High performance low-cost polarizer using depolarization of a polarized light by reactive mesogen

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Abstract: Currently, the polyethlene terephthalate (PET) film challenges to substitute Tri-acetyl cellulouse (TAC) film which is a protection film in a polarizer layer, because of low cost of PET film. On the contrary, the PET film shows an optical problem such that color shift or interference optical pattern in oblique direction can occur because the film is made with the lamination process, which induces high phase retardation. In this paper, we propose a color shift free low cost polarizer by polymerization of random oriented reactive mesogen (RM) on the PET film. We calculate the viewing angle performance of the polarizer with the conventional PET film, with the TAC film and with the proposed PET film. As a result, we confirm that the proposed optical configuration can satisfy the optical performance equivalent to that of conventional TAC film uses in addition to the cost-down.

OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices.

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1. Introduction

In modern display devices, liquid crystal display (LCD) became one of the most important display devices. Performance of image quality of the LCD is rapidly improving by applying the advanced mode LC modes, instead of conventional twisted nematic (TN) [1, 2], such as in-plane switching (IPS) [3–5], fringe field switching (FFS) [6–8], polymer stabilized vertical alignment (PS-VA) [9–13], photo-aligned UV vertical alignment [14]. In addition, high speed LCD modes such as blue phase LCD [15–17], which provides several μs of response time, are also developing for three-dimensional display. Thus, industrial mature of the LCD device triggers improvement of the electro-optical property of the LCD by solving the various technical problems. On the other hands, cost-down of LCD is always demanded so that LCD industries are focusing on reducing the cost not only in manufacturing but also optical components such as glass, color filter, polarizer, optical compensation film and brightness enhancing films. Considering materials cost of LCDs, a polarizer is one of the most expensive optical components [18–20]. In general, the polarizer is made of polyvinyl alcohol (PVA) with stretching and dying process so that protection films are required at one side of the PVA film. The conventional protection film applies a tri-acetyle cellulous (TAC) because of optically zero retardation and reliability; however, it is highly expensive. In order to reduce the polarizer cost, a polyethylene terephthalate (PET) is being considered a substitutable material for protection film because of the low cost. However, the PET film can exhibit high retardation in process of stretching, so that this could make an optical performance such as color shift and narrow viewing angle deteriorate because light from backlight can be polarized due to use of the dual brightness enhancement film (DBEF) in the backlight module and also linearly polarized light coming from the top PVA film in LCD could make interference pattern in oblique viewing direction.

In this paper we propose an enhanced polarizer which applies the low cost PET protection film with polymerized reactive mesogen (RM) layer with its optic axis in random orientation. The RM layer in the proposed polarizer can make a light from backlight to be effectively depolarized, so that the deterioration of the optical viewing angle and the color shift of the LCD can be removed. The proposed polarizer exhibits low cost characteristic and high optical performance, simultaneously.

2. Color characteristics of the VA LCD with adoption of PET film

Figure 1 shows the optical configuration of the VA LC cell with polarizer using the TAC or PET films and its calculated optical viewing property evaluating luminance and color according to use of different polarizers. For calculations of optical property in the paper, a commercially available simulation tool "TechWiz LCD" (Sanayi-system, Korea) has been used. In the VA cell, the LC is vertically aligned in dark state and tilts downward in four

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different azimuthal angles to give a wide-viewing-angle in white state. In the device, two TAC or PET films for protection of PVA film are used, and two retardation films in one side of both PVA films to suppress light leakage of the VA LCD in oblique viewing directions were used, as shown in Fig. 1(a). In backlight unit, the DBEF film is used, which means that the light incident on the optical films is polarized. The optical parameters of the used layers are shown in Table 1. The used parameters R_o, R_{th}, N_z and P_y imply the retardation in normal direction, retardation factor for oblique direction, parameter of the refractive index and polarization ratio, respectively. These can be described as bellows,

$$R_0 = (n_x - n_y) \times d \tag{1}$$

$$R_{th} = \left\{ \frac{n_x + n_y}{2} - n_z \right\} \times d \tag{2}$$

$$N_Z = \frac{n_x - n_z}{n_x - n_y} = \frac{R_{th}}{R_0} + \frac{1}{2} \tag{3}$$

$$Py(\%) = \sqrt{\frac{T_{TD} - T_{MD}}{T_{TD} + T_{MD}}} \times 100 \tag{4}$$

where, n_x, n_y and n_z are the refractive index in x, y and z direction ($n_x > n_y > n_z$). T_{TD} and T_{MD} represent the transmittance of the parallel polarizers and the crossed polarizers in entire wavelength range, respectively.

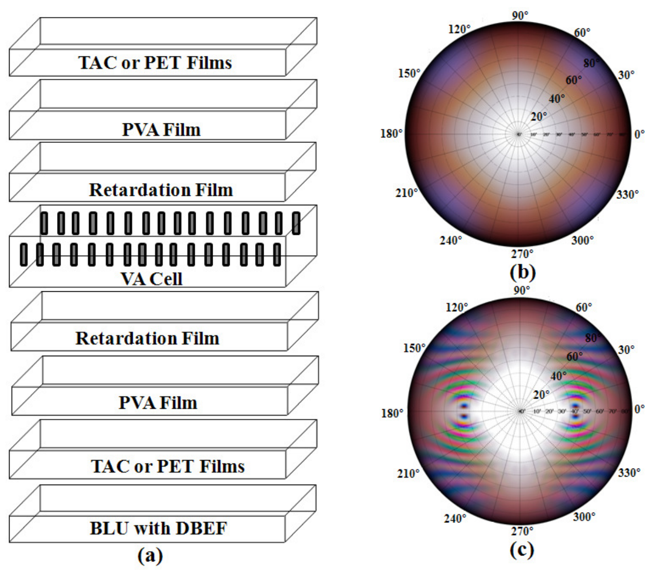

Fig. 1. Optical configuration of polarizer using the TAC or PET films (a) and calculated color contour with brightness of polarizer using the TAC (b) and PET (c) films, respectively.

As clearly indicated in Table 1, R_o and R_{th} of PET is much higher than those of the TAC film which may cause interference optical pattern at off-normal axis. In order to compare optical performance of two different films in the white state, iso-luminance and color contour is calculated as shown in Fig. 1(b) and (c) using a simulation tool "TechWiz LCD" (Sanayi-system, Korea). When the conventional TAC film is used, the white color with high luminance at normal direction changes to slightly brownish white color and bluish color with decreased luminance as the viewing-angle increases. On the other hand, when the TAC film is replaced by low cost PET film, a strong color fringe pattern with a symmetric distribution (we

#148556 - $15.00 USD Received 1 Jun 2011; revised 21 Jul 2011; accepted 22 Jul 2011; published 4 Aug 2011

call it color mura) along horizontal direction appears as the polar angle increases over 40°, as shown in Fig. 1(c). In general, the retardation films in the LCD cell as shown in Fig. 1(a) play role in blocking the deterioration of the viewing angle property especially in the off state. Therefore, the color mura in the figure is obviously due to the high retardation of the PET film and the polarized light of the backlight source.

Generation of the high retardation in the PET film can be occurred by laminating process for the large scale product. As shown in Table 1, the retardation value of the PET film almost reaches to 1.5 µm, which is almost 4 times larger than the retardation of the LC layer, so that the retardation value can be enough to make deterioration of the color property in oblique direction. Furthermore, light after propagating the DBEF from the backlight may have component of the polarized light. As a result, serious color mura in oblique direction has occurred.

Table 1. Optical property for each optical component in polarizer

Structure	Optical Property	Axis angle
PET Film (TAC Film)	R_0=1500nm, R_{th}=3750nm, Nz = 5 (R_0=0nm, R_{th}=30nm)	Slow axis 90° (-)
PVA Film	Py=99.997%	Absorption axis 90°
Retardation Film	R_0=50nm, R_{th}=125nm, Nz=3	Slow axis 90°
VA Cell	4 Domain Full White	-
Retardation Film	R_0=50nm, Nz=3	Slow axis 0°
PVA Film	Py=99.997%	Absorption axis 90°
PET Film (TAC Film)	R_0=1500nm, R_{th}=3750nm, Nz=5 (R_0=0nm, R_{th}=30nm)	Slow axis 0° (-)
BLU	With DBEF	Transmittance axis 0°

Figure 2 shows the comparison of photographs of the VA LC cell using the low-cost PET film and the TAC film. In normal direction, color mura is not shown at both sides of the LC cell for TAC and PET films, as shown in Fig. 2 (a). However, we could observe the color mura in the oblique incident direction (azimuthal angle ϕ = 0°, polar angle θ = 30°) at the PET film side. From the results, we could confirm the experimental result is well coincident with the calculated results in Fig. 1. This indicates that the PET film for polarizer protection is cost effective but can induce the serious color mura.

In the previous case, an incident light to the first film of the bottom polarizer was assumed to be polarized due to the DBEF film since its measured value of P_y is about 90%. When the incident light is polarized, and it propagates along the high retardation film, strong phase retardation between extraordinary and ordinary is induced, causing color mura. Therefore, we observed viewing angle property of the VA LC cell without using DBEF film in the backlight module, that is, an incident light is not polarized at all.

#148556 - $15.00 USD Received 1 Jun 2011; revised 21 Jul 2011; accepted 22 Jul 2011; published 4 Aug 2011

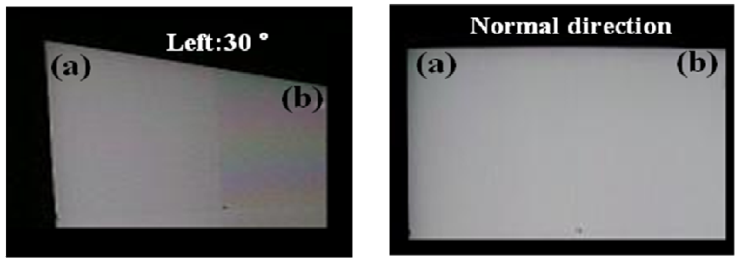

Fig. 2. Comparisons of the photographs of PVA LC cell applying the TAC film and PET film (a) in the normal direction, (b) in the oblique direction. (a) and (b) in the figure show the visible part in the LC cell for the TAC film and the PET film, respectively

Figure 3 (a) shows the optical configuration of the PVA LC cell without DBEF film and it is the same as before except for non-polarized incident light. In spite of the removal of the DBEF film, the calculated color mura is still shown in the oblique viewing direction, although the strength of the color mura decreased quite much, as shown in Fig. 3(b).

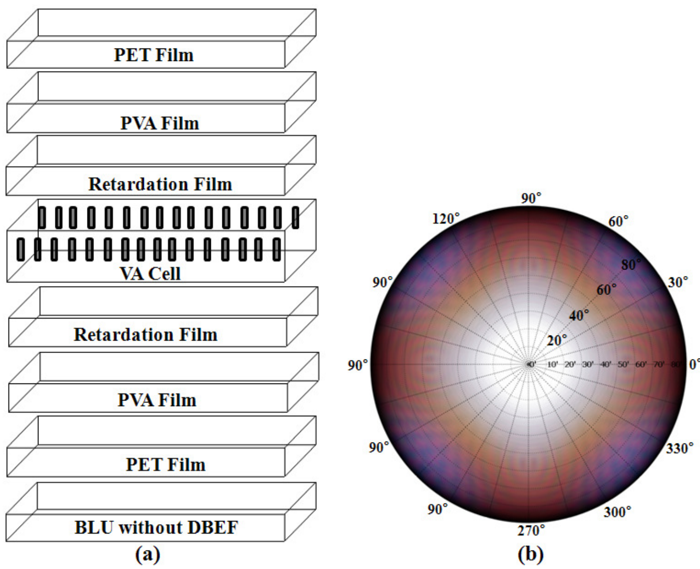

Fig. 3. Optical configuration (a) and calculated contour with brightness (b) of the low-cost polarizer in BLU without DBEF

The color mura at off normal axis in the VA LC cell without DBEF film can be induced from the difference of the transmission ratio for two light components, which are the transverse magnetic (TM) wave and the transverse electric (TE) wave, in oblique incidence. In the normal direction, which means transverse electric and magnetic (TEM) wave, the polarization of the incident light keeps random in all direction. However, the transmission ratio of the TM wave and the TE wave can be different from each incident polar and azimuthal angle, so that this can induce the polarization component of the light when to pass the PET film layer Transmission coefficients for TM and TE wave can be simply achieved by using Fresnel Eq. as below (5),

$$T_{te} = 1 - \frac{n_i \cos\theta_i - n_2\sqrt{1-(\frac{n_i}{n_2}\mathrm{Sin}\,\theta_i)^2}}{n_i \cos\theta_i + n_2\sqrt{1-(\frac{n_i}{n_2}\mathrm{Sin}\,\theta_i)^2}}\ ,\ T_{tm} = 1 - \frac{n_i\sqrt{1-(\frac{n_i}{n_2}\mathrm{Sin}\,\theta_i)^2} - n_2\cos\theta_i}{n_i\sqrt{1-(\frac{n_i}{n_2}\mathrm{Sin}\,\theta_i)^2} + n_2\cos\theta_i} \quad (5)$$

#148556 - $15.00 USD Received 1 Jun 2011; revised 21 Jul 2011; accepted 22 Jul 2011; published 4 Aug 2011

where, T_{te} and T_{tm} represent the transmission coefficients for TM and TE wave in oblique incidence, n_i and n_2 represent the refractive index of the air and the PET layer, respectively, and θ_i is the incident angle. In order to simplify the calculation, we handle the refractive index of the PET film as 1.5. From the Eq. (6), we can calculate the transmission coefficient ratio and calculate the polarization ratio of the light (DOP) which is defined as below,

$$DOP = \frac{\sqrt{S_1^{\,2} + S_2^{\,2} + S_3^{\,2}}}{S_0} \times 100 \qquad (6)$$

where, S_0, S_1, S_2 and S_3 are stoke's parameters and imply the total intensity of the light, horizontal/vertical linear polarized light component, 45°/-45° linearly polarized light component and circularly polarized light component, respectively. For example, DOP should be 0 for perfect unpolarized light.

Figure 4 shows the calculated DOP as a function of the incident angle. It is evident that the polarization ratio of the incident light to the LC cell can be increased as the incident angle becomes larger. This implies the color mura could be shown even if we remove the DBEF film in the backlight module.

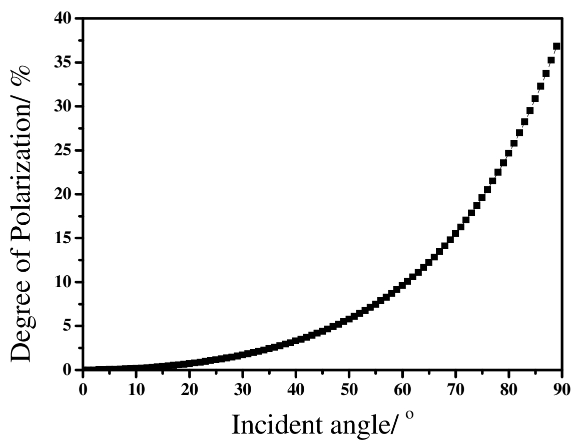

Fig. 4. Degree of polarization according to an incident angle

3. Application of an optical film with randomly oriented reactive mesogen (RM) to the PET layer for the depolarization of the incident light

In order to depolarize the light passing through the PET layer, we coated RM on the substrate without any surface treatment. In this way, the RM is randomly oriented and then UV is exposed to polymerize RM by chemical reaction between UV and RM. Finally, the randomly aligned RM layer makes polarization of the light to be locally random polarization state. For an experiment, the RMS03-013C (birefringence = 0.137 at 589 nm in polymer film) from Merck is used. The uncured RM film is dried at 55±5°C for 1 minute after spin-coating, and then UV (High-pressure HG lamp, UV-A) is exposed for 60 seconds with intensity 20±5mw/cm^2 in air atmosphere at room temperature. The thickness of cured RM film was 2.99μm so that its retardation value is about 0.4μm if the RM molecules are homogenously aligned.

To confirm orientation of RM molecules in film state, polarizing optical microscope (Nikon DXM1200) images of the cured RM film were taken in transmittance mode, as shown in Fig. 5. The film was rotated under crossed polarizers but the level of disclination lines were about the same irrespective of rotating angle of the film. As clearly indicated, randomly oriented disclination lines are observed, indicating that the optic axes of cured RM film are

#148556 - $15.00 USD Received 1 Jun 2011; revised 21 Jul 2011; accepted 22 Jul 2011; published 4 Aug 2011

locally oriented in random direction like in polycrystalline state in a crystal. As a result, incident polarized will obviously change its polarization state into random polarization state after passing through the cured RM film due to the random orientation of the RM directors. Finally, depolarized output light can be observed. In order to evaluate depolarization of the light by the RM film, we inserted the cured RM film under two crossed polarizers and measured transmittance while rotating the sample, as shown in Fig. 6. For comparison we also measured transmittance with insertion of a quarter-wave retardation film. The quarter-wave retardation film makes the linearly polarized light propagated from the input polarizer circularly polarized light for a single wavelength depending on the angle between its optic axis and transmission axe of crossed polarizers. Therefore, the transmittance of the cell varied as a function of the rotating angle of the quarter-wave retardation film. When the angle is 45° and 135°, the optical transmittance is maximum. On the other hand, we have observed almost no change of the optical transmittance when the cured RM film is rotated. This implies the polarization of the light passed through the RM layer can be depolarized.

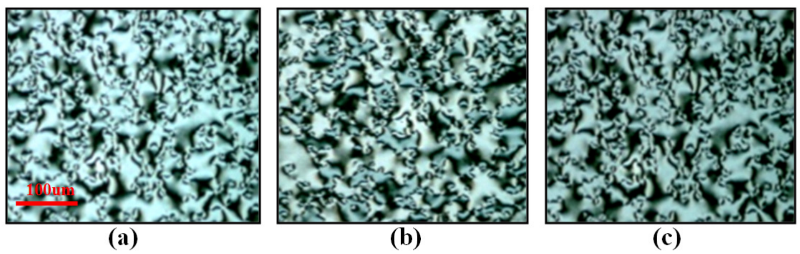

Fig. 5. POM microphotographs depending on rotation of the cured RM film between two crossed polarizers: 0° (a), 45° (b), and 90° (c).

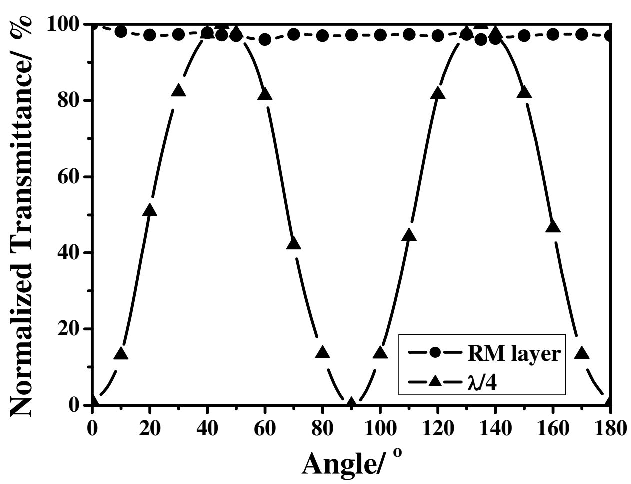

Fig. 6. Comparison of the optical transmittance of the light in accordance with angle of rotation of quarter-wave retarder (triangle) and the polymerized RM layer (circle) between two crossed polarizer.

Figure 7(a) shows the optical configuration applying the PET film for low-cost protection film with RM layer. In order to depolarize the incident light to the PET film, we coated the randomly aligned RM layer in front of the PET film. The RM layer can depolarize the polarization of the light due to the DBEF film and the DOP effect in oblique direction. The upper RM layer is also coated for depolarization of the light passing though the upper polarizer of the LC cell. Figure 7(b) shows the calculated optical viewing angle property. As

#148556 - $15.00 USD Received 1 Jun 2011; revised 21 Jul 2011; accepted 22 Jul 2011; published 4 Aug 2011

clearly indicated, the color mura is greatly reduced compared to that without RM layers in Fig. 1(c), indicating depolarization effects by applying the RM layer.

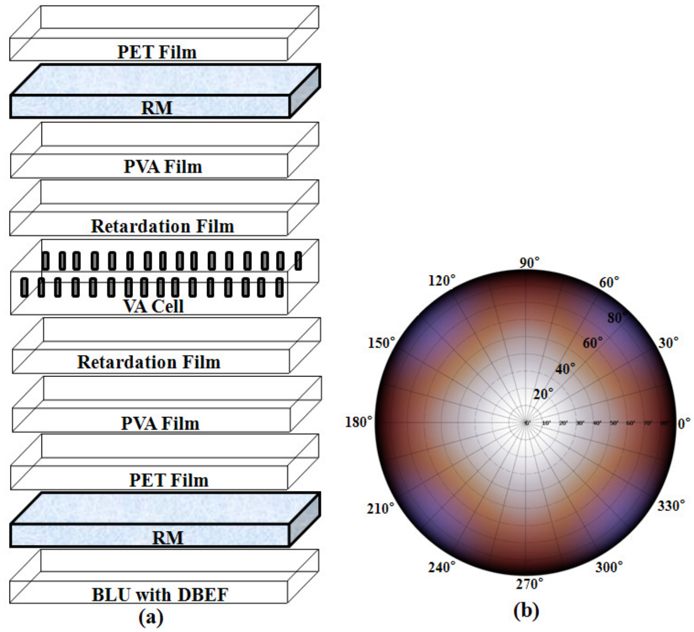

Fig. 7. Optical configuration (a) and color contour with brightness (b) of the low-cost polarizer using RM in BLU with DBEF

4. Summary

The application of the PET film as a protection layer of the polarizer is highly important because of the low-cost material. In spite of the requirement for the PET film, it has serious demerit such that very high retardation value is induced through lamination process, so that when it is applied to LCDs, serious color mura is occurred in oblique directions. In order to overcome such intrinsic problems, we propose an optical configuration which applies the randomly aligned RM layer to the PET film for removing the color mura in viewing angle property. By simply coating the RM layer to the PET film, we could achieve the excellent depolarization property in front of the PET layer. As a result, we could remove the color mura phenomenon even though we applied the PET film. We strongly believe that this proposal can effectively reduce the cost of the polarizer in the LC cell and can make LCD device more important in the display market.

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