Ultraviolet-light-treated polyimide alignment layers for polarization-independent liquid crystal Fresnel lenses

S.-J. Hwang · T.-A. Chen · K.-R. Lin · S.-C. Jeng

Abstract The surface energy of a conventional homeotropic polyimide (PI) alignment layer was altered via ultraviolet (UV) light irradiation, and the pretilt angle of the PI was changed along with the surface energy. The surface energy can be controlled by either UV exposure time or irradiation intensity. A switchable liquid crystal Fresnel lens (LCFL) was created by the UV-treated alignment layers to form a Fresnel zone-distribution hybrid alignment, vertically aligned and hybrid aligned LC in the odd and even zones, respectively. The LCFL was made polarization-independent by circular buffing, and it had a diffraction efficiency of ~22% at a low driving voltage of ~1.2 V.

1 Introduction

Alignment of liquid crystal (LC) molecules is a mature technology used by the LC display (LCD) industry. In the conventional manufacturing process, polyimide (PI) alignment layers are mechanically buffed to provide a certain molecule orientation. Usually, the pretilt angle of an LCD is either near zero degrees or 90 degrees for homogeneous and homeotropic alignments, respectively. However, it was observed that the pretilt angle of an alignment layer can be controlled by UV irradiation [1–4]. UV irradiation on PI alignment films can induce extensive physical and chemical

S.-J. Hwang · T.-A. Chen · K.-R. Lin
Department of Electro-Optical Engineering & Optoelectronics
Research Center, National United University, Miaoli 360, Taiwan

T.-A. Chen · S.-C. Jeng (✉)
Institute of Imaging and Biomedical Photonics, National Chiao
Tung University, Tainan 711, Taiwan
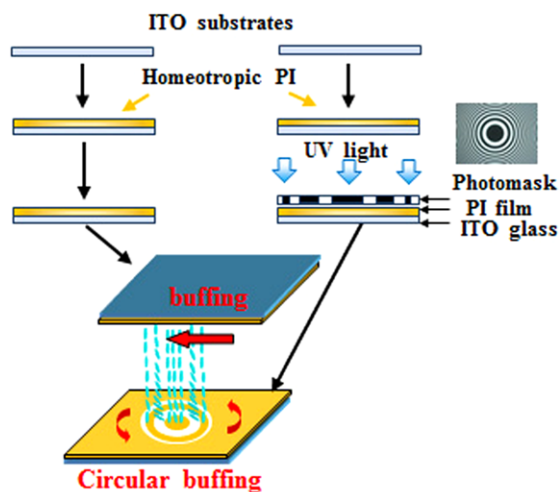e-mail: scjeng@faculty.nctu.edu.tw
Fax: +886-6-3032535

modifications of PI [3, 4]. Techniques of photo-alignment by polarized or nonpolarized UV had been intensively investigated in the 1990s and have recently matured to practical methods for producing large LCDs [1–10]. The photo alignment process also enables a pixel of LCD to be divided into several domains and improves the viewing angle [6]. Recently, Sharp has successfully implemented photo alignment processes for fabricating large size LCD-TV panels [10].

UV-treated PI films have also been recently applied to single-cell-gap transflective LCDs and LC Fresnel lens (LCFL) [11, 12]. The desired pretilt angle can be achieved by using UV irradiation to control the surface energy of a PI film. However, data on the influence of UV irradiation on the surface energy and anchoring strength of PI films is scarce. Application of an electric field on the LCFL induces a phase difference between the odd and even zones by rotating the LC molecules. Thus, the diffraction efficiency of an LCFL can be electrically controlled. We have demonstrated creation of an LCFL using UV-induced surface modification of PI films [12]. However, the operation of the LCFL depends strongly on the polarization direction of the incident light due to the unidirectional alignment of LCs. Several methods have been developed to obtain polarization-independent LCFLs [13–18], such as orthogonal alignment of LC molecules in neighboring zones. Although these approaches provide a polarization-independent LCFL, they have some drawbacks, such as requiring precise alignments and complicated electrode designs.

We have studied the influence of UV irradiation on conventional homeotropic PI films and demonstrated using UV-treated PI films with alternating hybrid aligned and vertically aligned LC zones to make a polarization-independent LCFL. The influence of UV irradiation on the surface energy and anchoring strength of PI films was studied. The LCFL was made polarization-independent by a circular buffing,

Fig. 1 The fabrication process of the proposed polarization-independent liquid crystal Fresnel lens

and a high diffraction efficiency of ∼22% was reached with a low driving voltage of ∼1.2 V.

2 Experimental

In order to determine the influence of UV irradiation on PI films, a conventional homeotropic PI (AL60101, JSR) was spin-coated onto ITO glass substrates to obtain a thin alignment film. Afterward, the PI was prebaked at 100°C for 10 minutes and post-baked at 200°C for 1 hour in order to cure the PI for forming the alignment film. This was followed by UV light irradiation with controllable intensity and exposure time. Then the surface of the PI film was mechanically buffed using a nylon cloth. The surface energy of the PI film was determined by measuring the contact angle of distilled water on the film according to the Girifalco–Good–Fowkes–Young model [19]. To determine the pretilt angle and the polar anchoring energy (PAE) of LC molecules on UV-treated PI alignment layers, anti-parallel LC test cells were fabricated with a cell gap of 6.7 μm and were capillary filled with positive dielectric anisotropic or negative dielectric anisotropic LC molecules (E7 and MLC 6882, Merck). Pretilt angles of the LC cells were measured by the modified crystal rotation method [20]. The PAE of the UV-treated alignment layers was measured by using the high-electric-field method [21].

Based on the UV-induced changes in the pretilt angle of the homeotropic PI films, a binary LCFL can be easily fabricated as shown in Fig. 1. An alternating pattern of hybrid aligned and vertically aligned LC cells was obtained by UV irradiation (intensity $I \sim 37$ mW/cm^2) of a homeotropic PI film through a photo mask with Fresnel zone patterns. Following UV irradiation, the homeotropic PI was modified to
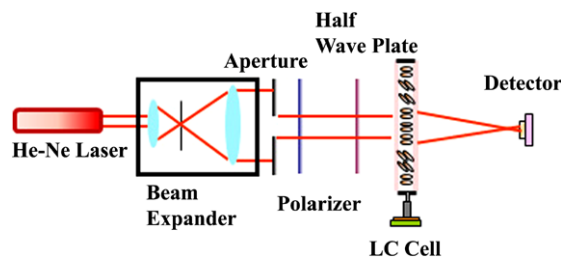
Fig. 2 The experimental setup for measuring the focus properties of the polarization-independent LC Fresnel lens

become horizontally aligned in the even zone areas. The design of the photo mask can be found in our previous work [12]. This photo mask was designed to have a primary focal length $f \sim 25$ cm at $\lambda = 632.8$ nm.

As shown in Fig. 1, a polarization-independent LCFL was fabricated by circular and horizontal buffing the UV-treated and the homeotropic PI films, respectively. Both buffed top and bottom substrates were then assembled into an LC cell with a cell gap of ∼10 μm maintained by spacers. The positive LC material was then injected into the empty cell.

To characterize the focus properties of the LCFL, the image quality and voltage-dependent diffraction efficiency were measured. As shown in Fig. 2, a He–Ne laser was magnified with a beam expander to approximately 1 cm in diameter corresponding to the active area of the LCFL. The polarization direction of the incident light with respect to the parallel buffing direction of the LCFL was controlled by a linear polarizer and a half wave plate. The focus properties of the LCFL can be measured by using a CCD camera or a photo detector set ∼25 cm from the LCFL.

3 Results and discussion

UV light-induced changes in the surface energy and pretilt angle of homeotropic PI films for different UV exposure times are shown in Fig. 3, and the surface energy as a function of UV intensity is shown in Fig. 4. The results indicate that UV irradiation of PI films can mediate and increase the surface energy of the PI films by increasing either UV exposure time or intensity. The pretilt angle of the buffed PI film is observed to continuously decrease with increasing surface energy as shown in Fig. 3. Hence, the pretilt angle of the buffed PI film can be controlled by exposure time and intensity of UV irradiation.
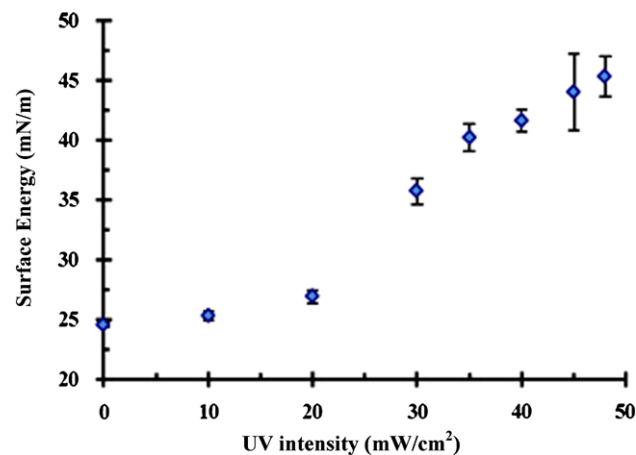
The influence of surface energy of an alignment layer on pretilt angle has been investigated [22–24]. We found that an alignment layer with more polar surfaces gives a lower pretilt angle due to the increased attractive strength between LC molecules and molecules of the alignment layer. One of the homeotropic PI films was continuously irradiated by UV

through the Fresnel zone mask till the pretilt angle reached nearly zero degree, a homogenous alignment. The effect of UV-modified pretilt angle of PI films was then utilized to create an LCFL with hybrid alignments.

The PAE of the UV-treated PI films for different exposure time of UV is shown in Fig. 5. The PAE increases from 1.3×10^{-4} J/m^2 to 4.0×10^{-4} J/m^2 as the exposure time of UV irradiation increases to 40 minutes. This indicates that the anchoring strength of UV-treated PI films is not degraded by UV irradiation. The increased PAE of the homogeneous PI film relative to the homeotropic PI film may be the result of
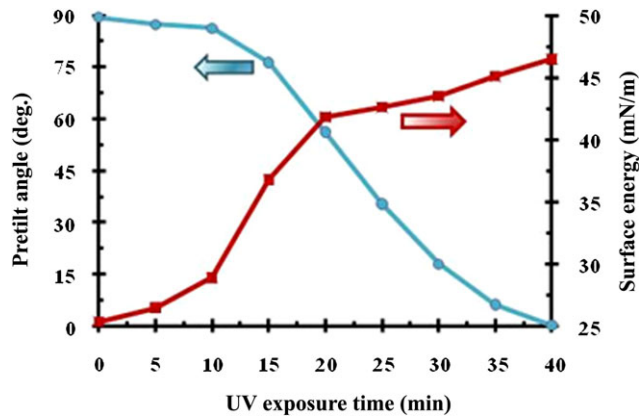
the increase in surface energy by UV irradiation. We believe that it deserves further study. This novel method of pretilt control by photo-alignment is applicable to fabrication of LCDs requiring a tunable pretilt angle with moderate PAE.

Polarized optical microscope photos of the polarization-independent LCFL operated at $V = 0$, 0.4, 0.7, and 7 V are shown in Fig. 6. At $V = 0$, the orientation of LC molecules on the odd and even zones are vertically and hybrid aligned, respectively. As the applied voltage increases, the color of even zones changes as shown in Figs. 6(b)–(d). The color changes in the even zones result from the voltage-induced phase retardation. When the applied voltage is above 7 V, all LC molecules are oriented nearly perpendicular to the substrates; the zone structures gradually disappear with increased voltage.

The results of the voltage-dependent first-order diffraction efficiency of a proposed polarization-independent LCFL and a polarization-dependent LCFL with linear polarization of the incident light at $\theta = 0°$, 45° and 90° with respect to the parallel buffing direction are shown in Figs. 7 and 8, respectively. The first-order diffraction efficiency is defined as the ratio of the first-order diffraction intensity at the primary focal point to the total transmitted intensity through the LCFL. The polarization-independent characteristics of the proposed LCFL are observed in Fig. 7. The maximum diffraction of ∼22% is obtained at ∼1.2 V. Two insets in Fig. 7 show a focus image and a defocus image at $V = 1.2$ V
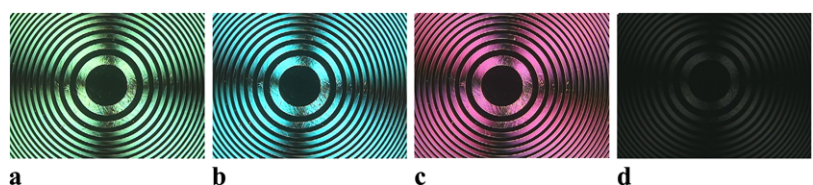

Fig. 3 Pretilt angle and surface energy of UV-treated PI films as functions of exposure time of UV irradiation, where the UV intensity was set at 37 mW/cm^2

Fig. 4 Surface energy of UV-treated PI films as a function of intensity of UV irradiation, where the exposure time of UV irradiation was set at 20 min
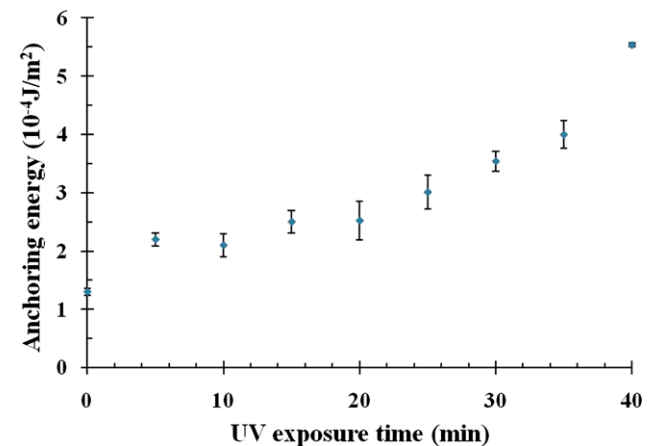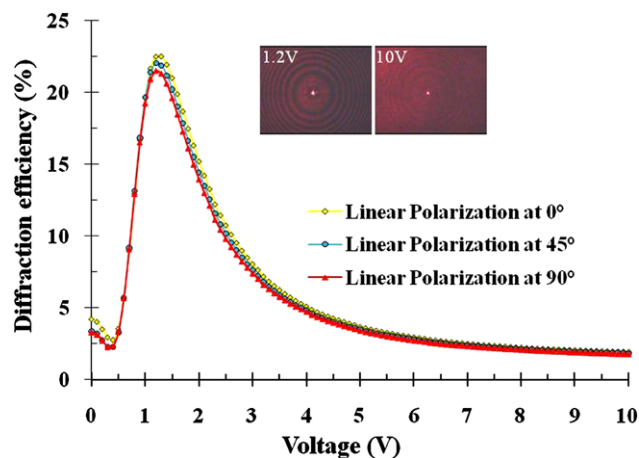

Fig. 5 Polar anchoring energy as a function of exposure time of UV irradiation, where the UV intensity was set at 37 mW/cm^2

Fig. 6 Photo images of the polarization-independent LC Fresnel lens cell observed by a polarized optical microscopy at (**a**) 0 V, (**b**) 0.7 V, (**c**) 1.0 V, and (**d**) 7.0 V, respectively

Fig. 7 The voltage-dependent diffraction efficiency of the polarization-independent LC Fresnel lens. Two insets of a focus image and a defocus image are shown at $V = 1.2$ V and $V = 10$ V, respectively
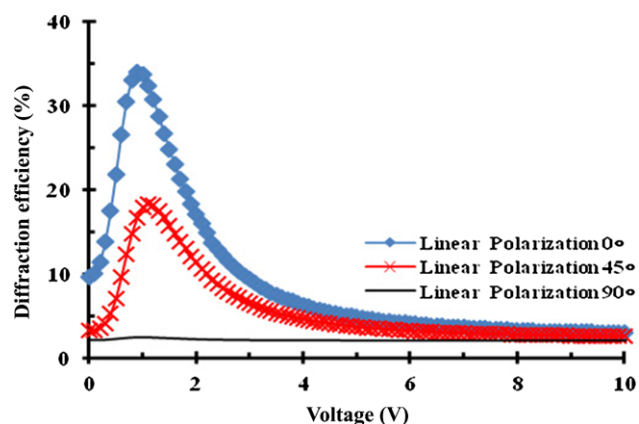
Fig. 8 The voltage-dependent diffraction efficiency of a polarization-dependent LC Fresnel lens

and $V = 10$ V, respectively. The diffraction efficiency of the first-order ($m = \pm 1$) diffracted beams is given by

$$\eta_m = \left[\frac{\sin\left(\frac{\frac{2\pi}{\lambda}(\Delta_{\text{even}} - \Delta_{\text{odd}})}{2}\right)^2}{\frac{m\pi}{2}} \right]$$

for a binary phase Fresnel lens, where Δ_{odd} and Δ_{even} are the optical paths through the odd and even zones of the LCFL, respectively [25]. When the phase difference of the LCFL between the odd and even zones, $\frac{2\pi}{\lambda}(\Delta_{\text{even}} - \Delta_{\text{odd}})$, is voltage-controlled to be π radians, the theoretical maximum value $\sim 41\%$ of first-order ($m = \pm 1$) diffraction efficiency can be obtained. The disclination of LC at the zone edges and the misalignment of circularly buffed processes at the center of the UV-treated PI film may cause the measured maximum diffraction efficiency ($\sim 22\%$) to be much lower than the theoretical value ($\sim 41\%$). In principle, several phase levels of Fresnel zone plate could be used to improve the diffraction efficiency [25]. For example, the theoretical diffraction efficiency can reach $\sim 95\%$ for an eight-level Fresnel lens. As shown in Figs. 3 and 4, the surface energy and pretilt angle of PI films can be controlled by UV exposure intensity. Therefore, many phase levels of LCFL could be fabricated by UV irradiation through a gray-tone mask, with regions of differing transparency to UV.

4 Conclusions

The influence of UV irradiation on the surface energy and the PAE of UV-treated PI films was investigated. The proposed techniques of UV-induced surface modification of the PI alignment film and circular buffing were applied to fabricate a polarization-independent LCFL with a diffraction efficiency of $\sim 22\%$ at a low driving voltage of 1.2 V.

References

1. J. Lu, S.V. Deshpande, E. Gulari, J. Kanickia, W.L. Warren, J. Appl. Phys. **80**, 5028 (1996)
2. H. Yoshida, Y. Koike, Jpn. J. Appl. Phys. **36**, L428 (1997)
3. K. Ichimura, Chem. Rev. **100**, 1847 (2000)
4. V.G. Chigrinov, V.M. Kozenkov, H.S. Kwok, *Photoalignment of Liquid Crystalline Materials: Physics and Applications* (Wiley, Chichester, 2008)
5. W.M. Gibbons, P.J. Shannon, S.-T. Sun, B.J. Swetlin, Nature **351**, 49 (1991)
6. M. Shadt, K. Schmitt, V. Hozinkov, V. Chigrinov, Jpn. J. Appl. Phys. **31**, 2155 (1992)
7. H. Yoshida, T. Seino, Y. Koike, Jpn. J. Appl. Phys. **36**, L1449 (1997)
8. M. O'Neill, S.M. Kelly, J. Phys. D, Appl. Phys. **33**, R67 (2000)
9. T. Mitsumoto, S. Oka, M. Kimura, T. Akahane, Jpn. J. Appl. Phys. **44**, 4062 (2005)
10. K. Miyachi, K. Kobayashi, Y.Y. Yamada, S. Mizushima, SID Int. Symp. Dig. Tech. Pap. **41**, 579 (2010)
11. Y.Y. Fan, H.C. Chiang, T.Y. Ho, Y.M. Chen, Y.C. Hung, I.J. Lin, C.R. Sheu, C.W. Wu, D.J. Chen, J.Y. Wang, B.C. Chang, Y.J. Wong, K.H. Liu, SID Int. Symp. Dig. Tech. Pap. **35**, 647 (2004)
12. S.-C. Jeng, S.-J. Hwang, J.-S. Horng, K.-R. Lin, Opt. Express **18**, 26325 (2010)
13. J.S. Patel, K. Rastani, Opt. Lett. **16**, 532 (1991)
14. H. Ren, Y.-H. Fan, S.T. Wu, Appl. Phys. Lett. **83**, 1515 (2003)
15. D.-W. Kim, C.-J. Yu, H.-R. Kim, S.-J. Kim, S.-D. Lee, Appl. Phys. Lett. **88**, 203505 (2006)
16. L.-C. Lin, H.-C. Jau, T.-H. Lin, A.Y.-G. Fuh, Opt. Express **15**, 2900 (2007)
17. K.-C. Lo, J.-D. Wang, C.-R. Lee, T.-S. Mo, Appl. Phys. Lett. **91**, 181104 (2007)
18. C.-H. Lin, H.-Y. Huang, J.-Y. Wang, IEEE Photonics Technol. Lett. **22**, 137 (2010)
19. http://www.firsttenangstroms.com/pdfdocs/SurfaceEnergy.pdf
20. Y.W. Li, J.Y.L. Ho, F.S.Y. Yeung, H.S. Kwok, J. Disp. Technol. **4**, 13 (2008)
21. Yu.A. Nastishin, R.D. Polak, S.V. Shiyanovskii, V.H. Bodnar, O.D. Lavrentovich, J. Appl. Phys. **86**, 4199 (1999)

22. S.H. Paek, C.J. Durning, K.W. Lee, A. Lien, J. Appl. Phys. **83**, 1270 (1998)

23. B.S. Ban, Y.B. Kim, J. Appl. Polym. Sci. **74**, 267 (1999)

24. H.Y. Wu, C.Y. Wang, C.J. Lin, R.P. Pan, S.S. Lin, C.D. Lee, C.S. Kou, J. Phys. D **42**, 155303 (2009)

25. J. Jahns, S.J. Walker, Appl. Opt. **29**, 931 (1990)