A Pico Projection System With Electrically Tunable Optical Zoom Ratio Adopting Two Liquid Crystal Lenses

Yi-Hsin Lin and Ming-Syuan Chen

***Abstract*—A pico projection system with electrically tunable optical zoom ratio adopting two liquid crystal (LC) lenses is first demonstrated. The projected image of the system is not only continuously focused, but also zoomed simultaneously by adjusting the focal lengths of LC lenses electrically. The related optical principle is discussed and a liquid-crystal-on-silicon (LCOS)-based pico projection system was used to demonstrate the designed concept. This study opens a new window in realizing pico projectors with electrically tunable optical zooms.**

***Index Terms*—Liquid crystal (LC) lens, projection system, zoom system.**

I. INTRODUCTION

PICO PROJECTORS can generate a portable instant screen for portable devices such as cell phones, digital cameras, and tablet personal computers (PCs). Three kinds of pico projectors are in general: liquid-crystal-on-silicon (LCOS)-based pico projectors, digital light processing (DLP)-based pico projectors, and laser-scanning pico projectors [1]–[3]. Except laser-scanning pico projectors, LCOS-based projectors and DLP-based projectors are manually focused and require projection lenses for focusing the projected image in the plane of the observation. To obtain an electrically tunable focusing pico projector, we can use an electrically tunable liquid crystal (LC) lens as an active element [4], [5]. However, the projected image in such a projection system can not be magnified or reduced (i.e., zoom-in or zoom-out) when the position of the observation plane is fixed. Therefore, the pico projectors with electrically tunable optical zoom still need to be developed.

In this paper, a pico projection system with electrically tunable optical zoom ratio adopting two liquid crystal lenses is first demonstrated. We start from the related optical principles of the designed system and then we use LCOS-based pico projection system to demonstrate the designed concept. From the experiments, the projected image is focused and zoomed at the same time by adjusting the focal lengths of LC lenses electrically. This study opens a new window in realizing pico projectors with electrically tunable optical zooms.

II. STRUCTURE AND OPERATING PRINCIPLES

The designed pico projection system with electrically tunable optical zooms consists of a projection system including a microdisplay (MD) and a projection lens (PL), two LC lenses (L_1 and L_2), and an observation plane, as shown in Fig. 1. The focal length of the projection lens is defined as f_{pj}. The focal lengths of L_1 and L_2 are $f_1(V_1, V_2)$ and $f_2(V_3, V_4)$ which depends on the applied voltages V_1, V_2, V_3 and V_4. We assume that the distances between MD and PL, between PL and L_1, between L_1 and L_2, and between L_2 and observation plane are s, x, d, and q, respectively. The image distance for PL is $(p + x)$ in Fig. 1. According to the image equation, the relation between s and $(p + x)$ is

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

After light passes through L_1, the image distance for L_1 is $(d - r)$. The objective distance and image distance for L_2 are r and q, respectively. Therefore, two image equations for L_1 and L_2 can be expressed as

$$\frac{1}{-p} + \frac{1}{d - r} = \frac{1}{f_1(V_1, V_2)} \tag{2}$$

$$\frac{1}{r} + \frac{1}{q} = \frac{1}{f_2(V_3, V_4)}. \tag{3}$$

From (2) and (3), the relation between f_1 and f_2 can be expressed as follows:

$$f_1(V_1, V_2) = \frac{f_2(V_3, V_4) \cdot (q \cdot p - d \cdot p) - d \cdot p \cdot q}{f_2(V_3, V_4) \cdot (d - p - q) + q \cdot (d - p)} \tag{4}$$

The image on MD is inversed. Then, from (1) to (3), the image magnification (M) for PL, L_1 and L_2 are $(x + p)/s$, $-(d - r)/(-p)$, and $-(q/r)$, respectively. Thus, the total magnification (M) of the system is

$$M = \frac{x + p}{s} \times \frac{d - r}{-p} \times \frac{q}{r}. \tag{5}$$

After we rearrange (1)–(3), and (5), M can be expressed as

$$M = \frac{q \cdot (x + p) \cdot [-f_1(V_1, V_2) \cdot p / (f_1(V_1, V_2) + p)]}{s \cdot p \cdot [f_2(V_3, V_4) \cdot q / (q - f_2(V_3, V_4)]}. \tag{6}$$

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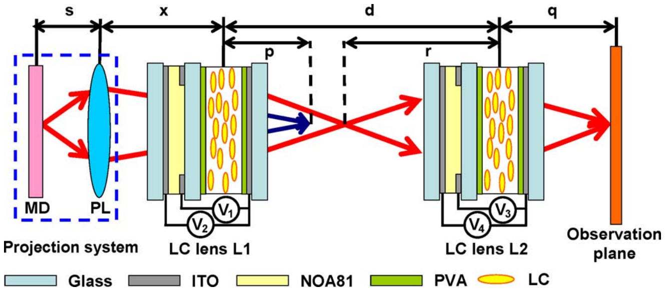

Fig. 1. The structure of the pico projection system. MD is microdisplay and PL is projection lens. $s = 22.05$ mm, $fpj = 21.92$ mm, and $x = 1$ cm.

This also means the magnification of the system depends on the focal lengths of LC lenses which are electrically tunable.

To further obtain the optical zoom ratio which is the ratio of maximum magnification to minimum magnification, we have to consider the constraints of the system. First, the projected image should be erect; as a result, M should be positive. Second, the focal lengths of L_1 and L_2 (i.e., f_1 and f_2) could be positive or negative due to two-mode switching, but are confined in a range [6]–[8]. In the experiment, the minimum focal length of the positive LC lens is usually shorter than minimum absolute value of focal length of the negative LC lens under two mode switching of a LC lens. After considering the constraints, when we adjust f_1 as a negative lens with a minimum absolute value of focal length (i.e., $|f_{\min} < 0|$), the system then has a minimum magnification $(M_{\min})$ which can be expressed as

$$M_{\min} = \frac{q \cdot f_{\min} \cdot (x+p)}{s \cdot (p \cdot f_{\min} - d \cdot f_{\min} - d \cdot p)}. \tag{7}$$

When f_2 equals to $f_{\min}$, the system has a maximum magnification $(M_{\max})$

$$M_{\max} = \frac{(x+p) \cdot (q \cdot f_{\min} + d \cdot f_{\min} - q \cdot d)}{s \cdot p \cdot f_{\min}} \tag{8}$$

$M_{\max}$ and $M_{\min}$ limit the range of the magnification of the projection system. The zoom ratio (ZR) of the projection system is the ratio of $M_{\max}$ to $M_{\min}$. From (7) and (8), the ZR turns out

$$ZR = \left(1 + \frac{d}{q} - \frac{d}{f_{\min}}\right) \cdot \left(1 - \frac{d}{p} - \frac{d}{f_{\min}}\right). \tag{9}$$

From (9), the zoom ratio of the system is related to four parameters: d, p, q, and $|f_{\min}|$. As a result, the zoom ratio only depends on the projected distance (q) when the system does not have mechanical moving elements (i.e., $d, p, |f_{\min}|$ are fixed numbers).

III. EXPERIMENTAL RESULTS AND DISCUSSION

To demonstrate the concept of the proposed pico projection system, we used a commercial LCOS-based pico projector (Himax, HX7027-3W50-May) which was manually focused. The pixel size of the pico projector was about 14 μm × 14 μm. The aperture size of the projection lens in LCOS-based pico projector was 11.28 mm. The structure of the LC lenses were based on two-voltage structure as shown in Fig. 1 [6]–[8]. We prepared two identical LC lenses. The structure of each LC lens consisted 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, a LC layer with a thickness of 50 μm, and mechanically buffered poly(vinyl alcohol) (PVA) layers within anti-parallel directions in order to align LC directors. The ITO layer of the middle ITO glass substrate was etched with a hole-pattern within a diameter of 1.5 mm in order to provide an inhomogeneous electric field to the LC directors. The MLC-2070 nematic LC mixture (Merck, $\Delta n = 0.26$ for $\lambda = 589.3$ nm at 20 °C) was used. Each LC lens was applied two voltages, as shown in Fig. 1. When $V_1 > V_2$ and $V_3 > V_4$, both of the LC lenses are positive lenses which means the focal lengths are positive. When $V_1 < V_2$ and $V_3 < V_4$, the LC lenses are negative lenses which means the focal lengths are negative. After we fabricated the LC lenses, the phase profiles of LC lenses at different applied voltages were observed under crossed polarizers. In the experiments, a laser diode with a wavelength (λ) of 532 nm was used as a light source. The rubbing direction of the LC lens was 45 deg with respect to one of the polarizers. The images of phase profiles were recorded, as shown in Fig. 2(a), and then were converted into the lens powers, defined as the inverse focal lengths [9], [10]. The converted voltage-dependent lens power of the LC lens L_1 is shown in Fig. 2(b). (We just show the results of one LC lens here.) The LC lens is operated as a positive lens with the switched lens power from 30.4 m^{-1} to 0 m^{-1} as $0 < V_2 < 80\ V_{\rm rms}$ at $V_1 = 80\ V_{\rm rms}$. The LC lens is operated as a negative lens with the switched lens power from -8.3 m^{-1} to 0 m^{-1} as $0 < V_1 < 40\ V_{\rm rms}$ at $V_2 = 40\ V_{\rm rms}$. From the experimental results, $f_{\min}$ is -12 cm which also indicates the lens power of -8.3 m^{-1}. The measured response time which is the sum of the rise time and the decay time is around 4 sec as we switched the voltages between the voltage pairs of $(V_1, V_2) = (80\ V_{\rm rms}, 80\ V_{\rm rms})$ and the voltage pairs of $(V_1, V_2) = (80\ V_{\rm rms}, 0\ V_{\rm rms})$. The response time can be improved by different driving methods [11], [12].

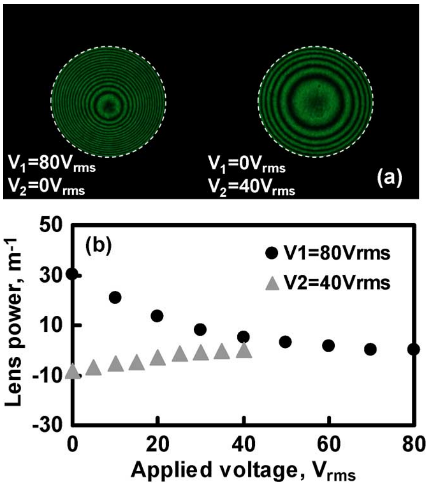

Fig. 2. (a)The phase profiles of LC lens under cross polarizers. (b) The lens power of the LC lens as a function of applied voltage V_1 when $V_2 = 40\ V_{\rm rms}$ (gray triangles) and the lens power of the LC lens as a function of applied voltage V_2 when $V_1 = 80\ V_{\rm rms}$ (black dots). $\lambda = 532$ nm.

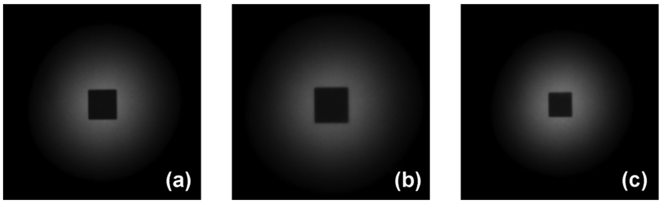

Fig. 3. Image performance of the projection system when $q = 50$ cm and $d = 2$ cm. (a) $M = 1$, $f_1 = \infty$ and $f_2 = \infty$. $s = 22.87$ mm. The system was manually focused. (b) $M = 1.15$, $f_1 = 12.1$ cm and $f_2 = -12$ cm. (c) $M = 0.8$, $f_1 = -12$ cm and $f_2 = 11.2$ cm. The zooming ratio is 1.44:1. In (b) and (c), s was 22.05 mm.

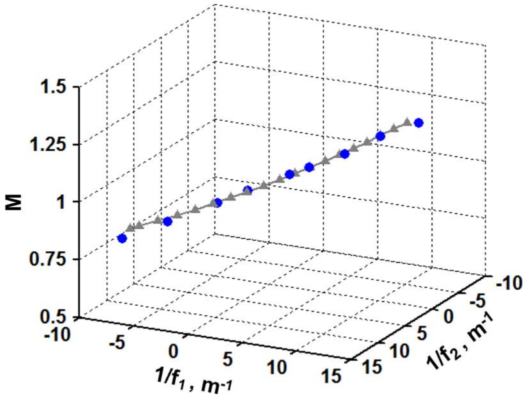

Fig. 4. Experimental magnifications and calculated magnifications as a function of the lens power $(1/f_1)$ of L_1 and of the lens power $(1/f_2)$ of L_2 when $q = 50$ cm and $d = 2$ cm.

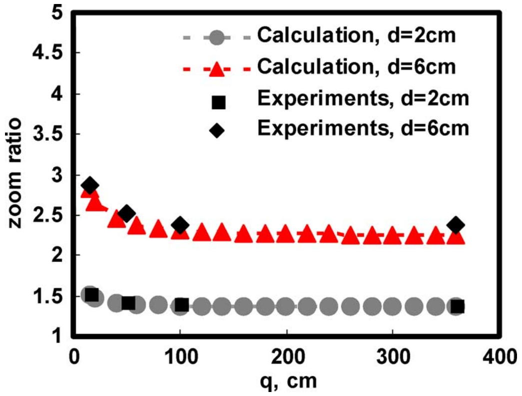

Fig. 5. Experimental zoom ratio and calculated zoom ratio as a function of projected image distance (q) at $d = 2$ cm and 6 cm.

To measure the projected image magnification of the system in Fig. 1, we attached one LC lenses (L_1) 1 cm away from the projection lens (i. e. $x = 1$ cm) and the distance between two LC lens was 2 cm (i.e. $d = 2$ cm). The rubbing directions of the LC lenses were parallel to the direction of linear polarized light which was the output light of the pico projector. We input an image of a back square to the microdisplay and projected the black square with the area of 0.54 mm × 0.54 mm. The distance between PL and MD in Fig. 1 was 22.87 mm (i.e. $s = 22.87$ mm). As a result, the projected image was focused at q of 50 cm when the lens powers of two LC lenses were zero (or no applied voltages to LC lenses). The projected image was shown in Fig. 3(a). The magnification in Fig. 3(a) was set as unity. For our pico projection system with electrically tunable optical zooms, s was set as 22.05 mm, so that the projected image was focused at 360 cm when two LC lenses were not applied any voltages. We then changed the applied voltages of L_1 and L_2 and recorded the images at $q = 50$ cm. When the focal length of L_1 was 12.1 cm and the focal length of L_2 was -12 cm, the magnification of the pico projector was the maximum ($\sim$1.15), as show in Fig. 3(b). When the focal length of L_1 was -12 cm and the focal length of L_2 was 11.2 cm, the magnification was the minimum ($\sim$0.8), as show in Fig. 3(c). Therefore, the zoom ratio of the pico projector for $q = 50$ cm was 1.44:1. By changing the focal lengths of L_1 and L_2, the magnification can be adjusted between 1.15 and 0.8. The focal lengths of L_1 and L_2 are determined by the applied voltages. The measured magnification of the pico projector as a function of $1/f_1$ and $1/f_2$ is shown in Fig. 4. (blue dots) In Fig. 4, the magnification is a continuously function of $1/f_1$ and $1/f_2$ between M of 1.15 and M of 0.8. This also means the magnification can be adjusted continuously between M of 1.15 and M of 0.8 by changing the focal lengths of two LC lenses. According to (2)to (8), the calculated magnification is plotted in Fig. 4. (gray triangles) The experimental results and calculated results agree well. Therefore, the electrically tunable magnification of the pico projector can be realized by two LC lenses and the magnification is limited by $f_{\min}$ of the LC lens.

To measure the zoom ratio at different projected image distance, we changed the location of the observation plane in Fig. 1 and repeated the measuring process as we mentioned above. The zoom ratio as a function of projected image distance (black squares and black diamonds) is shown in Fig. 5. In Fig. 5, the zoom ratio decreases from 1.53:1 to 1.39:1 for $d = 2$ cm with an increase of q. (black squares) To enlarge the zoom ratio, we can increase the distance between two LC lenses. When d is 6 cm and we increase q, the zoom ratio decreases from 2.87:1 to 2.37:1, as shown in Fig. 5. (black diamonds) According to (8), the calculated zoom ratio as a function of q is also plotted in Fig. 5 (gray dots and red triangles). The calculated results and experimental results agree well. Increasing d can enlarge the zoom ratio; however, the projection area decreases because the change of location of the field stop results in the reduction of the field of image. To further reduce d, the zoom ratio decreases, but we can increase the tunable range of the lens power of the LC lenses in order to maintain large zoom ratio and small d. To obtain large projection area meanwhile maintain the large zoom ratio, the aperture size of LC lenses should be enlarge. When the aperture size of LC lenses increases, we have to increase the birefringence of liquid crystals or thickness of LC layers in order to obtain the same lens power of LC lenses. The composite LC lens which adds a polymeric lens into the LC lens could be a solution to enlarge the zoom ratio [10].

To evaluate the influence of the chromatic dispersion of LC materials, we measured the refractive index of MLC-2070 at two different wavelengths using Abbe interferometer. The measured n_e is 1.864 and n_o is 1.567 at the wavelength of 450 nm. The measured n_e is 1.768 and n_o is 1.513 at the wavelength of 650 nm. When the wavelength changes from 450 to 650 nm, $f_{\min}$ changes from -11.3 cm to -13.4 cm. From (9), the zoom ratio changes from 1.424:1 to 1.359:1 with the parameters: $d = 2$ cm, $q = 50$ cm, and $p = 360$ cm. Thus, the chromatic dispersion of LC materials in the visible range results in the ZR variation of 0.065.

IV. CONCLUSION

We have demonstrated a pico projection system with electrically tunable optical zoom ratio adopting two liquid crystal lenses. Such a pico projection system can be continuously focused and zoomed at the same time by adjusting the applied voltage of LC lenses. The zoom ratio depends on the projection distance. The related optical principle is also discussed. The size of projected image of our designed pico projection system can be changed electrically without the change of the position of the observation plane. With the electrically optical zoom, the pico projector does not need to change the position of the observation plane in order to obtain the magnification or reduction of the projected image. We here use LCOS-based pico projection system to demonstrate the concept. As to DLP-based pico projection systems whose output light is unpolarized, we can still realize a pico projection system with electrically tunable optical zoom ratio by using LC lenses; however, four LC lenses are needed. We need two pairs of identical LC lenses. The rubbing directions of one pair of LC lenses are orthogonal in order to obtain polarization independent LC lenses. We believe this study opens a new window in realizing pico projectors with electrically tunable optical zoom.

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