P-106: Optical Performance of Bistable Reflective and Transflective Ferroelectric LCDs

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Abstract

We study optical properties of bistable reflective and transflective direct view ferroelectric liquid crystal displays (FLCDs). Single and double polarizer FLCDs with and without a retardation film are considered. Maximal contrast ratio versus optical retardation of liquid crystal layer for different configurations of FLCDs is calculated. Advantages and disadvantages of each configuration are discussed.

1. Introduction

A lot of modern portable devices require reflective or transflective bistable displays. In this case, an excellent candidate can be FLCDs [**1**]. Although bistable FLCDs were proposed two decades ago [**2**], they have not found wide application. The main reasons for this are instability for mechanical shocks and difficulty to obtain gray scale. However, recently it was demonstrated that photoalighment technology enables us to overcome such difficulties [**3,4**] which, in turn, made FLCDs attractive again and perspective for many applications.

Like TN- and STN- LCDs, reflective FLCDs can be single or double polarizer with or without a retardation film [1,**5**] (Fig.1).

a)

b)

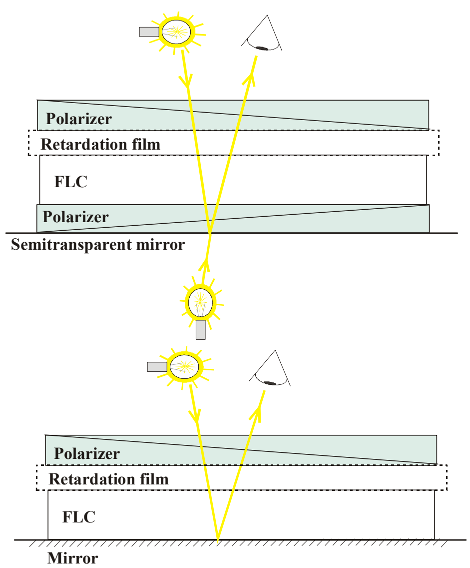

Fig.1. Structures of an FLCD. a) double polarizer reflective (transflective) FLCD b) single polarizer reflective FLCD. Dashed lines depict the location of the retardation film, if it is used.

Each configuration has its own advantages and disadvantages. Visible characteristics (luminance and contrast ratio) of FLCDs critically depend on display structure and its parameters such as the optical retardation of the liquid crystal layer, the cone angle of molecules, orientations of the polarizers and the retardation film (if it is used). In order to reach a display with perfect visible characteristics, first of all, it is necessary to make a theoretical analysis of its optical performance and determine an optimal structure.

A lot of papers studies optical properties and reports about optimized results for TN- and STN- LC cells. As for ferroelectric LC cells, publications considered only structures without a retardation film and with the cone angle of molecules equal to 22,5^{o}. However, a retardation film, which affects the polarization state of light passed through it, can improve visible characteristics of FLCDs and makes it possible to use ferroelectric LC with another cone angle. In addition, it is difficult to judge about advantages and disadvantages of single or double polarized reflective FLCDs without detailed study of their optical properties.

The goal of this paper is to fill the gap in the optimization of FLCDs. In the paper we shall focus on analysis of maximal contrast ratio versus retardation of LC layer for different configurations and consider the following cases:

a) double polarizer reflective and transflective FLCD without a retardation film;
b) double polarizer reflective and transflective FLCD with a retardation film;
c) single polarizer reflective FLCD without a retardation film;
d) single polarizer reflective FLCD with a retardation film.

Discussion and comparison of the obtained results for different configurations will be done. During calculations we shall assume that the ferroelectric LC has a perfect "bookshelf" uniaxial alignment and that additional layers of the FLCD (glass substrates, ITO, alignment layer) do not affect the optical properties.

2. Double polarizer reflective and transflective FLCD without a retardation film

Consider an FLCD that consists of an LC layer sandwiched between a pair of polarizers, and one side includes either a reflector (for reflective FLCDs) or semitransparent mirror (for semireflective FLCDs) (Fig.1a). Let orientations of polarizers in a

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FLCDs be described by angles α, and β, optical axis of the LC layer of one of the stable states is orientated at φ, and optical retardation of LC cell is Δnd. In this case, luminance intensity of an FLCD in one of two stable states can be written as

$$B(\alpha,\beta,\Delta nd,\varphi)=\int Y(\lambda)\{L^r(\lambda)r_{ar}(\lambda)+\frac{r}{2}L^r(\lambda)T(\alpha,\beta,\frac{\Delta nd}{\lambda},\varphi)+\frac{1-r}{2}L^t(\lambda)T(\alpha,\beta,\frac{\Delta nd}{\lambda},\varphi)\}d\lambda \qquad (1)$$

where $Y(\lambda)$ is the relative visibility of the average human eye, $L^r(\lambda)$ is illuminant spectral intensity of light that falls on the top surface of the FLCD, $r_{ar}(\lambda)$ is reflectivity of the antireflected coating, r is reflectivity of the rear mirror, $T(\alpha,\beta,\frac{\Delta nd}{\lambda},\varphi)$ is the transmittance of the LC layer sandwiched between a pair of polarizers, and $L^t(\lambda)$ is illuminant spectral intensity of backlight. From Ref.[**6**] it follows:

$$T(\alpha,\beta,\frac{\Delta nd}{\lambda},\varphi)=\cos^2(\beta-\alpha)-\sin 2(\beta-\varphi)\sin 2(\alpha-\varphi)\sin^2\frac{\pi\Delta nd}{\lambda}. \qquad (2)$$

Let us choose a coordinate system in such way that the orientation of the director can be either 0 or 2θ, where θ is the smectic C cone angle. If the bright state is observed for $\varphi=2\theta$ then the contrast ratio is defined as

$$C(\alpha,\beta,\Delta nd,\varphi)=\frac{B(\alpha,\beta,\Delta nd,2\theta)}{B(\alpha,\beta,\Delta nd,0)} \qquad \text{otherwise}$$

$$C(\alpha,\beta,\Delta nd,\varphi)=\frac{B(\alpha,\beta,\Delta nd,0)}{B(\alpha,\beta,\Delta nd,2\theta)}. \qquad (3)$$

From mathematical point of view we have a function of four variables for which it is necessary to find the global maximum. Analyzing Eqs.(1-3), it is possible to conclude that $C(\alpha,\beta,\Delta nd,\varphi)$ reaches its maximum when both $B(\alpha,\beta,\Delta nd,0)$ and $B(\alpha,\beta,\Delta nd,2\theta)$ have extremes (the numerator has a maximum, and the dominator has a minimum). From Eq. (1) follows that derivatives of $B(\alpha,\beta,\Delta nd,2\theta)$ are equal to 0 when derivatives of $T(\alpha,\beta,\frac{\Delta nd}{\lambda},\varphi)$ are also equal to 0. Differentiating Eq.(2) and equating it to zero, we obtain the following conditions under which $T(\alpha,\beta,\frac{\Delta nd}{\lambda},\varphi)$ reaches the global extremes (0 or 1): 1) α=β or α=β±π/2; 2) α or β must be equal to one of the values: 0, ±π/2, 2θ, 2θ±π/2; 3) 2θ=±π/4; 4) $\Delta nd=\lambda(0{,}5+N)$, where N is an integer. In our case we can take such value of λ when the expression $Y(\lambda)\left(rL^r(\lambda)+\frac{1-r}{2}L^t(\lambda)\right)$ has a maximum.

The calculated maximal contrast ratio versus the optical retardation for several θ and the fixed wavelength ($\lambda=500nm$) is shown in Fig.2 and Fig.3 by the dashed curves. The calculations were done for reflective FLCDs ($L^t(\lambda)=0$), it was assumed that $\frac{r_{ar}}{r}=0{,}01$ and polarizers are ideal. If an FLCD is a transflective one, then the presented results must be multiplied by $\frac{(1-r)L^t(\lambda)}{2rL^r(\lambda)}$. The maximal contrast ratio is proportional to $\sin^2 4\theta$, that is why $\theta=22{,}5^o$ is the optimal value for FLCDs without retardation film.

3. Double polarizer reflective and transflective FLCD with a retardation film

In general, transmission of an LC layer and a retardation film sandwiched between a pair of polarizers can be calculated according to the formula [**6**]

$$T=\mathrm{Re}(E_1E_1^*\cos^2(\varphi-\beta)+E_2E_2^*\sin^2(\varphi-\beta)+\frac{1}{2}(E_1E_2^*+E_2E_1^*)\sin(\varphi-\beta)), \qquad (4)$$

where

$$E_1=(\cos(\alpha-\gamma)\cos(\gamma-\varphi)e^{i\varphi_r^o}+\sin(\alpha-\gamma)\sin(\gamma-\varphi)e^{i\varphi_r^e})e^{i\varphi_{LC}^o},$$

$$E_2=(\sin(\alpha-\gamma)\cos(\gamma-\varphi)e^{i\varphi_r^e}+\cos(\alpha-\gamma)\sin(\gamma-\varphi)e^{i\varphi_r^o})e^{i\varphi_{LC}^e},$$

$$\varphi_r^o=2\pi\frac{d_r n_r^o}{\lambda}, \qquad \varphi_r^e=2\pi\frac{d_r n_r^e}{\lambda}, \qquad \varphi_{LC}^o=2\pi\frac{d_{LC}n_{LC}^o}{\lambda},$$

$\varphi_{LC}^e=2\pi\frac{d_{LC}n_{LC}^e}{\lambda}$, γ is the angle described orientation of the optical properties of the retardation film, d_r, d_{LC} are thicknesses of the retardation film and LC layer, respectively, $n_r^o, n_r^e, n_{LC}^o, n_{LC}^e$ are principal refractive indexes of the retardation film and LC, and index * means complex conjugation.

Substituting Eq.(4) into Eq.(1) and Eq(3), we find the contrast ratio. The calculated maximal contrast ratio versus optical retardation for several θ and the fixed wavelength ($\lambda=500nm$) is shown in Fig.2 by the solid curves. The calculations were done for reflective FLCDs ($L^t(\lambda)=0$), it was assumed $\frac{r_{ar}}{r}=0{,}01$ and polarizers are ideal. As mentioned above, for a transflective FLCD the calculated values of the contrast ratio must be multiply on $\frac{(1-r)L^t(\lambda)}{2rL^r(\lambda)}$

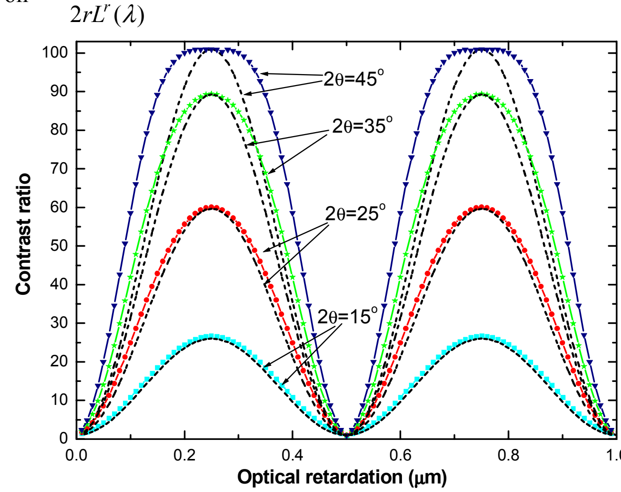

Fig. 2. Contrast ratio of double polarizer FLCD versus optical retardation for several θ. Dashed curves correspond to FLCD without the retardation film; solid curves correspond to FLCD cells with the retardation film.

It is interesting to investigate the maximal contrast ratio with growing angle θ (more then 22,5°). The calculated results are shown in Fig.3.

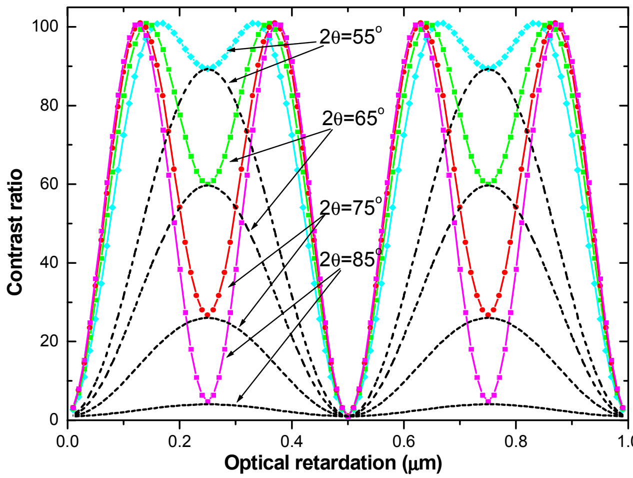

Fig. 3. Contrast ratio of double polarizer FLCD with a retardation film versus optical retardation for 2θ>45°. Dashed curves correspond to FLCD without the retardation film; solid curves correspond to FLCD cells with the retardation film.

Comparing results obtained with and without the retardation film, we can conclude the following 1) using the retardation film makes the range of deviations for the optical retardation wider with the high contrast ratio. 2) The retardation film is more effective for large values of the angle θ. 3) The maximal contrast ratio of an FLCD with the retardation film can not exceed the maximal contrast ratio of an FLCD without it for 2θ <45°. The maximal contrast ratio is reached when $\Delta nd=\lambda(0{,}5+N)$, where N is an integer. 4) The minimal contrast ratio (C=1) is observed when $\Delta nd=\lambda N$, and it does not depend on parameters of the retardation film. 5) The retardation film significantly can increase the contrast ratio for 2θ >45°. The maximal values are reached when the optical retardation (Δnd) approximately equals to either $\lambda(0{,}25+N)$ or $\lambda(0{,}75+N)$.

4. Single polarizer reflective FLCD without a retardation film

Since single polarizer FLCD cannot be a transflective one, in this and in the next section, we consider only reflective displays.

Luminance intensity of a reflective single polarized FLCD with a polarizer orientated at angle α, optical retardation Δnd and molecules orientated at angle φ is

$$B(\alpha,\Delta nd,\varphi)=\int Y(\lambda)L^{r}(\lambda)R(\alpha,\frac{\Delta nd}{\lambda},\varphi)d\lambda\,, \qquad (5)$$

where

$$R(\alpha,\frac{\Delta nd}{\lambda},\varphi)=r_{ar}(\lambda)+r\left[1-2\sin 2(\alpha-\varphi)\sin^{2}\frac{2\pi\Delta nd}{\lambda}\right]. \qquad (6)$$

Analyzing the contrast ratio as a function of Δnd, θ, α we can conclude that maximal contrast ratio is reached under the following conclusion 1) α can be equal to 0, ±90°, 2θ, 2θ±90°; 2) 2θ =45°; 3) $\Delta nd=0.5\lambda(0{,}5+N)$, where N is an integer. In our case, it is possible to substitute such λ for which the expression $Y(\lambda)L^{r}(\lambda)R(\alpha,\frac{\Delta nd}{\lambda},\varphi)$ has maximum. The calculated maximal contrast ratio is shown in Fig.4 and Fig.5 by the dashed curves. In the calculations we assumed that $\frac{r_{ar}}{r}=0{,}01$ and polarizers are ideal. The obtained results are the same as those that were obtained for double polarizer FLCDs, but the optical retardation is two times less.

5. Single polarizer reflective FLCD with a retardation film

Reflectivity of a single polarizer reflective FLCD with a retardation film can be calculated according to the formula

$$R(\alpha,\frac{\Delta nd}{\lambda},\varphi)=\mathrm{Re}\{E_1E_1^{*}\cos^{2}(\varphi-\alpha)+E_2E_2^{*}\sin^{2}(\varphi-\alpha)+$$

$$\frac{1}{2}(E_1E_2^{*}+E_2E_1^{*})\sin(\varphi-\alpha)\,, \qquad (7)$$

where

$$E_1=(\cos(\alpha-\gamma)\cos(\gamma-\varphi)e^{i\varphi_r^{o}}+\sin(\alpha-\gamma)\sin(\gamma-\varphi)e^{i\varphi_r^{e}})e^{i\varphi_{LC}^{o}}\,,$$

$$E_2=(\sin(\alpha-\gamma)\cos(\gamma-\varphi)e^{i\varphi_r^{e}}+\cos(\alpha-\gamma)\sin(\gamma-\varphi)e^{i\varphi_r^{o}})e^{i\varphi_{LC}^{e}}\,,$$

$$\varphi_r^{o}=4\pi\frac{d_r n_r^{o}}{\lambda}\,,\qquad \varphi_r^{e}=4\pi\frac{d_r n_r^{e}}{\lambda}\,,\qquad \varphi_{LC}^{o}=4\pi\frac{d_{LC}n_{LC}^{o}}{\lambda}\,,$$

$\varphi_{LC}^{e}=4\pi\frac{d_{LC}n_{LC}^{e}}{\lambda}$, γ is the angle described orientation of the optical axis of the retardation film, d_r, d_{LC} are thicknesses of the retardation film and LC layer, respectively, $n_r^{o},n_r^{e},n_{LC}^{o},n_{LC}^{e}$ are principal refractive indexes of the retardation film and LC, index * means complex conjugation.

Substituting Eq.(7) into Eq.(5) and Eq.(3), we can calculate the contrast ratio. Applying a procedure for finding a global minimum of a function of several variables, we obtained the maximal contrast ratio versus the optical retardation of LC layer and different θ. The obtained results for $\theta\leq$ 45° are shown in Fig.4 by the solid curves, and for θ>45° they are depicted in Fig.5.

Analyzing the results obtained with and without the retardation film, it is possible to make the following conclusions 1) similar to double polarizer FLCDs, use of the retardation film enabled us to increase the maximal contrast ratio and to make wider the range of the deviations of the optical retardation with high contrast ratio. 2) The retardation film is effective for FLCDs with large values of the angle θ. 3) The maximal contrast ratio of an FLCD with the retardation film can not exceed the maximal contrast ratio of an FLCD without it for 2θ <45°. The maximal contrast ratio is reached when $\Delta nd=0{,}5\lambda(0{,}5+N)$, where N is an integer.4) The minimal contrast ratio (C=1) is observed when $\Delta nd=0{,}5\lambda N$, and it does not depend on parameters of the retardation film. 5) The retardation film significantly can increase the contrast ratio for

2θ>45°. Maximal values are reached when the optical retardation (Δnd) approximately equals to either 0,5λ(0,25+N) or 0,5λ(0,75+N).

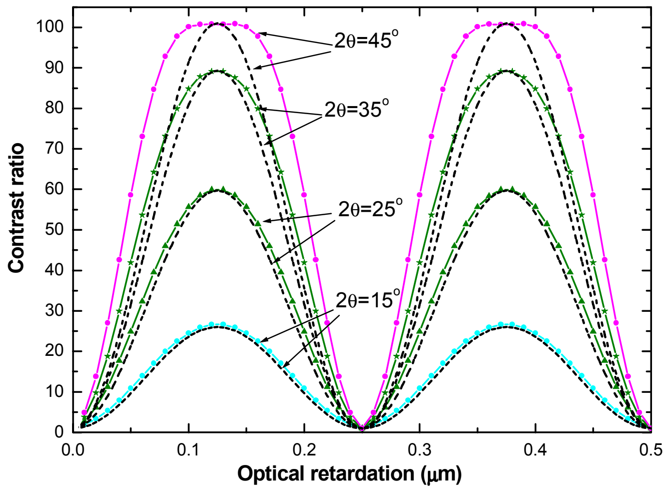

Fig. 4. Maximal contrast ratio of single polarized FLCD versus optical retardation for several θ (2θ<45°). Dashed curves correspond to FLCD without a retardation film, solid curves correspond to FLCDs with a retardation film.

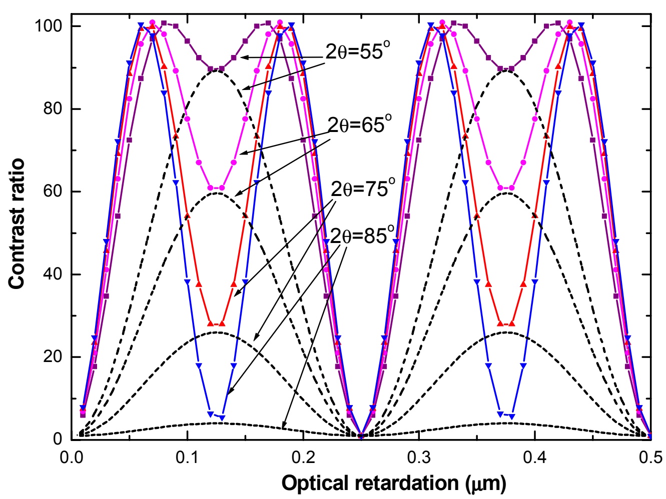

Fig. 5. Maximal contrast ratio of single polarized FLCD with a retardation film versus optical retardation for several θ. Dashed curves correspond to FLCD without the retardation film; solid curves correspond to FLCD cells with the retardation film

In general, these conclusions are similar to ones made for double polarizer FLCDs. The essential difference between them is only in the values of optical retardations for which we can obtain the maximal contrast ratio. Since cell gap affect on electro-optical properties and stability of the FLCDs, this fact must be take into account during a display design.

6. Summary

We demonstrate a way for calculation of optical properties of direct view bistable FLCDs. It was studied both single and double polarizer reflective and transflectve FLCDs with and without the retardation film. We obtained maximal contrast ratio versus optical retardation of the LC layer for different cone angles of molecules. Analysis and discussions of the obtained results are presented. We demonstrated that visible characteristics of FLCDs can be essentially improved for certain retardations of LC layer, cone angles of LC molecules by using a retardation film.

7. Acknowledgements

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8. References

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