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Obliquely Tilted Discotic Phase Compensation Films

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A three-step method was developed to fabricate the obliquely tilted discotic negative birefringence phase compensation films. Model fitting reveals that the tilt angle of the discotic directors is about 46° from surface normal. The total phase retardation value of the film can be controlled by the discotic layer thickness. These asymmetric phase retardation films are useful for widening the viewing angle of a liquid crystal display device.

KEYWORDS: oblique discotic film, liquid crystal display, wide view angle

1. Introduction

Phase compensation films have been used for widening viewing angle and/or reducing operation voltage of a liquid crystal display (LCD) device. For widening view angle, a negative birefringence film[1)] ($\Delta n < 0$) is used for compensating the light leakage caused by the LC layer ($\Delta n > 0$) at oblique angles. On the other hand, to lower operation voltage a positive birefringence film is used to cancel the residual phase retardation of a LC layer at a high voltage state.[2)]

Several different phase retardation film structures have been studied, namely A, C, O and biaxial plates. If Z-axis represents the film thickness direction, then an A-plate is a polymer film which is uniformly stretched in one axis, say X-axis. Both positive ($n_x > n_y = n_z$) and negative ($n_x < n_y = n_z$) birefringence A-plates could be made.[3)] If the film is stretched in the X and Z axes such that $n_x > n_z > n_y$, or in the X and Y axes such that $n_x > n_y > n_z$, then a biaxial film is formed. A biaxial film is useful for widening viewing angle and reducing operation voltage simultaneously.[4)] On the other hand, a C-plate is isotropic in the X-Y plane and could also have a negative ($n_x = n_y > n_z$) or positive ($n_x = n_y < n_z$) birefringence along the Z-axis.[5)] Two methods for preparing negative birefringence C-plate have been reported: spin-coating of a polymer solution[6,7)] and alternating depositions of thin SiO_2 and TiO_2 layers.[8)] Finally, an O-plate has its molecular axis uniformly tilted at an oblique angle.[9)]

Among these various films, discotic film exhibits a unique splayed structure, asymmetric angular-dependent phase retardation, negative birefringence and is particularly suitable for compensating the viewing angle of a twisted-nematic cell.[10)] To prepare such a discotic film, a substrate with thin rubbed polyimide (PI) was first prepared. Then, discotic monomers were spin coated or rolled over the PI surface. In the air-film interface, the discotic layer is splayed naturally at an angle ($\phi \sim$ 40–68°), as shown in Fig. 1(a). The molecular tilt angle continuously evolves within the film. Both negative A and C plates can be produced using different alignment layers.[11)] In this paper, we demonstrate a three-step process that results in a discotic O-plate wherein the LC directors tilt at an angle as shown in Fig. 1(b).

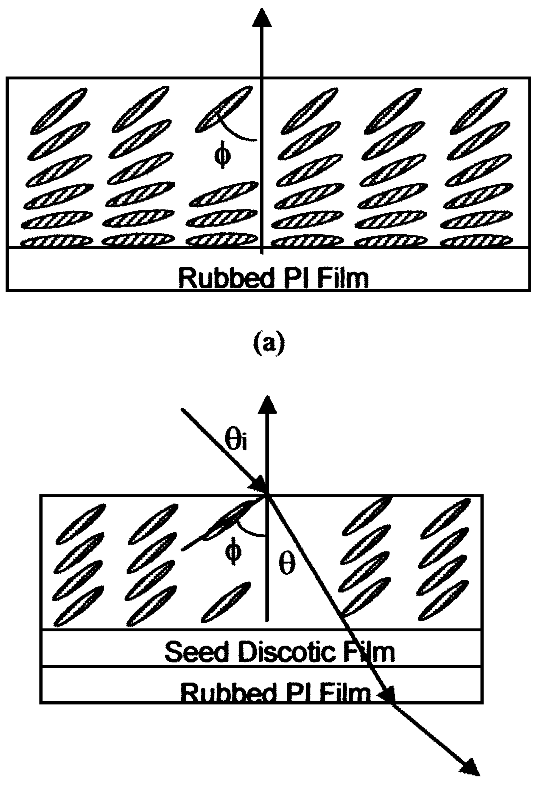
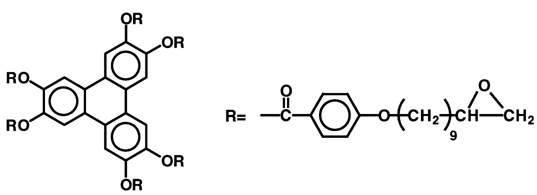


Fig. 1. Structural differences between a Fuji discotic film (a) and the discotic O-plate (b). In a Fuji film, the LC directors exhibit a splayed structure.

2. Experimental

The molecular structure of the discotic compound used in this study is shown below:



The triphenylene-based disk-shaped compound was first found to exhibit a nematic phase by a French group[12)] and later devised by a Fuji group[13)] as a phase compensation film for improving the viewing angle of a LCD. The thermal behavior of this discotic compound is described below. In the heating scan it exhibits a columnar to discotic nematic transition at 50.6°C and a discotic nematic to isotropic transition at 164.2°C. While in the cooling scan, it reveals an isotropic to discotic nematic at 162.3°C and a discotic nematic to columnar phase transition at 8.7°C.

The fabrication processes of our discotic O-plate are described as follows. First, a 150 nm thick polyimide film was spin-coated on a glass substrate. The film was baked at $T = 230$°C for two hours and then rubbed to generate 1.5° pretilt angle. Second, a thin (∼1 μm) discotic layer was coated over the polyimide film to generate a hybrid (splay) structure within the discotic film. The film was cured at $T = 114$°C and irradiated with UV light to form cross-linked structures. Third, more discotic layers were coated over this *seed* discotic layer to yield the desired phase retardation value. By contrast, the hybrid Fuji film only involves the first and third steps; the second step for generating *seed* discotic layer is not needed. In this study, in order to examine the layer to layer difference, we prepared the O-plate by spin coating. For practical application involving thick discotic layer, the roller coating method is more economic.

To compare the performance differences, we have also prepared a Fuji film using the same discotic monomer as we used for preparing our discotic O-plate. The recipes for preparing each discotic layer are summarized in Table I. The discotic monomer and photo-initiator (diphenyliodonium hexafluoroarsenate) were dissolved in methyl ethyl ketone (MEK). In Table I, rows 1 to 3 describe the recipes for making the seed discotic layer, subsequent discotic O-plate, and Fuji discotic film, respectively. The optical properties of the films were measured using an Otsuka Multi-channel System, RETS-2000 (Osaka, Japan).

3. Results and Discussions

Figure 2 shows the measured angular-dependent phase retardation (at $\lambda = 550$ nm) of the 1–5 layer discotic films we fabricated. The film thickness was measured to be 1.2, 1.8, 2.5, 3.3 and 4.0 μm, respectively. The phase retardation results from the rubbed polyimide film surface is so small ($d\Delta n \sim 2$–5 nm) that it can be ignored.[14] From Fig. 2, the desired phase retardation can be controlled by the film thickness. The angular dependence of the film is similar to that of a Fuji film.[10] Thus, this discotic O-plate is equally suitable for wide view LCD applications.

To reveal the difference between the discotic O-plate and the Fuji film, we normalize the measured phase retardation shown in Fig. 2 to the film thickness. Results are plotted in Fig. 3. Please note that this normalized phase retardation can only be called as effective birefringence and is not the intrinsic film birefringence due to the tilt angle involved. A detailed explanation will be given later.

From Fig. 3, the seed discotic layer (filled circles) has the smallest effective birefringence. It should be noted that the birefringence reported in Fig. 3 has negative value and, for simplicity, we only refer to its magnitude. As the number of discotic layer increases, the effective birefringence remains almost the same for the 2–5 layer films and this value is larger than that of the first (seed) layer. This indicates that the first discotic layer exhibits a splayed structure, as sketched in Fig. 1(a). Within the layer, the tilt angle gradually increases. The subsequent spin-coated layers basically follow the top layer orientation of the seed film. Thus, the measured effective birefringence increases and remains roughly the same as the film thickness is increased. We have also prepared some discotic O-plates using different seed layer thickness (varying from 0.13 to 1 μm), however, no significant difference was observed.

To determine the tilt angle of the discotic directors and intrinsic refractive indices of the discotic film, we have fabricated a 14 μm film (17 layers) using a 1.1 μm thick seed discotic layer. The angular-dependent phase retardation of the discotic O-plate was measured and results are plotted as open circles in Fig. 4. The solid lines in Fig. 4 represent fittings to

Table I. Recipes for preparing various discotic films.

Discotic Films	Discotic Compound	Photo Initiator	MEK (m*l*)
Seed Discotic layer	0.1 g	0.7 mg	4 m*l*
Discotic O-plate	0.1 g	0.7 mg	1 m*l*
Discotic Fuji film	0.2 g	1.4 mg	1 m*l*

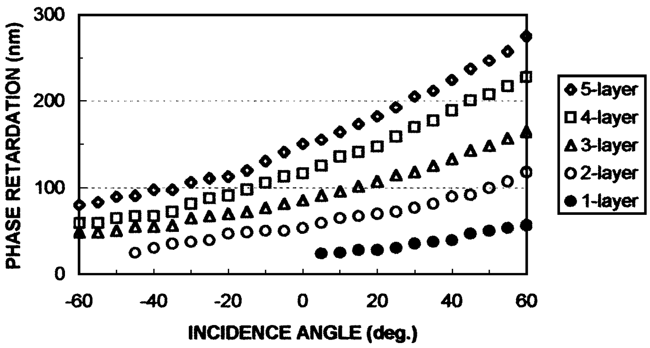


Fig. 2. Measured phase retardation of the 1–5 layer discotic film coated over a rubbed polyimide film. $\lambda = 550$ nm. The 1–5 layer film thickness is 1.2, 1.8, 2.5, 3.3 and 4.0 μm, respectively.

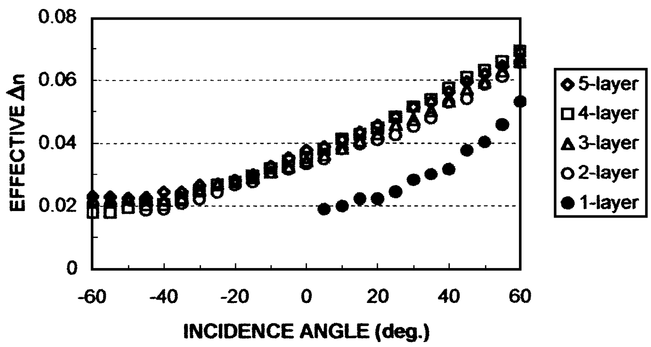


Fig. 3. Effective birefringence of the 1–5 layer discotic film coated over a rubbed polyimide film. $\lambda = 550$ nm. The first seed layer which has similar structure as a Fuji film has the smallest effective birefringence.

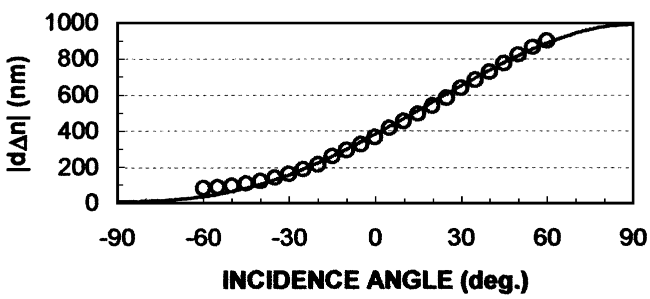


Fig. 4. Angular-dependent effective phase retardation $(d\Delta n)_{\text{eff}}$ of a 14-μm discotic O-plates at $\lambda = 550$ nm. Circles are measured data and solid lines represent fittings with eq. (1) using $n_e = 1.576$, $n_o = 1.522$ and $\phi \sim 46°$.

the theory modified from negative C-plate by taking a uniform molecular tilt into account:[14)]

$$(d\Delta n)_{\text{eff}} = \frac{d}{\cos\theta}\left[\frac{n_e n_o}{\sqrt{n_e^2\cos^2(\theta+\phi)+n_o^2\sin^2(\theta+\phi)}} - n_o\right] \quad (1)$$

In eq. (1), d is the film thickness at the normal angle, θ is the angle inside the film as shown in Fig. 1(b), ϕ is the tilt angle of the discotic O-plate, and n_e and n_o are the refractive indices for the extraordinary and ordinary rays, respectively. Also from Fig. 1(b), the angle θ can be calculated from the incidence angle θ_i in the air through the Snell's law:

$$n_{\text{air}}\sin\theta_i = n\sin\theta \quad (2)$$

Here, the average refractive index n is equal to $(n_e + 2n_o)/3$.

Three unknowns in eq. (1) are identified: n_e, n_o, and ϕ. They are treated as adjustable parameters while fitting with the experimental data. Results are shown as solid lines in Fig. 4. From fittings, we find $n_e = 1.576$, $n_o = 1.522$, and $\phi = 46°$. Such fitting is sensitive to the tilt angle ϕ and birefringence ($\Delta n = n_e - n_o$), but not too sensitive to the individual refractive indices as long as their difference is kept the same. The tilt angle determines the shape and birefringence determines the magnitude of the curve.

Phase matching is another important parameter for a compensation film. Ideally, the wavelength-dependent birefringence[15)] of a phase retardation film should be similar to that of the LC mixture employed. Under such circumstance, good phase compensation can be simultaneously satisfied for all the three primary colors and high device contrast ratio can be obtained. The wavelength-dependent birefringence of a 12-layer discotic O-plate was measured at normal incidence angle. To compare the phase matching property with LC mixtures, we normalize the measured birefringence value to that of $\lambda = 550$ nm and compare their trend. Results are plotted in Fig. 5. Also included in Fig. 5 are the ratios of $\Delta n/(\Delta n)_{\lambda=550\,\text{nm}}$ of two LC mixtures: ZLI-4792 (TFT mixture) and ZLI-5600-100 (STN mixture). The birefringence of ZLI-4792 and ZLI-5600-100 is 0.097 and 0.15, respectively. Mixture ZLI-4792 consists of mainly fluorinated cyclohexane-phenyl ring compound and ZLI-5600-100 is a biphenyl mixture. On the other hand, the discotic compound used in this study has molecular conjugation larger than that of ZLI-4792 and similar to that of ZLI-5600-100. Thus, its wavelength-dependent birefringence is somewhat stronger than that of ZLI-4792, but very similar to that of ZLI-5610-100.

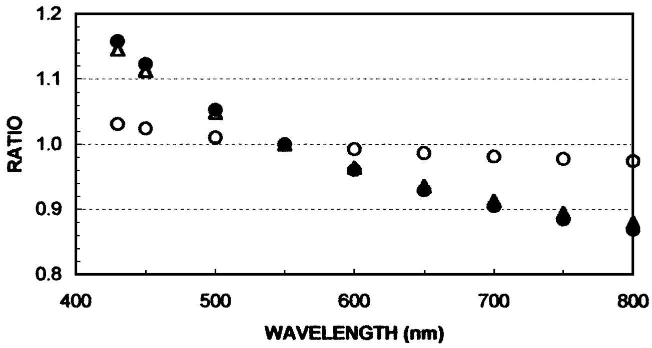


Fig. 5. The birefringence dispersion of a discotic O-plate (filled circles), ZLI-4792 (open circles) and ZLI-5600-100 (triangles) LC mixtures. To see the phase matching behavior, the measured birefringence values are normalized to that of $\lambda = 550$ nm.

4. Conclusion

An obliquely tilted discotic retardation film was developed. The tilt angle is predetermined by the seed discotic film which is spin-coated on the rubbed polyimide film. The new discotic O-plate can be used to compensate the inclined components of the liquid crystals in the display panel. The total phase retardation value can be controlled by the film thickness.

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