Dual Direction Overdriving Method for Accelerating 2D/3D Switching Time of Liquid Crystal Lens on Auto-Stereoscopic Display

Chih-Wei Chen, Yi-Pai Huang, and Po-Chuan Chen

***Abstract*—In this paper, we investigate the dual direction overdriving method to accelerate both the 3D-on and 3D-off time of the lenticular liquid crystal (LC) lens. The experimental results indicated that the response time ($\tau_{3D\text{-}on}$ and $\tau_{3D\text{-}off}$) was successfully improved for a factor of 4 as a thick (60 μm cell gap) LC lens. The LC lens was also implemented on an auto-stereoscopic display to yield fast 2D/3D switching ability.**

***Index Terms*—Liquid crystal (LC) lens, overdriving method, 3D display.**

I. Introduction

THREE-DIMENSIONAL (3D) displays have been regarded as a critical technology for next generation display application. An existing work, multiplexed-2D method in auto-stereoscopic 3D displays field [1]–[5], is emerging rapidly due to its easy implementation and glasses-free capability. Moreover, the 2D/3D switchable auto-stereoscopic displays using tunable liquid crystal (LC) lens [6], [7] are further proposed to display high resolution images in 2D mode and low resolution images in 3D mode [8]–[11]. However, the electrical-driven LC (ELC) lens [9], [10], which is easy to fabricate but has a thick LC-cell gap, brings about a very slow response time (around 10 s). Therefore, improving the response time issue of the ELC lens for fast switching between 2D and 3D modes becomes important before consumer implementation.

There are existing works, such as the overdriving method [12], [13] and the polymer network method [14], [15] that have been proposed. The overdriving method utilizes the high driving voltage to affect the LC molecules rotating quickly to reduce the 3D-on time (from without driving to with driving, $\tau_{3D\text{-on}}$); however, the time ($\tau_{3D\text{-off}}$), from the 3D-on state to 3D-off state is not reduced due to no extra force being applied during this time. The polymer network method generates strong internal forces between the LC and polymer molecules to let the LC reorient back to the initial alignment quickly for 3D-off state; while, the longer 3D-on time and higher driving voltage are the trade-off. Thus, neither the two previous works can improve both the 3D-on and 3D-off time simultaneously. In this paper, we propose a dual direction overdriving method which provides different directions of electric fields to reduce the LC lens' response time. Thus, both the 3D-on and 3D-off time can be successfully reduced.

Manuscript received July 12, 2012; revised August 17, 2012; accepted August 17, 2012. Date of current version September 12, 2012. This work was supported in part by National Science Council of the Republic of China, Taiwan, under Academic Project NSC101-2221-E-009-120-MY3.

The authors are with the Department of Photonics & Institute of Electro-Optical Engineering/Display Institute, National Chiao Tung University, 30010 Hsinchu, Taiwan (e-mail: tedd0202.di96g@g2.nctue.du.tw; boundshuang@mail.nctu.edu.tw).

Color versions of one or more of the figures are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JDT.2012.2216856

II. Dual Direction Overdriving Method

According to the LC response time formula [16], the response time can be accelerated by applying the strong voltage (i.e., inducing strong electric filed) onto the cell. Consequently, the scheme of dual direction overdriving method and driving waveform that can provide extra electric fields for both the 3D-on and 3D-off states are proposed and illustrated in Figs. 1 and 2. In this paper, the liquid crystal, E7 (Merck), is used and aligned as a homogeneous type as well as perpendicular to the direction of the striped electrodes. The multiple electrodes on both top and bottom sides in the LC cell is designed to produce specific electric fields; a square wave with constant 1 KHz frequency is used as well. A detailed description of the proposed method is as follows: for the 3D-on state [see Fig. 1(a)], the strong vertical electric field between the top and bottom side electrodes are induced by high voltages (several times the stable voltage with a short period), as shown in Fig. 2 (phase I). Thus, the LC molecules tend to quickly align vertically with the electric field direction. From there, the voltage is switched to the stable voltage to form a parabolic curvature LC lens curvature (at 3D-on state) (phase II in Fig. 2). The bottom electrodes always apply the reference voltage (0 V_{rms}) for the phases I & II. For the 3D-off state, the high operating voltage and reference voltage are first applied alternately on both the top and bottom side electrodes simultaneously [see Fig. 1(b)] for a short time (phase III in Fig. 2). Therefore, a lateral electric field along with the initial LC alignment is generated as illustrated in Fig. 1(b). Following, an internal voltage is made to supply small energy for the LC molecules which still do not reorient to the initial alignment (phase IV in Fig. 2). Finally, all the applied voltages are switched off (phase V in Fig. 2) to perform the 3D-off state, (i.e. non-lens curvature). Consequently, both the 3D-on and 3D-off time can be successfully reduced by applying the extra electric fields.

III. Experiment and Discussion

In the experimental session, the response time of the LC lens using the proposed dual direction overdriving method is illustrated first. Then, the light distribution for 6-views auto-stereoscopic display using the LC lens is also obtained.

The parameters of the LC lens used in this paper are as follows: the cell gap is 60 μm (i.e. much thicker than general LC panel (<5 μm), the lens width is 188 μm, and both electrode width and slit width are 14.5 μm. The focal length is set 1 mm under 5 V_{rms} driving in the measurement.

Because both the overdriving voltage and period of each phase, as illustrated in Fig. 2, significantly controlled the input electric energy on the LC cell, finding the optimized parameters is needed [17]. Ideally, a higher voltage is used, the shorter the response time is. However, according to the free energy formula

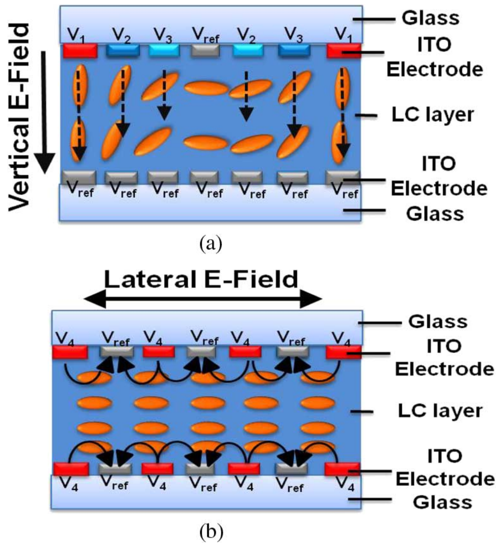

Fig. 1. Scheme of dual direction overdriving method and corresponding electric field direction for (a) 3D-on state and (b) 3D-off state ($\mathrm{V_{ref}}$ is reference voltage, and $\mathrm{V_1} \sim \mathrm{V_4}$ represent different voltages).

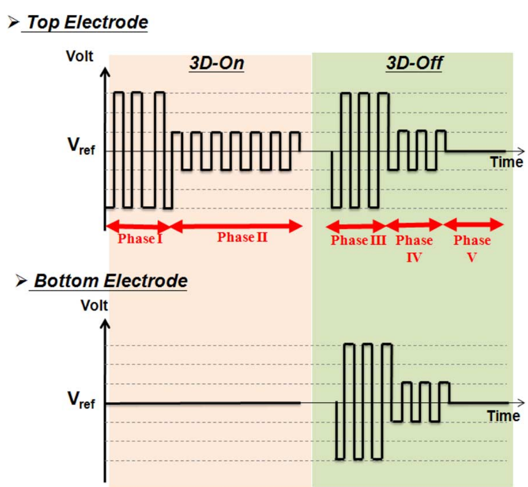

Fig. 2. Driving waveform for 3D-on and 3D-off time on both top and bottom electrode, respectively.

of LC [16], applying too high a driving voltage or too long of a period is not always useful because the LC molecules may be overdriven. Thus, the LC takes longer time to reach steady state. In the experiment, the voltage region is chosen within 5–12.5 $V_{\rm rms}$; the higher voltage is impractical for the real product. By varying the conditions, the experimental results of the 3D-on and 3D-off times are obtained as shown in Fig. 3.

For the 3D-on state, the higher overdriving voltage and shorter driving time is a better choice. It means that the strong electrical energy is generated in a short time (phase I in Fig. 2).From the experiments, the optimized parameter of 12.5 $\mathrm{V_{rms}}$ under 50 ms driving period for fast 3D-on time is obtained [Fig. 3(a)]. The 3D-on time is successfully reduced to 20%. On the other hand, the optimized parameter of $7.5V_{\rm rms}$ under 250 ms for the 3D-off state is also obtained after experiment [Fig. 3(b)]. It is found that the 3D-off time is also successfully reduced to 33%. For the 3D-off state, because the high voltage with long overdriving period will cause the strong electric field

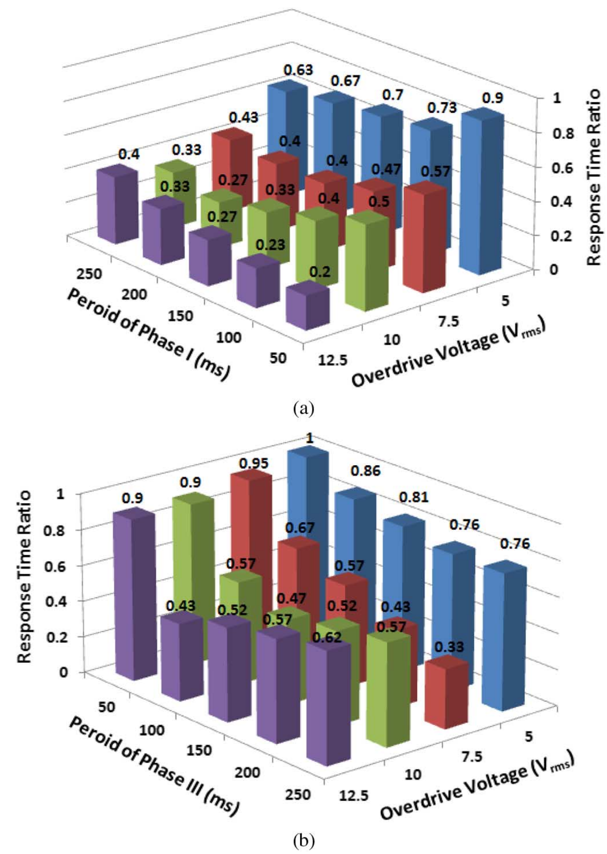

Fig. 3. Measured response time of (a) ratio of 3D-on time by voltages versus periods (Normalized to reference time (6 s) which doesn't drive by the proposed method), and (b) ratio of 3D-off time by voltages versus periods (Normalized to reference time (4.2 s) which doesn't drive by the proposed method)).

to vertically orient the LC more than the lateral orientation. Thus, the 3D-off driving should be set at the optimized voltage (7.5 $V_{\rm rms}$) with longer period of phase-III (250 ms) rather than other driving sequences. In addition, the voltage and period of phase IV in Fig. 2 is set as 2.5 $V_{\rm rms}$ and 50 ms for each condition due to it affecting the response time inconsequentially. The sequential images as well as the light distributions recorded at the final times of 3D-on and 3D-off state, respectively, are captured and shown in Fig. 4. The result proved that the light really focused after passing through the LC lens. As a result, the total response time ($\tau_{\rm 3D-on}$ and $\tau_{\rm 3D-off}$) is successfully reduced to 25% (from 10.2 s to about 2.6 s) compared to the LC lens which isn't driven by the proposed dual-direction overdriving method.

After demonstrating the improvement of reducing the lens response time, the lens array for 3D display is further fabricated and measured. The light intensity distribution of a six-view auto-stereoscopic 3D display is shown in Fig. 5. The LC lens array is slanted with 9.46° relative to vertical directions of pixel. The detail design of lenticular type 3D display can be referred to [2], [4], [18]. The crosstalk value is around 12% according to the multi-view formula [19] yet this crosstalk still has to be further reduced for higher quality 3D images. In a short summary, the lenticular multi-electrode LC lens driven by the proposed dual direction overdriving method is successfully implemented on an auto-stereoscopic display to yield fast 2D/3D

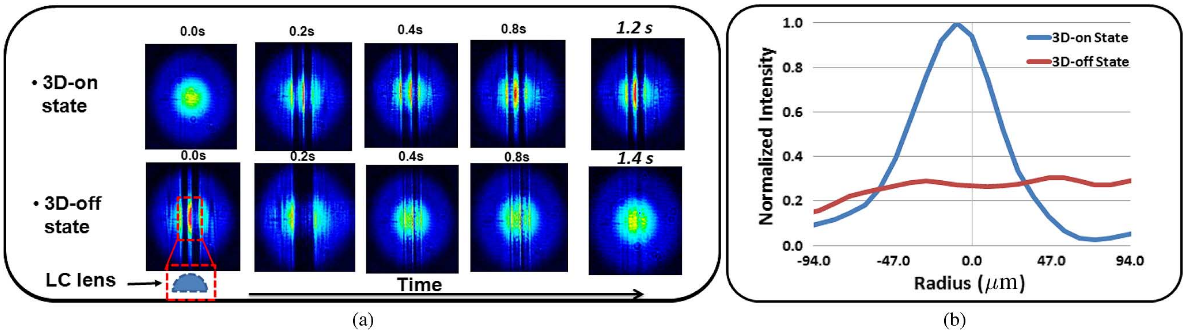

Fig. 4. (a) Sequentially focusing pictures of LC lens driven by the dual direction overdriving method for 3D-on state and 3D-off state. (b) Light intensity distributions that recorded at the final time of the 3D-on state and 3D-off state, respectively.

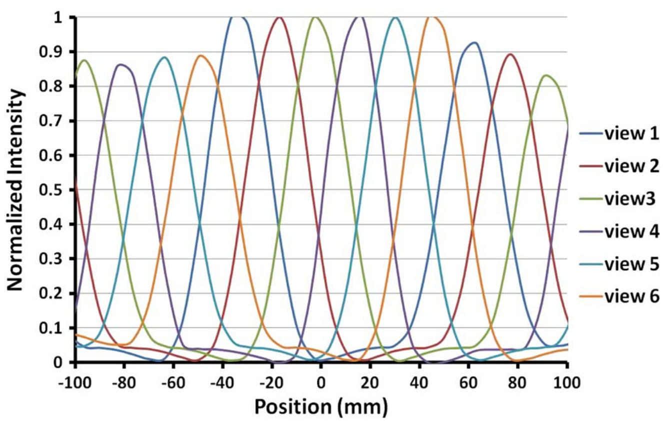

Fig. 5. Light intensity distribution at viewing plane for 6-views auto-stereoscopic 3D display.

switching (∼1 s for 3D-on or 3D-off). The multi-electrode structure can generate the smooth changed voltage distribution along with obtaining a low crosstalk value. In addition, the proposed dual direction overdriving method can also be used to further accelerate the scanning time of superzone Fresnel LC lens [18] for high resolution temporal scanning 3D displays.

IV. Conclusion

The LC lens for 2D/3D switchable display has been proposed for years, yet the response time is still an issue. The previous overdriving method can only improve the 3D-on time, while the polymer network method only improved the 3D-off time. Neither the two previous works can improve both the 3D-on and 3D-off time simultaneously. In this paper, we proposed a novel dual direction overdriving method that could generate the vertical and lateral electric-fields to supply extra energy for LC reorienting rapidly. The experiment results showed that the total response time of LC lens was four times faster than the LC lens which wasn't driven by the dual direction overdriving method. In addition, the crosstalk value was also calculated to verify the quality for displaying 3D image. Consequently, it is believed that the proposed driving method with multi-electrode lenticular LC-lens has high potential for realizing fast switching 2D/3D auto-stereoscopic display.

Acknowledgment

The authors would like to thank A. Markman, University of Connecticut, Storrs, and J. J. Li, SuperD Ltd., China, for their valuable discussion and technical support.

References

[1] J. Y. Son *et al.*, "Three-dimensional image methods based on multiview images," *J. Display Technol.*, vol. 1, no. 1, pp. 125–140, Sep. 2005.
[2] W. Maphepo *et al.*, "Enhancing the brightness of parallax barrier based 3D flat panel mobile displays without compromising power consumption," *J. Display Technol.*, vol. 6, no. 6, pp. 60–62, Jun. 2010.
[3] M. Tsuboi *et al.*, "Design conditions for attractive reality in mobile-type 3-D display," *J. Soc. Inf. Display*, vol. 18, pp. 698–703, 2010.
[4] Y. Takaki, "Multi-view 3-D display employing a flat-panel display with slanted pixel arrangement," *J. Soc. Inf. Display*, vol. 18, pp. 476–482, 2010.
[5] J. Y. Son *et al.*, "Recent developments in 3D imaging technologies," *J. Display Technol.*, vol. 6, no. 10, pp. 394–403, Oct. 2010.
[6] S. Sato, "Liquid-crystal lens-cells with variable focal length," *Jpn. J. Appl. Phys.*, vol. 18, pp. 1679–1684, 1979.
[7] H. Ren *et al.*, "Tunable-focus cylindrical liquid crystal lens," *Jpn. J. Appl. Phys.*, vol. 43, pp. 652–653, 2004.
[8] O. H. Willemsen *et al.*, "2-D/3-D switchable displays," *J. Soc. Inf. Display*, vol. 14, pp. 715–722, 2006.
[9] H. K. Hong *et al.*, "Electric-field-driven LC lens for 3D/2D autostereoscopic display," *J. Soc. Inf. Display*, vol. 17, pp. 399–406, 2009.
[10] Y. P. Huang *et al.*, "2-D/3-D switchable autostereoscopic display with multi-electrically driven liquid-crystal (MeD-LC) lenses," *J. Soc. Inf. Display*, vol. 18, pp. 642–646, 2010.
[11] J. G. Lu *et al.*, "2-D/3-D switchable display by fresnel-type LC lens," *J. Display Technol.*, vol. 7, no. 4, pp. 215–219, Apr. 2011.
[12] S. T. Wu, "Nematic liquid crystal modulator with response time less than 100 us at room temperature," *Appl. Phys. Lett.*, vol. 57, pp. 986–988, 1990.
[13] L. Y. Liao *et al.*, "Marginal electrodes with over-drive method for fast response liquid crystal lens applications," *SID Symp. Dig.*, vol. 41, pp. 1766–1769, 2010.
[14] Y. H. Fan *et al.*, "Switchable Fresnel lens using polymer-stabilized liquid crystals," *Opt. Express*, vol. 11, pp. 3080–3086, 2003.
[15] H. Ren *et al.*, "Prism grating using polymer-stabilized nematic liquid crystal," *Appl. Phys. Lett.*, vol. 82, pp. 3168–3170, 2003.
[16] S. T. Wu and D. K. Yang, *Reflective Liquid Crystal Displays*. New York: Wiley, 2001.
[17] Y. Li *et al.*, "Fast-response liquid-crystal displays using crossed fringe fields," *J. Soc. Inf. Display*, vol. 16, pp. 1069–1074, 2008.
[18] Y. P. Huang *et al.*, "Superzone Fresnel liquid crystal lens for temporal scanning auto-stereoscopic display," *J. Display Technol.*, accepted for publication.
[19] M. Salmimaa *et al.*, "Effect of number of views to the viewing experience with autostereoscopic 3-D displays," *J. Soc. Inf. Display*, vol. 17, pp. 449–458, 2009.