Vertically Aligned LCD Designs Optically Compensated by Thin Birefringence Films

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ABSTRACT

We developed optical compensation for Vertically Aligned mode LCDs using thin coatable birefringent films produced by Crysoptix Ltd. The new coatable retarder films compensate both the liquid crystal layer and polarizers. The new retarders provide near perfect viewing angle properties in the visible spectral range. We present data of numerical optimization and experimental results for Vertical Alignment mode LCD.

INTRODUCTION

It is well known that in order to achieve adequate optical performance, the liquid crystal (LC) layers in LCDs should be optically compensated. Optimal compensation depends on a particular mode of liquid crystal alignment utilized in the LCD. The vertically aligned (VA) mode, where the LC layer is aligned almost homeotropically (a tilt angle of about 2^o is still necessary), allows solving the problem of compensation and deliver perfect viewing angle characteristics. If the electric field is switched off then the homeotropically aligned LC layer represents so-called positive C-plate, which has the optical axis along the *z*-axis perpendicular to the LC layer *xy*-plane. From the fundamental physics principles it is well known that a positive C-plate (the difference of principal refractive indices $\Delta n = n_z - n_x > 0$) can be compensated by a negative C-plate ($\Delta n < 0$) with equivalent phase retardation. This idea was efficiently applied for many LCD types including VA mode that is described, for instance, in [1]. However, the compensation of LC layer is not the only sufficient condition to provide excellent viewing angle properties of commercial LCD designs. Along with optical compensation of the LC layer, compensation of polarizers is also required. The light leakage appearing even through the ideal crossed polarizers at an oblique light incidence in planes, which bisect the polarizer axes, needs to be eliminated. The physics reasons for appearance of such light leakage and methods for its suppressing are described in [2, 3]. Thus, in general, the problem of optimal optical compensation is reduced to the compensation of both LC layer and polarizers.

In this work we discuss the application of new set of materials used for thin birefringent film (TBF^{TM}) retarders [4] for complete compensation of VA LCDs [5].

NEW TBF MATERIAL PROPERTIES

TBF is produced from materials forming lyotropic liquid crystal phases [4]. Different coating techniques, such as roll-to-roll slot die method or shear technique based on using the micro-grooved rods [4, 6, 7], can be applied to prepare thin films. Control of concentration of compounds in the water solution allows producing films of different thickness in the range of 100 - 1500 nm.

We have developed a new set of materials, which are transparent in the visible spectral range. TBF based on these materials can provide high optical anisotropy (the birefringence Δn can reach values up to 0.4 in the visible range). These properties allow preparation of different types of thin film retarders. Depending on a particular material both optically uniaxial and biaxial TBF can be created. Figure 1 shows spectral dependences of the refractive indices for the Crysoptix TBF A002.

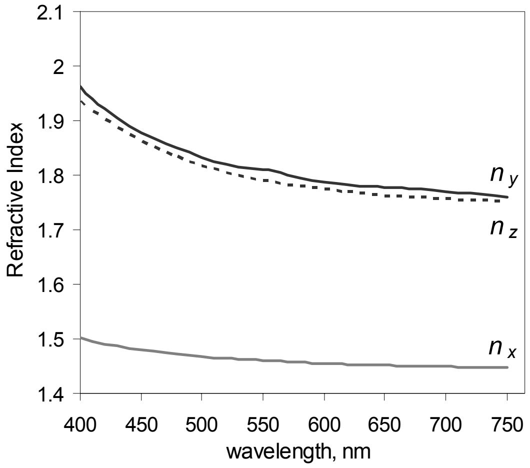

Fig. 1 Spectral dependencies of the refractive indices for TBF A002.

The films based on this material are characterized by fast optical axis *A* lying in the film plane along the coating direction *x*. The refractive indices along the other principal directions *B* (the in-plane axis *y*) and *C* (a normal along *z*-axis), which are orthogonal to the optical axis, are found to be equal within the limits of accuracy of our measurements. Thus TBF A002 films provide retardation properties characteristic of negative A-plate. At a wavelength of 550 nm, TBF A002 is characterized by an optical birefringence of Δn=0.34.

SIMULATION APPROACH

The LCD's optical simulation is based on exact matrix formulation of Maxwell equations for one-dimensional inhomogeneous and anisotropic media. The Berreman 4×4 matrix approach [8] with numerical algorithm described in [9] is used to calculate the angular and spectral dependencies of transmission and contrast ratio. The basics of this approach are as follows. If the media is homogeneous in the *xy*-plane, the wave propagation can be described by four first order differential equations

$$\frac{\partial}{\partial z}\Psi = \frac{i\omega}{c}\mathbf{\Delta}\cdot\Psi \quad , \qquad (1)$$

where the components of Δ–matrix are expressed in terms of dielectric tensor components [8, 9], and the electromagnetic field column Ψ is defined through the electric ($E_{x,y}$) and magnetic field ($H_{x,y}$) components as follows:

$$\Psi = \begin{pmatrix} E_x & H_y & E_y & -H_x \end{pmatrix}^T \qquad (2)$$

It is evident that the solution of (1) for a homogeneous optically anisotropic slab of thickness *h* is

$$\Psi(h) = \exp(i\omega\, h\mathbf{\Delta}/c)\Psi(0) \equiv P(h)\Psi(0), \qquad (3)$$

where $\Psi(0)$ and $\Psi(h)$ are the electromagnetic field columns at the input ($z=0$) and output ($z=h$) of the slab, respectively. According to (3), the problem is reduced to calculation of the exponent of the matrix Δ and finding the propagation matrix $P(h)$. In case of multilayered optical systems one needs to calculate the product of matrices $P_i(h_i)$ of the individual layers the system consists of. Also, in the case of the inhomogeneous LC layer, the problem is solved by space discretization over the whole layer thickness along the z-axis and finding the product of the corresponding matrices. The details on how to efficiently evaluate the field, transmission and reflection are described in [9]. The algorithm described in [9] is based on Sylvester theorem and Laguerre method for determining the eigen values that allows making very efficient (low time-consuming) and accurate simulations even for the biaxial layers.

BASIC DESIGNS AND RESULTS

In this paper we present the use of TBF only for compensation of single domain vertically aligned liquid crystals. However the films can also be efficiently used for the compensation of other LCD modes, such as, for instance, in-plane switching (IPS) mode.

In order to make low-cost designs we have applied a set of restrictions to the optimization procedure. The basic one is related to cost effectiveness and use of least expensive protective (TAC) films as substrates for the TBF coating. Another requirement is related to the compatibility with the roll-to-roll lamination method of the polarizing sheet fabrication. Thus it was necessary to keep the option of the compensation for cases of the two orthogonal orientations of the TBF fast axis with respect to the polarizer absorption axes.

Figure 2 illustrates two types of optically compensated VA designs. In the both cases the LC layer has the retardation of 275 nm. The TAC films play a dual role. Along with protective features they also have an out-of-plane optical retardation characteristic of negative C-plates. Experimentally we have found that typical and least expensive TAC films can provide the optical retardation $d(n_z\text{-}n_x)$ in a range of -50 to -60 nm. The two designs shown in Fig. 2a and Fig. 2b differ in orientation and retardation of TBF A002 films.

The Figure 3 shows the optimization map for the design in Fig. 2a. The map shows the dependence of the transmission coefficients versus the front and rear TBF thickness at a fixed retardation of the TAC film equal to -60 nm. The transmission is calculated in the field-off liquid crystal state at a light incidence angle of 60°. In this case the azimuth angle of the incidence plane is +45° that corresponds to bisecting the polarizer axes. In practice this azimuth can correspond to horizontal viewing plane for an observer. Values of TBF thickness of 1300 nm for the minimal value of the transmission insure the low light leakage and high contrast ratio of the LCD.

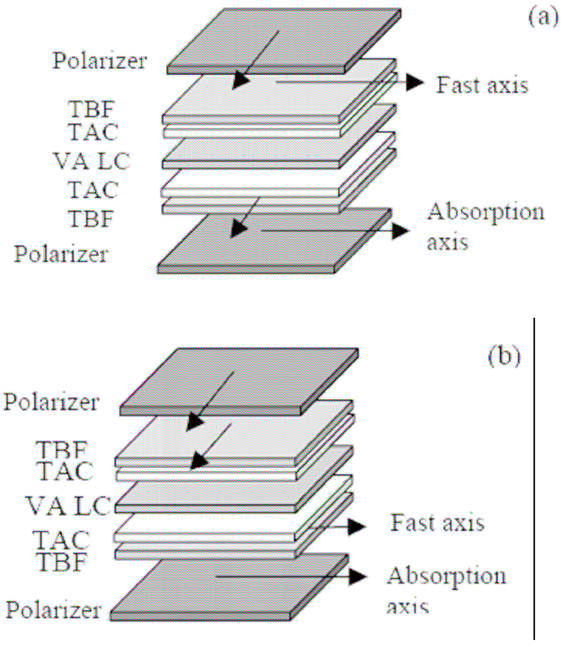

Fig. 2 Two types of optical designs based on TBF A002.

The design shown in Fig. 2a needs the TAC films of low absolute retardation equal to -60 nm. Such TAC films are the least expensive on the market. However, in this design the optical axis of the TBF, which coincides with the coating direction, should be oriented perpendicular to the absorption axis of the polarizer. The latter can result in some additional difficulties for the use of roll-to-roll manufacturing. In the design presented in Fig. 2b the TBF coating direction coincides with the polarizer absorption axis, which makes the roll-to-roll method highly applicable. In this case the TAC requirement is the absolute retardation of 130 nm at an optimal TBF A002 thickness of 750 nm.

Both designs result in near perfect viewing angle properties at 550 nm, Fig. 4. The results in Fig. 4a and Fig. 4b correspond to designs in Fig. 2a and Fig. 2b respectively. The contrast ratio exceeds a value of 100 even at extremely oblique angles close to 90 degrees with respect to the normal. Some decrease in contrast ratio takes place for the incidence plane at +45°. This is due the incompletely planar LC director orientation in the field-ON state and small tilt (~2°) of the LC optical axis with respect to the normal in the field-off state. This small tilt is necessary for defining the reorientation plane for the LC director.

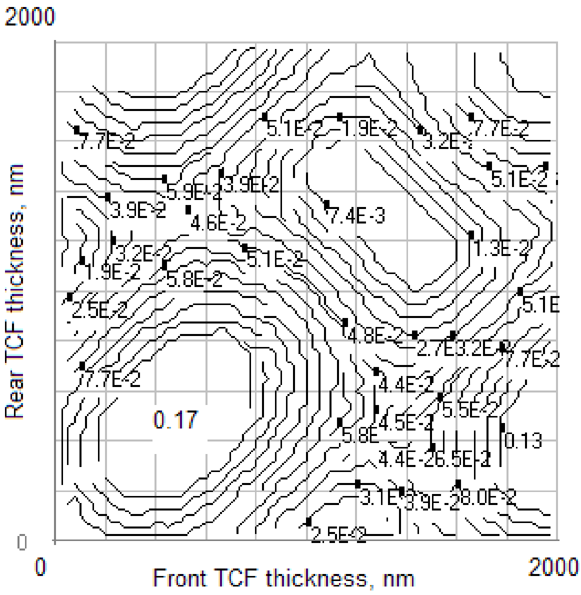

Fig. 3 Iso-transmission curves at an incidence angle of 60° in field-off LC layer state. The wavelength is 550 nm.

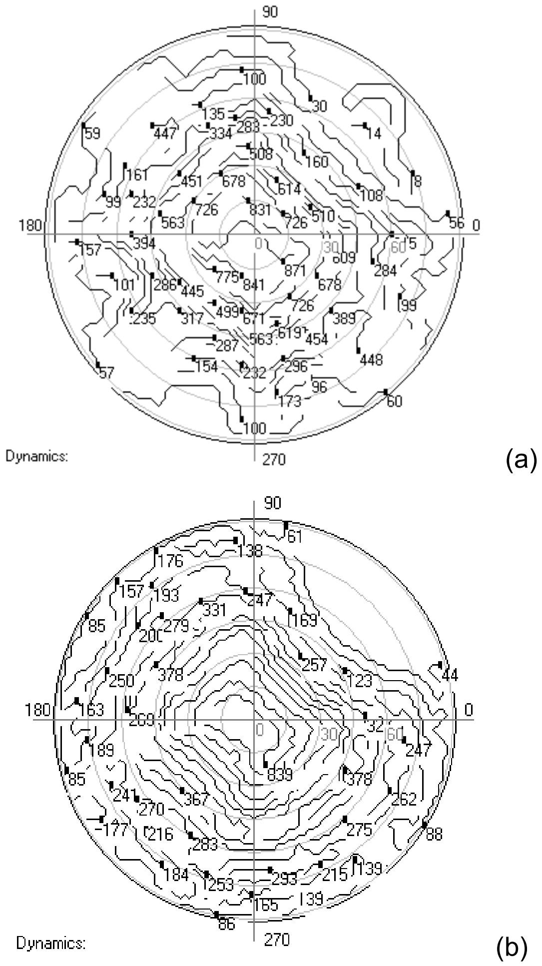

Fig. 4 Iso-contrast curves in field-off LC layer state. The wavelength is 550 nm.

The spectral performance is illustrated in Fig. 5. Figure 5 shows the angular dependencies of the contrast ratio for the design in Fig. 2b at three wavelengths (450, 550 and 650 nm) for an azimuth angle of -45^o. As one can see, in spite of the spectral dispersion of the refractive indices illustrated in Fig.1 the compensation effect remains very significant in "blue" and "red" spectral range.

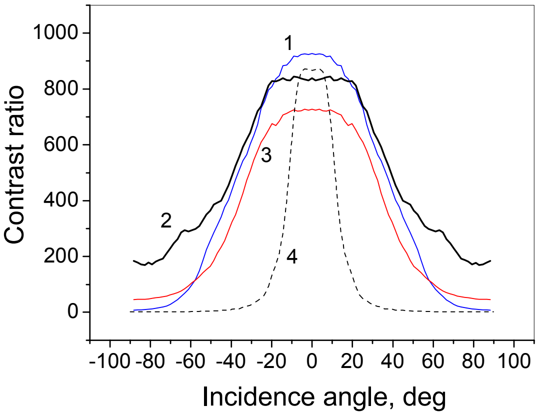

Fig. 5 Contrast ratio versus incidence angle at different wavelength: 1- λ=450 nm, 2 - λ=550 nm, 3 - λ=650 nm. The dashed curve 4 is for the non-compensated design at 550nm.

EXPERIMENTAL

We have prepared a single-domain VA LC cell of large area (5×5 cm^2). The LC cell gap of 3 μm in thickness was filled with a specially developed LC material providing negative dielectric anisotropy ($\Delta\varepsilon$=-3) at low frequencies and optical anisotropy Δn=0.085. The use of special polyimide alignment layers allowed us to get very low tilt angle of LC director (~2-3^o) with respect to the normal. One half of this cell was compensated by TBF and TAC films, while the other was non-compensated. The design was built in accordance with the scheme shown in Fig.2b. The design performance has confirmed our simulation results. The optical compensation effect is very well displayed by visual comparison of the two parts of the cell as shown by the photograph in Fig. 6. The photo demonstrates suppressing the light leakage by the compensated part of the cell, when the LC is in the field-off state.

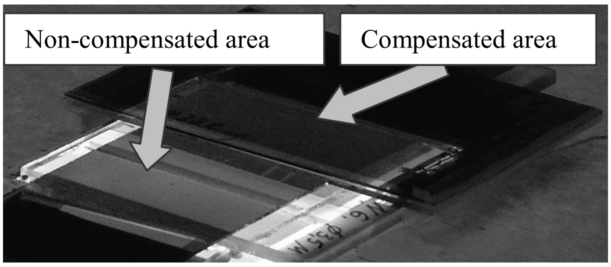

Fig. 6 VA LC cell design in field-off state. One half of the LC cell is compensated by TBF and TAC films in accordance with schematic drawing in Fig. 2b.

CONCLUSION

We have developed new set of coatable materials for TBF^{TM} retarders. We have demonstrated in simulations and experimental VA LCD that the new retarders can efficiently enhance the viewing angle properties of liquid crystal displays operating in VA mode.

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