Microsecond Switchable 8-Focus Artificial Ferroelectric Liquid Crystal Lenses for Virtual Reality

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Abstract

In this paper, we propose a fast switchable lens system with multiple focal points. Specifically, the combination of the Electrically Suppressed Helix Ferroelectric Liquid Crystal (ESHFLC) based polarization rotator and a passive polarization-dependent LC lens can switch the focal points at high speed (50µs). Moreover, a cascaded assembly of 3 such lens units shows 8-focal points, with a fast response time of 50µs. This device shows promising potential for VR and depth-mapping.

Keywords

Fast-switchable multi-focus lenses system, Ferroelectric liquid crystal lens, Virtual reality

1. Introduction

For the AR/VR application, a fast switchable lens without optical defects can be a key to solve some of their critical limitations, for instance, small Front of View (FOV), limited depth of field (DOF) and perceptual distortions. Various liquid crystal lenses are proposed to solve the problems due to its merits like larger aperture ratio, high efficiency, and optical isotropy. However, bottleneck still exists, ranging from the color dispersion, slow response and low resolution induced by fringe field effect [1][2].

In this article, we disclose a switchable lens device having a combination of the fast FLC based polarization rotation unit and a passive polarization-dependent LC lens. A cascaded combination of three such lens units generate 8 different focal points at a speed of 50 μs. This device shows promising potential in VR, depth-mapping and optical trapping applications.

2. Experiment

2.1 ESHFLC based fast switchable multi-focus LC lenses

Electrically Suppressed Helix Ferroelectric Liquid Crystals (ESHFLCs) show extremely fast switching with no hysteresis, no fringe filed effect, good electro-optic performance, and shock stability[5]. These benefits offer it a promising potential to be used as polarization rotator or shutter in combination with a polarization-dependent passive LC lens for blossoming applications[6][7]. The ESHFLC show binary electro-optical operations and need small driving voltage of ~5 V. The switching time for the half waveplate ESHFLC at this driving voltage is in the range of 50-100 µs. Thus, the ESHFLC unit may work for the polarization rotation unit. The out-going light from the ESHFLC cell and polarization-dependent lens in the two states (i.e., E_{out1} and E_{out2}) can be written in the form of Jones matrix:

$$E_{out} = M_{Lense}.M_{FLC}$$

$$= \begin{bmatrix} e^{-j\varphi(x,y)} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{-j\sigma} & 0 \\ 0 & e^{j\sigma} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} e^{-j\varphi(x,y)} \\ 0 \end{bmatrix} E_{in}. \quad (1)$$

where $\sigma = \frac{\pi \Delta n d}{\lambda}$, M_{Lense} and M_{FLC} is the Jones matric representation of the LC lenses and ESHFLC rotation unit for light propagation. θ is the angle between the polarizer and the direction of the FLC molecular. A combination of polarization-dependent LC lens and an ESHFLC cell provides two focuses in the binary fashion. As shown in Figure. 1(a) –(b), the unpolarized light gets polarized after passing through the polarizer. The ESHFLCs have two switching positions. When the polarization azimuth of the polarized light is parallel to one of the two switching positions. The light then sees the LC lens and the UV glue template as one block having RI and passes through without focusing (Figure. 1(b)). Following this theory, for N combination units, the lens has 2^N focal points that can switch with µs switching time. In this proposal, 3 lens stages can generate 8-focal points at high speed, which providing a possible solution to the vergence-accommodation conflict of VR system. Furthermore, the small form factor of the lens offers it high flexibility in assembling for imaging and non-imaging systems.

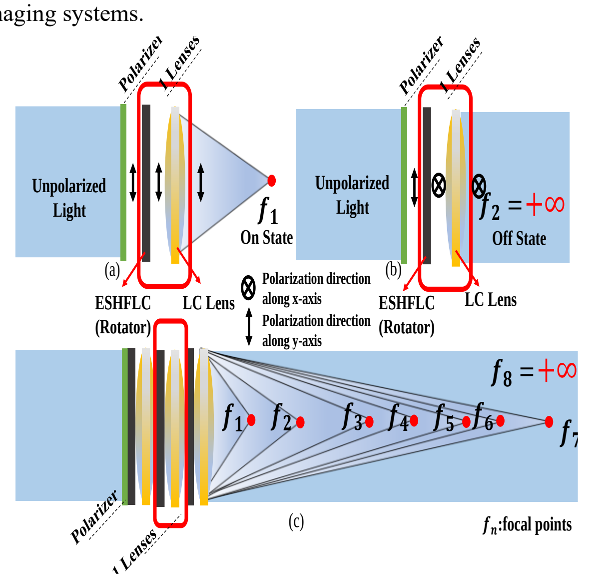

Figure 1. The schematic for focusing state at (a) on and (b) off state of the FLC rotator. (c). The schematic for assemble of 3 units

with 8 switchable focal points.

*2.2 F*abrication Process

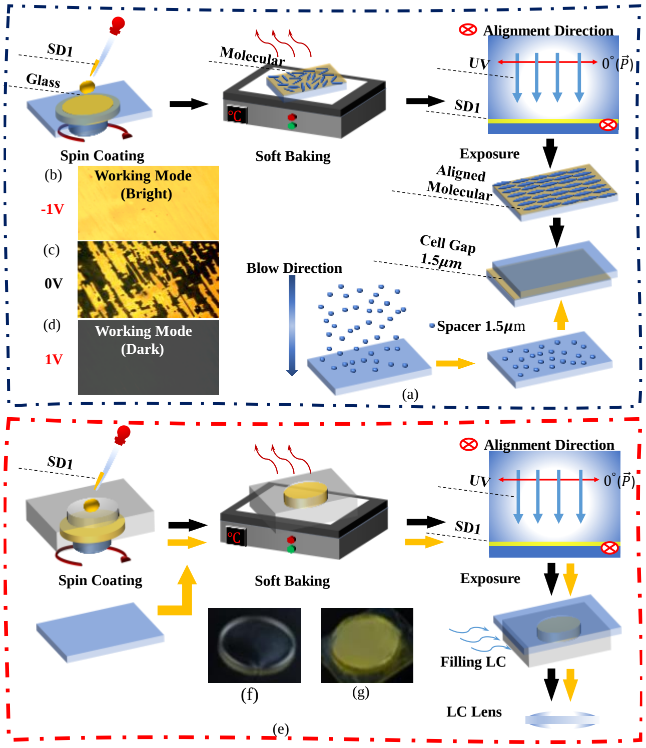

Figure 2. (a). The fabrication process of ESHFLC polarization state rotator. (b). The POM (Polarizer optical diagram) of bright state for ESHFLC rotator at -1V. (c). The POM (Polarizer optical diagram) for ESHFLC rotator when no voltage applied. (d) The POM (Polarizer optical diagram) of dark state for ESHFLC rotator at 1V. (e). The fabrication process of passive LC lens. (f). The dark state of LC lens. (g). The bright state of LC lens.

The ESHFLC polarization rotation unit is fabricated by coating both the glass substrates with SD1 after exposing the substrates to UV ozone (Figure. 2 (a)) [8][9]. The cell is then assembled. The thickness of the cell is maintained at 1.5 µm by the glass spacers. Lastly, the cell is filled with ESHFLC based on capillary phenomenon. The ESHFLC is characterized by high contrast ratio and fast microsecond response. As shown in Figure. (b)-(d), ESHFLC shows no hysteresis and defect at working mode. Fabrication of the lens is shown in Figure. 2. The lens is fabricated using a PDMS mold, which was fabricated using the glass lens. Three different concave glass lenses of the focal length of 1 m, 3 m, and 5 m have been used to fabricate the mold. The two states of LC lens is shown in Figure.2(g)-(f). The schematics of the lens unit consisting of the LC polarization-dependent lens, FLC polarization rotation cell, and the polarizer is shown in Figure. 3 (a). When the ESHFLC cell is switched under the electric field, the FLC molecules switch between the two states (Figure. 3(b)). These two states are symmetric along the alignment directions. To achieve the 0 to $\pi/2$ phase difference, one of the two switching positions is aligned with the polarization azimuth of the impinging light. Thus, in one state, the ESHFLC cell works as a half waveplate and rotates the polarization azimuth of the impinging light by 90º, while in the second state, it does not affect the impinging light. Under crossed polarizers, both the states can be seen in Figure. 2(g)(f). The response time of the FLC has been characterized. At 500 Hz frequency, switching time of the FLC is ~50µs at low driving voltage of 10V (Figure 3(c)).

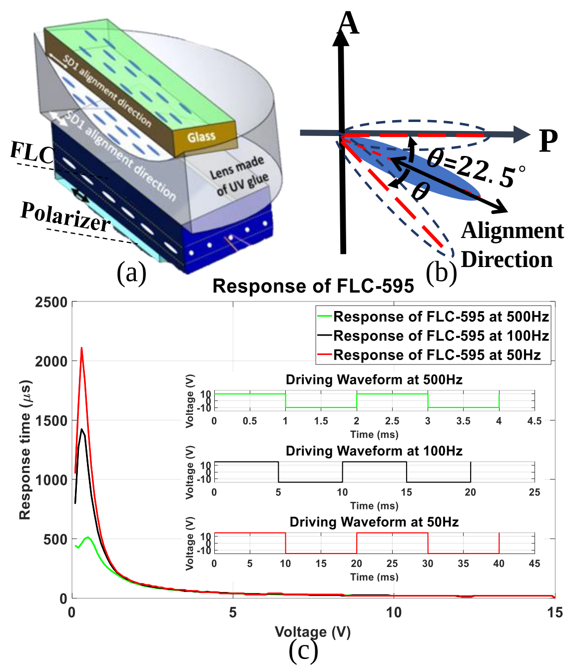

Figure 3 (a) The structure and the alignment direction of a single lenses. (b) The switching of the FLC molecules with respect to the polarizer. (c)The response time of ESHFLC, which is 50μs at 5V.

Moreover, to suppress the reflection losses, the ESHFLC cell and the LC lens are glued using the index-matching liquid. The refractive index of the glue is 1.44. The refractive index of glass is 1.5, and the refractive index of the cured UV glue is 1.56. The transmission is 100% for the bare glass. The single lens and ESHFLC interface, through the air, shows the transmission of around 85%. The addition of index matching liquid between the two units improves the reflection losses and results in the transmission of ~96%. The ESHFLC polarization rotation units are driven using Arduino Mega. Each FLC cell is individually driven to achieve the switching sequence shown in Table.1. The 0 in truth table represents off-state of the FLC rotator. The 1 represents the on state of the FLC rotator. For example. 1 for Lenses 2 means it is focusing and 0 means defocusing.

3. Results

The mechanism of lensing for a combination of a polarizer, ESHFLC polarization rotation unit and the polarization dependent LC lens is shown in Figure. 1 (a)-(b). The unpolarized light gets polarized after passing through the polarizer. As the polarized light impinges onto the ESHFLC cell, based on the states of the ESHFLC molecule, the polarization azimuth of light could be tuned at a fast speed. If this polarization is aligned with the optic axis of the polarization-dependent LC molecules in the lens, the refractive index is 1.732. This is the extraordinary refractive index, $n_{e,}$ which is different from the refractive index of the LC lens material. The refractive index of cured UV glue is 1.56. This higher refractive index results in the lens effect. The focal length of the lens is given by

$$f = \frac{r^2}{2d\Delta n}. \quad (3)$$

Where, f is the focal length, r is the radius of curvature, d is the thickness of the lens and Δn is the birefringence.

Table 1. Truth table of working state for 3 lenses

State of each lenses (1: on state; 0: off state)			Output f (m)
$f_1 = 2m$	$f_2 = 2m$	$f_3 = 2m$	
0	0	0	∞
0	0	1	5.0
0	1	0	3.0
0	1	1	1.9
1	0	0	2.0
1	0	1	1.4
1	1	0	1.2
1	1	1	1.0

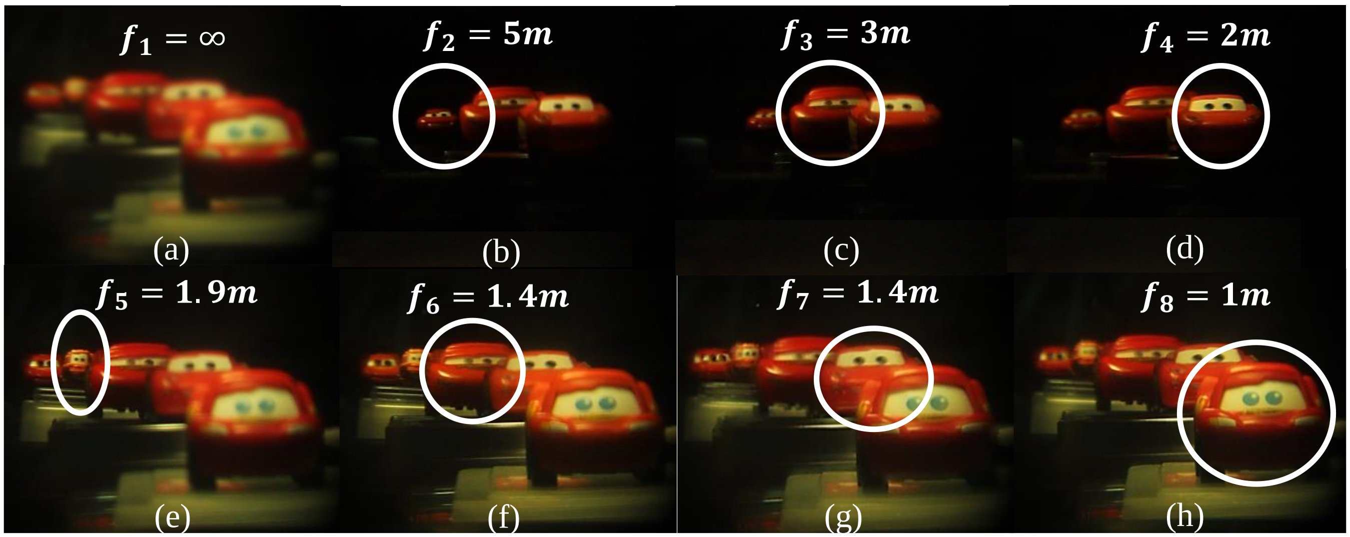

Figure 4. (a)-(h). The defocusing and focusing effect of the FLC lenses. .

When the ESHFLC molecule is switched to the first switching position (Figure. 3(b)), since the ESHFLC cell acts as a half wave plate, a nearly 90° rotation of the polarization azimuth direction is achieved. The polarization direction is perpendicular to the optic axis of the LC molecules in the polarization-dependent lens unit that manifest the ordinary refractive index (n_o). The n_o of the NLC used is 1.52. This is close to the refractive index of the cured UV glue. The light passing through the device regards the NLC and the lens as one refractive index and hence no lensing occurs. As shown As discussed before each unit of a FLC and a lens produces 2^N states. Using a combination of 3 FLC cells and 3 LC lens successively in a cascading pattern, along with a polarizer, 8 focuses can be obtained. When lenses with focal length of 2 m, 3 m, and 5 m are used, the corresponding focal lengths can be obtained from the truth table. To evaluate the performance of the combination, firstly, three objects at distances of 2 m, 3 m and 5 m have been placed. As shown in Figure 5, three focal planes have been separately accessed. Secondly, 5 objects are placed at distance 2m, 1.9m, 1.4m and 1m. Moreover, the speed of these switching focal planes are $50\mu s$.

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