Time-Multiplexed Dual-View Display Using a Blue Phase Liquid Crystal

Jian-Peng Cui, Yan Li, Jin Yan, Hui-Chuan Cheng, and Qiong-Hua Wang

***Abstract*—A time-multiplexed dual-view display device using a blue phase liquid crystal is proposed. In this design, a vertical field switching blue phase liquid crystal display (VFS-BPLCD) panel is used to achieve high transmittance and fast response. Combined with a directional backlight module, this device can present two different images to viewers sequentially. The proposed device has advantage in full spatial resolution.**

***Index Terms*—Blue phase, dual-view, liquid crystal display (LCD).**

I. Introduction

MULTI-VIEW display is a device which can display different images to viewers at different viewing directions. For example, a dual-view liquid crystal display (LCD) in a car can display navigation information to the driver and meanwhile display movie to the passenger. The driver and the passenger can observe different images because they are viewing the LCD at different directions. So far, only a few display approaches have been proposed to achieve this function. These approaches can be classified into two types: spatial-multiplexed and time-multiplexed dual-view display devices. For spatial multiplexing, the main pixel of LCD comprises a right sub-pixel and a left sub-pixel, and two different images are presented to viewers who are viewing at different directions. Parallax barriers [1] and lenticular lenses [2] are two typical approaches to route light from two sub-pixels to different viewing directions. Recently, some single panel spatial-multiplexed dual-view LCDs have been demonstrated, in which no additional optical elements are needed [3], [4]. However, spatial-multiplexed dual-view displays have some problems, such as loss of spatial resolution and crosstalk. Compared with spatial multiplexing, time-multiplexed dual-view display provides two different images to viewers sequentially, which has no loss of spatial resolution. For time multiplexing, a LCD panel with fast response time is required due to high refresh rate.

Manuscript received November 06, 2012; accepted November 28, 2012. Date of publication January 08, 2013; date of current version February 11, 2013. This work is supported by the International Science & Technology Cooperation Program of China under Grant 2012DFG11610 and by the National "863" Program of China under Grant 2012AA011901.

J.-P. Cui is with the College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA, and also with the School of Electronics and Information Engineering, Sichuan University, Chengdu 610065, China (e-mail: cuijianpeng2010@gmail.com).

Y. Li, J. Yan, and H.-C. Cheng are with the College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA.

Q.-H. Wang is with the School of Electronics and Information Engineering, Sichuan University, Chengdu 610065, China, and also with the State Key Laboratory of Fundamental Science on Synthetic Vision, Sichuan University, Chengdu 610065, China (e-mail: qhwang@scu.edu.cn).

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

Digital Object Identifier 10.1109/JDT.2012.2231398

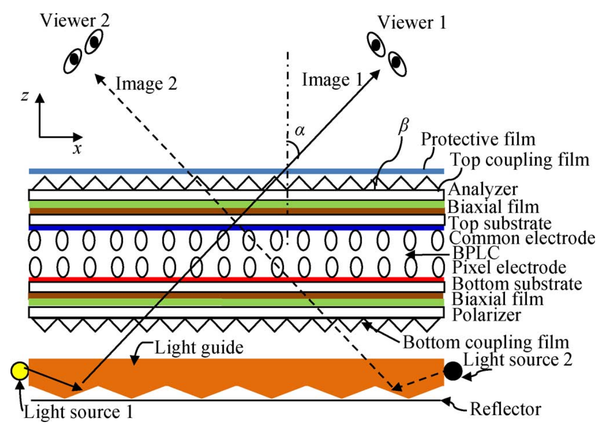

Fig. 1. Schematic of the proposed dual-view display device structure.

Polymer-stabilized blue phase liquid crystal (BPLC) [5]–[8] is emerging as next-generation display and photonic technology [9]–[11] because of its fast response time, isotropic dark state, and no need for alignment layers. In particular, the fast response time not only reduces motion blur but also enables color sequential displays.

In this paper, we propose a time-multiplexed dual-view display device using a BPLC. To achieve high transmittance and fast response, vertical field switching blue phase liquid crystal display (VFS-BPLCD) panel is used in this design. Combined with directional backlight module, the device can present two different images to different viewers sequentially.

II. Device Structure

In the voltage-off ($V = 0$) state, BPLC is optically isotropic. As the applied voltage increases, the Kerr effect-induced birefringence is along the electric field direction, provided that the employed LC has a positive dielectric anisotropy [12]. For a VFS-BPLCD [13], [14], the induced birefringence is in the longitudinal direction. Thus, there will be no phase retardation for the normal incident light; only those at oblique angles can experience a phase retardation effect. Thus, a directional backlight module [15] is required to provide collimated and oblique incident light.

Fig. 1 shows the schematic of the proposed dual-view display device structure. This device consists of two major components: a directional backlight module and a VFS-BPLCD panel. In the backlight module, two light sources (1 and 2) are disposed at the left side and right side of the light guide. Shallow prismatic extraction feature is formed at the bottom of the light guide, which can reflect the light at two oblique directions. And a specular reflector is used to recycle the backward extracted light. This kind of directional backlight has been used in some

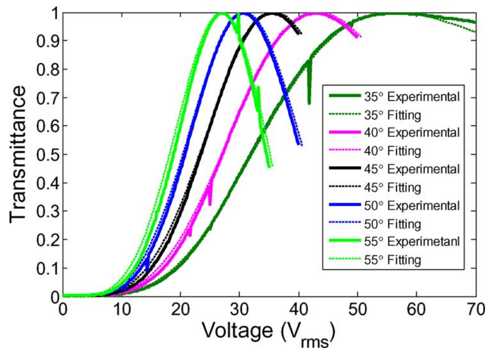

Fig. 2. VT curves of the VFS-BPLC cell at the specified incident angles. Cell gap $d = 10\ \mu$m, $\lambda = 633$ nm, and $T \sim 23\ ^\circ$C.

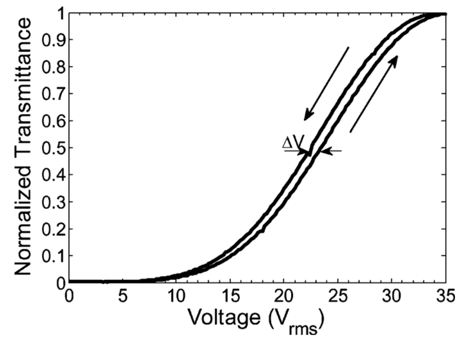

Fig. 3. Measured hysteresis of the VFS-BPLC cell at $\theta_{\mathrm{i}} = 45^\circ$.

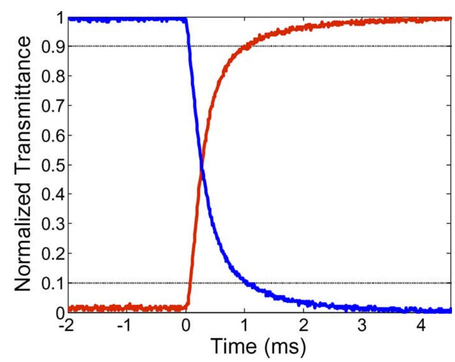

Fig. 4. Measured rise time and fall time of the VFS-BPLC cell. $\theta_{\mathrm{i}} = 45^\circ$, $\lambda = 633$ nm, and $T \sim 23\ ^\circ$C.

stereoscopic display [16]–[18]. The LCD panel is disposed in front of the backlight module. BPLC layer is sandwiched between two crossed linear polarizers. The absorption axes of the polarizer and analyzer are set at 45° and -45° with respect to x axis. To achieve a good dark state, two biaxial films are used to compensate the light leakage at oblique angles. To couple the oblique incident light into and out of the BPLC layer, two coupling films are laminated to the top and bottom of the LCD panel, respectively. And a protective film is utilized to protect the top coupling film. Here, α is the incident angle and β is the base angle of the prism; α and β should be complementary in order to achieve high coupling efficiency. In this design, light sources 1 and 2 must be synchronized with images 1 and 2 on the display panel, respectively. When light source 1 is on, the LCD panel displays image 1 for viewer 1. Similarly, when light source 2 is on, the LCD panel displays image 2 for viewer 2. As a result, we can achieve a time-multiplexed dual-view display by presenting two different images to viewers 1 and 2 sequentially.

III. Experiments and Simulations

To study the angular dependence of the BPLC cell, we prepared a polymer-stabilized VFS-BPLC cell with 10 μm cell gap using JNC JC-BP01M [19]. The LC host has a birefringence $\Delta n = 0.17$ and dielectric anisotropy $\Delta\varepsilon \sim 94$. In our experiment, we used the same setup as [13]. In the device design, the two polarizers are crossed for normal incident light but become non-crossed at large incident angles. The two biaxial films are used to compensate for the light leakage at oblique incident angles. The function of the biaxial films is to rotate the polarization state so that the incident linear polarization is at 45° to the slow axis of the BPLC sample under an applied voltage. In the experimental setup, the light is normally incident on the polarizers to achieve a good dark state. With this experimental setup, the polarization state is at 45° to the slow axis of the BPLC sample without compensation. Therefore, the experimental setup can be used to simulate the device structure. All the electro-optic measurements were conducted at room temperature ($T \sim 23$ °C) with a He-Ne laser ($\lambda = 633$ nm).

According to extended Kerr effect model, the induced birefringence is expressed as [20]

$$\Delta n_{\mathrm{ind}} = \Delta n_{\mathrm{sat}} \left(1 - \exp\left[-\left(\frac{E}{E_{\mathrm{s}}}\right)^2\right]\right) \tag{1}$$

where Δn_{sat} stands for the saturated induced birefringence and E_{s} is the saturated field. Fig. 2 shows the voltage-dependent (VT) curves of the VFS-BPLC cell at specified incident angles. Each VT curve is normalized to the transmittance of two parallel polarizers. The solid lines represent the experimental data and the dash lines represent the fitting curves using (1) with $\Delta n_{\mathrm{sat}} = 0.145$ and $E_{\mathrm{s}} = 4.95\ \mathrm{V}/\mu$m at $\lambda = 633$ nm. As the incident angle (θ_{i}) increases from 35° to 55°, the on-state voltage at the peak transmittance decreases from $V_{\mathrm{p}} \sim 55\ \mathrm{V_{rms}}$ to 27 $\mathrm{V_{rms}}$. This is because a larger θ_{i} accumulates more phase retardation, which helps to reduce V_{p}. Furthermore, when $\theta_{\mathrm{i}} = 45^\circ$, the coupling films have the highest coupling efficiency. So we choose $\theta_{\mathrm{i}} = 45^\circ$ in the following measurements. However, for a selected viewing angle $\theta_{\mathrm{i}} = 45^\circ$ with operating voltage from 0 to 35 $\mathrm{V_{rms}}$, the gray scale inversion appears if the viewing angle is larger than 45°. Therefore, the backlight is required to be collimated. Moreover, we can use a light diffuser to make the output light more uniform.

For polymer-stabilized BPLCD devices, hysteresis [21], [22] is a common problem, which affects the accuracy of grayscale controls. Hysteresis is defined by the voltage difference at the half-maximum transmittance between forward and backward scans. Fig. 3 shows the measured hysteresis of the VFS-BPLCD at $\theta_{\mathrm{i}} = 45^\circ$. The operating voltage is $V_{\mathrm{p}} \sim 35\ \mathrm{V_{rms}}$ and hysteresis $\Delta V \sim 1\ \mathrm{V_{rms}}$, which corresponds to $\Delta V/V_{\mathrm{p}} \sim 2.8\%$. For display applications, this ratio should be smaller than 5%.

For this time-multiplexed dual-view display, two sequential images are displayed for viewer 1 and viewer 2 at a refresh rate of 120 Hz. So a LCD panel with a fast response time is required. Fig. 4 shows the rise time and fall time of full-on and full-off transitions. Here, rise time and fall time were measured

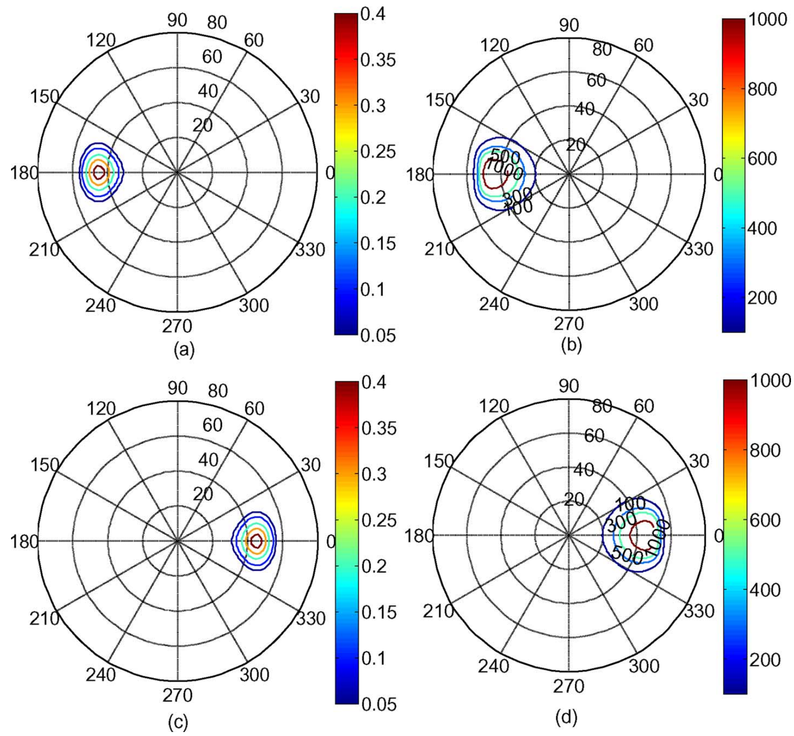

Fig. 5. Simulated (a) intensity distribution of the bright state and (b) isocontrast contour plots as the light source 2 is on; (c) intensity distribution of the bright state and (d) isocontrast contour plots as the light source 1 is on. Backlight $\mathrm{FWHM} = 20^\circ$, $\theta_\mathrm{i} = 45^\circ$ and $\lambda = 550$ nm.

between 10% and 90% transmittance. From Fig. 4, the rise time is 0.959 ms and the fall time is 0.985 ms. The fast response time of VFS-BPLC makes it suitable for sequential displays.

To analyze the viewing angle properties of the proposed device, we use MATLAB program to simulate the intensity distribution and contrast ratio distribution. Since the display is usually optimized for $\lambda = 550$ nm, we take the wavelength dispersion [23] into account and set $\Delta n_\mathrm{sat} = 0.151$ and $E_\mathrm{s} = 4.95\ \mathrm{V}/\mu\mathrm{m}$ at $\lambda = 550$ nm. With these parameters, the on-state voltage is $V_\mathrm{p} \sim 32.6\ \mathrm{V_{rms}}$ at incident angle $\theta_\mathrm{i} = 45^\circ$. The backlight module is assumed to have a Gaussian distribution with the center at 45° and FWHM $\sim 20^\circ$. The bottom and top biaxial films are set at 45° and -45°, respectively. And both of the optimized biaxial films have the same film thickness $d = 98.6$ nm and $N_\mathrm{z} = (n_\mathrm{y} - n_\mathrm{z})/(n_\mathrm{x} - n_\mathrm{y}) = 0.743$. When light source 1 is on, a viewing cone can be obtained by viewer 1 at $+45^\circ$ viewing direction, as shown in Fig. 5(a). The intensity larger than 0.2 is limited to $\sim 15^\circ$ viewing cone. As a reference, the transmittance for two parallel polarizers is 0.44. From Fig. 5(b), we can find that the contrast ratio larger than 100:1 is limited to $\sim 35^\circ$ viewing cone. The viewing angle seems to be wider in terms of contrast ratio. This is because the contrast ratio is mainly determined by the dark state, while the intensity is determined by the distribution of the backlight module as well as the angular dependent transmittance of the bright state. When light source 2 is on, a similar viewing cone can be obtained by viewer 2 at -45° viewing direction, as shown in Fig. 5(c) and (d).

Image crosstalk is a familiar issue for time-multiplexed displays. At the moment the light source is turned on, the panel still retains a part of former image, which leads to image crosstalk. A LCD panel with faster response time helps to reduce this effect. Meanwhile, a re-designed driving scheme can be another approach of this issue. Fig. 6(a) shows the driving scheme when dual-view images are displayed. $\mathrm{I_1}$ and $\mathrm{I_2}$ represent images 1 and 2, respectively. LS1 and LS2 respectively represent driving waveforms of light sources 1 and 2. Here, light source is on when the waveform is at a high level. Each frame comprises of two sub-frames: image 1 and image 2. The frame rate of 60 Hz is employed to avoid image flickering, which means the refresh rate of the LCD panel is 120 Hz. As shown in Fig. 6(a), images 1 and 2 are scanned to the LCD panel sequentially. When light source 1 is on, the LCD panel displays image 1 for viewer 1, and then light source 2 is on, the LCD panel displays image 2 for viewer 2. To avoid image crosstalk, both of light sources are turned off while refreshing one image to the other, which is called black time. Although inserting a black time between two frames will cause some brightness loss, it will reduce the cross-talk and improve the image quality. Since the BPLC has submillisecond response time, the black time should be < 1 ms. So the transmittance could be $> 88\%$ for 120 Hz driving frequency.

Furthermore, we can control the light sources and image data to display an identical image for both viewers 1 and 2 simultaneously. Fig. 6(b) and (c) show the driving schemes when the identical image is displayed at a refresh rate of 120 Hz and 60 Hz, respectively. Here, $\mathrm{I_d}$ represents the identical image. As a result, this device can work as dual-view mode or identical-view mode adaptively.

IV. Conclusion

We have proposed a time-multiplexed dual-view display using a blue phase liquid crystal. In this design, we used a VFS-BPLCD panel to achieve high transmittance and fast response time, while using a directional backlight module to provide a large oblique incident angle. By controlling the

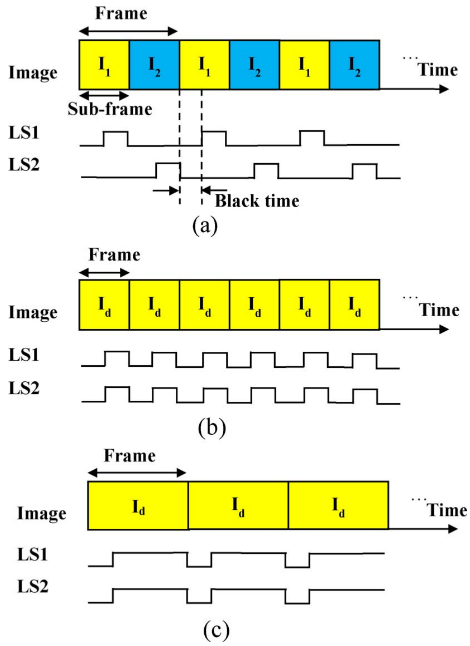

Fig. 6. Driving schemes of the proposed display device: (a) dual-view mode at refresh rate of 120 Hz; (b) identical-view mode at refresh rate of 120 Hz; and (c) identical-view mode at refresh rate of 60 Hz.

light sources and image data, the device can display two different images to different viewers sequentially. As a result, a time-multiplexed dual-view display device is achieved, which has a full spatial resolution. Moreover, this device is switchable between dual-view mode and identical-view mode.

REFERENCES

[1] D. U. Kean, D. J. Montgomery, G. Bourhill, and J. Mather, "Parallax barrier and multiple view display," U.S. Patent 7 154 653B2, Dec. 26, 2006.

[2] M. P. C. M. Krijn, S. T. de Zwart, D. K. G. De Boer, O. H. Willemsen, and M. Sluijter, "2-D/3-D displays based on switchable lenticulars," *J. Soc. Inf. Display*, vol. 16, no. 8, pp. 847–855, 2008.

[3] C. P. Chen, J. H. Lee, T. H. Yoon, and J. C. Kim, "Monoview/dual-view switchable liquid crystal display," *Opt. Lett.*, vol. 34, no. 14, pp. 2222–2224, 2009.

[4] C. T. Hsieh, J. N. Shu, H. T. Chen, C. Y. Huang, C. J. Tian, and C. H. Lin, "Dual-view liquid crystal display fabricated by patterned electrodes," *Opt. Express*, vol. 20, no. 8, pp. 8641–8648, 2012.

[5] H. Kikuchi, M. Yokota, Y. Hiskado, H. Yang, and T. Kajiyama, "Polymer-stabilized liquid crystal blue phases," *Nat. Mater.*, vol. 1, no. 1, p. 6468, 2002.

[6] J. Yan, L. Rao, M. Jiao, Y. Li, H. C. Cheng, and S. T. Wu, "Polymer-stabilized optically-isotropic liquid crystals for next-generation display and photonics applications," *J. Mater. Chem.*, vol. 21, pp. 7870–7877, 2011.

[7] Y. Chen, J. Yan, J. Sun, S. T. Wu, X. Liang, S. H. Liu, P. J. Hsieh, K. L. Cheng, and J. W. Shiu, "A microsecond-response polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.*, vol. 98, p. 201105, 2011.

[8] Y. Li, Y. Chen, J. Yan, Y. Liu, J. P. Cui, Q. H. Wang, and S. T. Wu, "Polymer-stabilized blue phase liquid crystal with a negative Kerr constant," *Opt. Mater. Express*, vol. 2, no. 8, pp. 1135–1140, 2012.

[9] Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S. T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.*, vol. 94, p. 101104, 2009.

[10] Y. Li, M. Jiao, and S. T. Wu, "Transflective display using a polymer-stabilized blue-phase liquid crystal," *Opt. Express*, vol. 18, no. 16, pp. 16486–16491, 2010.

[11] J. Yan, Y. Li, and S. T. Wu, "High-efficiency and fast-response tunable phase grating using a blue phase liquid crystal," *Opt. Lett.*, vol. 36, no. 8, pp. 1404–1406, 2011.

[12] L. Rao, Z. Ge, and S. T. Wu, "Viewing angle controllable displays with a blue-phase liquid crystal cell," *Opt. Express*, vol. 18, no. 3, pp. 3143–3148, 2010.

[13] H. C. Cheng, J. Yan, T. Ishinabe, and S. T. Wu, "Vertical field switching for blue-phase liquid crystal devices," *Appl. Phys. Lett.*, vol. 98, p. 261102, 2011.

[14] Y. H. Kim, S. T. Hur, C. S. Park, K. W. Park, S. W. Choi, S. W. Kang, and H. R. Kim, "A vertical-field-driven polymer-stabilized blue phase liquid crystal mode to obtain a higher transmittance and lower driving voltage," *Opt. Express*, vol. 19, no. 18, pp. 17427–17438, 2011.

[15] M. Oe and I. Chiba, "Plane Light Source Unit," U.S. Patent 5 126 882, Jun. 30, 1992.

[16] T. Sasagawa, A. Yuuki, S. Tahata, O. Murakami, and K. Oda, "Dual directional backlight for stereoscopic LCD," in *SID Symp. Dig.*, 2003, pp. 399–401.

[17] K. W. Chien and H. P. D. Shieh, "Time-multiplexed three-dimensional displays based on directional backlights with fast-switching liquid-crystal displays," *Appl. Opt.*, vol. 45, no. 13, pp. 3106–3110, 2006.

[18] R. Brott and J. Schultz, "Directional backlight light guide considerations for full resolution autostereoscopic 3D displays," in *SID Symp. Dig.*, 2010, pp. 218–221.

[19] L. Rao, J. Yan, S. T. Wu, S. Yamamoto, and Y. Haseba, "A large Kerr constant polymer-stabilized blue phase liquid crystal," *Appl. Phys. Lett.*, vol. 98, p. 081109, 2011.

[20] J. Yan, H. C. Cheng, S. Gauza, Y. Li, M. Jiao, L. Rao, and S. T. Wu, "Extended Kerr effect in polymer-stabilized blue-phase liquid crystals," *Appl. Phys. Lett.*, vol. 96, no. 7, p. 071105, 2010.

[21] K. M. Chen, S. Gauza, H. Xianyu, and S. T. Wu, "Hysteresis effects in blue-phase liquid crystals," *J. Display Technol.*, vol. 6, no. 8, pp. 318–322, Aug. 2010.

[22] L. Rao, J. Yan, S. T. Wu, Y. C. Lai, Y. H. Chiu, H. Y. Chen, C. C. Liang, C. M. Wu, P. J. Hsieh, S. H. Liu, and K. L. Cheng, "Critical field for a hysteresis-free BPLC device," *J. Display Technol.*, vol. 7, no. 12, pp. 627–629, Dec. 2011.

[23] M. Jiao, J. Yan, and S. T. Wu, "Dispersion relation on the Kerr constant of a polymer-stabilized optically isotropic liquid crystal," *Phys. Rev. E.*, vol. 83, no. 4, p. 041706, 2011.

Jian-Peng Cui is working toward the Ph.D. degree in optical engineering from the School of Electronics'Information Engineering, Sichuan University, Chengdu, China.

His recent research interest is information display technologies.

Yan Li received her Ph.D. degree from the College of Optics and Photonics, University of Central Florida, Orlando.

She is currently working at Magic Leap as an optical engineer.

Jin Yan is currently working toward the Ph.D. degree from the College of Optics and Photonics, University of Central Florida, Orlando.

Her research interest includes device physics and materials of polymer-stabilized blue phase and isotropic phase liquid crystal displays.

Hui-Chuan Cheng received his Ph.D. degree from the College of Optics and Photonics, University of Central Florida, Orlando.

He is currently working at Magic Leap as an optical engineer.

Qiong-Hua Wang received the M.S. and Ph.D. degrees from the University of Electronic Science and Technology of China (UESTC), in 1995 and 2001, respectively.

She was a Post-Doctoral research fellow in the School of Optics/CREOL, University of Central Florida, during 2001–2004. She worked at UESTC in 1995–2001, and at Philips Mobile Display Systems, Philips Shanghai, in 2004. She is currently a professor of optics in the School of Electronics and Information Engineering, Sichuan University, Chengdu, China. She has published more than 170 papers and held more than 29 U.S. and Chinese patents. Her recent research interests include optics and optoelectronics, especially display technologies.

Dr. Wang is a senior member of the Society for Information Display (SID).