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Light-reflecting characteristics of optically rewritable electronic paper

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Abstract. Light-reflecting characteristics play a crucial role in optically rewritable liquid crystal display (electronic paper). By using a special optimizer software, light-reflecting characteristics of the twisted nematic cell were calculated. The achieved values of the normalized reflection coefficients range within $\sim 0.03 - 0.43$, which is comparable or better than other commercial technologies. The calculated contrast ratio of the device is 10 : 1. A 2D image, which can be displayed on the electronic paper was obtained. Comparison of the simulated background color and contrast ratio is very similar with the results, which were obtained in experimental cells of other studies. Our calculations indicate that angular dependence of the reflectance coefficient is almost uniform within a wide range of viewing angles.

1. Introduction

Optical properties of liquid crystal (LC) displays can be easily tuned if its layer is placed between electrodes. The consequent response to the electric field definitely leads to the change of reflective or transmittive characteristics of the display. There also exists another way to control reflectance/transmittance of the display: exposing azo dye coated substrate surface to ultraviolet light. This idea is the basis for light-printed images, which is the concept of optically rewritable electronic paper (ORW e-paper).

There exist many other technologies of e-paper fabrication, where high reflection coefficient (%) is crucial. For example, electrophoretic (E-Ink, $\sim 40\%$), electrowetting (Liquavista, $\sim 50\%$), cholesteric liquid crystal (Kent Displays Inc., $\sim 30\%$), electrochromic (NTerra Inc., $\sim 45\%$, DIC, $\sim 65\%$), micro-electromechanical interference (Qualcomm Inc., $\sim 25\%$) and liquid powder (Bridgestone, $\sim 40\%$). However, reflection characteristics of all these technologies are lower than those of a typical white paper (over than 80%) [1].

The function of ORW e-paper is to store and display graphical information, generated by polarized light on thin flexible paper-like carrier with good reflective characteristics (preferably, $\gtrsim 40\%$) [2]. Optically rewritable technology represents a modified method of azo dye photoalignment with high azimuthal anchoring energy and reversible in-plane alignment. Optically rewritable LC cells consist of two substrates with different properties [3]. One substrate is optically passive, while another one is optically active, i.e., by manipulating with the polarization plane and the absorbed dose of the incident radiation, different alignment directions



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can be achieved on the same cell. Here, the key element in the ORW e-paper is photosensitive azo dye SD1. This compound is sensitive to ultraviolet light, and if one of the glass plates is coated with SD1, the cell performs new optical properties [4]. High thermal stability of SD1 makes this compound promising for many applications in optical devices. In particular, azo dye SD1-coated substrate produces continuous anchoring energy, which is proportional to the expose energy. Polar and azimuthal anchoring strengths between SD1 molecules and LC boundary are about 10^{-4} J/m², which is comparable with the rubbing technique (e.g., [5]).

In order to observe a reflected image, a reflective polarizer film is placed below the photo-stable aligning film [6]. A number of reflective characteristics of the ORW e-paper have not received proper consideration. This enables us to formulate the problem of estimation of ORW e-paper reflective characteristics.

Optimization of optical characteristics in LC cells has always been in the center of interest of liquid crystal studies [7, 8, 9, 10]. Indeed, during almost five decades of development, LC models have been transformed from lattice [11] to atomistic with predictive calculations [12, 13].

In this article we aim to show potential characteristics of e-paper by using universal Modelling and Optimization System of Liquid Crystal Devices (MOUSE-LCD, developed by the Hong Kong University of Science and Technology and the Saratov State University) [7, 14, 15]. In particular, we simulate image formation by changing boundary conditions on SD1-coated substrate. Then we introduce 8×8 transfer matrix description for computation of reflective characteristics and contrast ratio. The obtained characteristics are consistent with other e-paper technologies [1, 16].

2. Model

Schematic cross-sectional view of the twisted nematic (TN) cell is shown in figure 1 (a), where the right substrate is a reflective polarizer film. This cell will have high optical performance in the reflective mode if the phase retardation is Δnd , where Δn is the birefringence and $d = 6.85 \mu\text{m}$ is the cell gap. As it was mentioned above, flexible (polyethersulfone, PES) substrates are indispensable in the ORW concept. Meanwhile, we consider only flat surfaces of dielectric media.

Schematic representation of the cross-sectional view of ORW e-paper is depicted in figure 1 (b). In order to obtain more realistic results, we have introduced dispersion in the model. Let the refractive indexes along and perpendicular to the long molecular axes of LCs range within $n_{\parallel} = 1.642 \dots 1.695$ and $n_{\perp} = 1.495 \dots 1.515$ for all wavelengths of the visible spectrum. The following elastic constants were used $K_1 = 1.3 \cdot 10^{-6}$, $K_2 = 6.5 \cdot 10^{-7}$, $K_3 = 1.95 \cdot 10^{-6}$ dyn in the model. Knowing these parameters, the static director distribution in the LC layer can be calculated.

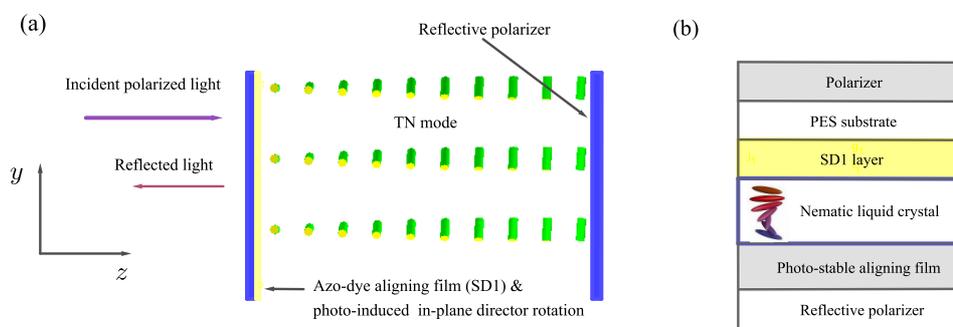


Figure 1. (a) Schematic representation of nematic liquid crystal cell after reorientation process occurs; (b) Device structure of ORW e-paper

When the incident polarized light beam propagates through the azo dye layer, its photoactive molecules change the alignment direction on the top substrate. Consequently, the twist angle can be changed from 0 to 90° , and grey levels can be continuously generated. The reorientation time is a very specific characteristic of the azo dye aligning film, and ranges within 5 – 20 s for intensities from 100 – 20 W/cm², respectively.

3. Simulation of performance characteristics

Reflective displays must be able to provide different grey scale levels and have more or less uniform reflectance characteristics versus different viewing angles. This suggests that viewing direction dependence must be described as the reflectance coefficient vs. viewing direction. Optics of multi-layered LC displays involves multiple reflections. It seemed earlier that a 4×4 differential-matrix technique [17] can solve the problem of multiple reflections. One of the drawbacks of this method is the necessity of spectral averaging, which involves time consuming numerical algorithms. Accurate and fast calculation of the reflective characteristics can be done by using 8×8 transfer matrix description for one-dimensional layered structures [14, 18].

By changing the twist angle in the boundary conditions (i.e., simulation of photo-induced in-plane director rotation) on the photo active substrate (left substrate in Figure 1 (a)), different chromatic colours can be generated. Thus, figure 2 depicts saturation trend of the normalized reflectance-twist angle curve. It is also possible to generate an image, which would appear on the e-paper. The image in the inset of figure 2 shows different grey levels, which we could achieve for different twist angles. One can see that the image quality is very close to the previously reported experimental results [19].

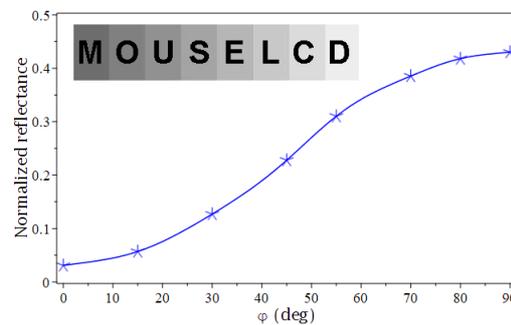


Figure 2. Normalized reflectance of ORW e-paper. Insert: computer generated-image with gray scales for different twist angles.

Normalized reflectance versus viewing angles can also be calculated. The isolines in Figures 3 show almost symmetric dependencies of the reflective coefficients for different twist angles. It can be clearly seen that higher twist angles increase the normalized reflectance coefficient. Similar simulations of the contrast ratio (the twist angle is 80°) show that it achieves 10 : 1 and reduces to 7 : 1 for viewing angles higher than $\sim 60^\circ$, which is acceptable result for e-paper displays [20].

These results show that when the reflection coefficient increases, the dark state is no longer dark. Consequently, the contrast ratio decreases.

4. Discussion

In order to model a standard set of electrooptical characteristics of LC displays, three fundamental computational problems must be sequentially solved.

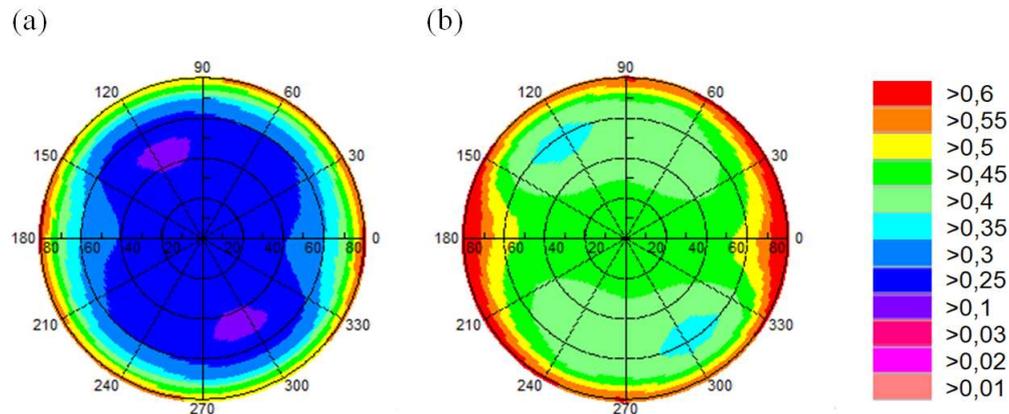


Figure 3. Angular dependence of the ORW reflectance coefficient: twist angle 45° (a) and 80° (b). The legend is relevant to both figures.

- (i) Computation of the equilibrium state of the director configuration in the LC layer for the determined boundary conditions and the applied voltage (if it exists).
- (ii) Computation of dynamics of the director field (if the external voltage is applied).
- (iii) Simulation of optical characteristics of the display with the given LC director field configuration.

The director field in LC layer was calculated by using numerical integration of Euler equations for the LC layer with the free energy minimization problem. The presented work does not involve computation of temporal characteristics, however the algorithm of MOUSE-LCD uses numerical integration of Ericksen-Leslie equations, which were solved by using the modified Eulers method.

It is clear that the reflective characteristics can be obtained by using using 4×4 -transfer matrix technique. Meanwhile, this technique requires computation of the spectral averaging, which is time consuming. Application of transfer 8×8 -matrix method provides a compromise between the accuracy and computational costs. Transfer 8×8 matrix method was developed to simulate optics in LC displays considering propagation of a quasi-monochromatic plane wave in a special one dimensional non-uniform layered structure. This method was derived from the theory of computation of optical characteristics in anisotropic media including partial coherence. Optimization tests with other cell thicknesses and LC compounds indicate no significant change in light reflectance and contrast ratio due to interference losses.

5. Conclusions

We have studied a TN configuration for ORW e-paper displays. Optical characteristics were calculated by using MOUSE-LCD optimizer. A 2D image, which would appear on e-paper was simulated. The achieved values of the normalized reflectance coefficients range within ~ 0.03 to 0.43 , which is higher or comparable with other commercial technologies. The calculated contrast ratio achieved $10 : 1$, which is also comparable with other studies. A significant advantage of ORW e-paper is that it does not require formation of static charges and electrodes. The calculations also indicate that angular dependence of the reflectance coefficient is almost uniform within a wide range of viewing angles.

Acknowledgments

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