A negative–positive tunable liquid-crystal microlens array by printing

H. T. Dai,[1] Y. J. Liu,[2] X. W. Sun,[1*] and D. Luo[1]

[1]*School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 639798, Singapore*
[2]*Department of Engineering Science and Mechanics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA*
**Corresponding author: exwsun@ntu.edu.sg*

Abstract: A tunable microlens array by printing was demonstrated. An UV-curable adhesive, NOA65, was printed and cured to form a lens array profile on an ITO glass. Then this microlens array ITO glass was assembled with a normal ITO glass to form a cell, which was later filled with a liquid crystal. The focal length of the lens array can be tuned by an electric field, which changes the index difference between liquid crystals and NOA65 due to the reorientation of the LC molecules. In our experiment, the focal length varied from -2.29 cm to 3.12 cm when the applied voltage was increased from 0 V to 13.26 V.

OCIS codes: (130.3750) Micro-optical devices; (230.3720) Liquid-crystal devices; (230.2090) Electro-optical devices; (220.3630) Lenses.

References and links

1. E. C. Tam, "Smart electro-optical zoom lens," Opt. Lett. **17**, 369-371 (1992).
2. J. Eschler, S. Dickmann, D. A. Mlynski, and H. Molsen, "Fast adaptive lens based on deformed helix ferroelectric liquid crystal," Ferroelectrics **181**, 21-28 (1996).
3. N. Sugiura and S. Morita, "Variable-focus liquid-filled optical lens," Appl. Opt. **32**, 4181-4186 (1993).
4. J. Arai, H. Kawai, and F. Okano, "Microlens arrays for integral imaging system," Appl. Opt. **45**, 9066-9078 (2006).
5. M. B. Chang, "Total internal reflection lens," Appl. Opt. **24**, 1256-1259 (1985).
6. T. Shibaguchi and H. Funato, "Lead-lanthanum zirconate-titanate (PLZT) electrooptic variable focal-length lens with stripe electrodes," Jpn. J. Appl. Phys. **31**, 3196-3200 (1992).
7. I. C. Khoo and S. -T. Wu, *Optics and Nonlinear Optics of Liquid Crystals* (World Scientific Publishing, Singapore, 1993).
8. S. Sato, "Liquid crystal lens-cell with variable focal length," Jpn. J. Appl. Phys. **18**, 1679-1684 (1979).
9. T. Nose, S. Masuda, and S. Sato, "Optical properties of a liquid crystal microlens with a symmetric electrode structure," Jpn. J. Appl. Phys. **30**, L2110-L2112 (1991).
10. S. T. Kowel, D. S. Cleverly, and P. G. Kornreich, "Focusing by electrical modulation of refraction in a liquid crystal cell," Appl. Opt. **23**, 278-289 (1984).
11. N. A. Riza and M. C. Dejule, "Three-terminal adaptive liquid-crystal lens device," Opt. Lett. **19**, 1013-1015 (1994).
12. A. F. Naumov, M. Y. Loktev, I. R. Guralnik, and G. Vdovin, "Liquid-crystal adaptive lenses with modal control," Opt. Lett. **23**, 992-994 (1998).
13. T. Takahashi, Y. Mao, and S. Sato, "Wavefront Aberrations of a Liquid Crystal Lens with Focal Length Variable from Negative to Positive Values," Jpn. J. Appl. Phys. **46**, 2926-2931 (2007).
14. Y. Mao, B. Wang, and S. Sato, "Liquid-crystal lens with a focal length that is variable in a wide range," Appl. Opt. **43**, 6407-6412 (2004).
15. L. G. Commander, S. E. Day, and D. R. Selviah, "Variable focal length microlenses," Opt. Commun. **177**, 157-170 (2000).

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009

16. Y. Choi, H.-R. Kim, K.-H. Lee, Y.-M. Lee, and J.-H. Kim, "A liquid crystalline polymer microlens array with tunable focal intensity by the polarization control of a liquid crystal layer," Appl. Phys. Lett. **91**, 221113 (2007).
17. H. W. Ren, Y. -H. Lin, and S. -T. Wu, "Adaptive lens using liquid crystal concentration redistribution," Appl. Phys. Lett. **88**, 191116 (2006).
18. Y. J. Liu, X. W. Sun, and Q. Wang, "A focus-switchable lens made of polymer-liquid crystal composite," J. Cryst. Growth **288**, 192-194 (2006).
19. Y. Choi, J. -H. Park, J. -H. Kim, and S. -D. Lee, "Fabrication of a focal length variable microlens array based on a nematic liquid crystal", Opt. Mater. **21**, 643-646 (2003).
20. C. R. Forest, M. A. Saez, and I. W. Hunter, "Microforging technique for rapid, low-cost fabrication of lens array molds," Appl. Opt. **46**, 8868-8873 (2007).
21. H. W. Ren, Y. -H. Fan, and S. -T. Wu, "Liquid-crystal microlens arrays using patterned polymer networks," Opt. Lett. **29**, 1608-1610 (2004).
22. H. W Ren and S.-T. Wu, "Tunable electronic lens using a gradient polymer network liquid crystal," Appl. Phys. Lett. **82**, 22-24 (2003).
23. V. V. Presnyakov and T. V. Galstian, "Electrically tunable polymer stabilized liquid-crystal lens," J. Appl. Phys. **97**, 103101 (2005).
24. Y. J. Liu, X. W. Sun, P. Shum, and X. J. Yin, "Tunable fly's-eye lens made of patterned polymer-dispersed liquid crystal," Opt. Express **14**, 5634-5640 (2006).
25. X. Wang, T. H. Dai, and K. S. Xu, "Tunable reflective lens array based on liquid crystal on silicon," Opt. Express **13**, 352-357 (2005).
26. H. W. Ren and S. -T. Wu, "Tunable-focus liquid microlens array using dielectrophoretic effect," Opt. Express **16**, 2646 -2652(2008).
27. S. Grilli, L. Miccio, V. Vespini, A. Finizio, S. De Nicola, and P. Ferraro, "Liquid micro-lens array activated by selective electrowetting on lithium niobate substrates," Opt. Express **16**, 8084-8093 (2008).
28. Y. L. Li, T. H. Li, G. H. Jiao, B. W. Hu, J. M. Huo, and L. L. Wu, "Research on micro-optical lenses fabrication technology," Optik **118**, 395-401 (2007).

1. Introduction

Tunable microlens arrays are used extensively as an important element in many optical systems, for example, optical interconnections, adaptive optics, high-density data storage, and integral imaging systems for three dimensional displays [1-4]. Many approaches to realize tunable lens have been introduced, such as total internal reflection lens [5], lead-lanthanum zirconate-titanate tunable lens with patterned electrodes [6], and liquid filled elastic lens [3]. Liquid crystal (LC) with an electrically tunable refraction [7] has been applied extensively [8-13]. Many different methods to fabricate LC and LC-polymer composite based tunable lens arrays have been reported previously [14-17]. Generally, they can be divided into two types according to their structures. One type is based on patterned electrodes to generate a special distribution of electric field, which is then used to align LC molecules, forming an index profile as a lens. The other type is based on the patterned relief surface structure using polymer or photoresist [18, 19]. Photolithography is commonly used to form either the electrode pattern or the surface relief structure. In addition, microforging technique can be used to form surface structures as well [20]. Tunable microlens arrays have also been realized by polymer-dispersed liquid crystals (PDLCs), polymer network liquid crystals (PNLCs) [21-24], and liquid crystal spatial light modulator [25]. Very recently, making use of dielectrophoretic [26] and eletrowetting [27], adaptive liquid microlenses made of isotropic media have also been developed. Compared to LC adaptive microlens based on effective index difference, those tunable microlenses based on changing the shape of liquid isotropic media have the advantages of large focal length tunability and broad spectral bandwidth. However, the power consumption is relatively higher [26, 27].

Recently, Li *et al.* [28] showed a method to fabricate microlens using ink-jet printing. This method provides a simple approach to fabricate microlens array. In this letter, we introduce a similar method to fabricate a negative-positive tunable LC-polymer microlens array based on

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009

printing, whose focusing property can be easily changed by either an applied voltage or the polarization direction of the incident light. In our experiment, the UV-curable adhesive was dispersed on the indium-tin-oxide (ITO) glass using a computer controlled dispersing machine. By varying the air pressure, temperature, or dispersing time, the radius and height of the microlens can be adjusted. Assembled with another piece of ITO glass, an empty microlens array cell was formed. After filling a proper LC into this cell (refractive index of polymer is between the ordinary and refractive indices of LC), microlens array with focal length tunable from negative to positive can be realized.

2. Fabrication and operation

Figure 1 shows the schematic diagram of the fabrication of the polymer microlens array and the operated mechanism of negative-positive tunable LC-polymer microlens array. A dispersing machine (Musashi-Shot mini 2005) was used to drop a controlled volume of pre-polymer on the surface of the ITO glass. Due to the surface tension at liquid-glass and liquid-air interfaces, the shape of the pre-polymer droplet shows a plano-convex-lens-like profile which was then immobilized by UV curing. The exposure intensity and time were 10 mW/cm^2 and 10 minutes, respectively.

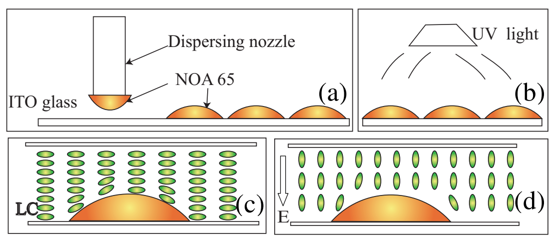

Fig. 1. Schematic diagram of the microlens array fabrication processes by printing (a), (b), and operation mechanism of the tunable LC microlens under an electric field (c), (d).

The pre-polymer used was Norland optical adhesive 65 (NOA 65) from Edmund Optics. It is a UV-curable photopolymer with a refractive index of 1.524 after cure. In our experiment, an 8×8 microlens array was prepared at room temperature, the diameter of the nozzle used was 120 μm, the distance between the nozzle and ITO glass was 60 μm and the air pressure applied was 0.05 MPa. To fabricate the LC-based tunable microlens array, the surface of ITO glass was coated with a polyimide layer rubbed for the LC alignment before dispersing NOA 65. After dispersing and curing of NOA 65 microlens array, this microlens ITO glass was assembled with a normal ITO glass (with rubbed polyimide layer) to form an empty LC cell. Their rubbing directions were parallel to each other. The thickness of the cell was about 51.4 μm. Then a selected LC material was filled into this cell. The LC used was MLC15700-000 from Merck, with ordinary index n_o and extraordinary index n_e of 1.489 and 1.609 at room temperature, respectively.

3. Characterization

The focal length was an important parameter to characterize the property of the microlens array, which can be measured using the experimental setup, as shown in Fig. 2. The Gaussian input laser beam (at λ=543 nm) is expanded, spatially filtered and collimated before it impinged on the microlens array. As shown in Fig. 2(a), a CCD camera is placed after the objective lens to record the intensity distribution. The distance between CCD and objective lens was fixed, while the position of the microlens array can be adjusted. We moved the microlens array backward or forward until the image of foci was clear so as to determine the focal length of the microlens array. This setup is suitable for all kinds of focal length

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009

measurement in our experiment, such as bare NOA 65 microlens array, LC tunable microlens array with various applied voltage and polarized incident light.

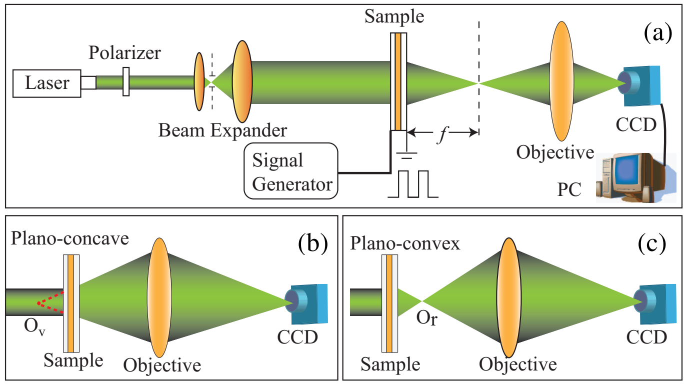

Fig. 2. Experimental setup to measure the focusing property (a), and schematic diagram of negative (b) and positive (c) focusing, O_v and O_r is the virtual and real focus respectively.

The focal length of the bare NOA 65 microlens array was measured using setup shown in the Fig. 2(a) with no applied voltage. The measured value was 2.925 mm. The focal length could also be calculated by the expression between the focal length and the structure parameters as below:

$$f = \frac{h^2 + r^2}{2h(n_p - n)} \tag{1}$$

where f, r, h, n_p, and n are the focal length, radius, height, index of the microlens and index of immersing materials (air here), respectively. In our experiment, the averaged height of NOA 65 microlens array after UV light cure was 23.291 µm measured by a surface profiler (Tencor P-10), the calculated focal length was 3.09 mm, which is in good agreement with the experimental result (2.295 mm). Figure 3(a) shows the microscopic image of the microlens array without LC. The designed diameter of each individual microlens is 550 µm, and the gap between adjacent micro-lenses is about 95 µm. Because of the low viscosity of NOA 65, the diameter of microlens printed is generally slightly larger. Once the microlens array was ready, its imaging performance was checked using an optical microscope (Olympus X71). Figure 3(b) shows a clear image pattern by the microlens array with a transparent plastic plate printed with character 'T' inserted into the light arm of the microscope as an object.

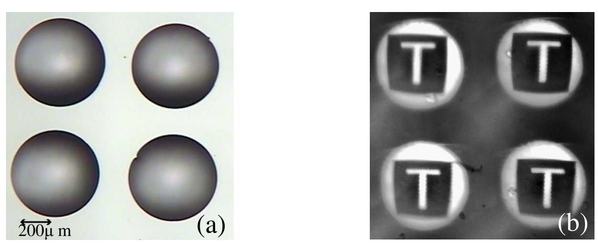

Fig. 3. (a) The optical microscopic image of the bare NOA 65 microlens array. (b) Imaging formed by the microlens array in (a).

There are two approaches to adjust the focusing properties of this microlens array in common. One is by varying the polarization direction of incident light. In our configuration, if the polarization direction of the incident light is parallel to the alignment direction, the effective index of LC is close to n_e. As $n_e > n_p$, the microlens array works as a plan-concave

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009

microlens array, showing a negative focal length. Whereas, if the polarization direction of the incident light is perpendicular to the rubbing direction, the effective index of LC is close to n_o. In this case, $n_o < n_p$, the microlens array works as a plano-convex microlens array, showing a positive focal length. Figures 4(a) and (b) show the CCD images of the real focal plane [Fig. 2(c)] of the microlens array when the polarization direction of the incident light was parallel and perpendicular to the alignment direction of LC molecule, respectively. It is worth mentioning that this approach does not provide a continuously tuning from positive to negative foci or vice visa.

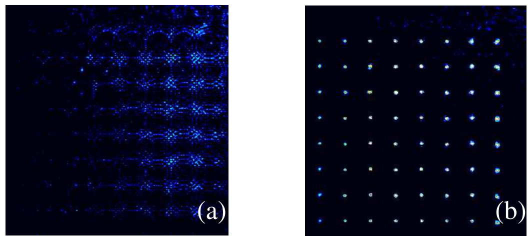

Fig. 4. CCD images showing the focusing of the microlens array for polarized incident light parallel (a) and perpendicular (b) to LC alignment direction.

Another way to tune the focusing properties of our microlens array is to apply an electric field. First a polarizing microscope (Olympus X71) was used to inspect the microlens array at different applied voltages. The rubbing direction of the cell was oriented at 45°with respect to the linear polarizer and the analyzer was crossed with the polarizer. Fig. 5(a)-(c) shows the status of microlens array under different applied voltages.

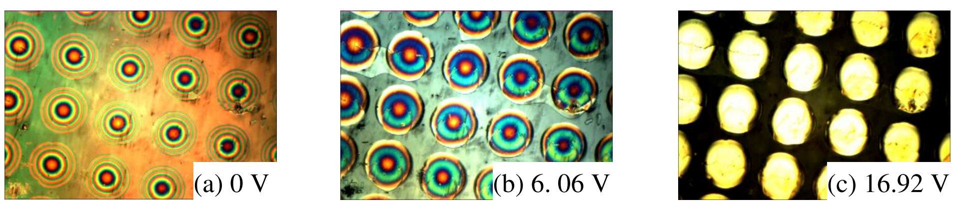

Fig. 5. Interference fringe patterns of the LC microlens array with various applied voltages of (a) 0 V_{rms}, (b) 6.06 V_{rms}, and (c) 16.92 V_{rms}.

According to Fig. 5(a), the interference rings of individual lens is clear when V=0 due to the effective index difference between LC materials and polymer. Increasing the applied voltage up to the threshold, the LC molecules start to align along the field direction, and then the effective index of LC decreases, consequently the number of interference rings reduces [Fig. 5(b)]. When the applied voltage further increases, which is larger than a critical value, the effective index of LC is less than that of NOA65. As a result, the microlens array becomes a plano-convex one [Fig. 5(c)]. In our experiment an applied voltage of 13.26 V_{rms} can fully aligned the LC molecules, the focal length do not change any more beyond 13.26 V_{rms}. There are some disordered structures on the microlens surface [Fig. 5(b)], which is caused by the misalignment of LC on the surface of the microlens (no alignment). The disordered structures, in turn, caused a reduced focusing efficiency (92%). A possible solution to overcome this problem is to adopt the photo-alignment technology. The electrically tunable property of microlens array with LC can also be characterized by the setup shown in Fig. 2(a). Without electric field applied, only virtual foci O_v can be imaged onto CCD [Fig. 2(b)], where the polarization direction of the incident light was parallel to the rubbing direction of LC sample. Fig. 6(a) shows the image of virtual focal points of the microlens array at V = 0. The virtual

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009

focal length measured was 22.9 mm, which is slightly less than theoretical calculation (23.7 mm). When the applied voltage is larger than Freedericksz threshold, the direction of LC molecules will reorient along the electric field direction, resulting in the decrease of the effective index of LCs. As a result, the focal length changed with the increasing voltage. With the distance between LC sample and objective lens unchanged, the intensity distribution after microlens array varies with the applied voltage [Figs. 6(a)-(d)]. As we can see, at V = 8.07 V_{rms}, the virtual focal points became illusive (not existing). At the same time, the real foci were found by moving LC sample [Fig. 6(g)]. When V= 13.26 V_{rms}, the virtual focal points disappear completely, and the real foci were the clearest [Fig. 6(h)]. Figs. 6(e)-(h) show the changes of intensity pattern of the real foci with voltages using setup in Fig. 2(c). The measured focal length was 31.2 mm at V=13.26 V_{rms}. Two real and virtual focal points were picked up from CCD photos, respectively, to show the intensity changes as a function of the applied voltage [Fig. 7]. With high transmittance of NOA65 and LC material in the visible range (close to 100%), the focusing efficiency of a single microlens exceeds 92% excluding the ITO glass surface reflection. The less ideal focusing efficiency is due to the light scattering caused by the disordered structures of LC (the surface of the microlenses was not rubbed) and the edge of the microlens.

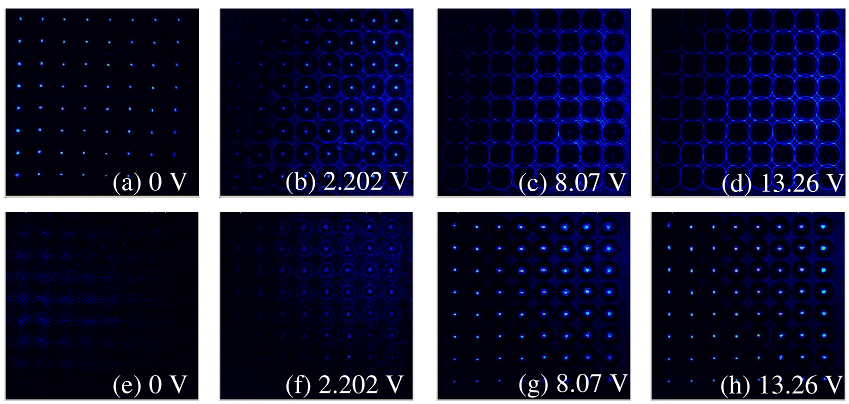

Fig. 6. CCD images of focusing properties under different applied voltages for the negative (a-d) and the positive (e-h) cases, using the setup in Figs. 2(b) and (c) respectively.

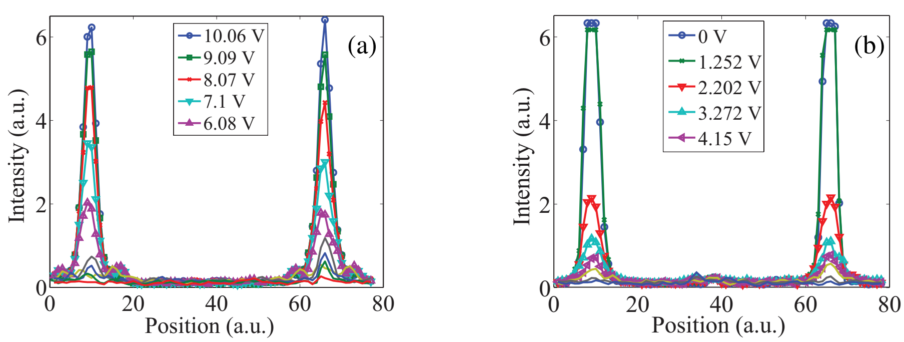

Fig. 7. Intensity profile of real (a) and virtual foci (b) at the focal plane with various applied voltages

4. Conclusion

In conclusion, a simple printing technique to fabricate negative-positive tunable microlens array using UV adhesive and LC was introduced. The focal length can be switched from

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009

negative to positive either by applied voltage or by varied the polarized direction of the incident of light. With careful control of printing, the filling factor of the microlens array could be improved and the dimension of microlens could be further decreased, both of which are highly desired for the integration systems.

#106084 - $15.00 USD Received 6 Jan 2009; revised 16 Feb 2009; accepted 25 Feb 2009; published 3 Mar 2009