Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Journal of Crystal Growth 288 (2006) 192–194
JOURNAL OF CRYSTAL GROWTH
www.elsevier.com/locate/jcrysgro

A focus-switchable lens made of polymer–liquid crystal composite

Y.J. Liu, X.W. Sun*, Q. Wang

School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore

Available online 18 January 2006

Abstract

A focus-switchable liquid crystal (LC) lens made of polymer–LC composite was fabricated by a molding technique. The focus-switchable LC lens fabricated had a diameter of 6.0 mm and center thickness of 67 μm. The focal length obtained was about 48 cm. The lens showed good optical properties and strong polarization dependence. Its focus can be switched either by applying a low driving voltage (about 3 V) or by changing the polarization of the incident light. Such focus-switchable polymer–LC lens fabricated by this kind of technique is potentially useful in many optical systems, such as optical tweezers, machine vision, eye glasses.

PACS: 42.79.Kr; 42.79.Bh; 83.50.Uv

Keywords: A1. Effective focal length; A1. Molding; A1. Polarization; B3. Liquid crystal lens

1. Introduction

Interest in using liquid crystals (LCs) for adaptive systems has significantly increased in the last decade. With a large birefringence and a low control voltage, LC distinguishes from other materials. Much research on the use of LCs is focused on the switchable lenses, where the aim is to produce a LC lens with electrically controllable focal length. Various techniques have been used to fabricate LC lens. In general, they can be divided into two types according to their structures. One is to use the patterned electrodes. Several kinds of LC lenses with specially designed electrodes structures have been reported previously [1–8]. With these special electrodes, an inhomogeneous electric field is generated, and LC director will align along the field direction; thus, a tunable lens is formed. The other one is to use the gradient polymer. Although two flat electrodes are used, an inhomogeneous electric field under two flat electrodes is still generated because of the concave polymer structures. Ren et al. [9,10] reported a LC lens array with a gradient polymer. In this paper, a focus-switchable polymer–LC lens with the diameter of 6.0 mm and center thickness of about 67 μm is fabricated using the molding technique. Compared with the other LC lenses using similar technique, it showed strong polarization dependence and can be switched by applying a very low driving voltage. This focus-switchable polymer–LC lens is potentially useful in optical tweezers [11], machine vision, photonics, and tunable eye glasses [3,12–15].

2. Experimental procedure

The fabrication procedure is shown in Fig. 1. Firstly, some prepolymer is poured on an indium–tin-oxide (ITO) glass substrate. The prepolymer is molded with a plano-convex lens and then exposed to UV light. After exposure for 10 min with the intensity of 10 mW/cm^2, with sample heating, the plano-convex lens can be easily peeled off without damage to the polymer structure. A spherical concave pattern is then formed. A surface profiler was used to determine the center thickness. To get a homogeneous cell, another ITO glass substrate with an alignment layer is covered on this structure with UV glue. So a cell with a concave pattern is formed. The LC is injected into the cell in vacuum at a temperature of 65 °C (above the clearing point of LC) and then cooled down gradually to room temperature. Finally, a homogenously aligned polymer–LC lens is fabricated.

*Corresponding author. Tel.: +65 6790 5369; fax: +65 6793 3318.
E-mail address: exwsun@ntu.edu.sg (X.W. Sun).

0022-0248/$ - see front matter
doi:10.1016/j.jcrysgro.2005.12.025

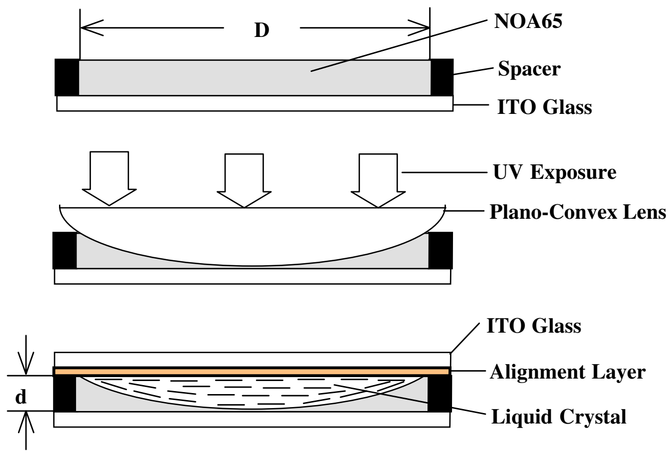

Fig. 1. The fabrication procedure of focus-switchable polymer–LC lenses, D is the diameter of spherical lens, and d is the center thickness of lens.

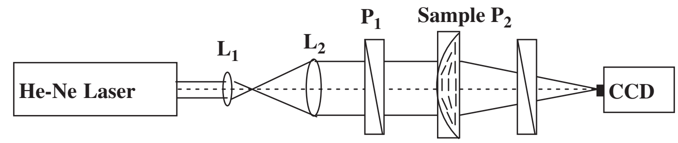

Fig. 2. Experimental setup to characterize the optical properties of the spherical lens. L_1 and L_2 are lenses to collimate the light beam. P_1 and P_2 are linear polarizers to control the polarization of light. A CCD is placed on the focus of the spherical polymer–LC lens to detect the facula.

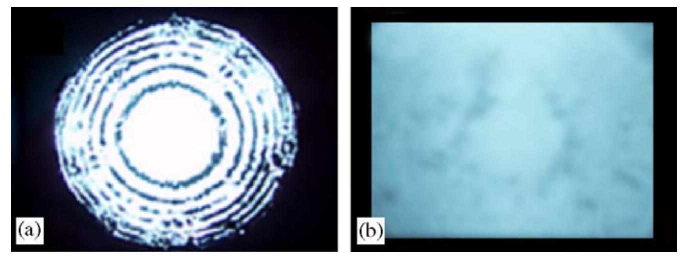

Fig. 3. The magnified interferogram pattern with no voltage applied. (a) and (b) show the magnified images obtained by CCD with no voltage applied when the rubbing direction of LC lens was orientated at 45° with respect to the fast axis of the linear polarizers and the rubbing direction was parallel to the polarizer's fast axis, respectively.

The prepolymer used is norland optical adhesive 65 (NOA65) from Edmund Optics. It is a UV-curable photopolymer and its refractive index, n_p, is 1.524. The LC used is E70 from Merck, with the ordinary refractive index, n_o, of 1.5269 and the extraordinary refractive index, n_e, of 1.7142. The material for the alignment layer used is polyimide and the pretilt angle is about 3–5°. In our configuration, the n_o of LC chosen should be as close as possible to the n_p of NOA65. This index matching plays an important role in switching the focusing of the lens. If an incident light is normal to the cell with no voltage applied, it will see the mean refractive index (or the effective refractive index), $\langle n \rangle$, of LC. When a sufficient voltage is applied on the cell, the LC molecules will completely reorientate along the direction of the electric field, and the light will see the ordinary refractive index, n_o, of LC. If the condition $n_o = n_p$ is met, the cell will become a uniform medium and the lens effect will disappear. In our experiments, a focus-switchable polymer–LC lens with the diameter of 6.0 mm and center thickness of about 67 μm is fabricated using the materials listed above.

3. Results and discussion

To characterize the optical properties of the spherical lens, the experimental setup used is shown in Fig. 2. A light beam from a He–Ne laser ($\lambda = 632.8$ nm) is collimated and then illuminates the LC lens, which is placed between two crossed linear polarizers. A CCD camera is placed in the optical path to determine the effective focal length and light intensity distribution of the focus. To measure the effective focal length, a CCD camera is placed near the focal point, and then the LC lens is moved until a sharp focal point is obtained. Then the distance between the sample and the CCD camera is equal to the effective focal length.

To inspect the optical quality of the LC lens, the gradient refractive index was investigated by observing the interference fringes between the ordinary and extraordinary light. Fig. 3(a) shows the magnified interference fringes with no voltage applied. The rubbing direction of LC lens was orientated at 45° with respect the fast axis of the linear polarizers. It can be seen from Fig. 3(a) that a series of concentrically annular rings were observed. When the LC cell was rotated to make the rubbing direction parallel to the polarizer's fast axis, the interference fringes disappeared, as shown in Fig. 3(b). This indicates the LC cell was homogeneous.

The voltage-dependent focal length of the LC lens was also investigated. At $V = 0$, the LC molecules are aligned along the surface of the spherical cavity and exhibits the largest refractive index gradient profile. So the focal length is the shortest. In our experiments, the focal length of the lens is about 48 mm. As reported before [10], the focal length is determined by the radius, r, of the lens, the LC cell gap, d, and the refractive index difference, δn, between the lens center and the polymer as $f = r^2/2d\delta n$. In our experiment, $r = 3$ mm, $d = 67$ μm, and $\delta n = 0.19$, and the corresponding focal length was about 35 cm. This calculation was in good agreement with the experimental result. For LC lens, after the threshold voltage, the focal length increases with the increase of the voltage applied. In our experiments, the focal length tunability was so small that it could be ignored compared to its original focal length. At about applied voltage of 3 V, the light beam became collimated and could be focalized again after removing the applied voltage.

Fig. 4 shows the facula versus different voltages at the place of the focal point. It can be seen that, with the increase of applied voltage, both the intensity of the facula and the bright region decrease. Fig. 5 shows the intensity

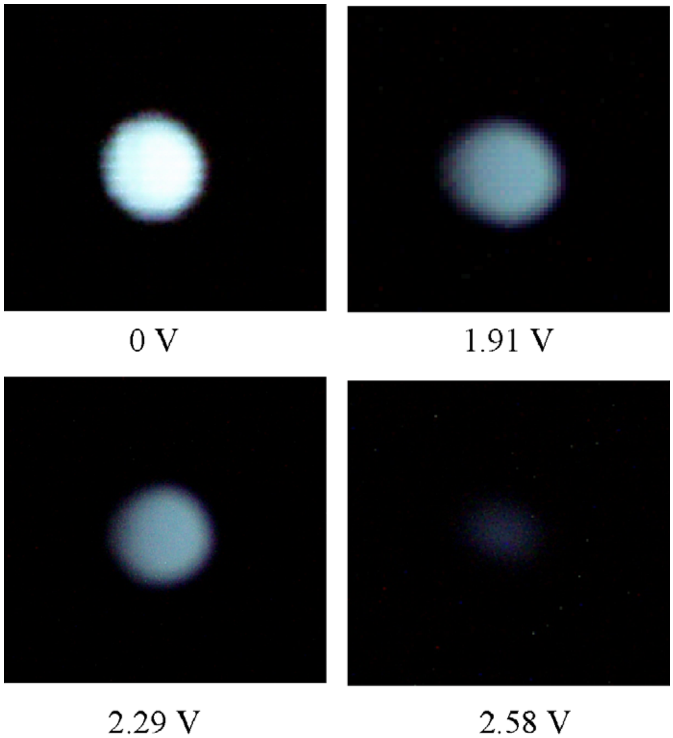

Fig. 4. The facula intensity at the focal point vs. different voltages applied. The applied voltages are 0, 1.91, 2.29, and 2.58 V_{rms}, respectively.

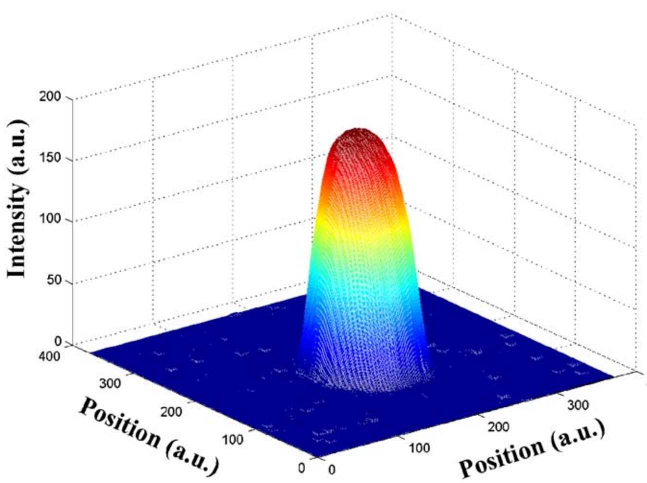

Fig. 5. The three-dimensional intensity distribution of the focal point.

distribution of the facula with no voltage applied on the cell, which indicates that the intensity distribution is approximately a Gaussian distribution.

Compared with many other LC lenses fabrication techniques, our fabrication technique has two big advantages. One is easy and simple fabrication processing. Any size from micrometer to centimeter can be fabricated by this technique. The other one is there is no need to fabricate specific structure electrodes. The electrodes on both substrates are flat.

A disadvantage for this kind of lens using the molding technique is that the scattering loss is relatively large. The scattering loss mainly comes from the irregular alignment of LC molecules and the irregular morphology of the interface between the polymer and LC. We believe the scattering loss can be effectively improved by careful control in the fabrication process.

4. Conclusion

In conclusion, we fabricated a focus-switchable polymer–LC lens. Its focus can be switched by either applying a low driving voltage or changing the polarization of the incident light. When the polarization direction of the incident light was along the rubbing direction of LC cell, the focusing is turned on. In contrast, when the polarization direction of the incident light is perpendicular to the rubbing direction of the cell, the focusing is turned off. The special optical properties of this kind of LC lens are potentially useful for optical tweezers, machine vision, eye glasses, etc.

References

[1] S. Sato, Jpn. J. Appl. Phys. 18 (1979) 1679.
[2] T. Nose, S. Sato, Liquid Crystals 5 (1989) 1425.
[3] A.F. Naumov, M.Yu. Loktev, I.R. Guralnik, G. Vdovin, Opt. Lett. 23 (1998) 992.
[4] L.G. Commander, S.E. Day, D.R. Selviah, Opt. Commun. 177 (2000) 157.
[5] M. Ye, S. Sato, Jpn. J. Appl. Phys. 41 (2002) L571.
[6] B. Wang, M. Ye, M. Honma, T. Nose, S. Sato, Jpn. J. Appl. Phys. 41 (2002) L1232.
[7] M. Ye, S. Sato, Opt. Commun. 225 (2003) 277.
[8] M. Ye, S. Hayasaka, S. Sato, Jpn. J. Appl. Phys. 43 (2004) 6108.
[9] H. Ren, Y.-H. Fan, S. Gauza, S.-T. Wu, Appl. Phys. Lett. 84 (2004) 4789.
[10] H. Ren, Y.-H. Fan, S.-T. Wu, Opt. Lett. 29 (2004) 1608.
[11] A. Ashkin, J.M. Dziedzic, J.E. Bjorkholm, S. Chu, Opt. Lett. 11 (1986) 288.
[12] S.T. Kowel, D.S. Cleverly, P.G. Kornreich, Appl. Opt. 23 (1984) 278.
[13] J.S. Patel, K. Rastani, Opt. Lett. 16 (1991) 532.
[14] T. Nose, S. Masuda, S. Sato, Jpn. J. Appl. Phys. 31 (1992) 1643.
[15] N.A. Riza, M.C. DeJule, Opt. Lett. 19 (1994) 1013.