Fast refocusing liquid crystal lens

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Keywords: FLC, adaptive optics, switchable lens

ABSTRACT

Optical devices like Virtual Reality (VR) headsets present challenges in terms of vergence accommodation conflict. To solve these challenges a fast switching device which uses ferroelectric liquid crystal (FLC) cell, response time in the micro-second range and a passive polarization dependent Liquid Crystal (LC) lens, is being presented in our studies.

1 INTRODUCTION

The vergence accommodation conflict (VAC) experienced in VR headsets present new challenges. In case of the normal vision, the vergence distance is the same as the accommodation distance. However, in case of headsets, when the display is fixed, the vergence distance may differ from the accommodation distance [1,2]. To overcome these challenges, several competing technologies have been tried. They include volumetric display and holographic displays. While in volumetric displays, occlusion is a challenge [3]. In case of holographic displays, wave front reconstruction and monochromatic light source makes applications difficult [4].

Another solution is to use lenses to create several focal points. Continuous focal length tunability has been tried using LC lenses. The liquid crystal used is mostly nematic liquid crystal (NLC). The response time of NLC is in the millisecond range [5]. To reduce the response time dual frequency LC has also been tried as the lens material. However, at high frequency it leads to dielectric heating causing performance degradation [6]. Polymer stabilized LC (PDLC) nano droplets have switching time in hundreds of micro-seconds range, but they require very high voltage to switch [7]. Optically isotropic materials like Blue Phase LC (BPLC) has also been tried [8]. They have limitations in the temperature range they can be used. Polymer stabilized BPLC is another option which makes the switching in the microsecond range but are not the fastest [9].

An effort to use solve these challenges has been to use a passive LC lens and a polarization rotation unit. Several polarization rotation units have been reported including twisted nematic (TN) cells [10] as well as OCB cells [11]. While TN cells have a response time in the scale of several milliseconds, the OCB cells have a lower response time in comparison. The response time of a human eye is 13 milliseconds [12]. Thus a response in the micro-second range will produce the least fatigue. Electrically suppressed helix ferroelectric liquid crystals (ESHFLCs) have shown extremely fast switching [13-15] and has a response time of 10 micro-second when 5V is applied. A combination of LC lens and a FLC cell provides two focuses. N such combinations provide 2^N focuses. When N=2, we have 4 focuses (Fig. 1).

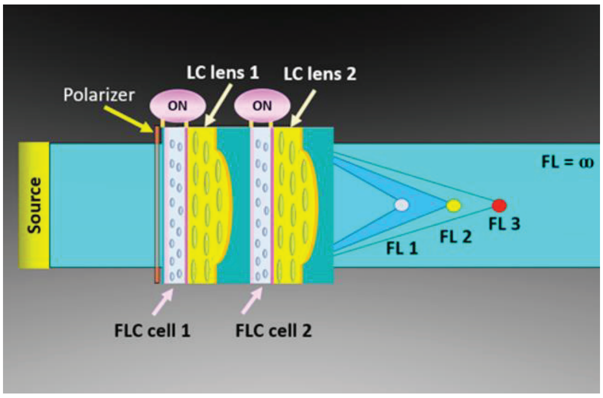


Fig. 1. Proposed structure consisting of a FLC cell and LC lens. The schematics show two such units, along with a polarizer, and four focal lengths (FLs) generated by it.

2 EXPERIMENT

Fabrication of the lens is carried out using a PDMS mold, created out of the glass lens. Three different concave glass lenses have been used to create three corresponding concave lenses of focal length 1m, 3m and 5m. Using a PDMS mold, the concave lens is created using a concave glass lens. The final lens is made of UV curable glue. The thickness of the fabricated lens is 1.3 mm.

The fabricated lens is then coated with alignment layer of 1% Sulphonic dye (SD1) (purchased from Dai-Nippon Ink and Chemicals) dissolved in ethylene glycol and spin coated. Ramp up speed is 800 rpm for 5 secs and spin speed is 2000 rpm for 30 secs (Fig. 2(a)). The coated lens is then dried (Fig. 2(b)), assembled (Fig. 2(c)), aligned with Linear Polarized UV (LPUV) (Fig. 2(d)), and filled with nematic LC (NLC) using vacuum (Fig. 2(e)).

The FLC cell is similarly fabricated by coating both the glass substrates with SD1 after exposing the substrates to UV ozone. 1% SD1 in ethylene glycol is spin coated onto the substrates. The spin speed is 3000 rpm. The SD1 is dried and aligned using UV (Fig. 2 (g)). The cell is then assembled. The thickness of the cell is 1.5 µm and spacers are used to create the cell gap (Fig. 2(h)). The cell is then filled (Fig. 2(i)).

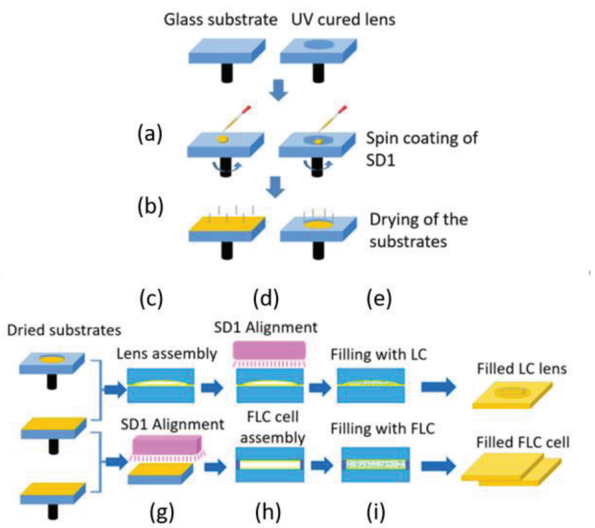


Fig. 2. The fabrication steps have been shown (a) SD1 is spin coated on both the glass substrates and the lens prepared using UV curable glue (b) Both the substrates are dried using the hot plate at 40°C (c) The lens is assembled using the coated glass and cured UV glue substrates (d) Alignment of SD1 is done using UV of wavelength 360nm (e) The assembled lens is filled with LC under vacuum (g) SD1 in both the coated glass substrates are aligned using UV of wavelength 360nm (h) The substrates are assembled with the coated surfaces facing each other (i) The cell is filled with FLC (j) The filled FLC cell

The FLC mode used here is ESHFLCs. When the FLC cell is switched using an electric field, the FLC molecules switches between two positions (Fig. 3(a)). These are position 1 and position 2. Both positions are symmetric to the alignment direction. When the molecule is at position 1, the FLC cell under crossed polarizers appear bright. While it appears dark when the molecule is at position 2 (Fig. 3(b)). The LC lens is also viewed under crossed polarizers. When the SD1 alignment direction is at 45° to the polarizer, it appears bright, while it appears dark when the alignment direction is aligned with the optic axis of the polarizer (Fig. 3(c)).

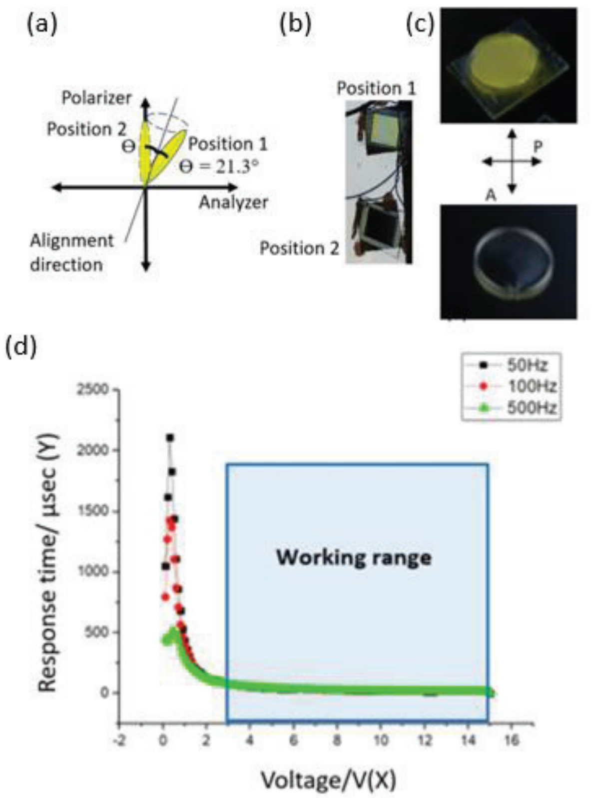


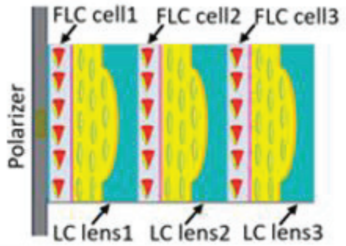
Fig. 3 (a) Schematics of the orientation of the FLC molecules during switching (b) The bright and dark states of the FLC cell which corresponds to position 1 and position 2 of the FLC molecules (c) The LC lens under crossed polarizers. The bright state is when the alignment layer is at 45° and the dark state is due to the alignment direction being parallel to the optic axis of the polarizer (d) The response time of the FLC cell as a function of voltage

The switching time of the FLC, for 500 Hz frequency, is around 10 µsec in the working range of 10V (Fig 3(d)).

3 RESULTS

Each unit of a FLC and a lens produces 2^N states. With N =3, along with a polarizer, 8 focuses can be obtained. The device is shown in Fig. 4 (a). When lens with focal length of 2m, 3m and 5m are used, the corresponding focal lengths can be obtained from the truth table (Fig. 4(b)). To evaluate the performance of the combination, three objects at distances of 1.2m, 1.9m and 5m have been placed. Three focal planes have been separately accessed (Fig. (c)-(e)).

(a)



(b)

Focal length of each lens (m)			
2	3	5	Combined Focal Length (m)
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

1 = Lens ON
0 = Lens OFF

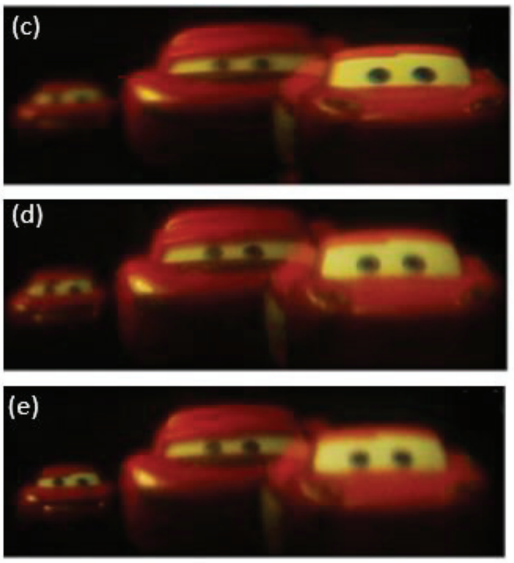


Fig. 4 (a) The FLC, lens and polarizer combination being used in the study. (b) Using the same combination, eight focusses can access as shown in the truth table. Three objects have been placed at distances of 1.2m, 1.9m and 5m. (c) Object placed at 1.2m in focus. (d) Object placed at 1.9m in focus. (e) Object placed at 5m in focus.

4 DISCUSSION

The mechanism of lensing for a combination of a polarizer, FLC polarization rotation unit and the LC lens has been shown in Fig. 5 (a)-(b). If this polarization of light impinging on the LC lens is aligned with the optic axis of the LC molecules, then lensing occurs. The other case where the FLC molecule moves by 42.6°, along with the rotation, the FLC cell acting as a half wave plate switches the polarization perpendicular to optic axis of the LC molecules in the lens. This causes the defocusing. The focal length of the lens is determined by eq. 1 [16]

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

$$f = \frac{r^2}{2d\Delta n} \qquad (1)$$

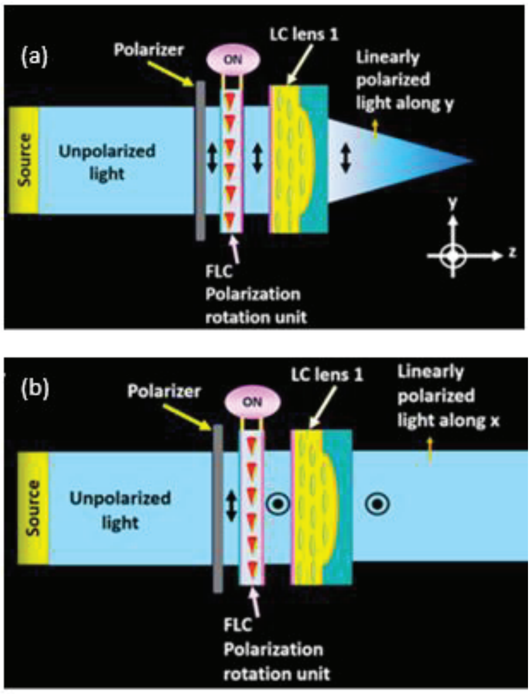


Fig. 5 (a) The focused state when the polarization direction is along the optic axis of the LC molecules (n_e) in the lens. (b) The defocused state when the polarization direction is perpendicular to the optic axis of the LC molecules in the lens (n_o).

5 SUMMARY

We have developed a fast switching device which can provide several accurate vergence cues to the user. It utilizes a combination of polarization rotation unit, the FLC cell, and a passive LC lens. The switching time of the device is in the microsecond range as compared to millisecond range as with other LC devices. The entire device can also be operated at low voltage. These advantages over other existing device can help to meet the accommodation-vergence challenges being faced by the user while using VR devices.

Acknowledgement

We acknowledge the support of The State Key Laboratory of Advanced Displays and Optoelectronics through the Innovations and Technology Commission of Hong Kong and Hong Kong Gov. Innovations and Technology Commission of Hong Kong grant number PRP/049/19FX.

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