AIP | Applied Physics Letters

A fast response and large electrically tunable-focusing imaging system based on switching of two modes of a liquid crystal lens

Hung-Chun Lin and Yi-Hsin Lin

Citation: Applied Physics Letters **97**, 063505 (2010); doi: 10.1063/1.3479051
View online: http://dx.doi.org/10.1063/1.3479051
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/97/6?ver=pdfcov
Published by the AIP Publishing

A fast response and large electrically tunable-focusing imaging system based on switching of two modes of a liquid crystal lens

Hung-Chun Lin and Yi-Hsin Lin[a)]
Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan

(Received 30 June 2010; accepted 20 July 2010; published online 10 August 2010)

We demonstrated a fast response and large tunable focusing imaging system consisting of a lens module and a liquid crystal (LC) lens based on the switching of two modes of a LC lens: the negative LC lens and positive LC lens. By discarding the conventional operation of a positive LC lens only in the imaging system, large tunable focusing range can be achieve from 300 to 10 cm owning to the phase change between the positive and the negative LC lens; meanwhile, the response time is fast (~433 ms). The potential applications are autofocused cell phones, and cameras. [doi:10.1063/1.3479051]

Electrically tunable-focusing imaging system using a liquid crystal (LC) lens has many potential applications, such as cell phones, cameras, and the night vision of hand-carried weapons. Compared to the autofocusing image system within mechanical moving parts, such as controlling the location of a lens module by voice coil motors, the advantages of electrically tunable-focusing imaging system using a LC lens are compact, light weight, and low power consumption. The electrically tunable focal length of LC lenses results from the gradient distribution of refractive indices due to the orientations of LC directors.[1–8] However, several problems of LC lenses need to be overcome. The requirement of a polarizer of LC lenses results in a low optical efficiency (~50%). Polarizer-free LC lenses are developed using different LC modes.[9] Under conventional operation of a positive LC lens only in the imaging system, the tunable focusing ranges of LC lenses are usually small because the tunable focusing ranges are determined by the phase changes of the LC lenses which depend on the birefringence of LC materials and the thickness of a LC layer. Generally, the birefringence of LC materials is small around ~0.1–0.44.[10,11] To enlarge the tunable focusing ranges of LC lenses, we can increase the thickness of a LC layer (~130 μm); nevertheless, the response time is slow (~50 s).[4] Complex electrode designs and driving schemes can reduce the response time but are not suitable for practical applications.[3,4] Ye *et al.*[12,13] showed the engineering performance of the image formation by operating the LC lens in positive and negative modes. However, the tunable focusing range is small (25 to 56 cm or 5 to 12 cm) and response time is still slow (~1.8 s). Nevertheless, the physical mechanism of two mode switching is not clearly discussed.

In this paper, on the basis of switching of two modes of a LC lens, we demonstrate a fast response time and a large tunable focusing range of an imaging system consisting of a lens module and a LC lens. By discarding the conventional operation of a positive LC lens only in the imaging system, we found that we can obtain the large tunable focusing range by the phase changes resulting from switching of two modes: the negative LC lens and the positive LC lens. The main mechanism is based on the phase change between positive and negative LC lens to achieve the large tunable focusing meanwhile maintaining the thin thickness of the LC layer. In this way, the object can be continuously imaged from 300 to 10 cm; however, the thickness of the LC lens is 25 μm to achieve the fast response time (~433 ms). The potential applications are autofocused cell phones and cameras.

To understand how to achieve a fast response time and a large tunable focusing range of an imaging system, an illustration of wave propagation in the image system consisting of a lens module and a LC lens is shown in Fig. 1. LC lenses are the phase modulators of light based on inhomogeneous refractive indices of a LC lens originating from the orientations of LC directors controlled by the electric fields in the LC lens. As a result, a LC lens can converts the radius of curvature of wave front. The focal length of the LC lens depending on aperture size (w), wavelength, (λ), and phase difference, (Δδ), can be expressed as follows:[1–8]

$$f_{\mathrm{LC}} = \frac{\pi \times w^2}{4 \times \lambda \times \Delta\delta}. \quad (1)$$

In Fig. 1, the objective distance is p and the image distance is q. When $p \gg \mathrm{w}$, the parabolic-incident wave $[\vec{E}_1(x,y,z)]$ arriving in front of the lens at the plane C can be expressed as follows:

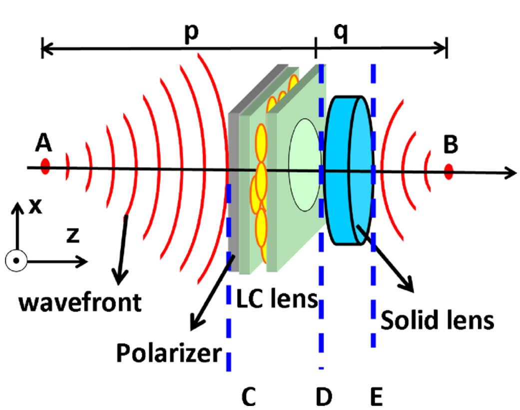

FIG. 1. (Color online) The image formation of a combination of a LC lens and a solid lens. A is the location of the objective, B is the location of the image, p is the objective distance and q is the image distance.

a)Electronic mail: yilin@mail.nctu.edu.tw.

$$\vec{E}_1(x,y,z) = \vec{E}_0 \cdot e^{-jk(x^2+y^2/2p)} \cdot e^{-jk \cdot z}, \quad (2)$$

where $\vec{E}_0$ is amplitude vector and k is the wave number. Under Fresnel approximation,[14] the output wave right after the solid lens at the plane E can be expressed as follows:

$$e^{jk(x^2+y^2/2q)} = e^{-jk(x^2+y^2/2p)} \cdot e^{jk(x^2+y^2/2f)} \cdot e^{jk(x^2+y^2/2f_{LC}(V))}, \quad (3)$$

where f is the focal length of the solid lens and $f_{LC}(V)$ is the voltage-dependent focal length of the LC lens. In an autofocusing imaging system, q is a fixed number determined by the location of an image sensor, and p should be adjusted from infinity to some distance (p_0) depending on the applications. As p changes, $f_{LC}(V)$ have to be adjusted accordingly by the applied voltages in order to maintain the relation in Eq. (3). In Eq. (3), when q equals to f, p equals to $f_{LC}(V)$. That means the tunable focusing range of the LC lens determines the tunable objective distance in the whole imaging system. Theoretically, when the imaging system should be eligible for the object at the infinity to p_0, $f_{LC}(V)$ should be positive and also be tunable from infinity to p_0. However, to obtain such a LC lens, the LC layer of the LC lens must be thick ($\sim$130 μm) whose response time is slow ($\sim$50 s) which is not suitable in most of electro-optical applications.[4]

By reconsidering Eq. (3), we can set the image distance not to equal to f. When $f_{LC}(V) \gg 0$, the image formation is determined by the solid lens and then Eq. (3) turns out

$$e^{jk(x^2+y^2/2q)} = e^{-jk(x^2+y^2/2p_s)} \cdot e^{jk(x^2+y^2/2f)}, \quad (4)$$

where p is defined as p_s. Compared Eq. (4) with Eq. (3), the relationship among p, p_s, and $f_{LC}(V)$ is as follows:

$$e^{-jk(x^2+y^2/2p_s)} = e^{-jk(x^2+y^2/2p)} \cdot e^{jk(x^2+y^2/2f_{LC}(V))}. \quad (5)$$

In Eq. (5), when $p_s < p < \infty$, the focal length of the LC lens should be negative. That means the LC lens should be operated as a negative (or concave) lens. When $0 < p_0 < p < p_s$, the focal length of the LC lens should be positive. That means the LC lens should be operated as a positive (or convex) lens. Therefore, by switching two lens modes of a LC lens: a positive lens and a negative lens, the conjugated image can be formed in point B in Fig. 1 when p is adjusted from infinity to p_0. The value of p_0 is dependent on the applications. The large tunable focusing range can thus be achieved. Moreover, the thickness of the LC layer can be reduced since the phase changes resulting from two lens modes, not single positive LC lens only. Therefore, the response time can be fast; meanwhile, the tunable range of the imaging system is still large.

To demonstrate the concept, we adopted the LC lens based on two-voltage structure which can be operated as a positive lens and a negative lens.[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 thickness of 35 μm, and a LC layer with thickness of 25 μm. The ITO layer of the middle ITO glass substrate was etched with a hole-pattern within a diameter of 2 mm in order to provide an inhomogeneous electric field to LC directors, and the opposite side of such an ITO glass substrate was coated with mechanically buffed polyvinylalcohol layer to align LC directors. The bottom ITO glass substrate was also coated with an alignment layer with mechanically buffed polyimide layer. The rubbing directions of two alignment layers are antiparallel. The nematic LC mixture MLC-2070 (Merck, $\Delta n = 0.26$ for $\lambda = 589.3$ nm at 20 °C) was used. The voltage applied between the hole-patterned ITO and the bottom ITO layer was defined as V_1. The other applied voltage was defined as V_2. When $V_1 > V_2$, the LC lens is operated as a positive lens. When $V_1 < V_2$, the LC lens is operated as a negative lens. In the experiments, the laser diode ($\lambda = 532$ nm) was used as a light source. A polarizer whose transmissive axis was parallel to the rubbing direction of the LC lens was attached on the LC lens. The measured focal length can be switched from infinity to 16.5 cm under the operation of the positive lens when we apply a voltage of V_2 at $V_1 = 90$ V_{rms}. As to the operation of the negative lens, the absolute value of the measured focal length can be switched from infinity to 20.8 cm when we apply a voltage of V_1 at $V_2 = 90$ V_{rms}.

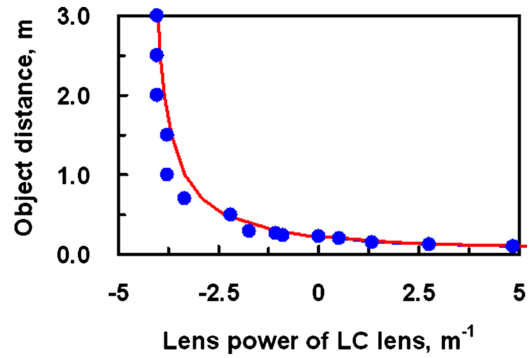

FIG. 2. (Color online) The objective distance of the imaging system as a function of the lens power of the LC lens. Blue dots represent the measured results and the red line represents the calculated result.

To measure the tunable focusing properties of the imaging system, the LC lens and a polarizer were attached on a webcam (Logitech Pro 9000). The webcam consists of a lens module with the effective focal length of 3.7 mm and an image sensor with 2 megapixels. After adjusting the location of the image sensor, the image sensor was placed 3.76 mm behind the lens module. According to Eq. (5), the p_s should be 23 cm without a LC lens. After attaching the LC lens with the polarizer on the webcam, we recorded the objective 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 0.625 line pair per millimeter (lp/mm) at $p = 10$ cm and 0.05 lp/mm at $p = 300$ cm. The measured objective distance as functions of lens power of the LC lens is shown in Fig. 2. The lens power is defined as the inverse of the focal length. In Fig. 2, the conjugated image can be obtained as the object at $p = 300$ cm to 10 cm while the LC lens changes the lens power from -4 and 4.85 m^{-1}. In our imaging system, we adopt two lens mode operation to image the object from 300 to 10 cm. We can calculate the objective distance as a function of the lens power of the LC lens and plotted in Fig. 2 (red solid line) based on Eq. (5). The measured results and calculated results are agreeable.

To measure the response time of the imaging system, we measured the response time of the LC lens. When the focal length of the LC lens is switched between -24.9 and 20.6 cm, the response time was 172 ms as the voltage pair switched from $(V_1, V_2) = (15\ V_{rms}, 90\ V_{rms})$ (i.e., $f_{LC} = -24.9$ cm) to $(V_1, V_2) = (90\ V_{rms}, 20\ V_{rms})$ (i.e., f_{LC}

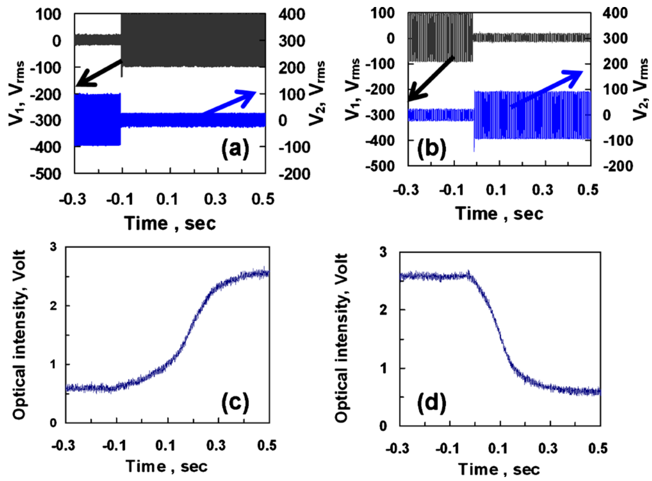

FIG. 3. (Color online) The measured response time of the LC lens. (a) When the voltage pair is switched from $(V_1,V_2)=(15\ V_{rms},90\ V_{rms})$ to $(V_1,V_2)=(90\ V_{rms},20\ V_{rms})$, (c) the measured response time of the LC lens is around 172 ms. (b) When the voltage pair is switched from $(V_1,V_2)=(90\ V_{rms},20\ V_{rms})$ to $(V_1,V_2)=(15\ V_{rms},90\ V_{rms})$, (d) the measured response time of the LC lens is around 261 ms. $\lambda=532$ nm.

$=20.6$ cm) and 261 ms from $(V_1,V_2)=(90\ V_{rms},20\ V_{rms})$ (i.e., $f_{LC}=20.6$ cm) to $(V_1,V_2)=(15\ V_{rms},90\ V_{rms})$ (i.e., $f_{LC}=-24.9$ cm). The results are shown in Figs. 3(a)–3(d). That means when the object distance is changed between $p=300$ cm and $p=10$ cm, the total response time is 433 ms, compared to conventional lens operation mode, the response time is ~50 s. Our image system under two lens mode operations not only has 100× faster response time but also has large tunable focusing range and is suitable for applications of cell phones and cameras which require response time of 500 ms in general. The fast response time is because of two reasons: one is the thin LC layer (~25 μm) and the other is the voltage effect instead of the slow free-relaxation of LC directors.[11] To further improve the response time, we can reduce the viscosity of LC materials, reduce the thickness of the LC layer or add polymer networks to enhance the anchoring force.[11]

Figures 4(a)–4(c) show the image performances of the imaging system consisting of a polarizer, the LC lens, a lens module, and the image sensor. The photos were taken under an ambient white light. The numbers in the photos indicate the locations of the objects. When we switched the voltage pair from $(V_1,V_2)=(15\ V_{rms},90\ V_{rms})$ to $(90\ V_{rms},90\ V_{rms})$ to $(90\ V_{rms},20\ V_{rms})$, the clear image was at 300, 23, and 10 cm. In Fig. 4, the image is sharpest at 23 cm because the lens power of the LC lens is 0. As a result, the image quality is determined by lens module. The image is slightly blurred at 10 cm because of the aberration of the LC lens when the LC lens has maximal lens power ($\sim 5\ m^{-1}$).

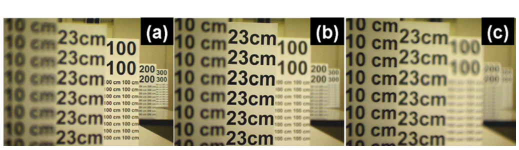

FIG. 4. (Color online) Image performance of the imaging system. The clear image for the objective distance of (a) 300 cm, (b) 23 cm, and (c) 10 cm. See Ref. 15.

In conclusion, we have demonstrated a fast response and large electrically tunable-focusing range of an imaging system based on the LC lens based on two lens mode switching. The object can be continuously imaged when the object is at 300 to 10 cm. The response time is around 433 ms. By operating two modes of LC lens: the negative lens and positive lens, the phase changes of the LC lens are sufficient to perform the image formation as an object is at 300 to 10 cm despite the thickness of the LC layer is only 25 μm. The thin LC layer helps to achieve the fast response time. Such a fast response and large electrically tunable-focusing range of an imaging system is usable in autofocusing cell phones and cameras.

The authors are indebted to Mr. Chuan-Chung Chang (ITRI) for the technical assistance. This research was supported by the National Science Council (NSC) in Taiwan under the Contract No. 98-2112-M-009-017-MY3.

[1] S. Sato, Jpn. J. Appl. Phys. **18**, 1679 (1979).
[2] H. Ren, Y. H. Fan, S. Gauza, and S. T. Wu, Appl. Phys. Lett. **84**, 4789 (2004).
[3] M. Ye and S. Sato, Mol. Cryst. Liq. Cryst. **433**, 229 (2005).
[4] B. Wang, M. Ye, and S. Sato, Opt. Commun. **250**, 266 (2005).
[5] Y. H. Lin, H. Ren, K. H. Fang-Chiang, W. K. Choi, S. Gauza, X. Zhu, and S. T. Wu, Jpn. J. Appl. Phys., Part 1 **44**, 243 (2005).
[6] Y. H. Fan, H. Ren, X. Liang, H. Wang, and S. T. Wu, J. Disp. Technol. **1**, 151 (2005).
[7] B. Wang, M. Ye, and S. Sato, IEEE Photonics Technol. Lett. **18**, 79 (2006).
[8] H. Ren, D. W. Fox, B. Wu, and S. T. Wu, Opt. Express **15**, 11328 (2007).
[9] Y. H. Lin, H. Ren, and S. T. Wu, Liq. Cryst. Today **17**, 2 (2008).
[10] S. Gauza, H. Wang, C. H. Wen, S. T. Wu, A. J. Seed, and R. Dabrowski, Jpn. J. Appl. Phys., Part 1 **42**, 3463 (2003).
[11] S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays* (Wiley, New York, 2001).
[12] M. Ye, B. Wang, S. Yanase, and S. Sato, IEICE Trans. Electron. **91-C**, 1599 (2008).
[13] M. Ye, B. Wang, M. Kawamura, and S. Sato, Jpn. J. Appl. Phys., Part 1 **46**, 6776 (2007).
[14] B. E. A. Saleh and M. C. Teich, *Fundamentals of Photonics* (Wiley, New York, 2007).
[15] See supplementary material at http://dx.doi.org/10.1063/1.3479051 for movie files of the image performance of the imaging system.