Fast-Response Blue-Phase Liquid Crystal for Color-Sequential Projection Displays

Sihui He, Jiun-Haw Lee, Hui-Chuan Cheng, Jin Yan, and Shin-Tson Wu, *Fellow, IEEE*

***Abstract*—Color sequential projection display using a vertical field switching (VFS) polymer-stabilized blue phase liquid crystal (BPLC) is proposed. The VFS-BPLC exhibits submillisecond response time which is useful for suppressing color breakup. The proposed projector also has a small throw ratio. With phase compensation, the distortion from oblique LC panel could be corrected.**

***Index Terms*—Blue-phase liquid crystal (BPLC), color-sequential projection, submillisecond response.**

I. Introduction

COLOR-SEQUENTIAL single-panel LCD projectors offer several advantages over the three-panel ones, such as higher optical efficiency, simpler projection optics for compact size, and lower cost [1], [2]. However, color breakup would be noticeable if the liquid crystal response time is not fast enough (< 1 ms) [3]–[5]. Presently, 90° twisted nematic cell [6] has been commonly used in three-panel transmissive LCD data projectors, while vertical alignment nematic [7], mixed-mode twisted-nematic [8], and ferroelectric LC [9] have been attempted for single-panel reflective LCOS projectors (or pico projectors using LED backlight). To achieve fast response time, the gap of these LC cells is controlled at around 1 μm which makes device fabrication challenging.

Polymer-stabilized blue-phase liquid crystal (BPLC) based on Kerr effect [10], [11] is emerging as a promising candidate for display applications. The major attractions are submillisecond response time, no need for molecular alignment layer, natural grayscale, and optically isotropic dark state. Recently, a vertical field switching (VFS) BPLC is proposed for direct-view display [12], [13]. Compared to in-plane switching (IPS) BPLC [14]–[16], VFS mode not only significantly reduces the operating voltage (< 10 V) but also suppresses the hysteresis. Effective as the result is, it faces a big challenge for direct-view displays, especially for achieving wide viewing angle and high contrast ratio.

In this paper, we propose a new color-sequential projection display using VFS BPLC. For projection display, viewing angle is no longer a problem, and it allows more space for generating a collimated backlight. However, the off-axis illumination light complicates the projection optics and need to be addressed.

To solve this oblique angle problem, we propose to apply data processing to compensate the phase distortion. Reflective projection is also proposed to lower the operation voltage.

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S. He, H. C. Cheng, J. Yan, and S. T. Wu are with the College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA (email: sihui.he@knights.ucf.edu and swu@mail.ucf.edu).

J. H. Lee is a Graduate with the Institute of Photonics and Optoelectronics, National Taiwan University, Taipei, Taiwan (email: jhlee@cc.ee.ntu.edu.tw).

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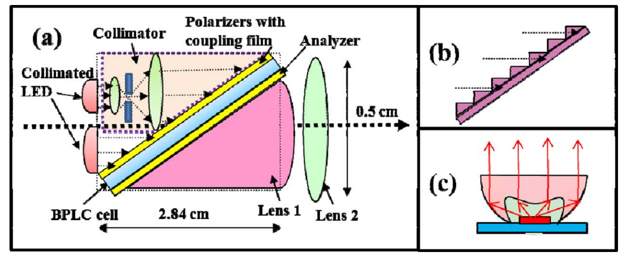

Fig. 1. Device structure of the proposed transmissive projection system. (a) Whole system. (b) Coupling film on top of the polarizer. (c) Collimated LED.

II. Device Structure

Fig. 1 depicts the proposed color sequential transmissive projection displays using VFS BPLCD. The projector consists of illumination system, BPLCD panel and projection optics. In the VFS-BPLC panel, the induced birefringence is along the electric field, which is vertical to the LC panel. In this case, normal incident light does not experience any phase retardation. Therefore, we have to tilt the BPLCD panel at an oblique angle. The larger the tilt angle, the larger the phase retardation, which leads to a lower operation voltage. In our design, we choose the incident angle to be 70°–80°. In so doing, the operating voltage is below 10 V and hysteresis is completely suppressed for the BPLC we employed. To obtain such a large incident angle inside the BPLC cell, top coupling film [see Fig. 1(b)] is laminated on the polarizer. On the output side, a prism is used instead of coupling film because the coupling film may degrade the image quality. Lens 1 is a combination of coupling prism and projection lens. The projection lens in lens 1 and lens 2 denote a tunable projection system, which is well developed and commercialized. Collimated RGB LEDs are used as backlight because of their high optical efficiency, long life, and small size.

Because the LCD panel is tilt at a large angle, as shown in Fig. 1(a), the upper portion of the panel is closer to the projection lens than the lower part, distortion compensation is required. With the powerful computation nowadays, it is easier to precompensate the distortion by data processing than by the optical means. As the incident light is parallel to the optical axis of the projection system, we could apply the paraxial optics for the calculation. The complex projection system can be viewed as a thick lens with effective focal length f as shown in Fig. 2.

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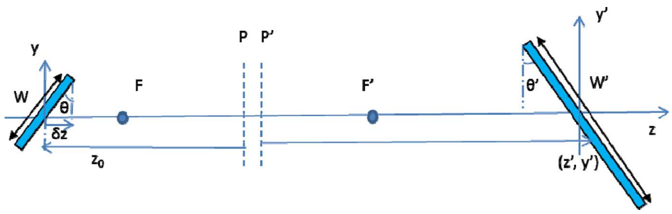

Fig. 2. Projection image of the BPLC panel. P and P′ are front and rear principle planes. F and F′ are front and rear focal points. The vectors are positive if they are pointing from left to right. The rectangle on the left denotes the BPLC panel; the longer rectangle on the right side denotes the projected image.

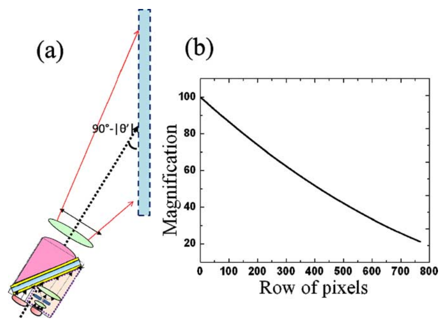

Fig. 3. (a) Application of the proposed projector as a short-throw projector. (b) Calculated magnification versus pixels on the vertical direction.

The position of the image in Fig. 2 is given by

$$\frac{1}{z'} - \frac{1}{z_0 + \delta z} = \frac{1}{f} \tag{1}$$

$$\frac{y'}{y} = \frac{z'}{z_0 + \delta z} \tag{2}$$

$$y = \delta z \cot \theta. \tag{3}$$

Here f is the focal length ($f > 0$), z_0 is the on-axis LC panel's distance from the front principle plane (P) of the projection system and $-2f < z_0 < -f$, z' is the image distance corresponding to the LCD pixel at $z_0 + \delta z$, and y, y′ are the distance from optical axis to pixels corresponding to at $z_0 + \delta z$ and z', respectively. y and y′ are positive if they are above the optical axis, and negative if below the optical axis. From (1), (2) and (3), the image position is found

$$y' = \frac{z_0 + f}{f \tan\theta} z' - \frac{z_0}{\tan\theta} \tag{4}$$

$$\theta' = \tan^{-1}\left(\frac{f}{z_0 + f}\tan\theta\right). \tag{5}$$

From (4) and (5), the image is in a plane which has an angle θ' with a plane normal to optical axis of the projection system. Note $\theta' < 0$, which means the image is upside down compared to that on the LC panel. From (5), we also get $|\theta'| > \theta$, thus the angle from the optical axis of the projector to the screen is very small, which is given by 90°-$|\theta'|$. This natural large angle off-axis projection gives a short throw projector, which can be used in tight place with less occlusion, as Fig. 3(a) shows.

The magnification of image at $z_0 + \delta z$ is given by

$$\left.\frac{dW'}{dW}\right|_{z_0+\delta z} = \frac{f\cos\theta\sqrt{(z_0+f)^2 + f^2\tan^2\theta}}{(z_0 + \delta z + f)^2}. \tag{6}$$

This shows that the magnification is inversely proportional to the square of object distance. The closer the object to the projection lens, the larger the image would be. Thus we need to compress the image in the BPLC panel which is closer to the lens while extend the farther-away part with the factor proportional to the square of the pixel to the effective focus of the projection system.

Assume the resolution of the projected image is $h' \times v'$ with intensity value in the ith row and jth column to be $I'(i,j)$, where i increases from bottom to top, and j counts from left to right. The distance from the rear principle plane to the on-axis point of the image plane is

$${z_0}' = \frac{z_0 f}{z_0 + f}. \tag{7}$$

Assume the image magnification is m_0, which corresponds to pixel $(1, j)$. And let the size of the screen to be $L' \times W'$, then the magnification $m(i,j)$ corresponding to the pixel (i,j) on the image screen is

$$m(i,j) = \frac{m_0\left[-{z_0}' + \left(\frac{i}{v'} - 0.5\right)W'\sin\theta' + f\right]^2}{\left[-{z_0}' + \left(\frac{1}{v'} - 0.5\right)W'\sin\theta' + f\right]^2}. \tag{8}$$

Equation (8) shows that the magnification decreases with increasing i, as expected. Thus the upper pixel in the image plane corresponds to more pixels in the BPLC panel. The intensity of pixels on the LC panel can be expressed as a block matrix $I(\boldsymbol{p}, q)$, where $\boldsymbol{p}$ is an array corresponding to the ith row of the projected image $I'(i,j)$, while q is a number corresponding to the j-th column of the projected image. Note that $\boldsymbol{p}$ increases from top to bottom of the LC panel and q counts from right to left, as the projected image is upside down compared to the image on LC panel. The array $\boldsymbol{p}$ has a dimension of $\dim(\boldsymbol{p}) = [m_0/m(\mathrm{i},j)]$, where the square brackets means taking the closest integer. Thus the resolution of the BPLC panel $h \times v$ needs to be higher than the image displayed on the screen. This reduction of resolution is the cost of short throw and distortion correction. Their relationship is given by

$$v = \sum_{i=1}^{v'} \dim(p) \tag{9}$$

$$h = h'. \tag{10}$$

All the elements in the array $\boldsymbol{p}$ have identical value, which describes the output intensity of the BPLC pixel and is given by

$$I(p,q) = \frac{I'(i,j)}{\dim(p)}. \tag{11}$$

For $\sim$ 70° incident light, the angle $|\theta'|$ is $\sim$ 80°. Let us assume the projected image is 2 m×1.5 m with resolution of 1024×768. That means $L' = 2$ m, $W' = 1.5$ m, $h' = 1024$, $v' = 768$, corresponding to $\sim$ 2 mm pixel size on the screen. If the pixel size in the LCD panel is 20 μm, then the magnification m_0 is $\sim$ 100. In (8), let $f - z_0' = 2$ m, which could be tuned by the projection system, then the magnification in the vertical direction changes with the row of pixel, as shown in the Fig. 3(b). Applying (9), we get $v = 1639$. Thus in this case, the resolution

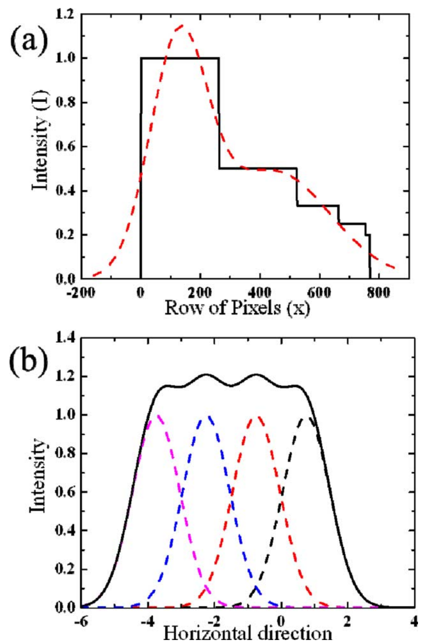

Fig. 4. (a) Intensity distribution of dual LED system in the vertical direction. The solid line is the ideal distribution calculated by (11), the dashed line is fitting using two Gaussian distributed LEDs. (b) Inntensity distribution of LED array in the horizontal direction. The dashed lines are the single LED intensity and the solid line denotes the total intensity.

is reduced by 2.1×. As each pixel is $\sim$ 20 μm, the size of the panel is $\sim$ 2.1 cm × 3.3 cm.

For a white image in the above case, the light intensity distribution in the vertical direction is shown as black solid line in Fig. 4(a), which is given by (11). It is a step function because the pixels are digital. To obtain such an intensity distribution, we proposed a dual LED system as shown in Fig. 1. Let us assume each collimated LED has Gaussian intensity distribution, the optimum fitting is given by

$$\text{Intensity} = a_1 \exp\left(-\frac{(x-x_1)^2}{{w_1}^2}\right) + a_2 \exp\left(-\frac{(x-x_2)^2}{{w_2}^2}\right)$$
$$a_1 = 1.02,\ x_1 = 126,\ {w_1}^2 = 18425.8$$
$$a_2 = 0.489,\ x_2 = 443,\ {w_2}^2 = 172555. \qquad (12)$$

The coefficients a_1 and a_2 denote the brightness of the LEDs, the parameters x_1 and x_2 give the position of the LEDs, and the parameters w_1 and w_2 control the collimation of the LEDs. Here the first term corresponds to the top LED in Fig. 1(a), which illuminates the pixels close to the projection lens. This LED needs to be brighter and better collimated, as the corresponding pixels have larger magnification, which means fewer pixels on the LCD panel are needed to describe one pixel on the projection screen. Hence the intensity of each pixel on the LCD panel needs to be higher. The requirement of collimation is more critical as the crosstalk would have greater influence on the image quality. Compared to a single LED system, this dual LED system could better meet our needs and have higher optical efficiency. To get a smooth and optimum distribution of light intensity, it requires accurate arrangement and coupling elements between them as well. More complicate it may be, it can save the power consumption as well as space for collimator.

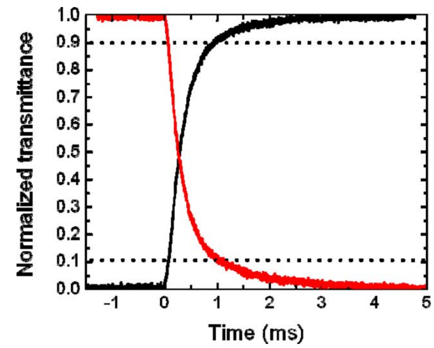

Fig. 5. Rise time and fall time of black-to-white transition, measured in transmissive mode with 80° incident angle at room temperature.

In the horizontal direction, the intensity of the LED backlight should be uniformly distributed. This could be achieved by placing an array of collimated LEDs in the horizontal direction. Fig. 4(b) shows an example of LED array. Each of them has Gaussian distribution and they are equally spaced. The fluctuation could be corrected by LCD panel.

The structure of a single collimated LED is shown in Fig. 1(c). The parameters of the collimator lens vary with the arrangement of the LED package. It is shown that similar LED module can collimate the light within 3.3° at 90% of total flux [17]. For the part of BPLC panel which is closer to the lens, an additional collimator is applied to achieve better collimation. The collimator is basically a Fourier transform system where the rear focus point of the first lens coincides with the front focus point of the second lens. A small aperture is placed at that focus to filter out the higher order modes, thereby gives a better collimated beam.

The optical efficiency of the system is given by

$$\eta = \eta_{\text{coll}} \times \eta_{\text{RGB}} \times \eta_{\text{disp}} \times \eta_{\text{lenses}} \qquad (13)$$

where η_{coll} is the efficiency for collecting light into the system, η_{RGB} is for color matching and rebalancing, η_{disp} is for display transmission including the polarizers, and η_{coll} is for in-line transmission of lens optics. In our system, we could estimate $\eta_{\text{coll}} \sim 80\%$, $\eta_{\text{RGB}} \sim 90\%$, and $\eta_{\text{lenses}} \sim 90\%$. In the case of large incident angle to the LCD panel, a simple approach to prevent crosstalk between two adjacent pixels is to fabricate TFT structure in the crosstalk region and add black matrix on it. This combined with the polarizers on the LCD panel would give $\eta_{\text{disp}} \sim 40\%$. Multiplying these numbers together, the overall optical efficiency is $\sim 25\%$. Compared with the conventional three-panel projection displays which has efficiency $< 20\%$, this design has a slight advantage on optical efficiency.

III. Results and Discussion

We prepared a polymer-stabilized VFS BPLC cell with 4.87 μm cell gap using JNC JC-BP01M [18]. The experiment was performed at room temperature with He-Ne laser ($\lambda = 633$ nm) and the incident angle was $\theta = 80°$. Fig. 5 shows that the rise time is $\sim$ 0.91 ms and the fall time is $\sim$ 0.95 ms. Here we measured the response time from 10% to 90% transmittance change. The rise time of gray-scale transitions depends on the bias voltage of the LCD panel and is generally slower than that

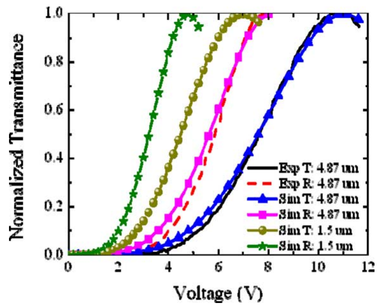

Fig. 6. Experiment and simulation of VT curve. "Exp" denotes experiment result, where the cell gap is 4.87 μm. "Sim" denotes simulation result, both 4.87 μm and 1.5 μm cell gaps are simulated. "T" denotes transmissive mode, and "R" denotes reflective mode.

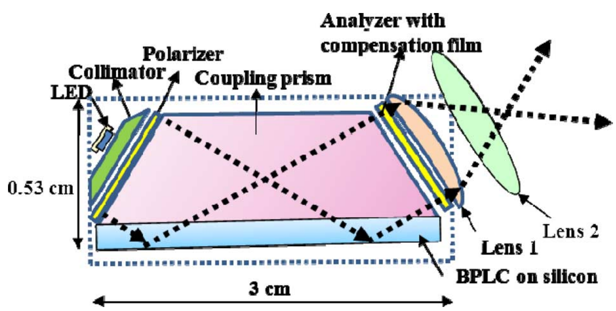

Fig. 7. Device configuration of a reflective BPLC projector.

of full-on time [19]. This commonly encountered problem can be overcome by the overdrive voltage method [20], [21] similar to nematic LCDs.

The measured voltage-dependent transmittance (VT) curves of transmissive mode (Fig. 1) and its simulation result are shown in Fig. 6, denoted as "Exp T: 4.87 μm" and "Sim T: 4.87 μm" respectively. The agreement is good and the peak voltage occurs at $\sim$ 11 V. To lower the operation voltage, we could reduce the cell gap or develop high Kerr constant BPLC materials. For example, if we reduce the cell gap to 1.5 μm, and the peak voltage is lowered to $\sim$ 7 V (denoted as "Sim T: 1.5 μm"). To further lower the voltage, we proposed using reflective mode (light passes through the cell twice), as shown in Fig. 7. The experimental and simulation results for the same cell are shown in Fig. 6 with peak voltage $\sim$ 8 V. If we use a 1.5-μm cell, the voltage could be lowered to 4.8 V.

Fig. 7 shows a reflective projection with 80° incident angle. The reflective mode is based on liquid-crystal-on-silicon (LCOS) technology. Compared to a conventional LCOS projector, this design does not need a polarizing beam splitter. A compensation film is laminated in front of the analyzer to compensate for the polarization change due to reflection. As the light traverses the BPLC cell twice, the driving voltage of this reflective mode is lower than that of transmissive mode. In this design using a 1.5-μm-thick VFS cell, the peak voltage is $\sim$ 4.8 V at $\lambda = 633$ nm.

Recently, a microsecond-response BPLC modulator has been demonstrated [22]. With such a fast response time, color sequential projection display with unnoticeable color breakup could be realized with a single panel. Compared with a conventional LCD projector, the inherent color convergence of this single-panel system brings better image quality and eliminates the need for convergence mechanics and adjustment. With fewer LCD panels, this projector design will give lower cost and smaller volume, which is promising for pico projectors.

IV. Conclusion

A color-sequential projection display using polymer- stabilized BPLC is proposed. The submillisecond response time of BPLC enables color-sequential technique to be implemented for LCD projector. The data processing and illumination system is briefly analyzed. Its further modification (reflective mode) is also discussed.

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Sihui He is currently working toward the Ph.D. degree from the College of Optics and Photonics, University of Central Florida (UCF), Orlando.

Her research interest includes blue phase liquid crystal displays, novel displays, and liquid crystal biosensors.

Currently, Ms. He is the secretary of IEEE Photonics student chapter at UCF.

Jiun-Haw Lee received the B.S.E.E., M.S.E.E., and Ph.D. degrees in electrical engineering in 1994, 1995, and 2000, respectively, all from National Taiwan University, Taipei, Taiwan.

From 2000 to 2003, he was with the RiTdisplay Corporation as the director. Since 2003, he has been with the faculty of Graduate Institute of Photonics and Optoelectronics and the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, where he is currently a full professor. His research interests include organic optoelectronic devices, display technologies, and solid-state lighting.

Dr. Lee is an associate editor of IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY.

Hui-Chuan Cheng received the B.S. degree in electrical engineering and M.S. degree in photonics from National Taiwan University, Taipei, Taiwan, in 2000 and 2005, respectively, and is currently working toward the Ph.D. degree in the College of Optics and Photonics, University of Central Florida (UCF), Orlando.

He was a senior engineer at AU Optronics from 2005 to 2007. His research interests include blue phase LCDs, sunlight readable LCDs, and touch panels.

Mr. Cheng is a recipient of 2011 SID Distinguished Student Paper Award. He was President of SID student chapter at UCF in 2011.

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

Her research interest includes device physics and materials of polymer-stabilized blue phase and isotropic phase liquid crystal displays. She has published 15 journal articles in several publications, including *Applied Physics Letters* and *Optics Express*.

Currently, Ms. Yan is the President of SID student chapter at UCF.

Shin-Tson Wu (M'98–SM'99–F'04) received the B.S. degree in physics from National Taiwan University, and Ph.D. degree from the University of Southern California, Los Angeles.

He is a Pegasus professor at College of Optics and Photonics, University of Central Florida, Orlando.

Dr. Wu is the recipient of 2011 SID Slottow-Owaki prize, 2010 OSA Joseph Fraunhofer award, 2008 SPIE G. G. Stokes award, and 2008 SID Jan Rajchman prize. He was the Founding Editor-in-Chief of IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY. He is a Fellow of the Society of Information Display (SID), Optical Society of America (OSA), and SPIE.