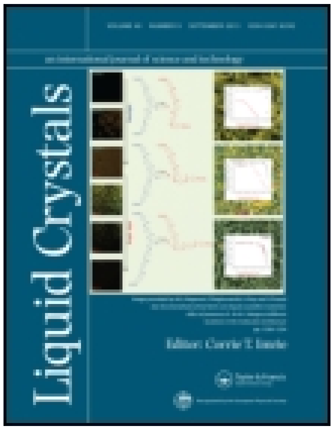

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Analysis of the rewriting time of liquid crystal optical rewritable e-paper

Yu Geng[a], Lishuang Yao[b], Vladimir Chigrinov[a] & Hoi Sing Kwok[a]

[a] Department of Electrical and Electronic Engineering, Hong Kong University of Science and Technology, Hong Kong, China

[b] State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China

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Yu Geng[a]*, Lishuang Yao[b], Vladimir Chigrinov[a] and Hoi Sing Kwok[a]

[a]*Department of Electrical and Electronic Engineering, Hong Kong University of Science and Technology, Hong Kong, China;* [b]*State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China*

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Theoretical and experimental analysis of the rewriting time of liquid crystal (LC) optical rewritable (ORW) e-paper was conducted. The equations of rewriting time of alignment molecule SD1 film with and without interaction with LC based on diffusion model were derived, which shows that the rewriting time of LC ORW e-paper could be shortened by enlarging light intensity or decreasing azimuthal anchoring energy. The rewriting time of pure SD1 films and LC ORW cells was measured under different light intensities. And LC ORW cells with different azimuthal anchoring energy were prepared for rewriting time measurement. A good agreement between experimental and theoretical results was obtained, which indicates that using larger light intensity and making LC cell with smaller azimuthal anchoring energy, ORW rewriting time could be decreased to the amount suitable for practical use.

Keywords: azo-dye; optical rewritable; photoalignment; rewriting time

1. Introduction

E-paper is one type of display device designed to mimic the ordinary paper, which requires ultra low or zero power consumption. We developed a liquid crystal (LC) optically rewritable (ORW) display by separating e-paper display unit from driving electronics, significantly reducing the complexity of the ORW e-paper structure.[1–10] This separation makes the ORW e-paper very durable and cheap and ready for the flexible challenge.

Using ORW technique, images of LC can be obtained in a one-mask exposure process. First, uniform alignment over the entire substrate is created. Then, exposure process was done using a mask with image information shadowed in desired regions, and finally the alignment in the non-shadowed area is simply rewritten to desired orientation. The images can be easily erased and rewritten by the same step described above. The process is fully compatible with standard photolithography exposure equipped with adjustable polariser.

The key in this process is the azo-dye alignment material SD1, which has the nature of reorientation to the direction perpendicular to the polarisation of activating light, which peaks at 372 nm and can be extended to over 450 nm.

This process was described as a diffusion model of the dye molecules under the action of the polarised light.[11] However, this model mainly describes the condition of pure SD1 film without interaction with LC, and rewriting time for the pure SD1 film and SD1-aligned LC cell is not well developed. In the meantime, not enough experiments were done to validate this model.

In this work, we first studied the rewriting time of pure SD1 film and SD1-aligned LC cell theoretically. And then experiments were done to compare with the theoretical results. A good agreement between the experimental results and theoretical model was obtained.

2. Theoretical analysis of ORW rewriting time

When the molecules of alignment material SD1 are illuminated by polarised light, the energy absorbed for the reorientation is proportional to the square of cosine ϑ, which is the angle between dye molecules and the polarisation vector of light. And the SD1 molecules will be stabilised perpendicular to the polarised light. This process is shown in Figure 1.

Without interaction between LC and SD1 molecules, this process could be determined by the diffusion model [11] as follows:

$$\left(1-u^2\right)\frac{\partial^2\rho}{\partial u^2}-2u\frac{\partial\rho}{\partial u}+A\rho\left(3u^2-1\right)-Au\left(1-u^2\right)\frac{\partial\rho}{\partial u}=\frac{1}{D}\frac{\partial\rho}{\partial t} \tag{1}$$

where $\rho=\rho(u,t)$ is the probability density function in a certain plane, $u=\cos\vartheta$, ϑ is orientation of SD1 molecules with respect to the polarisation vector of light, A is the coefficient of relative potential energy

*Corresponding author. Email: ygeng@ust.hk

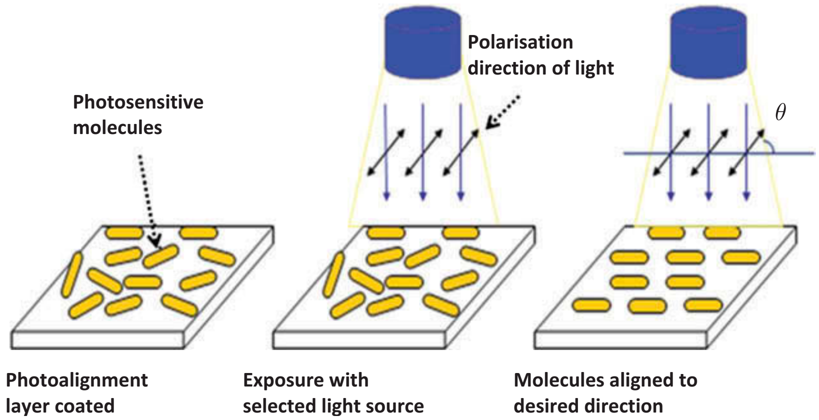

Figure 1. (colour online) SD1 photoalignment by polarised light.

Φ, t is the illumination time and D is rotational the diffusion coefficient.

Φ can be expressed as follows:

$$\Phi = \frac{1}{2} A \cos^2 \theta, \quad A = \frac{I\alpha V_M \tau}{kT} \tag{2}$$

where I is the light intensity, α and V_m are the absorption coefficient and molecular volume of SD1, respectively, T is an absolute temperature, k is the Boltzmann constant and τ is the relaxation time after light turned off, which is a constant and in the order of 10^{-4} s.

D can be expressed as follows:

$$D = \frac{kT}{6\pi\eta\alpha_m} \tag{3}$$

where η is the viscosity, α_m is the characteristic size of the SD1 molecule. When $u = \cos\vartheta = \cos\pi/2$, the absolute value of the order parameter reaches its maximal, $S_m = -1/2$. The value of relative order parameter $s = S/S_m$ is between 0 and 1. Our previous experiments show that s can be as large as 0.8 after light exposures for enough time.[12]

In the case of small light intensity, $A << 1$ and the relative uniaxial order parameter can be derived as [13] follows:

$$s = \frac{2A}{15}[1 - \exp(-6Dt)] \tag{4}$$

The saturation value of uniaxial order parameter is linearly dependent on the light intensity in this case. In e-paper application where light intensity is larger than 50 mW/cm^2, s is always saturated at about 0.8 after long time light illumination, which contradicts with Equation (4). This contradiction indicates that in this case, light intensity cannot be seen as small enough such that $A << 1$.

In the case of large light intensity, $A << 1$ and s would be saturated at a constant value and can be derived as [13] follows:

$$s = 1 - \exp(-0.8ADt) \tag{5}$$

It shows that s is 1 at $t = \infty$ and is not dependent on the light intensity.

Substituting Equations (2) and (3) into Equation (5), it becomes:

$$s = 1 - \exp\left(-\frac{2}{15}\frac{\alpha V_M \tau}{\pi\eta\alpha_m} It\right) \tag{6}$$

It can be seen that s is dose dependent, which matches with our previous experiment results.[14]

From Equation (6), the time at which s reaches 0.8, which is the saturation value by experiment, can be expressed as follows:

$$t = \frac{\ln 5}{0.8AD} \tag{7}$$

where AD can be expressed as follows:

$$AD = \frac{\alpha V_M \tau}{6\pi\eta\alpha_m} I \tag{8}$$

It shows that AD *i*s directly proportional to the light intensity and all other parameters are material dependent. As shown in Figure 2, rewiring time could be dramatically decreased when AD is larger, corresponding to larger light intensity.

For ORW cells filled with LC, the situation becomes different as there would be additional interaction between LC and SD1 molecules due to

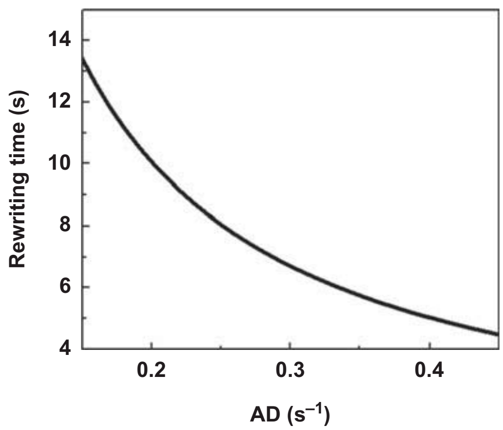

Figure 2. The time at which s reaches 0.8 with different ADs.

the anchoring energy of SD1 with LC. It can be seen as a resistance for the SD1 molecules to rotate and will need additional energy to overcome this resistance, which is dose dependent.[15] In this case, larger anchoring energy would consume more light intensity, leaving less light intensity to rotate the SD1 molecules. So Equation (8) would be changed to the following form:

$$AD = \frac{\alpha V_M \tau}{6\pi\eta\alpha_m} I_{eff} \tag{9}$$

$$I_{eff} = I - I_{anch} \tag{10}$$

where I is the total light intensity, I_{eff} is the effective light that rotate the SD1 molecules and I_{anch} is the light intensity used to overcome the anchoring energy.

Hence, based on Equations (7), (9) and (10), increasing the light intensity and decreasing the anchoring energy can both decrease the LC ORW rewriting time.

3. Experiments and discussions

The standard preparation processes of SD1 alignment layer are shown as follows: First SD1 is spin coated on cleaned glass with 3000 revolutions per minute (RPM) for 30 s. Then SD1 film was baked at 140°C for 15 min.[14] For the ORW LC cell, one substrate of the cell was rubbed polyimide 3744 (PI 3744) and the other was azo-dye SD1 layer. LC was filled in the cell to do rewriting time experiments under the light intensity of 125 mW/cm^2. In the following discussions, all the process parameters are the standard parameters shown above without specific statement.

3.1 *Rewriting time of pure SD1 film*

The rewriting time of pure SD1 film was first investigated. When the SD1 molecules are aligned in one direction, the absorption spectra of the orthogonal polarised lights would be different. It is defined as one rotation cycle when the SD1 molecules rotate from one direction to its perpendicular direction, which is characterised by the absorption peak exchange of the x and y direction.

The absorption spectra change of SD1 alignment layer without filling LC is shown in Figure 3, which shows that the absorption peak moves from the y direction in the initial stage to x direction in about 5 s.

Equation (7) shows that SD1 rewriting time is dependent on light intensity, so the rotation time by different light intensities were tested. The experimental data were fitted with the theoretical AD–time curve as shown in Figure 4, which shows that the

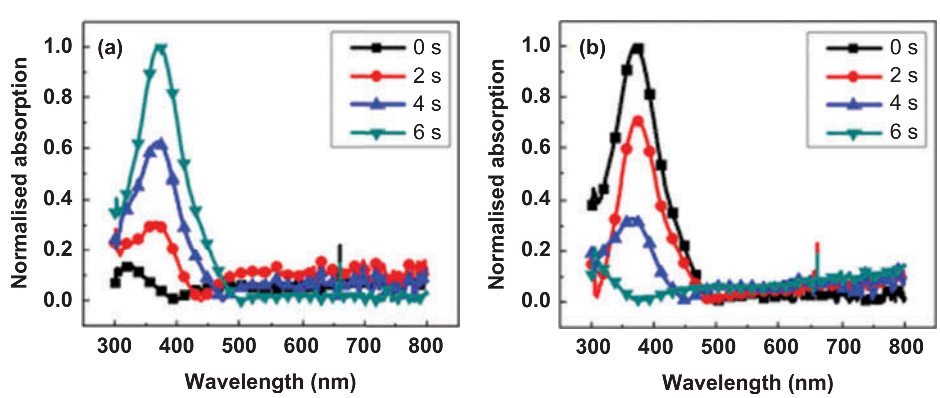

Figure 3. (colour online) The absorption spectra for orthogonal polarised lights under the light intensity of 125 mW/cm^2. (a) Absorption in x direction. (b) Absorption in y direction.

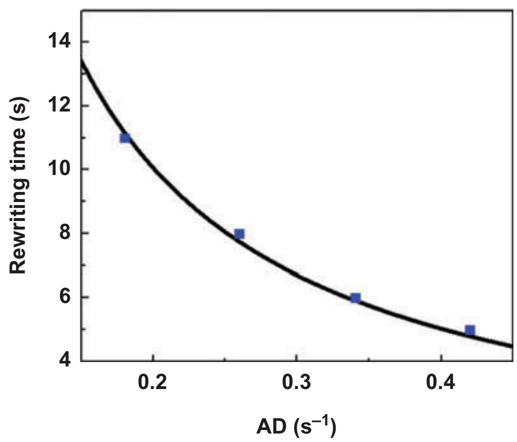

Figure 4. (colour online) SD1 rewriting time with different light intensities. (The solid line is the theoretical result and the dots are the experimental data corresponding to the condition of light intensity of 50 mW/cm^2, 75 mW/cm^2, 100 mW/cm^2 and 125 mW/cm^2.)

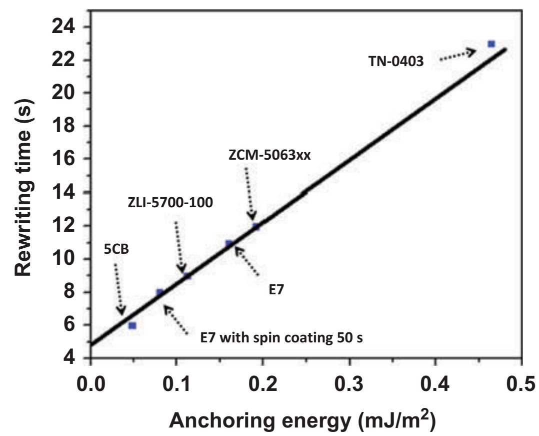

Figure 5. (colour online) Rewriting time of LC ORW cells with different azimuthal anchoring energy. (The solid line is the theoretical result and the dots are the experimental data corresponding to the condition of filling LC 5CB, E7 with spin coating 50 s, ZLI-5700-100, E7, ZCM-5063xx, TN-0403, respectively. All the spin coating time is 30 s without specific statement.)

SD1 rewriting time could be decreased by increasing the light intensity.

3.2 Rewriting time of SD1 photoaligned LC cells

The rewriting time of LC cells was measured by light transmittance curve, which is dependent on the LC twist angle cause by the rotation of SD1. The cell would change between dark and bright state during the 440 nm wavelength LED light illumination, depending on the light polarisation.[14] The effects of anchoring energy and light intensity were investigated.

3.2.1 Azimuthal anchoring energy

The azimuthal anchoring energy of SD1 with LC would give a resistance for the SD1 molecules to rotate. According to Equations (9) and (10), this will lead to longer SD1 rewriting time and less azimuthal anchoring energy could give rise to shorter rewriting time.

Experiments to demonstrate the relation of azimuthal anchoring energy and rewriting time were done as follows. In order to have different azimuthal anchoring energy, two methods were adopted. One was by coating SD1 film with various spin coating time, which gave different azimuthal anchoring energy by different SD1 film thickness.[12] The spin coating was done with 3000 RPM for 30 s and 50 s, respectively. And E7 was filled in the prepared cells. Then azimuthal anchoring energy for each sample was measured to be 0.16 mJ/m^2 and 0.08 mJ/m^2.

Another method to get different azimuthal anchoring energy was to use LCs with different twist elastic constant K_{22}. We have shown that LCs with smaller K_{22}, which have smaller azimuthal anchoring energy, have shorter rewriting time. For two well-known LC materials, E7 (K_{22} is larger) and 5CB (K_{22} is smaller), it required 11 s and 6 s,respectively, to change the alignment direction for generating image information.[14] And it should be also noted that all the rewriting time of LC cells is longer than that of pure SD1 films in the same condition, which have no anchoring effect between LC and SD1 molecules. Because the anchoring energy needs additional dose to conquer, it can be seen from Equations (7), (9) and (10) that rewriting time is linearly dependent on the anchoring energy.[15] The rewriting time of 5CB, ZLI-5700-100, E7, ZCM-5063xx and TN-0403 was measured in experiments. The theoretical and experiment measured rewriting time with different anchoring energy can be seen in Figure 5, which shows that with larger azimuthal anchoring energy, the rewriting time is also larger.

The above experiments demonstrate that larger azimuthal anchoring energy gives rise to larger rewriting time.

3.2.2 Light intensity

Based on Equations (9) and (10), it could be seen that with the same resistance by azimuthal anchoring energy, larger light intensity should lead to shorter rewriting time for the SD1 aligned cells. We tested the rewriting time under different light intensities, which is shown in Figure 6. It is clear that larger light intensity with the same ORW cell condition leads to shorter rewriting time.

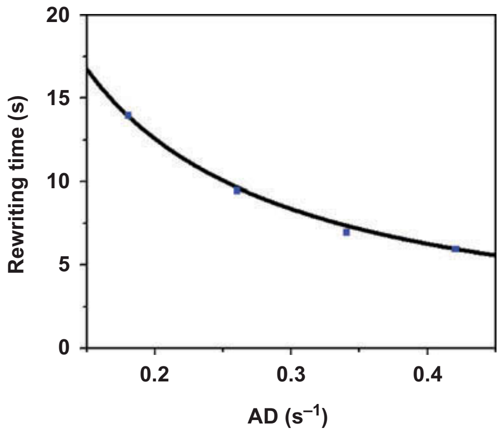

Figure 6. (colour online) Rewriting time of LC ORW cells under different light powers. (The solid line is the theoretical result and the dots are the experimental data corresponding to the condition of light intensity of 50 mW/cm^2, 75 mW/cm^2, 100 mW/cm^2 and 125 mW/cm^2.)

4. Conclusion

Theoretical expressions for the rewriting time of pure SD1 films and LC ORW e-paper cells are derived. And various experiments show good agreement with the theoretical expression. Both theoretical and experimental results demonstrate that rewriting time is greatly affected by effective light intensity, which could be increased by increasing the light intensity itself and decreasing the azimuthal anchoring energy. These results will improve operation speed of ORW technology for e-paper application by selecting higher light intensity and LC cells with smaller azimuthal anchoring energy, making ORW technology promising for industrial applications.

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