Film patterned retarder for stereoscopic three-dimensional display using ink-jet printing method

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Abstract: We propose a film patterned retarder (FPR) for stereoscopic three-dimensional display with polarization glasses using ink-jet printing method. Conventional FPR process requires coating of photo-alignment and then UV exposure using wire-grid mask, which is very expensive and difficult. The proposed novel fabrication method utilizes a plastic substrate made of polyether sulfone and an alignment layer, poly (4, 4' - (9, 9 - fluorenyl) diphenylene cyclobutanyltetracarboximide) (9FDA/CBDA) in which the former and the latter aligns reactive mesogen along and perpendicular to the rubbing direction, respectively. The ink-jet printing of 9FDA/CBDA line by line allows fabricating the cost effective FPR which can be widely applied for 3D display applications.

OCIS codes: (230.2090) Electro-optical devices; (230.3720) Liquid-crystal devices.

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1. Introduction

The technology for the three-dimensional (3D) display has been actively studied after a commercial success of the Hollywood movie "Avatar" in 2009 year because the display users want to feel real image. The technology of the 3D display is classified into two separate branches, i.e., with glasses [1–10] and non-glasses type [11–20]. Although the glasses type has to use glasses, the viewer could feel comfortably perfect 3D image. Accordingly, these days 3D technologies applied to liquid crystal display television (LCD-TV) are glasses type. At present, two types of glasses are commercialized such as shutter glasses [1–3] and polarized glasses using patterned retarder [4–7] and active retarder [8, 9]. Among them, the 3D technology using shutter glasses has several drawbacks such as luminance is extremely reduced, crosstalk is generated in the large size display, and the weight of wearing glasses is heavy compared with patterned retarder. On the other hand, initial product of the patterned retarder made by Arisawa Manufacturing Co., Ltd. has many demerits such as expensive process, heavyweight of the display panel, image parallax, and crosstalk since the retarder is fabricated on a glass substrate with thickness close to a millimeter [10]. Recently, film patterned retarder (FPR) which uses a plastic film as a base substrate becomes main trend in the 3D display market owing to its lightweight and thinness that reduces image parallax. However, conventional FPR process requires coating of photo-alignment on a plastic substrate and then UV exposure using wire-grid photo mask to achieve the patterned retarder on plastic film, which is very expensive and difficult, and also a long time fabrication process, as shown Fig. 1(a).

In this paper, we propose a novel fabrication method for FPR in which a polymer base film and an ink-jet printed alignment layer associated with rubbing process play the role of aligning reactive mesogen (RM) with its slow axes orthogonal to each other line by line. This proposed method features an easy fabrication and low-cost process of the FPR.

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2. Simple fabrication process of the FPR using ink-jet printing method

Figure 1 illustrates the comparison between conventional and proposed ink-jet printing methods in making FPR. In the conventional method [Fig. 1(a)], photo-alignment layer which yields homogenous alignment by ultra-violet (UV) exposure was coated by spin coating on a plastic film. Then, the polarized UV was exposed to the alignment layer through zig-zag shaped nano wire-grid photo mask which renders polarized light from unpolarized UV light. Here, angle difference between axes of the polarized UV in line by line is 90°. Hence, when reactive mesogen (RM) was coated by spin coating and then cured by UV irradiator, its slow axes between lines became orthogonal to each other. The conventional method requires two times UV exposure and the use of high-cost photo mask. On the contrary, the proposed ink-jet printing method requires only one time UV exposure without the use of photo-mask and basically it is composed of just 3 steps including ink-jet printing, rubbing process, and RM coating as shown in Fig. 1(b). At the first step, an alignment layer which allows alignment of RM director orthogonal to a rubbing direction is printed in a form of line by line above a plastic substrate using ink-jet printing and then a rubbing process to the substrate using a rubbing machine is performed. Finally, the RM is coated and then UV is exposed to the film that results the final FPR in which the slow axes of the RM in the neighboring domains are orthogonal to each other. The key fundamentals behind this results comes from the plastic substrate and the alignment layer used in this process allows alignment of the RM director parallel and perpendicular to the rubbing direction, respectively. Therefore, development of proper substrate and alignment layer as well as optimization of ink-jet printing process is highly important to achieve a FPR with a high quality.

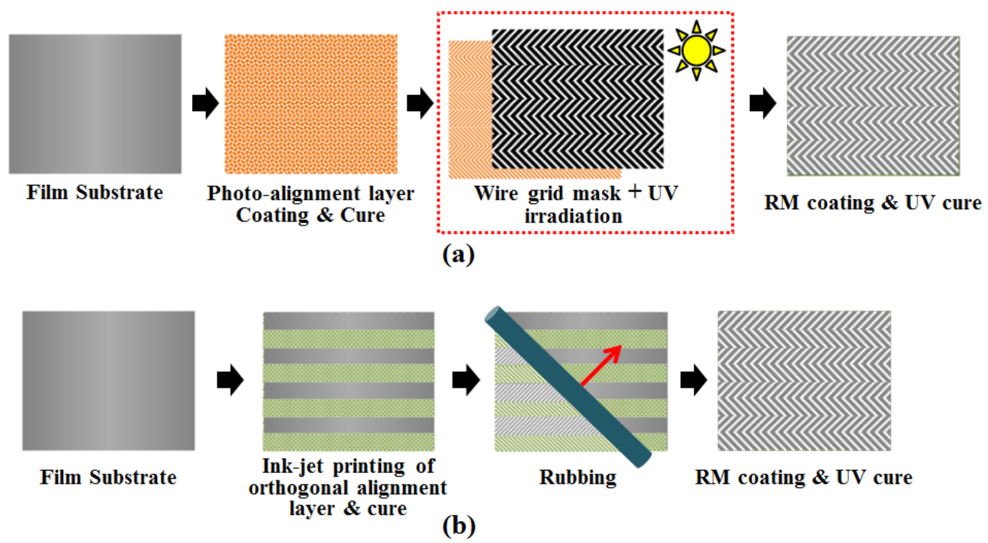

Fig. 1. Comparison of processes for forming patterned retarder on film substrate: (a) a conventional process and (b) proposed ink-jet printing process. Here, orange and green colors are photo and orthogonal alignment layers, respectively.

3. Results and discussion

The first key step to realize the proposed FPR is to find an alignment layer which gives rise to orthogonal alignment of either liquid crystal (LC) or RM to a rubbing direction because either most of substrates or polymer-type alignment layers align LC parallel to the rubbing direction in association with physicochemical effect. The well-known polymer for the purpose is polystyrene (PS) [21]. At first, the PS dissolved in a solvent was coated on a glass substrate by spin coating and then once it was cured mechanical rubbing was performed to the surface. When the nematic LC was dropped on the surface of the PS, we could confirm that the LC

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was aligned perpendicular to the rubbing direction as expected. However, when the RM solution (RMS 03-013C, Merck) in which the RM with birefringence (Δn) of 0.137 at 589nm was dissolved in propylene glycol monomethyl ether acetate was coated on the surface of the PS, the RM did not show uniform alignment as shown in polarizing optical macroscopic (POM) image of the coated RM in Fig. 2(a). We understood that the anchoring energy of the PS surface is not strong enough so that it is damaged by the solvent in the RM solution. As an alternative, we synthesized poly (4, 4' - (9, 9 - fluorenyl) diphenylene cyclobutanyltetracarboximide) (9FDA/CBDA) [22] and dissolved it in γ-butyrolactone with concentration of 5 wt% for the orthogonal alignment layer. After spin coating the 9FDA/CBDA, the same rubbing strength was applied to the surface and then the RM solution was coated on the substrate. As indicated in the POM image in Fig. 2(b), a perfect and uniform positive A optical symmetry birefringent polymer film was achieved.

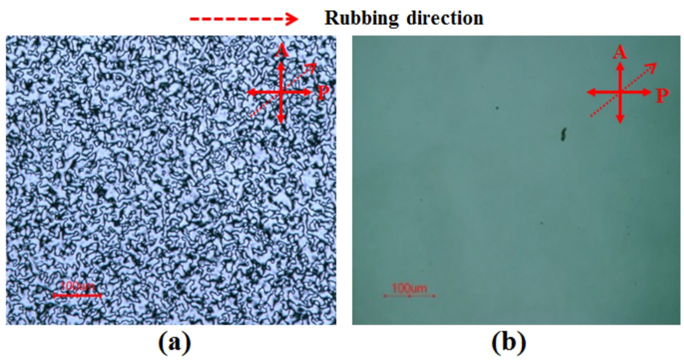

Fig. 2. POM images of a polymerized RM formed on (a) PS and (b) 9FDA/CBDA after rubbing process using glass substrate.

The second key step to realize the proposed FPR is patterned ink-jet printing of the alignment layer 9FDA/CBDA in a line shape on a plastic film. For this purpose, an ink-jet printing machine (Fuji Film Dimatix, Japan) was used [23]. The plastic substrate used in this study is polyether sulfone (PES) film (SCL 2000, I-components) with thickness of 240μm and for surface cleaning, UV light (Lightning cure, HAMAMATSU) was exposed with 5 mW/cm^2 for 1 min. Once the 9FDA/CBDA was printed, its coating quality and precision level in dimension was investigated by optical microscopy (Nikon ECLIPSE E600 POL, Japan). As shown in Fig. 3, both width and line spacing of the 9FDA/CBDA lines with orthogonal alignment characteristic were measured to be 539μm with good uniformity, though the surface has some roughness indicating that uniformity in thickness of the printed layer with ink-jet printing needs to improved further. Once the printing was confirmed, the solvent was evaporated and then the rubbing was performed to the substrate. Finally, the RM solution was coated on PES film with the patterned 9FDA/CBDA and after evaporating a solvent the UV light with 25 mW/cm^2 was exposed for 1min for the polymerization of RM.

Figure 4 show POM images of the fabricated FPR on PES film. The retardation value of the FPR was measured to be 127.9nm at 550nm using REMS-150 (Sesim Photonics). In order to check alignment property of the patterned 9FDA/CBDA using ink-jet printer on PES film, the POM images of the dark and white states were observed. When the slow axes of the FPR were either parallel or perpendicular to the transmittance axes of the crossed polarizer, the dark state appeared as shown in Fig. 4(a) and when the FPR was rotated by 45°, the white state was observed as expected [see Fig. 4(b)]. Unfortunately, some level of light leakage in the dark state was observed due to non-uniform coating of the 9FDA/CBDA in line associated with overlapping of ink droplets on PES film, we believe this problem could be solved using other printing methods or optimized process and also by optimizing viscosity of the materials. Nonetheless, the dark state clearly indicates that the optic axis exists in the FPR. Next, in order to find out an optic axis of the FPR, a quarter wave plate (λ/4 film) is inserted between the FPR and the polarizer while rotating the FPR by 45° clockwise and anticlockwise with

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respect to the crossed polarizer. When the slow axes of the FPR and the λ/4 film are parallel or perpendicular to each other, the POM image would show a bright state or a dark state, respectively. As clearly presented in Fig. 4(c) and Fig. 4(d), in the regions where the PES substrate itself and the 9FDA/CBDA are used as an alignment layer of the RM, the bright state appears in conditions that the rubbing direction is parallel to and perpendicular to the slow axis of the λ/4 film, respectively. This clearly indicates the slow axis of the polymerized RM film is oriented parallel and perpendicular to the slow axis of the λ/4 film in the neighboring domains, achieving the ideal FPR which changes the polarization of light passing through the neighboring domains to left- and right-circular polarized for the 3D displays.

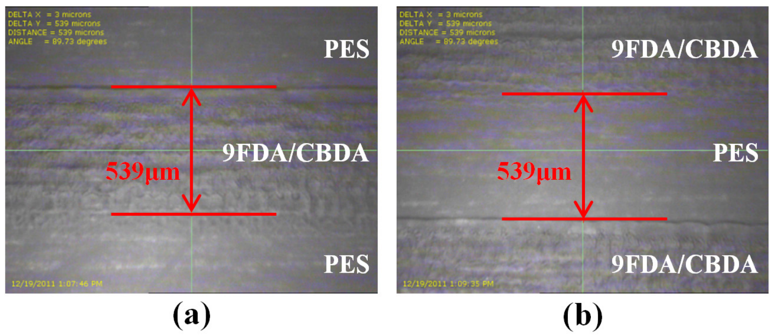

Fig. 3. Optical microscopic images of the 9FDA/CBDA formed on PES film with UV surface treatment: (a) width and (b) line spacing of the 9FDA/CBDA lines.

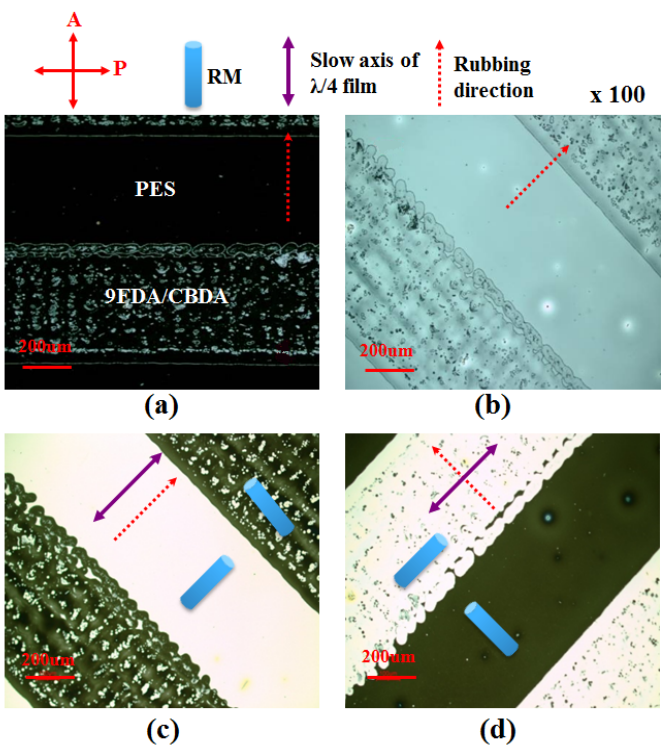

Fig. 4. POM images of a polymerized RM on surfaces of the 9FDA/CBDA and the PES film. The rubbing direction is parallel (a) and makes 45° (b) to the crossed polarizer. The λ/4 film is inserted into between the polarizer and the FPR while the FPR is rotated clockwise (c) and anticlockwise (d), where the bright state is observed in the region with the 9FDA/CBDA (c) and the PES film (d), respectively.

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Figure 5 shows photographs that demonstrate the developed FPR with an area of 3.8cm x 4cm between crossed polarizers with λ/4 film. The FPR is uniformly formed in a large area although the film was torn in a middle part due to handling issue of a thin film during fabrication. When the slow axis of the λ/4 film was parallel to the rubbing direction of the 9FDA/CBDA layer, the dark image on the patterned 9FDA/CBDA layer was observed, as shown in Fig. 5(a), whereas the white image on the patterned 9FDA/CBDA layer was observed when the λ/4 film was rotated by 90°, as shown in Fig. 5(b).

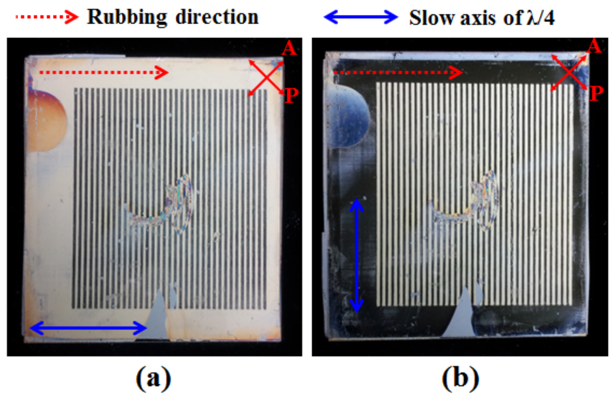

Fig. 5. Macroscopic images of the FPR with insertion of λ/4 films between crossed polarizers. When an angle between the slow axis of the λ/4 films and the rubbing direction is (a) 0° and (b) 90°, the dark and bright lines in the odd and even columns change to the bright and dark lines, respectively. Total area of the FPR is 3.8cm x 4cm and a defect in a center area is associated with handling mistakes during fabrication.

4. Summary

We proposed a novel cost-effective method for the fabrication of FPR without using a wire grid photo-mask but utilizing the ink-jet printing method and simple rubbing process. In addition, an alignment layer 9FDA/CBDA with orthogonal alignment characteristic was coated onto the PES film in line shape by ink-jet printer, and then rubbing was done in one direction. Then the coated RM aligns with its slow axis orthogonal to each other between neighboring domains having different alignment layers. Finally, UV light was exposed to the RM coated film and consequently the RM film where the slow axes of the neighboring domains were orthogonal to each other was obtained. The proposed FPR can be made with low cost and simple fabrication process, which has a strong potential to be applicable to 3D displays.

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