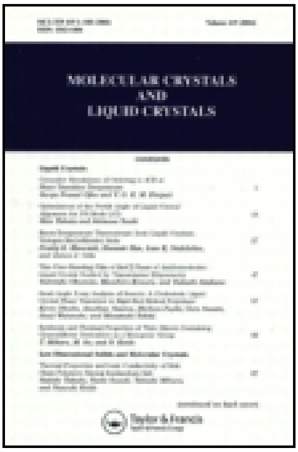

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

An Electrically Tunable Focusing Pico Projector Using a Liquid Crystal Lens as an Active Optical Element

H. C. Lin [a] , M. S. Chen [a] & Y. H. Lin [a]
[a] Department of Photonics , National Chiao Tung University , Hsinchu, Taiwan, R.O.C
Published online: 14 Jun 2011.

To cite this article: H. C. Lin , M. S. Chen & Y. H. Lin (2011) An Electrically Tunable Focusing Pico Projector Using a Liquid Crystal Lens as an Active Optical Element, Molecular Crystals and Liquid Crystals, 544:1, 150/[1138]-156/[1144], DOI: 10.1080/15421406.2011.569288

To link to this article: http://dx.doi.org/10.1080/15421406.2011.569288

Mol. Cryst. Liq. Cryst., Vol. 544: pp. 150/[1138]–156/[1144], 2011

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/15421406.2011.569288

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An Electrically Tunable Focusing Pico Projector Using a Liquid Crystal Lens as an Active Optical Element

H. C. LIN, M. S. CHEN, AND Y. H. LIN

Department of Photonics, National Chiao Tung University,
Hsinchu, Taiwan, R.O.C

An electrically tunable pico projector adapting a liquid crystal (LC) lens as an active optical element is demonstrated. The electrically tunable focusing properties of the pico-projectors with different aperture sizes of the LC lenses are also investigated. The tunable ranges of the electrically tunable pico projectors are 350 cm to ∼14 cm. The response times are 1.2 sec for the LC lens of 2 mm aperture and around 5 sec for the LC lens of 4 mm aperture. The image performance of the electrically tunable focusing pico projector is demonstrated.

Keywords Liquid crystal; liquid crystal lens; pico projector

1. Introduction

Pico projectors generating a portable instant screen for pocket devices are important in many applications, such as cell phones, digital cameras, and tablet personal computers (PCs) [1–3]. 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]. Moreover, LCOS-based systems and DLP-based systems require focusing elements or projection lenses for focusing the projected image on the screen for observation. By changing the position of the projection lens, the focal length in the LCOS-based or DLP-based pico projectors is manually tunable. However, manually focused pico projectors are bulky due to the manual switching device. Therefore, in order to obtain a pico projector with reduced weight and electrically tunable focusing properties, we can replace the manually switchable projection lenses with electrically tunable lenses. To achieve the electrically tunable focusing of pico projectors, the developed electrically tunable lenses can be adopted, such as liquid lenses and liquid crystal (LC) lenses [4–10].

In this paper, we demonstrated an electrically tunable focusing LCOS-based pico-projector by using a LC lens as an active optical element. Without attaching a polarizer on the LC lens, the optical efficiency is not decreased by the polarizer.

Address correspondence to Y. H. Lin, Department of Photonics, National Chiao Tung University, Hsinchu, Taiwan 30010, R.O.C. Tel.: +886-3-5712121 ext 56376; Fax: +886-3-5737801; E-mail: yilin@mail.nctu.edu.tw

The tunable range of the focal length of the pico projector depends on the position of the projection lens. We also study the electrically tunable focusing properties of the pico-projectors with different aperture sizes of the LC lenses. The image performance of the electrically tunable focusing pico projector is demonstrated.

2. Structure and Operating Principles

Figure 1 illustrates the structure of the electrically tunable pico projector using a LC lens as an active optical element. In Figure 1, 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 focal length of the LC lens at different voltages, the location of the focused and 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 polarizers owing to the polarization-dependent lens properties. Since the light passing through the projection lens is already linearly polarized in LCOS-based pico projectors, we do not attach any extra polarizer on the LC lens. At $V = 0$, the focal length of the LC lens is infinity. The image distance of the whole projection system is determined by the projection lens only. Typical pico projectors do not have a LC lens, and the image plane is manually adjusted by varying the position of the projection lens. The objective image is generated by the LCOS panel and then is imaged on the observation plane by both the projection lens and the LC lens. PP_1 and PP_2 indicate two principal planes of the projection lens. In our system, the position of the projection lens is set to be fixed. The objective 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 lengths of the projection lens and LC lens are denoted as f_{pj} and f_{LC}, respectively. 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, first image formed by the

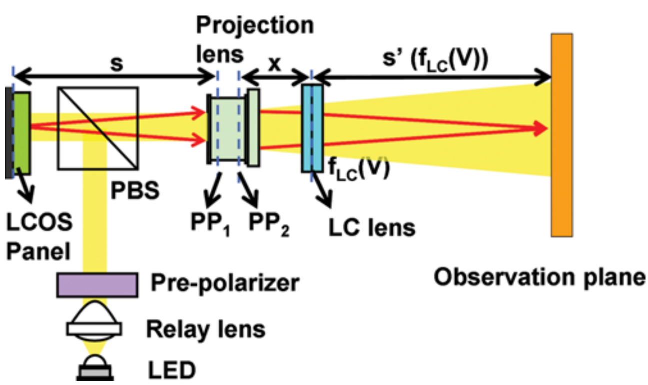

Figure 1. Structure of the projection system of an electrically tunable focusing pico projector. PP_1 and PP_2 are the two principal planes of the projection lens. (Figure appears in color online.)

projection lens and second image formed by the LC lens can be expressed as [11]

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

$$\frac{1}{f_{LC}} = -\frac{1}{p} + \frac{1}{s'} \tag{2}$$

We can combine Eqs. (1) and (2) by eliminating p to obtain Eq. (3):

$$s'(f_{LC}(V)) = \frac{f_{LC}(V) \cdot \left(\frac{f_{pj} \cdot s}{s - f_{pj}} - x\right)}{f_{LC}(V) + \frac{f_{pj} \cdot s}{s - f_{pj}} - x} \tag{3}$$

where $f_{LC}(V)$ is the voltage-dependent focal length of the LC lens. In Eq. (3), s' depends on the focal length of the LC lens. Therefore, the imaging plane of the pico projection system is electrically tunable.

3. Experiments and Results

To demonstrate the concept of the proposed pico projector, a commercial LCOS-based pico projector (Himax, HX7027-3W50-May), which is manually focused, was adopted. A LC lens was attached on a projection lens whose aperture size was 11.28 mm. The structure of the LC lens was based on two-voltage structure proposed by Prof. Sato [6,7]. The structure of the LC lens consists of three indium tin oxide (ITO) glass substrates of thickness 0.7 mm, a polymeric layer of NOA81 (Norland Optical Adhesive) with a thickness of 35 μm for isolating the electrode. The ITO layer of the middle ITO glass substrate was etched with a hole pattern in order to provide an inhomogeneous electric field to the LC directors. The opposite side of this ITO glass substrate was coated with a mechanically buffed poly(vinyl alcohol) (PVA) layer to align the LC directors. The bottom ITO glass substrate was also coated with an alignment layer with mechanically buffed polyimide layer. The rubbing directions of the two alignment layers are anti-parallel. The MLC-2070 nematic LC mixture (Merck, $\Delta n = 0.26$ for $\lambda = 589.3$ nm at 20°C) was used. For comparison, we prepared two LC lenses with different aperture sizes. One is the aperture size of 2 mm with the cell gap of 25 μm and the other is 4 mm with the cell gap of 50 μm. Theoretically, the shortest focal length of the LC lens with the aperture size of 4 mm is four times longer than that of the LC lens with the aperture size of 2 mm. In order to have comparable focal length of the LC lens we increased the cell gap of the LC lens with the aperture size of 4 mm. The voltage applied between the hole-patterned ITO layer and the bottom ITO layer was fixed and was defined as the holding voltage (V_H). The other applied voltage was controllable and was defined as the operating voltage (V_o). The main purpose of the holding voltage is to first generate a phase profile of a positive lens, and then the phase profile is adjusted by varying the operating voltage. In this way, the focal length of the LC lens is positive and electrically tunable with good imaging properties. We define the difference between V_H and V_o as ΔV ($=V_H - V_o$).

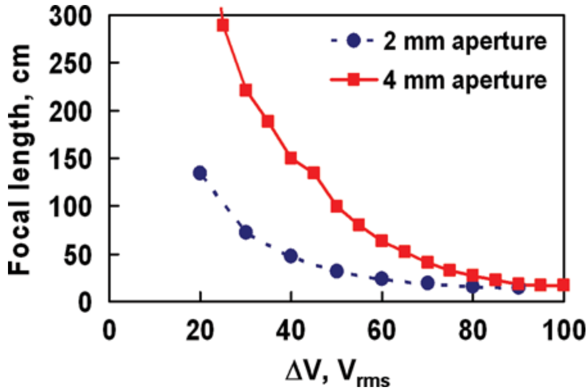

Figure 2. Measured voltage-dependent focal length of the LC lens with the aperture size of 2 mm (the blue dotted line) with $V_H = 90\,V_{rms}$ and the LC lens with the aperture size of 4 mm (the red solid line) with $V_H = 100\,V_{rms}$. $\lambda = 532$ nm. (Figure appears in color online.)

Figure 2 is the measured voltage-dependent focal length of the LC lens with a fixed holding voltage. The blue dotted line indicate the results of the LC lens with the aperture size of 2 mm when $V_H = 90\,V_{rms}$, and the red solid line indicate the results of the LC lens with the aperture size of 4 mm when $V_H = 100\,V_{rms}$. In the experiments, a laser diode with a wavelength (λ) of 532 nm was used as a light source. Since $V_H \geqq V_o$, the LC lens was operating as the positive lens. The measured focal length of the LC lens can be switched from infinity to 14.46 cm with the aperture size of 2 mm and from infinity to 17 cm with the aperture size of 4 mm. The larger aperture size causes the higher holding voltage because of the requirement of larger gradient electric field.

To realize the electrically tunable focusing pico projector, we measured the image distance (s' in Fig. 1) of a focusing image as a function of the applied voltage ΔV of the LC lens. The measured results are shown in Figure 3. The image distance decreases with ΔV. The image distance was tunable from 350 to 14 cm when attached

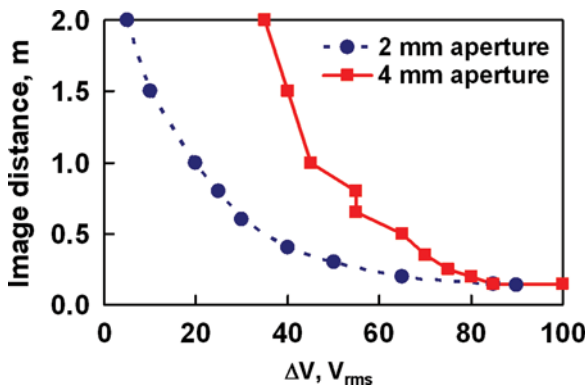

Figure 3. The image distance as a function of ΔV. V_H was $90\,V_{rms}$ for the LC lens with the aperture size of 2 mm (the blue dotted line) and V_H was $100\,V_{rms}$ for the LC lens with the aperture size of 4 mm (the red solid line). (Figure appears in color online.)

the LC lens with the aperture size of 2 mm ($V_H = 90\,V_{rms}$) and from 350 to 15 cm. when attached the LC lens with the aperture size of 4 mm ($V_H = 100\,V_{rms}$). Therefore, using an electrically tunable focusing LC lens as an active imaging element, we can obtain the electrically focused pico projector. The tunable ranges of the image distance are similar in both LC lenses. That is because the wave after passing through the projection lens is nearly a plane wave, and then the LC lens is an effective phase modulator to the plane wave. As a result, the change of the image distance is limited by the LC lens power when a voltage is applied to the LC lens. Since the tunable focal lengths of both LC lenses are comparable, the tunable image distances are similar to each other. The operating voltage of the LC lens with aperture size of 4 mm is still higher than that of the LC lens with aperture size of 2 mm at a fixed image distance.

To further discuss the tunable focusing range of the electrically tunable pico projector, we defined s'_m, the distance between the first image and the LC lens, can be expressed as

$$s'_m = \frac{f_{pj} \cdot s}{s - f_{pj}} - x \tag{4}$$

By replacing Eq. (3) with Eq. (4), Eq. (3) can be expressed as

$$s'(f_{LC}(\Delta V)) = \frac{f_{LC}(V) \cdot s'_m}{f_{LC}(V) + s'_m} \tag{5}$$

From Eq. (5), when the LC lens operates in the low lens power range ($s'_m \ll f_{LC}(\Delta V)$). the image distance s' approximately equals to s'_m, and when the LC lens operates in the high lens power range ($s'_m \gg f_{LC}(\Delta V)$) s' approximately equals to $f_{LC}(\Delta V)$. That means the image distance is tunable from s'_m to the focal length of the LC lens, as shown in Figure 3.

The response time of the LC lens is also important for the applications. The measured response time of 2 mm aperture was 880 ms when the operating voltage was switched from 90 to $0\,V_{rms}$, and was 313 ms when the operating voltage was switched from 0 to $90\,V_{rms}$. The response time of 4 mm aperture is around 5 second. The slow response time is due to the large cell gap.

Figures 4(a)–4(f) show the image quality of the manually focusing pico projector and the electrically tunable focusing pico projector when we input a photo to the LCOS panel. The screen was placed at the distance of 40 cm away from the LC lens. To compare the transmittance in the same aperture of the system, we placed an aperture stop of 2 mm and 4 mm in diameters between the LC lens and projection lens. We then removed the LC lens and then adjusted the location of the projection lens until the image was clear and then take the photo by using the digital camera, the results shown in Figure 4(a) and 4(d). After that, we placed back the LC lens and then take photos. The images are shown in Figures 4(b) and 4(e) by applying voltage to two LC lenses with the aperture sizes of 2 mm and 4 mm at the image distance of 40 cm when $s'_m = 350$ cm. Figures 4(c) and 4(f) are the images observed without the applied voltage of two LC lenses with the aperture sizes of 2 mm and 4 mm. To compare Figures 4(b), 4(c), 4(e) and 4(f), the pico projector with the LC lens indeed shows a good electrically tunable performance in both aperture sizes. In Figure 4,

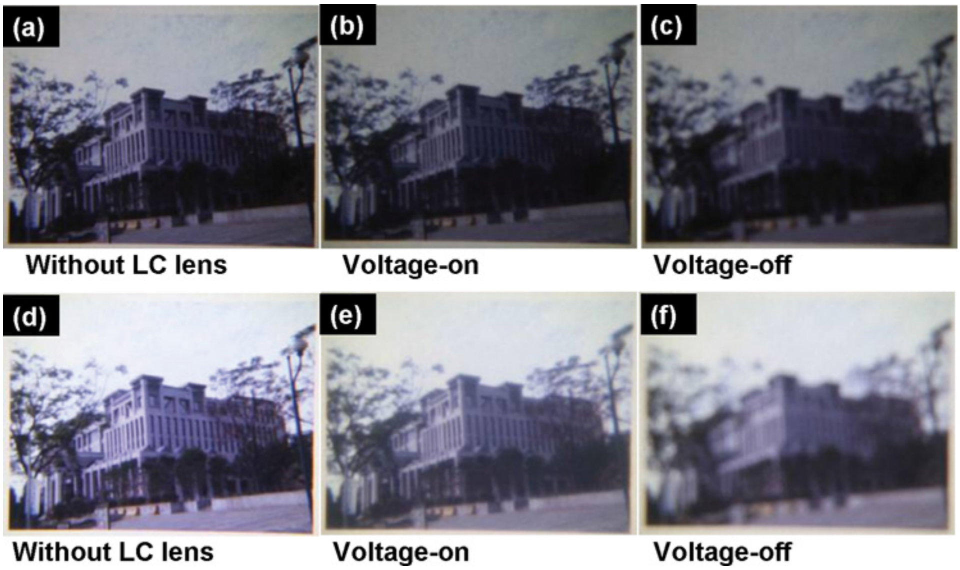

Figure 4. The image of the manually focusing pico projector by using (a) the LC lens with the 2 mm aperture and (d) the LC lens with the 4 mm aperture. The images of electrically tunable focusing pico projector at (b) $V_o = 40\,V_{rms}$ and $V_H = 90\,V_{rms}$ and (c) at $V_o = V_H = 0$ by using the LC lens with the aperture size of 2 mm, and at (e) $V_o = 32\,V_{rms}$ and $V_H = 100\,V_{rms}$ and (f) at $V_o = V_H = 0$ by using the LC lens with the aperture size of 4 mm. The screen was placed 40 cm away from the LC lens. (Figure appears in color online.)

the photos were taken under the same exposure time. Due to the large aperture, the photos taken by the LC lens with the aperture size of 4 mm are brighter than the photos taken by the LC lens with the aperture size of 2 mm. By comparing the photos of manually focusing and electrically focusing, the brightness of the focused image did not change significantly when the LC lens was used as an active optical element. This is because we did not attach an extra polarizer to the LC lens since the polarization of the projected light from the LCOS-based projection system was linearly polarized. Although the LC lens with the aperture size of 4 mm can have higher light efficiency, the large cell gap would result in the light scattering and slow response time.

4. Conclusions

We have demonstrated electrically tunable pico projectors by adopting a LC lens as an active optical element. The electrically tunable range of pico projectors depends on the tunable focal length of the LC lenses. Two LC lenses with different aperture sizes are studied. The tunable ranges of the electrically tunable pico projectors are $\sim$350 cm to $\sim$14 cm. The response times are $\sim$1.2 second for the LC lens of 2 mm aperture and around 5 second for the LC lens of 4 mm aperture. The response time depends on cell gap of the LC lens. Because no extra polarizer is used, the brightness of the projected image does not decrease dramatically by adopting an LC lens. However, the aperture size would affect the brightness of the image. To obtain the same tunable focusing range of the pico projectors, the LC lens with smaller aperture has better image quality and the fast response time due to the thinner cell gap was used, but the brightness decreases a lot. To increase the brightness of the image, we can use the LC lens with large aperture; however, the tradeoffs are the image quality and the response time. We believe that the achievements of this study open a new window for electrically tunable focusing pico projectors.

Acknowledgment

. . . The pico projectors were sponsored by Himax Display Inc. The authors are indebted to Dr. Kuan-Hsu Fan-Chiang (Himax Display Inc.), Dr. Jinn-Chou Yoo (Shinyoptics Corp.), and Dr. David Chao (Young Optics Inc.) and Dr. Chuan-Chung Chang (ITRI) for technical support and discussions. This research was supported by the National Science Council (NSC) in Taiwan under contract no. 98-2112-M-009-017-MY3.

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