60.1: Optical Rewritable Electronic Paper with Fluorescent Dye Doped Liquid Crystal

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Abstract

New optical rewritable (ORW) electronic paper is the joint result of advanced photoalignment of liquid crystals, optical engineering and flexible LCD technologies. We report improvement of both dark and bright states of reflective ORW e-paper by doping LC with fluorescent dye, which absorb blue light & emit in green with high efficiency.

1. Introduction

The vast term of electronic paper comprises various perspective display techniques, which aims to store and display information generated by computer on a light weight thin flexible and robust, paper-like carrier with good brightness, high contrast and full viewing angle. In the contrast to flexible or rollable display, the frame rate is not the proper merit of e-paper performance, as the environmental, paper saving, aspect suggest competition not with the flat panel displays but the paper itself. Here the ultra low power consumption is highly desired, meaning reflective operation. It can be done by versatile means with the preference to the usability, durability and low paper-like cost.

The progress in LC photoalignment and our recent development of optical rewritable (ORW) e-paper [1] have made it possible to separate e-paper display-unit [2] and driving optoelectronics part [3]. That results into significant reduction of complexity of our ORW e-paper structure, having made device properties and cost both paper-like.

2. ORW Operation Principle

The image recording by surface photo-patterning in NLC cells was suggested before by every known photoalignment mechanisms, such as: photo-crosslinking [4], azo-dye adsorption [5], cis-trans photo isomerization [6] and azo-dye rotation [7]. We use the advanced azo-dye rotation technique, which fits the best for the wavelength and dose requirements of cycling operation. Here lower doses are required and faster operation, while the exposure wavelength should be tolerable by the photostability of liquid crystal material, which is a concern for the UV light.

The operation principle of ORW e-paper is the optical rewritable photoalignment of liquid crystals, which is carried out by the blue LED light and require the lowest doses of about 0.4J/cm^2 to form the orientation direction of the nematic liquid crystal in the reversible manner. The joint reorientation of the azo-dye molecules perpendicular to the polarization of the exposed light induces rotation of the alignment direction of the photoalignment layer perpendicular to the polarization of the exposed light.

There are two alignment layers in ORW LC cell. One of them is the azo-dye layer, while the second layer alignment is not photosensitive. The control of exposure polarization creates controlled LC twist angle. The optics of twist LC cell is well understood once the two polarizers are attached in the wave guiding mode.

3. ORW E-paper

3.1 Device Realization

We use single PES plastic substrate with thin SiO$_2$ layer to spin-coat SD1 azo-dye from 1% DMF solution. The substrate is baked at 100°C degree for 5 min on the hot plate. The opposite substrate is the reflective polarizer, which is coated with low temperature aligning material for plastic substrates, baked at 100°C for 5 min and treated to create the fixed alignment direction along the reflection axis of the polarizer. The two substrates are glued together with UV-epoxy NOA65, Norland.

The cell is filled in vacuum with liquid crystal E7, Merck. The cell is sealed. The gap is controlled by 8μm sticky spacers, which provides the resultant cell gap sufficiently large to obtain LC cell phase above the second Mauguin minima. In fact, for the waveguiding mode there is no need for precise control of the cell gap, as the optics of the twisted structure works very well for the whole VIS range being cell-gap independent. As even ±50% deviation in the cell gap will not cause significant change of the displayed image. Thus ORW e-paper can operate and display the image even being bent, which is necessary for flexible and robust image display

The top polarizer is attached parallel or perpendicular to the reflective polarizer. It is the special purple polarizer, which is capable to transmit both polarization components of the blue light, while for the green and red light it is a good polarizer. Thus though purple polarizer it is possible to see the image and to drive the ORW e-paper with the polarized blue light.

3.2 Blue Dark State

Following the fabrication steps described above we end up with the ORW e-paper (Fig.1), which was demonstrated on 14th International Display Workshop'07, Japan [2].

Figure 1. ORW e-paper on plastic substrates

The blue colour of the dark state is coming from the purple polarizer applied. On the one hand the special transmission characteristic of the polarizer is the required demand of the ORW e-paper. The device is driven by polarized light, sent to the rewritable aligning film. Through the transmission wavelength-window of the blue spectrum range the angle of incident light polarization remains almost unaffected. Thus ORW e-paper can be reversibly switched between dark and bright states by commercial blue LED that can already supply sufficient power. On the other hand, once the polarizer transmits in blue region, the dark state of ORW e-paper is blue.

Traditionally, the dark state of the display is black and is not blue. In order to cure the excess of blue light we added fluorescent dye dopant into the liquid crystal.

3.3 Fluorescent Dye Dopant

We successfully improved optical properties by doping the LC material with fluorescent dye that absorb blue light and emit in green. On Figure2 we present first prototype of ORW e-paper on glass with improved dark and bright states.

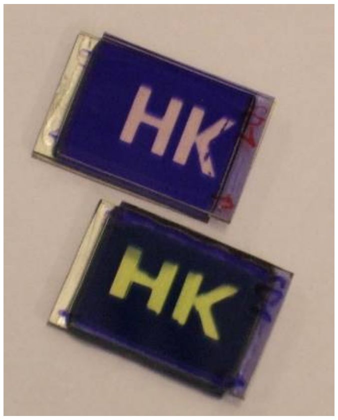

Figure 2. ORW e-paper on glass: top – regular, bottom – with improved dark state (better see electronic version for colour view)

The physics of the improvement can be best understood from the reflection spectra (Fig.3). The reflection spectra were recalculated from measured transmission spectra assuming white light and ideal reflective polarizer. The dye is aligned in LC with the dichroic ratio 5 and has quantum efficiency 0.9. It absorbs the excess of blue light and converts it to green, which is emitted with respect to anisotropic orientation in liquid crystal.

The normalized absorption and luminescence spectra of the fluorescent dye measured in DMF solution are shown on the Figure 4.

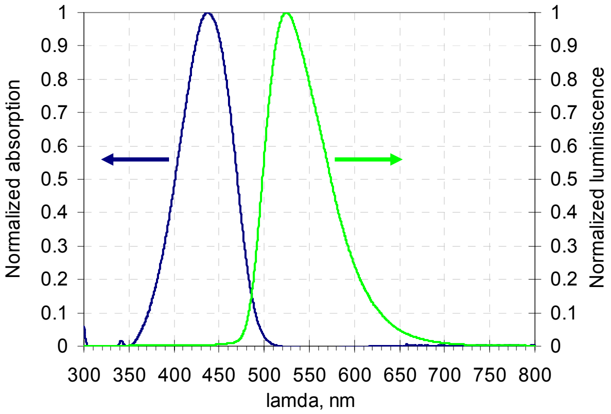

Figure 4. Normalized absorption and luminescence spectra of the fluorescent dye measured in DMF solution

For the dark state the orientation of LC on the top substrate corresponds to the absorption axis of top polarizer. Thus the polarizer can absorb the excess of re-emitted green light and improve the dark state. On the contrary, for the bright state the orientation of LC on the top substrate corresponds to the transmission axis of top polarizer. Thus the polarizer can transmit the excess of re-emitted green light and improve the bright state.

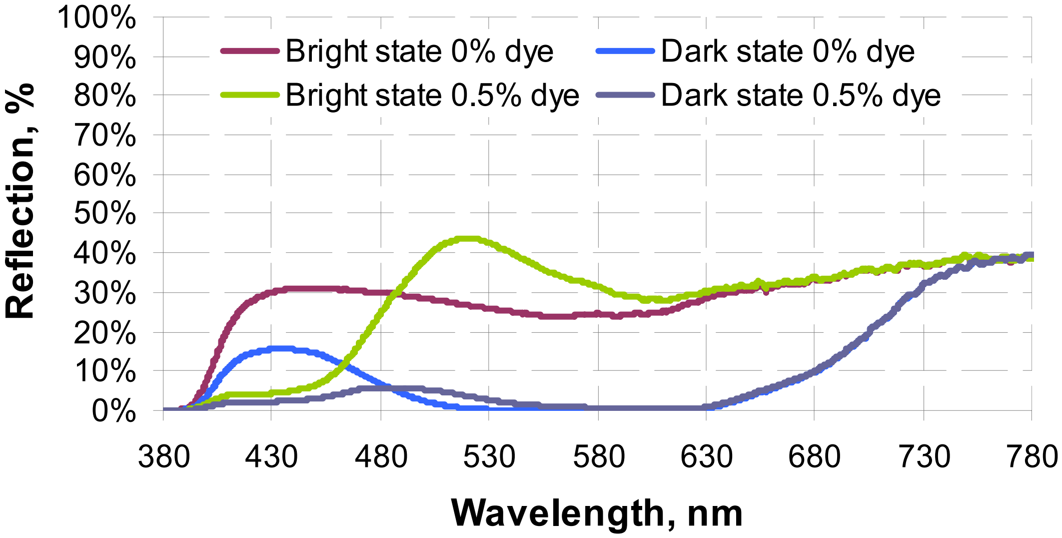

Figure 3. Reflection spectra of dark and bright states for 0% and 0.5% dye

3.4 Image Improvement

When take the untwisted mode of liquid crystal as, for example, the bright state the top transmissive and bottom reflective polarizers are parallel (Fig.5). The excess of blue light is converted into additional green light resulting into higher output photopic reflection.

Interesting remarkis that the more blue light exists in the background lighting the more green light is reflected by ORW e-paper with fluorescent dye doped LC. That is exactly the case of white LED general lighting, where the blue peak is converted to white light by phosphor material.

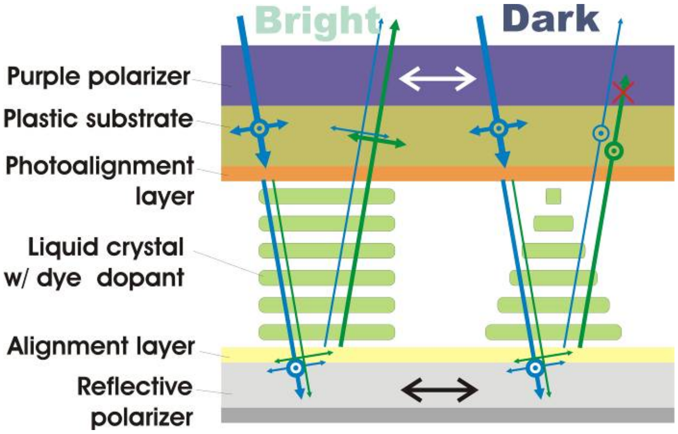

Figure 5. Schematic reflection of the blue light by ORW e-paper

At the same time fluorescent dye helps to improve the twisted i.e. dark state of the reflective ORW e-paper (Fig.5). The orientation of dye doped LC is arranged in the way that the dye helps to absorb the blue light in the absorbing direction of the top polarizer. The absorbed blue light (peak wavelength ~430nm) is converted by the fluorescent dye into the green light (peak wavelength ~520nm), which can be efficiently absorbed by the top polarizer. It provides the enhancement of the dark state of the ORW e-paper. On the Figure 6 we present the ORW e-paper with improved image by fluorescent dye doped LC.

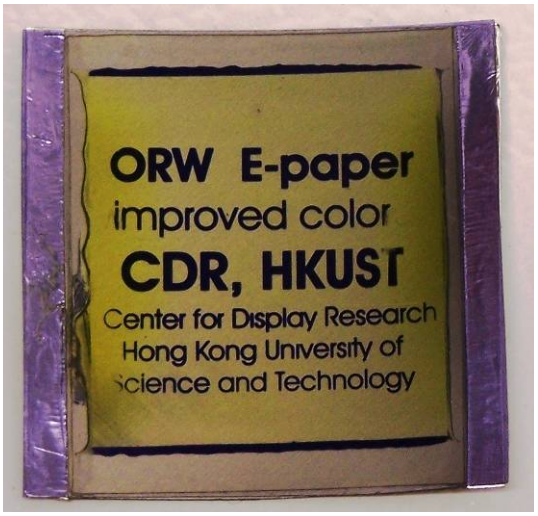

Figure 6. ORW e-paper with improved image by fluorescent dye doped LC (top and bottom polarizers are parallel)

4. Security Application

Once the top polarizer is removed the stored image can not be easily seen without the polarizer. On the contrary when the polarizer is attached the image can be easily seen (Fig.7).

Figure 7. ORW e-paper with fluorescent dye doped LC with top polarizer removed

Here the concealed image can be partially seen because of the birefringence of LC and related to it unequal reflection at the LC-substrate interface. That is underlining the surface nature of switch of the LC alignment direction.

5. Conclusions

The application of fluorescent dyes provides significant improvement for the ORW e-paper both dark and bright state without any influence on image writing and rewriting capabilities. Moreover, it is possible to optimize the reflection spectra of the bright state by changing the concentration percent of the fluorescent dye dopant. At the same time, dye doping is a cheap and simple way of obtaining coloured images.

ORW e-paper can be applied for various security applications, where it is reasonable to utilize polarized light, which may stem from the polarizer key of even polarized light on the LCD for online security.

Humans are using paper for about thousand of years and it is unlikely to come up with complete paper replacement at once. Still implementation of ORW e-paper has large paper replacement potential in labels, electronic newspapers and even regular office printing, as ORW e-paper saves both paper and ink.

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7. References

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