Journal of Nonlinear Optical Physics & Materials
Vol. 20, No. 4 (2011) 477–484

DOI: 10.1142/S0218863511006273

AN ELECTRICALLY TUNABLE FOCUSING PICO PROJECTION SYSTEM BASED ON A LIQUID CRYSTAL LENS ADOPTING A LIQUID CRYSTAL AND POLYMER COMPOSITE FILM

HUNG-CHUN LIN, MING-SYUAN CHEN and YI-HSIN LIN*

Department of Photonics and Institute of Electro-Optical Engineering,
National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C.
**yilin@mail.nctu.edu.tw*

Received 2 September 2011

An electrically tunable liquid-crystal-on-silicon (LCOS)-based pico projection system based on a liquid crystal lens adopting a liquid crystal and polymer composite film (LCPCF) is demonstrated. The LC lens consists of two built-in sub-lenses: one is an electrically tunable focusing lens controlled by a LC layer and the other is a fixed focused LCPCF lens. The electrically tunable focusing range of the pico projection system is 200 cm to $\sim$7 cm when the voltage is from 0 to 35 V_{rms}. The image performance is also demonstrated. The related optical analysis is discussed. This study opens a new window for electrically tunable focusing pico projection system.

Keywords: Liquid crystals; liquid crystal lenses; LC lenses; projection; tunable focusing.

1. Introduction

Pico projectors are usually combined or built into other electronic devices, such as digital cameras, cell phones, and tablet personal computers. Generally speaking, three kinds of pico projectors are developed: liquid-crystal-on-silicon (LCOS)-based pico projectors, digital light processing (DLP)-based pico projectors, and laser-scanning pico projectors.[1–3] Except the laser-scanning pico projectors, the focusing properties of all the pico projectors available on the market are manually controlled. The manual focusing systems are bulky. Therefore, electrically tunable focusing pico projection systems or pico projectors are required. To achieve the electrically tunable focusing of pico projection system, the developed electrically tunable lenses can be adopted, such as liquid lenses and liquid crystal (LC) lenses.[4–16] We have demonstrated a LCOS-based electrically tunable focusing pico projector by using a liquid crystal (LC) lens and discussed the optical mechanism.[6] However, the voltage is still high ($\sim$90 V_{rms}), and the tunable focusing range should be improved.

In this paper, we demonstrated an electrically tunable focusing LCOS-based pico projection system by using a LC lens consisting of two built-in sub-lenses: one is an electrically tunable focusing lens controlled by a LC layer and the other is a fixed focused lens which is a liquid crystal and polymer composite film (LCPCF), called LCPCF lens.[10,17–20] The focal length of the LCPCF can be adjusted by the applied voltage during photopolymerization. Thus, the initial focal length of the LC lens is determined by LCPCF, and the focusing range of the LC lens is electrically tunable. The electrically tunable focusing range of the LCOS-based pico projection system is from 200 cm to ∼7 cm. The driving voltage is less than 35 V_{rms}, with a response time of 1.1 sec. The image performances of the electrically tunable focusing LCOS-based pico projection system are also demonstrated.

2. Structure and Operating Principles

Figure 1(a) illustrates the structure of the electrically tunable focusing LCOS-based pico projection system. In Fig. 1(a), the white light from a light-emitting diode (LED; XRE-Q5 CREE) passes through a relay lens in order to obtain a beam with uniform irradiance. A pre-polarizer and a polarizing beam splitter (PBS) are used for obtaining the crossed polarization of light with a high extinction ratio when the light is incident to and then reflected by a reflective LCOS panel. We use a projection lens to project the image from the LCOS panel. By controlling the

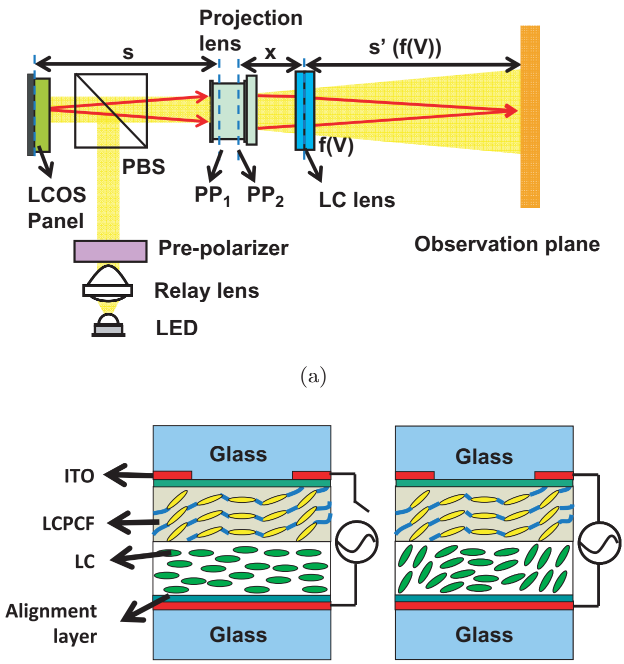

Fig. 1. (a) Structure of an electrically tunable focusing pico projection system. PP_1 and PP_2 are the two principal planes of the projection lens and (b) the structure of the LC lens.

focal length of the LC lens at different voltages, the projected image or the image distance (s') can be electrically adjusted. The projected image is then observed on the observation plane. Conventional LC lenses require a polarizer owing to the polarization-dependent lens properties. Since the output light of LCOS-based pico projection system is already linearly polarized, we do not attach any extra polarizer on the LC lens. The objective image is generated by the LCOS panel and is then projected by both the projection lens and the LC lens. PP_1 and PP_2 indicate two principal planes of the projection lens. The structure of the LC lens is depicted in Fig. 1(b). In Fig. 1(b), the structure of the LC lens consists of two built-in sub-lenses: one is an electrically tunable focusing lens controlled by a LC layer and the other is a fixed focused LCPCF lens. At $V = 0$, the focal length of the LC lens is f_p determined by the initial focal length of the LCPCF layer. When we apply a voltage (V), the focal length $[f(V)]$ of the LC lens is contributed by two sub-lenses: one is the LC layer whose focal length $[f_{\mathrm{LC}}(\mathrm{V})]$ is electrically tunable and the other is LCPCF layer whose focal length (f_p) is fixed. $f(V)$ can be expressed as[10]:

$$\frac{1}{f(V)} = \frac{1}{f_{LC}(V)} + \frac{1}{f_p} \tag{1}$$

In our system, the position of the projection lens is set to be fixed. The object distance between the LCOS panel and principal plane PP_1 of the projection lens is s, and the distance between the LC lens and principal plane PP_2 of the projection lens is x. The focal length of the projection lens is denoted as f_{pj}. After the first image is formed by the projection lens, we can assume that the distance between the LC lens and the first image is p. According to the image equation, the first image formed by the projection lens and second image formed by the LC lens can be expressed as[6]:

$$\frac{1}{f_{pj}} = \frac{1}{s} + \frac{1}{x+p}, \tag{2}$$

$$\frac{1}{f(V)} = -\frac{1}{p} + \frac{1}{s'}. \tag{3}$$

By combining the Eqs. (2) and (3), can be expressed as:

$$s'(f(V)) = \frac{f(V) \cdot [\frac{f_{pj} \cdot s}{s - f_{pj}} - x]}{f(V) + \frac{f_{pj} \cdot s}{s - f_{pj}} - x}. \tag{4}$$

In the Eq. (4), s' is the function of the focal length of the LC lens. Therefore, the imaging plane of the pico projection system is electrically tunable.

3. Experiments Results and Discussion

To demonstrate the electrically tunable focusing pico projection system, a commercial LCOS-based pico projector (Himax, HX7027-3W50-May), which is manually focused, was adopted. The LC lens consists of two Indium tin oxide (ITO) glass substrates coated with mechanically buffered PVA (Polyvinylalcohol) to align the LC molecules, a LC layer and a LCPCF layer. The top ITO layer was etched with a hole-pattern within a diameter of 1.68 mm in order to provide an inhomogeneous electric field to LC directors. To fabricate the LCPCF layer, we first filled nematic LC (Merck, MLC-2070), reactive mesogen (Merck, RM82), and photoinitiator (Merck, IRG-184) at 30:69:1 wt% ratios into two ITO glass substrates coated with mechanically buffered PVA. On the top substrate, the ITO layer was etched with a hole-pattern within a diameter of 1.68 mm, and the bottom ITO substrate was not etched. A voltage of 70 V_{rms} (f = 1 kHz) was applied to the cell, which was irradiated with UV light ($\sim$1.25 mW/cm^2) for 40 min. The thickness of the LCPCF was 35 μm. After photopolymerization, we peeled off the bottom substrate by a thermal releasing process. Then we sandwiched nematic LC mixture MLC-2070 (Merck, $\Delta n = 0.26$ for $\lambda = 589.3$ nm at 20°C) between the LCPCF layer and another ITO substrate coated with mechanically buffered PVA in order to construct the structure as shown in Fig. 1(b). The thickness of the LC layer in Fig. 1(b) was 25 μm. The LCPCF layer has a fixed focal length because of the lens-like distribution of refractive indices. The LC directors in the LC layer aligned by the LCPCF layer and PVA were aligned homogeneously with a pretilt angle of $\sim$2 degrees.[17–20]

To determine the focal length of the LC lens, we observed the image of the LC lens at different voltages under crossed polarizers. The rubbing direction of the LC lens was 45 degrees with respect to one polarizer. The number of concentric rings is proportional to the phase profile of the LC lens. We also tested the LCPCF layer only by applying voltages. The phase profile of the LCPCF layer did not change with the voltage. That means the LCPCF layer is a lens with a fixed focal length. The focal length of the LCPCF layer does not change with the voltage due to the high concentration of the monomer. The focal length of the LCPCF layer is $\sim$8.82 cm, according to the relation: $f = D^2/8\lambda N$, where D is the aperture size, λ is the wavelength, N is the number of rings of the phase profile.[15] Figure 2(a) shows the voltage-dependent focal length of the LC lens. In the experiments, a laser diode with a wavelength (λ) of 532 nm was used as a light source. We plotted the focal length of the LC lens as a function of applied voltage, as shown by the blue squares in Fig. 2(a). The initial focal length is 8.82 cm, which is determined by the LCPCF layer. The focal length then decreases when $V > V_{th}$. At 35 V_{rms}, the LC lens has a minimal focal length of $\sim$4.41 cm. From Eq. (1), we calculated the focal length contributed from the LC layer to be from infinity to 8.82 cm, as shown by the magenta dots in Fig. 2(a). The measured response time of the LC lens was $\sim$350 ms when the voltage of the LC lens is switched from 0 to 35 V_{rms}, and $\sim$740 ms when the voltage of the LC lens is switched from 35 to 0 V_{rms}.

To measure the voltage-dependent image distance of the pico projection system, we projected the photo of a resolution chart. We recorded the image distance of a focused image of a resolution chart by changing the different voltages of the LC lens. The spatial frequency of the resolution chart was 0.05 line pair per millimeter (lp/mm). The image distance (s') as a function of the applied voltage of the LC

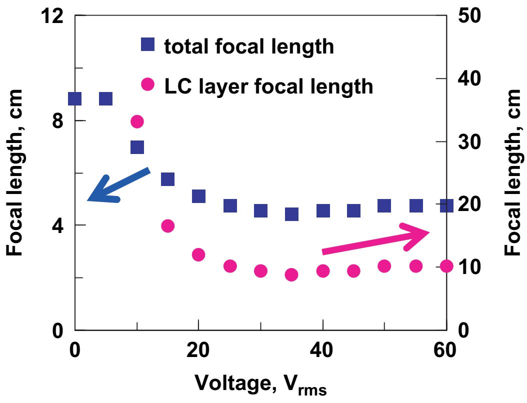

Fig. 2. The total focal length of the LC lens shown by blue squares and the focal length of the LC layer shown by magenta dots.

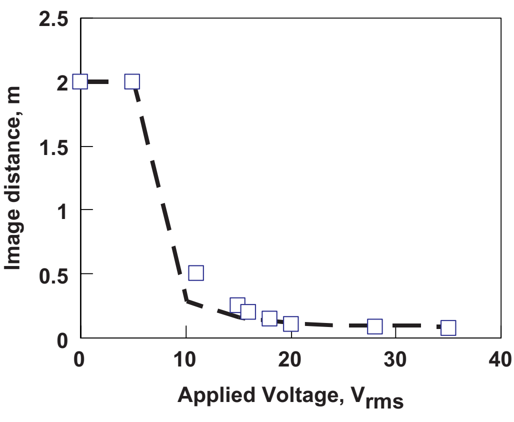

Fig. 3. The measured image distance (hollow square) and the calculated image distance (dash line) as a function of applied voltage.

lens is shown in Fig. 3 (hollow squares). The image distance can be tuned from 200 cm to ∼7 cm with the applied voltage from 0 V_{rms} to 35 V_{rms}. The threshold voltage is ∼5 V_{rms}. Therefore, we can obtain the electrically focused pico projection system using an electrically tunable focusing LC lens as an active element. The calculated image distance (s') of a focusing image as a function of the applied voltage of the LC lens is shown by dash line in Fig. 3, obtained by substituting the experimental parameters: $s = 15.85$ mm, $x = 15.15$ mm, and $f_{pj} = 19.95$ mm into Eq. (4). The calculated results agree well with the experimental results. As a result, the applied voltage is below 35 V_{rms}, which is lower than the case for LC lens with glass insulating layer (< 90 V_{rms}).[9] The reason for the low driving voltage is that the thickness of the polymeric layer (∼35 μm) is much thinner than the

(a)

(b)

Fig. 4. The images of electrically tunable focusing LCOS pico projection system at (a) 0 V_{rms} and (b) 27 V_{rms}. The screen was placed 8 cm away from the LC lens.

glass insulating layer of the previous structure ($\sim$0.7 mm). Moreover, the tunable focusing range obtained by using our LC lens is larger than that obtained using the LC lens with a glass insulating layer. This is because of the large tunable focal length of the LC lens with the LCPCF layer.

Figures 4(a) and 4(b) show the images of the electrically tunable focusing pico projection system at V = 0 and V = 27 V_{rms} when we input a photo to the LCOS panel. The screen was placed 8 cm away from the LC lens. The brightness of the focused image did not change significantly because we did not attach an extra polarizer to the LC lens. However, the aperture mismatch between the projection lens ($\sim$11.28 mm) and the LC lens ($\sim$1.68 mm) decreased the brightness of the image. Enlarging the aperture of the LC lens can increase the brightness.[7] As for the image quality, we can adjust the phase profile of the LCPCF lens and sub-LC lens to be more parabolic.

From Eqs. (3) and (4), we can have

$$\frac{1}{f_{LC}(V)} + \frac{1}{f_p} = -\frac{1}{p} + \frac{1}{s'}. \quad (5)$$

To achieve the electrically tunable pico projection system with large tunable range, the tunable focal length ($f_{\mathrm{LC}}(\mathrm{V})$) of LC lens should be large. Conventionally, the focal length of the conventional LC lens without a LCPCF lens is larger than 10 cm.[6–9] With LCPCF lens, the focal length of the LC lens can be smaller ($<$10 cm). In addition, the focal length of the LCPCF lens can be adjusted by fabrication process, such as the curing voltage of the photopolymerization, thickness and birefringence of LC in LCPCF. As a result, the image distance (s') can be made smaller by adjusting f_p in Eq. (5) without changing the structure of the pico projection system.

4. Conclusion

We have demonstrated an electrically tunable focusing pico projection system based on a liquid crystal lens adopting a liquid crystal and polymer composite film. The tunable range of the electrically tunable pico projection system is from 200 cm to ∼7 cm. The driving voltage is less than 35 V_{rms}. The response time is 1.1 sec. Because no extra polarizer is used, the brightness of the projected image does not decrease dramatically by adopting an LC lens. We believe that the achievements of this study open a new window for electrically tunable focusing pico projection systems.

Acknowledgments

The pico projectors are sponsored by Himax Display Inc. The authors are indebted to Dr. Kuan-Hsu Fan-Chiang (Himax Display Inc.) and Dr. Jinn-Chou Yoo (Shiny-optics Corp.) for the technical support and discussions. This research was supported by the National Science Council (NSC) in Taiwan under the contract no. 98-2112-M-009-017-MY3.

References

1. D. Armitage, I. Underwood and S. T. Wu, *Introduction to Micro Display* (Wiley, New York, 2006).
2. E. H. Stupp and M. S. Brennesholtz, *Projection Display* (Wiley, New York, 1999).
3. J. W. Pan, S. H. Tu, C. M. Wang and J. Y. Chang, High efficiency pocket-size projector with a compact projection lens and a light emitting diode-based light source system, *Applied Optics* **47** (2008) 3406.
4. B. Berge and J. Peseux, Variable focal lens controlled by an external voltage: An application of electrowetting, *Eur. Phys. J. E* **3** (2000) 159.
5. H. Ren and S. T. Wu, Variable-focus liquid lens, *Opt. Express* **15** (2007) 5931.
6. H. C. Lin and Y. H. Lin, An electrically tunable focusing pico projector adopting a liquid crystal lens, *J. Jpn. Appl. Phys.* **49** (2010) 102502.
7. H. C. Lin, M. S. Chen and Y. H. Lin, An electrically tunable focusing pico projector using a liquid crystal lens as an active optical element, *Mol. Cryst. Liq. Cryst.* **544** (2011) 150.
8. B. Wang, M. Ye and S. Sato, Liquid crystal lens with focal length variable from negative to positive values, *IEEE PHOTONICS TECHNOLOGY* **18** (2006) 79.
9. B. Wang, M. Ye, M. Honma, T. Nose and S. Sato, Liquid crystal lens with spherical electrode, *Jpn. J. Appl. Phys.* **41** (2002) L1232.
10. H. C. Lin and Y. H. Lin, An electrically tunable focusing liquid crystal lens with a built-in planar polymeric lens, *Appl. Phys. Lett.* **98** (2011) 083503.
11. Y. H. Lin, M. S. Chen and H. C. Lin, An electrically tunable optical zoom system using two composite liquid crystal lenses with a large zoom ratio, *Opt. Express* **19** (2011) 4714.
12. H. C. Lin and Y. H. Lin, A fast response and large electrically tunable-focusing imaging system based on switching of two modes of a liquid crystal lens, *Appl. Phys. Lett.* **97** (2010) 063505.
13. F. Naumov, M. Y. Loktev, I. R. Guralnik and G. Vdovin, Liquid-crystal adaptive lenses with modal control, *Opt. Lett.* **23** (1998) 992.

14. G. Q. Li, D. L. Mathine, P. Valley, P. Ayras, J. N. Haddock, M. S. Giridhar, G. Williby, J. Schwiegerling, G. R. Meredith, B. Kippelen, S. Honkanen and N. Peyghambarian, Switchable electro-optic diffractive lens with high efficiency for ophthalmic applications, *Proc. Natl. Acad. Sci. USA* **103** (2006) 6100.
15. H. W. Ren, D. W. Fox, B. Wu and S. T. Wu, Liquid crystal lens with large focal length tunability and low operating voltage, *Opt. Express* **15** (2007) 11328.
16. K. Asatryan, V. Presnyakov, A. Tork, A. Zohrabyan, A. Bagramyan and T. Galstian, Optical lens with electrically variable focus using an optically hidden dielectric structure, *Opt. Express* **18** (2010) 13981.
17. Y. H. Lin, H. Ren and S. Gauza, Single-substrate IPS-LCD using an anisotropic polymer film, *Proc. SPIE* **5936** (2005) 59360O.
18. Y. H. Lin, H. Ren, S. Gauza, Y. H. Wu, Y. Zhao, J. Fang and S. T. Wu, IPS-LCD using a glass substrate and an anisotropic polymer film, *J. Display Technology* **2** (2006) 2.
19. Y. H. Lin, J. K. Li, T. Y. Chu and H. K. Hsu, A bistable polarizer-free electro-optical switch using a droplet manipulation on a liquid crystal and polymer composite film, *Opt. Express* **18** (2010) 10104.
20. Y. P. Chiu, C. Y. Shen, W. C. Wang, T. Y. Chu and Yi-Hsin Lin, Electrically surface-driven switchable wettability of liquid crystal/polymer composite film, *Appl. Phys. Lett.* **96** (2010) 131902.

This article has been cited by:

1. Yu-Shih Tsou, Kai-Han Chang, Yi-Hsin Lin. 2013. A droplet manipulation on a liquid crystal and polymer composite film as a concentrator and a sun tracker for a concentrating photovoltaic system. *Journal of Applied Physics* **113**:24, 244504. [CrossRef]