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FLEXIBLE OPTICALLY REWRITABLE E-PAPER BASED ON NANOTECHNOLOGY

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Abstract
Aim. Development of low-cost flexible Optically Rewritable E-paper using nanotechnology to address the challenge of aligning liquid crystals on plastic substrates.
Methodology. The approach is based on nanosized azo-dye photoaligning layers, which enable high-quality liquid crystal alignment on flexible plastics without the high-temperature processes required by conventional methods.
Results. The fabricated E-paper demonstrates fast response (<2 s), low writing energy (<1 J/cm^2), and over 1000 rewrite cycles. The device is mechanically robust, complex driving electronics is not needed
Research implications. This technology enables a mass production of low-cost, durable flexible displays for applications like price tags, advertising and smart cards, positioning optically rewritable E-paper as a strong competitor in the E-paper market.
Keywords: azo dye, flexible substrates, nematic liquid crystal, optically rewritable electronic paper, photoalignment
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Научная статья

ГИБКАЯ ПЕРЕЗАПИСЫВАЕМАЯ ЭЛЕКТРОННАЯ БУМАГА НА ОСНОВЕ НАНОСТРУКТУРИРОВАННЫХ МАТЕРИАЛОВ

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Аннотация

Цель: разработка гибкой оптически перезаписываемой электронной бумаги (ORW E-paper) с использованием нанотехнологии для решения проблемы ориентации жидких кристаллов на гибких пластиковых подложках.

Процедура и методы. В основе метода лежит использование наноразмерных фотоориентирующих слоёв на основе азокрасителей, которые обеспечивают высококачественную ориентацию жидких кристаллов на гибких пластиках без высокотемпературных процессов, требуемых традиционными методами.

Результаты. Созданная электронная бумага демонстрирует высокое быстродействие (<2 с), низкую энергию записи (<1 Дж/см^2) и возможность более 1000 циклов перезаписи. Устройство механически устойчиво, не требует сложной управляющей электроники и отличается низкой себестоимостью.

Теоретическая и практическая значимость. Технология открывает путь к массовому производству недорогих и долговечных гибких дисплеев для применения в ценниках, рекламе, смарт-картах и т. д., позиционируя ORW E-paper как конкурентоспособного игрока на рынке электронной бумаги.

Ключевые слова: азокраситель, гибкие подложки, нематический жидкий кристалл, оптически перезаписываемая электронная бумага, фотоориентация

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Introduction

The idea behind electronic paper (E-paper) is to store and display information on a paper-like carrier with ultra-low or zero power consumption during the non-updating period. Flexibility, readability, and multi-functionality are the main expectations for E-paper [1]. In particular, electrophoretic displays (EPDs), in which charged particles are electrically controlled, are the most widely used technology for E-paper, with applications in e-readers, shelf labels, and so forth [2]. However, with liquid crystal displays (LCDs) dominating the flat panel display market for decades, several liquid crystal (LC)-based candidates have also been developed for E-paper, the most mature being cholesteric LCDs [3], zenithal bistable devices (ZBDs) [4] and bistable nematic (BiNem) displays [5]. Generally, the power consumption of traditional LCDs is related to the driving frequency, and the applied voltage on individual pixels must be maintained even for a steady image. However, similar to EPDs' inherent behavior of bistability, LC E-paper only consumes power if the image is updated, and the refreshed image can be maintained for years with zero power consumption. LC molecules between the crossed polarizers work as the shutter with an applied voltage to realize bright or dark states. Meanwhile LC E-paper suffers from high-level complexity of the driving electronics, which often fail for flexible displays due to the insufficient durability of the flexible conductor and contact bonding.

Flexible liquid crystal E-paper possesses evident advantages over the existing E-paper technologies in color, video rate (fast response) and image quality. The color gamut is much better, as stable continuous fray scale (multi-stability) is possible. The large area LCD and thin film transistor (TFT) driving is possible. However, the LC alignment on plastic substrates is really a problem, as rubbed polyimide layers usually used in LC alignment require a very high imidization temperature (> 250єC), which is incompatible with typical plastic substrates. New nanosize (3-10 nm thick) photoaligning (PA) materials were developed for this purpose [6–10]. They have (i) high order parameter; (ii) excellent alignment quality of the LCD with a high contrast ratio in liquid crystal electrooptical modes; (iii) temperature and UV-stability due to the polymerization and cross-linking effects in the dye layers; (iv) perfect adhesion and high azimuthal and polar anchoring energy; (v) excellent sensitivity, which enables roll-to-roll processing.

Photoalignment of nematic liquid crystals represents an emerging technology for the production of liquid crystal devices with novel properties, e.g., lenses, reconfigurable optical networks, index-tunable antireflective coatings and optically rewritable phase gratings [6]. One of these devices is flexible optically rewritable electronic paper (ORW E-paper), which is a reflective display with a photosensitive substrate coated by an azo dye layer with a thickness of 10-15 nm. This display technology has gained significant attention from scholars due to its light weight, low cost, small thickness and easy processing [7–11].

Photoalignment of liquid crystals has obvious advantages over substrate-rubbing technology due to its application on curved and flexible substrates, high resolution and absence of mechanical damage on the surface. Nanosized photoaligning layers are very good materials for implementation of flexible ORW E-paper [10; 11], since the photoaligning films are robust and possess rather good LC aligning properties with sufficiently high anchoring energies, image sticking and voltage holding ratios. Another advantage of photoalignment technology for e-paper is its thermal stability up to 100єC. Thus, photopatterning techniques, mechanical flexibility characteristics, thermally stable birefringence characteristics enabled us to fabricate flexible and lightweight color.

Further investigation in flexible ORW e-paper should be devoted to the following questions: (i) extension of color performance with a wide color triangle; (ii) effective outdoor performance under direct sunlight; (iii) further optimization of photoalignment azo dye materials and LCs used for the purpose with a high stability and fast writing/erasing time. We foresee possible applications of flexible ORW E-paper in the following: (i) indoor and outdoor sign and advertising labels; (ii) price labels in supermarkets; (iii) displays on flexible cards; (iv) conference labels; (v) personal digital assistants (PDAs) [12].

Results of ORW E-paper

Flexible LC E-paper possesses evident advantages over the existing E-paper technologies in color, video rate (fast response) and image quality. The color gamut is much better, as stable continuous fray scale (multi-stability) is possible. The large area LCD and thin film transistor driving is possible.

However, the LC alignment on plastic substrates is really a problem, as rubbed polyimide layers usually used in LC alignment require a very high imidization temperature (> 250єC), which is incompatible with typical plastic substrates. New nanosize (3-10 nm thick) photoaligning materials were developed for this purpose.

They have (i) high order parameter; (ii) excellent alignment quality of the LCD with a high contrast ratio in liquid crystal electrooptical modes; (iii) temperature and UV-stability due to the polymerization and cross-linking effects in the dye layers; (iv) perfect adhesion and high azimuthal and polar anchoring energy; (v) excellent sensitivity, which enables roll-to-roll processing.

We will show certain results of ORW E-paper below.

Fig. 1 shows, how that the quality of LC alignment strongly depends on the thickness of the PA layer. The thickness of the azodye alignment layer should be properly adjusted, especially in case of ferroelectric liquid crystal (FLC) materials with a high spontaneous polarization [13].

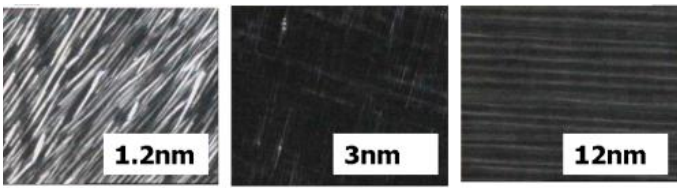

Fig. 1 / Рис. 1. The best quality of ferroelectric LC alignment is achieved at 3 nm thickness of nano-size PA layer / Наилучшее качество выравнивания сегнетоэлектрического ЖК достигается при толщине наноразмерного слоя PA 3 нм

Source: [13].

The new photo-aligning materials and novel LCD based on nanoscale photo-aligning layers were investigated. Both photo-polymerized and photo-cross linked azo-dye PA films were studied, as well as new dye-polymer PA systems.

Photoalignment possesses obvious advantages in comparison with a wide-spread rubbing treatment of the liquid crystal. Possible benefits for using this technique include [6]:

(i) Elimination of electrostatic charges and impurities as well as mechanical damage of the surface;

(ii) Controllable pretilt angle and anchoring energy of the liquid crystal cell, as well as high thermal, UV stability and ionic purity;

(iii) Possibility to produce the structures with the required LC director alignment within the selected areas of the cell, thus allowing pixel dividing to enable new special LC device configurations for transflective, multi-domain, 3D and other new display types;

(iv) Potential increase of manufacturing yield, especially in LCDs with active matrix addressing, where fine tiny pixels of a high resolution LCD screen are driven by thin film transistors on a silicone substrate;

(v) New advanced applications of LC in fiber communications, optical data processing, holography and other fields, where traditional rubbing alignment is not possible due to the sophisticated geometry of LC cell and/or high spatial resolution of the processing system;

(vi) Ability for efficient LC alignment on curved and flexible substrates;

(vii) Manufacturing of new optical elements for LC technology, such as patterned polarizers and phase retarders, tunable optical filters, polarization non-sensitive optical lenses, with voltage controllable focal distance etc.

The ability to align liquid crystals highly depends on the presence and the position of several groups within the molecular structure. It affects the interaction of molecules with each other in the thin solid photosensitive film, as well as the interaction of liquid crystal with such photoalignment films. We are very close on the understanding of the photoalighment on the molecular level. To clarify the phenomena additional experiments and synthesis of several clean compounds are necessary.

We have concentrated on the aspects of the new materials, which are critical for the LCD technology such as good adhesion to flexible substrates, UV and IR stability, non-absorbance in the visible region, surface uniformity and fine resolution of the photo-induced surface, acceptable voltage holding ratio (VHR) and residual DC current (RDC) to minimize the effect of ions. We had a first look for the mixtures of azo-dye structures with very good results. Photoalignment of azo-dye molecules in a nano-layer perpendicular to the polarization of the incident light is shown on Fig. 2.

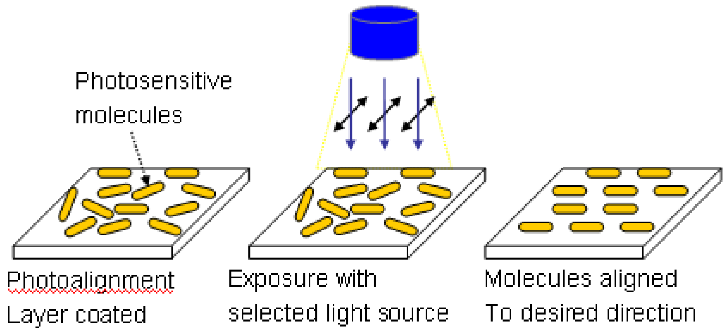

Fig. 2 / Рис. 2. Photoalignment of azo-dye molecules in a nano-layer perpendicular to the polarization of the incident light / Фотоориентация молекул азокрасителя в нанослое перпендикулярно поляризации падающего света

Source: [6].

The order parameter of the dye layer should be sufficiently high to obtain a good quality of LC alignment. Our goal is to develop PA materials, which exhibit sufficiently high anchoring energies to avoid the surface defects of the LC. Another goal is to get any pretilt angle on the PA substrate. We have already developed the methods of UV-light illumination, which provide the promising results. We hope that new PA materials as well as sandwich and heterogeneous structures, which exhibit both homeotropic and homogeneous tendency for LC aligning, will help to solve the problem of getting any desirable value of the LC pretilt angle on the flexible PA substrate. We have developed the novel types of LCD on flexible substrates, using the photoaligning technology in nanoscale alignment layers. The success in this development was guaranteed by a proper choice of the PA layer, ITO coating, LC material and controlling method.

The new developments included Optically Rewritable LC technology (new E-paper) that provides controllable patterned, reversible planar or vertical, liquid crystal alignment. The image is truly stable, written to grey level with saturation and rewritten a large number of times with high reproducibility of properties. We have come out with low power consuming high efficiency ORW-device which have three major parts: optically rewritable azo-dye photoalignment and ORW LCD with polarizer-substrates, LED-exposure light source and phase-mask LCD polarization rotator. The new E-paper is lightweight thin, paper-like image carrier with good brightness, high contrast and full viewing angle and capable to display either 2D or both 2D&3D images. The principle of the ORW E-paper is based on the reversible photoalignment of the PA nanolayer, which involves the corresponding realignment of the adjacent LC layer wit changing the twist angle (Fig. 3). The picture becomes visible, if put between the pair of the polarizers (Fig. 3). The image can be written and erased reversibly thousands of times with a high resolution.

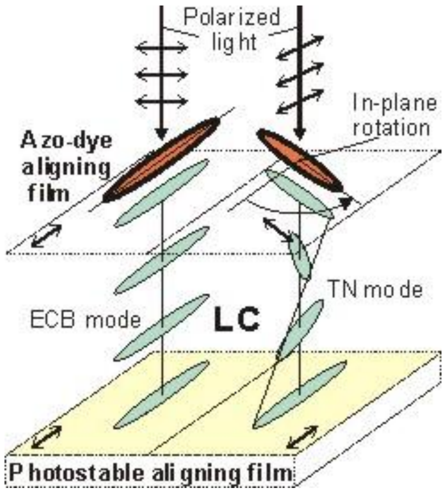

Fig. 3 / Рис. 3. Reversible LC realignment in a twst LC layer / Обратимая переориентация жидкого кристалла в слое жидкого кристалла с обратной ориентацией (twst LC)

Source: [6].

The image can be bright on the dark background or dark on the bright background depending on the location of the polarizers, crossed or parallel to each other (Fig. 4).

Fig. 4 / Рис. 4. ORW E-paper image under crossed and parallel polarizers / Изображение на оптически перезаписываемой электронной бумаге при использовании скрещенных и параллельных поляризаторов.

Source: [6].

We elaborated the new highly sensitive ORW photoaligning materials and liquid crystal layers with the following characteristics: response time less than 2 sec, writing energy less than 1 J/cm^2 with more than 1000 reversible cycles and implemented the blue LED light printer as an exposure light source. Optically rewritable technique is highly desirable, as E-paper displays suffer from the high level complexity of driving electronic due to the insufficient durability of flexible conductor and contact bonding.

The advantages of ORW E-paper: no drivers, no current conducting layer, high thickness tolerance, the technology is very cheap (the price of ORW E-paper is equal to the price of two polarizers, i.e. about 20 USD/m^2). The ORW technology is highly compatible with flexible substrates. The new ORW technology is a pioneer innovation in flexible LCD E-paper and will easily find its application in E-paper market. The possible but not limiting applications of the optically rewritable liquid crystal displays based on photoalignment are light printable rewritable paper, labels and plastic card displays, as well as rewritable 3D paper for security applications (Fig. 5).

Fig. 5 / Рис. 5. From left to right: ORW E-paper for advertisements, plastic cards and security applications / Слева направо: оптически перезаписываемая электронная бумага для рекламы, пластиковых карт и приложений безопасности

Source: [6].

Flexible E-paper LCD new cell can tolerate pressure, hitting and bending. As shown in Fig. 6, we can still see the image clearly with good quality due to the sticky spacers and fixed LC cell gap.

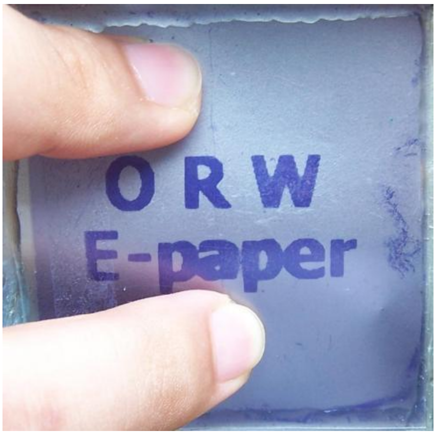

Fig. 6 / Рис. 6. ORW E-paper in plastic substrates is tolerant to mechanical pressure / Оптически перезаписываемая электронная бумага на пластиковых подложках устойчива к механическому давлению

Source: [6].

Conclusions

A series of our research studies developed an approach to deal with flexible substrates. Flexible optically rewritable E-paper may successfully compete with other E-paper technologies, including electronic ink. The possible production of flexible ORW E-paper was shown using the DMD and roll-to-roll processes. The images on flexible E-paper were demonstrated on a smart card. Potential applications of flexible ORW E-paper include price labels in supermarkets, indoor and outdoor advertisements, conference labels, etc.

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