderate reflectance in the light state (less than 25%) and a negative type of image contrast.[5,6] An LC display

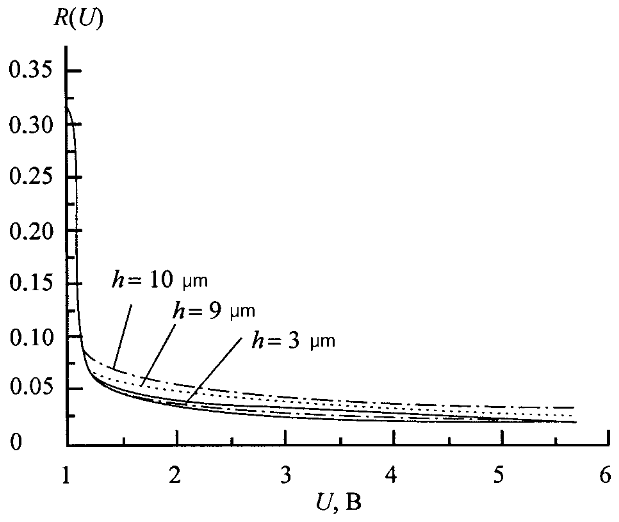

FIG. 3. Reflectance calculated at the wavelength of the absorption maximum of the dye vs control voltage for various thicknesses *h* of the LC layer. See text for further explanation.

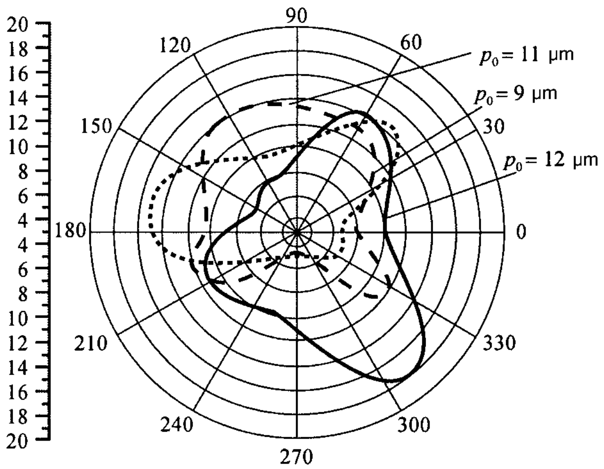

FIG. 4. Angular distributions of the maximum contrast of a reflective LC display, calculated at the wavelength of the maximum absorption of the dye for various values of the step p_0 of the helix of the chiral additive with the light incident at 45°. See text for explanation.

that includes LCs with negative dielectric anisotropy has a substantially lower degree of multiplexing (no more than 60:1) when the contrast is at least 4:1, but has high reflectance in the light state (more than 35%) and a positive type of image contrast.

Figure 3 shows how the reflectance of an LC display that operates at the nematic–cholesteric transition depends on the control voltage for various thicknesses of the LC layer. It was assumed in the calculations that the mean optical density of the dye and its dichroic ratio remained constant, while only the thickness of the layer varied. Moreover, the ratio of the thickness to the step of the helix of the chiral additive that corresponds to the maximum of the $N(p_0)$ dependence was kept fixed in the calculations. As can be seen from this figure, decreasing the thickness of the LC layer under the conditions enumerated above increases the image contrast and the slope of the $R(U)$ dependence. We should point out that decreasing the thickness of the LC layer has at the same time a positive effect on the dynamics of the transition between the ON state and the OFF state, but it is possible to reduce the thickness of the LC layer and simultaneously keep the mean optical density of the LC cell constant only by increasing the dye concentration in the LC. This raises the problem of the solubility of the dye in the LC, which substantially limits how much the thickness of the LC layer can be decreased while keeping the mean optical density and the dichroic ratio of the dye constant. On the other hand, simply decreasing the thickness of the LC layer while keeping the dye concentration constant substantially reduces the image contrast, and this is of course undesirable.

Figure 4 shows the angular distributions of the maximum contrast for a reflective display with a phase compensator but no polarizer, operating at the nematic–cholesteric transition, for various values of the step of the helix of the chiral additive and a 45° angle of incidence of the light on the display. As can be seen from this figure, the image contrast does not fall below 4:1 for any viewing angles, even though the shape of the distribution for all p_0 values is fairly complex and has two distinct directions along which the contrast is maximal. If a comparison is made with analogous angular distributions for devices based on the cholesteric–nematic transition, it can be said that there are directions for such devices in which, although high image contrast is achieved, the reflectance values for the light state are small (less than 10%) in those directions, and this limits their viewing angles. There are no such limitations for a display that uses the nematic–cholesteric transition, since the light state in such a device is isotropic and independent of the observation direction. Angular distributions computed for ON and OFF states that provide high levels of multiplexing coincide in shape with those shown above, but directions appear along which the image contrast is close to unity.

Figure 5 shows the angular distributions of the maximum contrast for a reflective display with a phase compen-

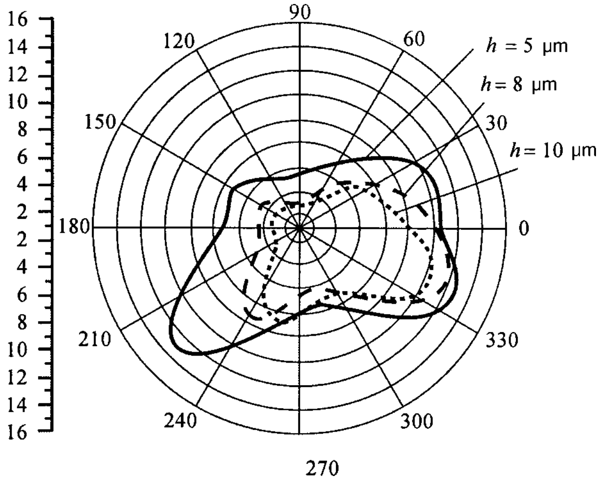

FIG. 5. Angular distributions of the maximum contrast of a reflective LC display, calculated at the wavelength of the maximum absorption of the dye for various thicknesses of the LC layer with the light incident at 45°. See text for explanation.

sator and no polarizing sheet, operating at the nematic–cholesteric transition, for various thicknesses of the LC layer when the angle of incidence of light on the display is 45°. It was assumed in the calculations that the mean optical density of the dye and its dichroic ratio remained constant, while only the thickness of the layer varied. Moreover, the ratio of the thickness to the step of the helix of the chiral additive that corresponds to the maximum of the $N(p_0)$ dependence was kept fixed in the calculation. As can be seen from this figure, the angular distributions of the contrast become wider as the thickness of the layer decreases, and therefore, from the viewpoint of the ergonomic characteristics of an LC display, thin cells with a large dye concentration are better than thicker ones with a lower dye concentration. However, as pointed out above, the use of thin LC cells with high dye concentrations is associated with the problem of the solubility of the dye in the LC, which is a natural limitation of the approach involving thinner LC layers.

It can thus be said that the proposed design for a reflective guest–host LC display with a phase plate but no polarizing sheet, operating at the nematic–cholesteric transition, is promising both from the viewpoint of the characteristics of the device and from the viewpoint of a simple design for the display. This design can simultaneously provide high values of the contrast and the brightness of the image, as well as a moderate level of multiplexing of the reflective display with a phase plate.

CONCLUSION

This paper has used computer modelling to study the design of a guest–host reflective LC display with a phase plate, operating at the nematic–cholesteric transition. It has been shown that, by choosing the parameters of the phase plate and the step of the helix of the chiral additive, it is possible to simultaneously obtain high reflectance and image contrast and also a moderate degree of multiplexing.

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[1] V. G. Chigrinov, *Liquid-Crystal Devices. Physics and Applications* (Artech House, Boston, 1999).

[2] A. S. Sukharier, *Liquid-Crystal Displays* (Radio i Svyaz', Moscow, 1991).

[3] G. V. Simonenko, ''Guest–host liquid-crystal information displays with a phase compensator,'' Opt. Zh. **66**, No. 6, 97 (1999) [J. Opt. Technol. **66**, 541 (1999)].

[4] V. G. Chigrinov and G. V. Simonenko, ''Optimization of 'guest–host' liquid-crystal display,'' Mol. Cryst. Liq. Cryst. **351**, 51 (2000).

[5] G. V. Simonenko, V. G. Chigrinov, and H. S. Kwok, ''High-image-contrast reflective liquid-crystal display of the guest–host type with no polarizer,'' Opt. Zh. **68**, No. 1, 60 (2001) [J. Opt. Technol. **68**, 48(2001)].

[6] G. V. Simonenko, V. G. Chigrinov, and H. S. Kwok, ''Optical characteristics of a reflective guest–host liquid-crystal display with a phase compensator and no polarizing sheet,'' Opt. Zh. **68**, No. 3, 63 (2001) [J. Opt. Technol. **68**, 216 (2001)].

[7] V. G. Chigrinov, Yu. B. Podjachev, G. V. Simonenko, and D. A. Yakovlev, ''The optimization of LCD electrooptical behavior using MOUSE–LCD software,'' Mol. Cryst. Liq. Cryst. **351**, 51 (2000).

[8] ''Liquid-Crystal Materials and Technologies of Organic Intermediates and Dyes Institute,'' Update December 1996.

[9] ''Merck Liquid-Crystal Mixtures for Electrooptic Displays,'' Update December 1994.