A Spatiotemporal Four-Primary Color LCD With Quantum Dots

Zhenyue Luo and Shin-Tson Wu, *Fellow, IEEE*

***Abstract*—A four-primary liquid crystal display (LCD) by hybrid color processing in spatial and temporal domains is presented. By integrating with quantum dots, the number of LED can be reduced and the emission spectrum optimized. This approach exhibits following advantages over conventional three-primary LCDs: 1) it has 1.5X higher spatial resolution and 2X higher light efficiency; 2) it can achieve 130% color gamut in CIE 1931 and 155% in CIE 1976 color space; and 3) it has a more relaxed LC response time requirement and can be readily integrated into commercial LCD products.**

***Index Terms*—Multi-primary colors, liquid crystal display (LCD), quantum dots (QDs).**

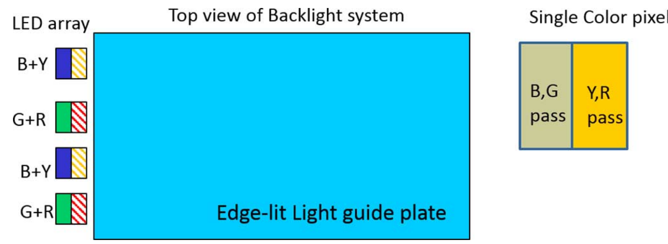

Fig. 1. Schematic of the backlight system. Inset shows the configuration of color filter arrangement.

I. Introduction

THE demand of wide-color-gamut display is ever increasing for visually superior image reproduction and accurate color reproduction. The present three-primary [i.e., red (R), green (G), and blue (B)] liquid crystal displays (LCDs) mainly use single-chip white light emitting diode (LED) as backlight [1], [2]. Its color gamut is only ~75% NTSC (National Television Standard Committee) because the emitted yellow band is fairly broad. Since natural objects and cinema have more colors than that a LCD can display, there is an urgent need to obtain wider color gamut in order to faithfully reproduce the original colors. Two different approaches have been attempted to widen color gamut: 1) more saturated RGB primaries and 2) multi-primary colors, such as RGB plus yellow.

Highly saturated RGB primaries can be obtained by employing narrow band color filters (CFs) or light sources. The former reduces the transmittance significantly and is not a favored option. Multi-chip RGB LEDs have excellent color purity, but it requires separate and complicated driving circuits. The use of multi-primary colors [3] leads to a large polygon-shaped color gamut. Several strategies have been explored, including four primaries [4], [5], five primaries [6]–[8] and six primaries [9]. Generally speaking, there are two basic approaches to realize multi-primary colors: 1) spatial color synthesis based on multi-primary color filter array and 2) temporal color synthesis based on field-sequential-color (FSC) technique [7], [10]–[12]. Each approach has its own pros and cons. Spatial color filters reduce resolution because more sub-pixels are required, while FSC demands a fast LC response time. If the response time is not sufficiently fast (<1 ms), color breakup becomes annoying.

Recently, LCD with quantum dot (QD)-enhanced backlight has extended color gamut to beyond 120% NTSC in CIE 1931 color space and 140% NTSC in CIE 1976 color space [13]. Moreover, QD can be conveniently integrated into existing production process with low cost. Therefore, it is a promising backlight solution for achieving vivid colors [14]–[16]. In this paper, we propose a four-primary LCD with hybrid spatiotemporal approach. The four primary colors are generated partly by spatial filtering and partly by time sequential. Moreover, we propose to use quantum dots to reduce the LED numbers and optimize the emission spectrum. This simple approach exhibits several advantages: high optical efficiency, high resolution density, wide color gamut, and a less-demanding LC response time (~4 ms). It can be readily integrated into existing LCD products.

II. System Configuration

Fig. 1 depicts the proposed backlight systems. The LED array is set along the edge of a typical edge-lit light guide plate. Two types of LEDs are employed: Type I emits blue and yellow colors, while Type II emits green and red. They are switched on and off alternatively to illuminate the display panel. The inset of Fig. 1 shows a single color pixel, which consists of two sub-pixels corresponding to two color filters. The first color filter transmits shorter wavelengths, such as blue and green, while the other transmits longer wavelengths, such as yellow and red.

Fig. 2 illustrates the image generation mechanism of the proposed hybrid method. A typical color image is split into

Manuscript received December 14, 2013; revised January 26, 2014; accepted February 26, 2014. Date of publication March 03, 2014; date of current version April 14, 2014. This work is supported by Industrial Technology Research Institute (ITRI), Taiwan.

The authors are with the College of Optics and Photonics, University of Central Florida, Orlando, FL 32816 USA (e-mail: zhenyueluo@knights.ucf.edu, swu@ucf.edu).

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

Digital Object Identifier 10.1109/JDT.2014.2309251

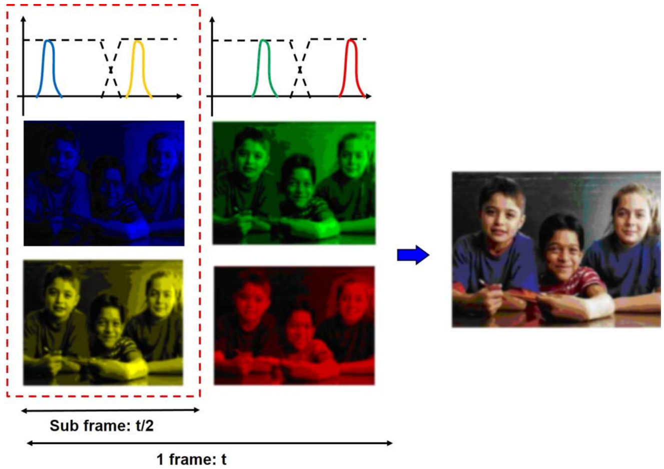

Fig. 2. Color generation of the proposed spatiotemporal 4-primary approach.

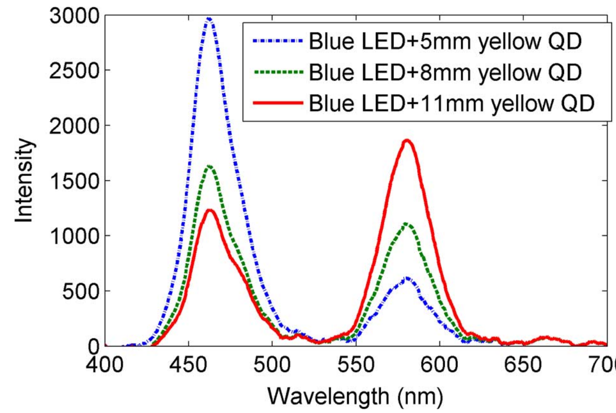

Fig. 3. Measured emission spectra of a blue LED with different QD thicknesses.

four sub-images corresponding to different primary colors. One frame of image is composed of two consequent sub-frames. During the first sub-frame, type-I LED is activated, and the blue and yellow components transmit through different color filters and illuminate two sub-pixels separately. During the second sub-frame, type-II LED is activated so that the green and red components transmit through different color filters and illuminate different sub-pixels. The LC arrays corresponding to the two sub-pixels are modulated independently to display the sub-images. Therefore, the four-primary-color LCD is achieved partly by spatial filtering and partly by time sequential signals. The viewer can observe a vivid color image by subconscious integration of four-primary color images. Langendijk, *et al.* [17], [18] reported a similar hybrid approach with different color filter designs, but the display is still three-primary and the color performance still has room for improvement.

The LED illuminant in Fig. 1 plays a key role determining the display performance. It can be realized with different methods. Taking type-I LED as an example, it can be a combination of blue and yellow LEDs, or a blue LED with yellow phosphor. Here, we propose to use blue LED with QD phosphor. QDs can partially absorb the blue light and convert it to yellow with high color purity. Fig. 3 shows the measured spectra of a blue LED covered with different yellow QD layer thicknesses. The concentration of QD is 0.5%. As the QD thickness increases, more blue light is absorbed and more yellow light is generated. As a result, the intensity ratio of blue and yellow can be readily tuned by varying the QD thickness or concentration.

As shown in Fig. 3, the emission spectrum of yellow QD is fairly sharp; its full-width-half-maximum $\mathrm{FHWM} \sim 30$ nm, which is very close to that of a commercial yellow LED emission. Combined with QD layers, a single LED can emit two high purity colors simultaneously. Thus, the required LED number can be reduced. Furthermore, commercial LEDs have limited primary colors (known as green gap), but the peak emission wavelength of QD phosphors can be tuned conveniently via optimizing QD size or composition. This offers another degree of freedom for device optimization. We can optimize the QD emission wavelength to match the transmission spectra of color filters for enlarging color gamut.

III. Performance Evaluation

The backlight spectrum affects the display system's performance significantly. In this section, we optimize the backlight spectrum by co-maximizing the system efficiency and color gamut, and compare the performance of hybrid four-primary LCD with conventional three-primary LCD. Also, we evaluate the color breakup phenomenon and compare it with conventional field-sequential color displays.

The input backlight spectrum power distribution (SPD) can be expressed as

$$\begin{aligned} P_{in,1}(\lambda) &= f_b S(\lambda, \lambda_b, \Delta\lambda_b) + f_y S(\lambda, \lambda_y, \Delta\lambda_y) \\ P_{\mathrm{in},2}(\lambda) &= f_g S(\lambda, \lambda_g, \Delta\lambda_g) + f_r S(\lambda, \lambda_r, \Delta\lambda_r) \end{aligned} \quad (1)$$

where $P_{\mathrm{in},1}(\lambda)$ and $P_{\mathrm{in},2}(\lambda)$ are SPD of type-I and type-II light sources, which are turned on and off alternatively. $S(\lambda, \lambda_{b,g,r,y}, \Delta\lambda_{b,g,r,y})$ represents the emission spectrum for red, green, blue and yellow color primaries. Each emission spectrum can be described as Gaussian function. $\lambda_i (i = b, g, r, y)$ stands for the central wavelength of blue, green and red color components, while $\Delta\lambda_i (i = b, g, r)$ and $f_i (i = b, g, r)$ are the FWHM and relative proportion of each color component.

After light passing through the LCD panel, the output SPD can be written as

$$\begin{aligned} P_{\mathrm{out}}(\lambda) &= P_{\mathrm{out},b}(\lambda) + P_{\mathrm{out},g}(\lambda) + P_{\mathrm{out},r}(\lambda) + P_{\mathrm{out},y}(\lambda) \\ &= P_{in,1}(\lambda) CF_1(\lambda) LC(\lambda) A_1 \\ &\quad + P_{in,2}(\lambda) CF_1(\lambda) LC(\lambda) A_2 \\ &\quad + P_{\mathrm{in},2}(\lambda) CF_2(\lambda) LC(\lambda) A_1 \\ &\quad + P_{in,1}(\lambda) CF_2(\lambda) LC(\lambda) A_2 \end{aligned} \quad (2)$$

where $P_{\mathrm{out},i} (i = b, g, r, y)$ is the output spectrum of each primary color. The $CF_{1,2}(\lambda)$ and $A_{1,2}$ are the transmission spectrum and aerial ratio of color filters. From Fig. 1, $A_{1,2} = 0.5$. $LC(\lambda)$ is the transmission spectrum of the employed LC mode. Here, let us take multi-domain vertical alignment (MVA) LC cell as an example; the MVA cell is at its maximum transmittance, i.e., voltage-on state [13], [19].

The total light efficiency (TLE) can be written as

$$\mathrm{TLE} = \frac{683 \frac{lm}{W_{\mathrm{opt}}} \int P_{\mathrm{out}}(\lambda) V(\lambda) d\lambda}{\int (P_{\mathrm{in},1}(\lambda) + P_{\mathrm{in},2}(\lambda)) d\lambda}. \quad (3)$$

This value indicates how much input light can be transmitted through the LCD panel and be perceived by human eyes. $V(\lambda)$ is the human eye sensitivity function, which is centered at $\lambda = 550$ nm. The maximum value of LER is 683 lm/W for a monochromatic light source at $\lambda = 550$ nm.

After knowing the output spectrum for each color primary $P_{out,i}(\mathrm{i} = b, g, r, y)$, one can calculate the color coordinates based on different color matching functions [20]. These four color primaries encircle a quadrilateral region in the CIE chromaticity diagram. All the colors within the region can be reproduced by proper mixing of the four primary colors. The area ratio between this quadrilateral and the triangle defined by NTSC is called color gamut. A large color gamut means better color reproducibility. Based on (1)–(3), we can quantitatively evaluate the influence of input SPD on the color performance and light efficiency of a LCD system. For comparison purpose, we choose D65 ($\mathrm{x} = 0.312, \mathrm{y} = 0.329$ in CIE1931 color diagram) as reference point. D65 is a typical white light close to the sunlight and is prevalent in most displayed images; it is a representative color for display performance evaluation.

The relative portions of each primary color should be properly chosen to render the targeted white color. The three-primary LCD has fixed intensity ratio for color rendering, while four-primary has one degree of reproduction redundancy and numerous intensity ratio combination can be used. This color reproduction redundancy [20] offers flexibility for color-reproduction and can be utilized to optimize the display performance, such as light efficiency, color breakup and color shift [3]. Here, we arbitrarily choose the relative portion of yellow f_y as a variable, then the relative portion of the other three color is linearly dependent on f_y. They can be given as [5]

$$\begin{bmatrix} f_r \\ f_g \\ f_b \end{bmatrix} = \begin{pmatrix} \frac{x_r}{y_r} & \frac{x_g}{y_g} & \frac{x_b}{y_b} \\ 1 & 1 & 1 \\ \frac{z_r}{y_r} & \frac{z_g}{y_g} & \frac{z_b}{y_b} \end{pmatrix}^{-1} \begin{bmatrix} \frac{x_w}{y_w} - \frac{x_y}{y_y} f_y \\ 1 - f_y \\ \frac{z_w}{y_w} - \frac{z_y}{y_y} f_y \end{bmatrix} \quad (4)$$

where the (x_w, y_w, z_w) is the color coordinates of the targeted white point, and $(x_i, y_i, z_i | i = r, g, b, y)$ are the color coordinates of the four primary colors.

An ideal display should have a large color gamut and high light efficiency. So we introduce the following two objective functions:

$$\begin{aligned} \text{Color gamut} &= F_1(\lambda_b, \Delta\lambda_b, \lambda_g, \Delta\lambda_g, \lambda_r, \Delta\lambda_r, \lambda_y, \Delta\lambda_y, f_y), \\ \text{TER} &= F_2(\lambda_b, \Delta\lambda_b, \lambda_g, \Delta\lambda_g, \lambda_r, \Delta\lambda_r, \lambda_y, \Delta\lambda_y, f_y). \end{aligned} \quad (5)$$

Most QD samples emit light with FHWM $\sim 30 - 50$ nm, depending on the size and composition distribution [16]. For practical applications, the following constraints are put on each free parameter: 400 nm $<\lambda_b<$500 nm, 500 nm $<\lambda_g<$550 nm, 500 nm $<\lambda_y<$600 nm, 600 nm $<\lambda_r<$700 nm, 20 nm $\leq \Delta\lambda_b \leq$ 30 nm, and 30 nm $\leq \Delta\lambda_g, \Delta\lambda_r, \Delta\lambda_y \leq$ 50 nm. Optimization is preformed to maximize the above two metric functions within the constrained nine dimensional searching space.

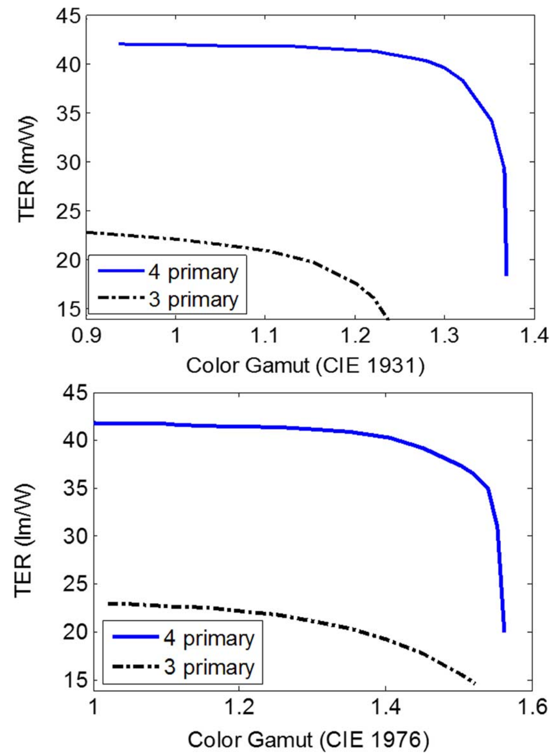

Fig. 4. Relationship between TER and color gamut for three-primary and four-primary LCDs. Color gamut is defined in: (a) CIE 1931, and (b) CIE 1976 color space. (LC mode: MVA).

For such a multi-objective problem, different objectives may be mutually exclusive. Therefore, a result that simultaneously satisfies each objective may not exist. Instead, a group of solutions could be obtained; any further improvement of the solution in terms of one objective is likely to be compromised by the degradation of another objective. Such solutions constitute a so-called *Pareto front*. In this paper we choose the particle swarm optimization algorithm [21] as optimization solver to find the *Pareto front*.

We performed the optimization for a MVA LCD. Since color gamut can be defined either in CIE 1931 or CIE 1976 color space, we performed two separate optimizations. Results are plotted in Fig. 4(a) and (b). In Fig. 4(a), the solid curve represents the *Pareto front* of the hybrid four-primary display, The LCD varies from low color gamut (95% NTSC) but high TER (41.8 lm/W) to high color gamut (137% NTSC) but low TER (<30 lm/W). The tradeoff between TER and color gamut is obvious because the gain of one metric results from the loss of the other.

The dashed lines in Fig. 4(a) represent the Pareto front of three-primary LCD with QD backlight. The detailed calculation procedures have been reported in [13], which proves that the three-primary LCD with QD backlight has superior performance to conventional CCFL and LED backlights. However, Fig. 4(a) indicates that the newly proposed 4-primary LCD has even better performance. It covers a larger color gamut, and more amazingly it has almost 2X higher optical efficiency.

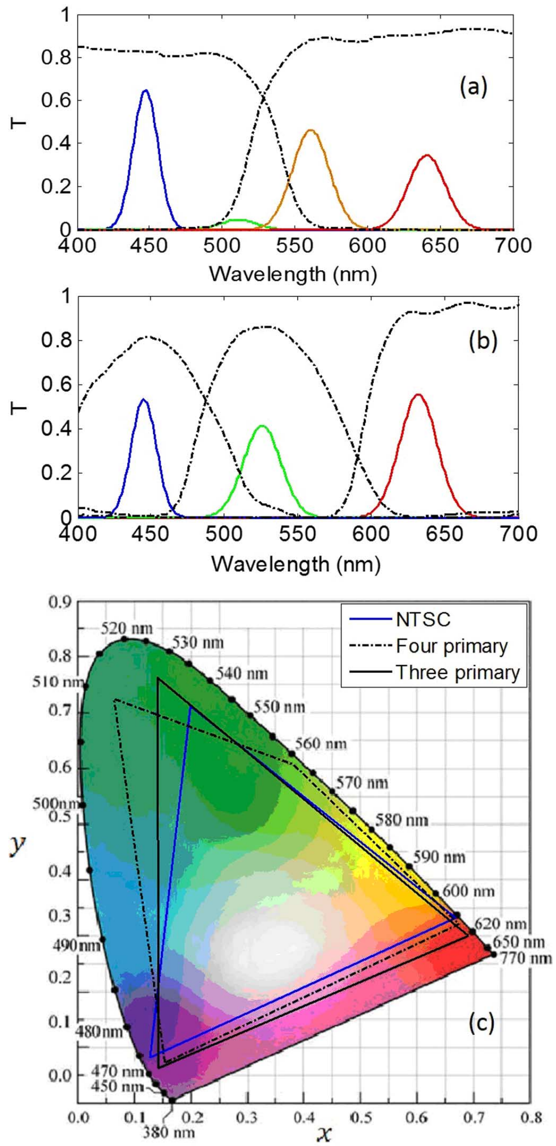

Fig. 5. (a) Optimized spectrum for the hybrid four-primary LCD and the transmission spectra of color filters. (b) Optimized spectrum for the three-primary LCD and transmission spectra of color filters. (c) Comparison of color gamut of the four-primary and three-primary displays and the NTSC standard in CIE 1931 color space.

Fig. 4(b) shows the Pareto front for TER and color gamut defined in CIE 1976 color space. Compared with CIE 1931 results shown in Fig. 4(a), the color gamut in CIE 1976 is correspondingly wider. The newly proposed 4-primary LCD can achieve $>$155% color gamut in CIE 1976 color space.

Fig. 5(a) depicts the emission spectrum of hybrid four-primary LCD. It is optimized to match the transmission spectra of color filters. CF1 transmits blue and green lights while CF2 transmits yellow and red lights. In the first sub-frame, blue and yellow emissions are activated, and in combination with color filters result in blue and yellow sub-pixel images. In the second sub-frame, green and red emissions are activated, analogously under the same color filters green and red sub-pixel images are generated. Fig. 5(b) plots the emission spectra of three-primary LCD. The three emission peaks are also optimized to match the transmission spectra of RGB color filters. Fig. 5(c) depicts the color gamut on the CIE1931 color space. The three-primary LCD with quantum dot backlight has very pure color and covers 120% NTSC, but its color gamut is still limited in a triangle region and has limited color rendering ability for yellow and cyan color. The hybrid four-primary LCD encircles a large quadrilateral region in the CIE color diagram. The color gamut exceeds 130% and covers almost every color defined in NTSC standard. Moreover, the color chromaticity coordinates of G primary move to shorter wavelength so that more cyan region is covered, and the new yellow color coordinates allow high purity yellow to be reproduced with high fidelity. According to image analysis [6], high purity cyan and yellow are very common in a typical display image, therefore our four-primary display can greatly enhance the visual experience compared to conventional three-primary display.

To further broaden color gamut, deeper blue and red colors can be considered. However, their emission band is farther away from 550 nm and thus the total brightness (or optical efficiency) is reduced. This leads to a fundamental tradeoff between light efficiency and color gamut, as Fig. 4 shows. Refining color filter is another approach for enhancing color performance. For example, if we can shift the cutoff wavelength of the long pass color filter to a longer wavelength, then we can use a more saturated green light ($\sim$520 nm) while mitigating the crosstalk in each color channel. Under these conditions, a 100% coverage of NTSC color gamut can be expected.

Next, we analyze the light efficiency. The three-primary LCD with input SPD shown in Fig. 5(a) has $\mathrm{TER} \sim 17.6$ lm/w. In comparison, the hybrid four-primary LCD with input SPD shown in Fig. 5(b) has $\mathrm{TER} \sim 35.2$ lm/w, which is almost 2X higher. This significant increase of light efficiency originates from two factors: 1) Reducing the sub-pixel number from three to two can increase light efficiency by 1.5X, since less light is absorbed in the color filters, and 2) Four-primary color LCD has color reproduction redundancy and we can use high ratios of yellow and green colors for color rendering. The image looks brighter under the same backlight power since human eye is sensitive to yellow and green. As shown in Fig. 5(a) and (b), the relative portion of green and yellow in hybrid four-primary display is higher than that of three-primary one. Therefore four-primary display has much higher light efficiency. Overall speaking, the hybrid four-primary LCD can reach a better tradeoff point compared to the three-primary. There is an urgent need to reduce LCD power consumption to meet Energy Star 6 standard. The proposed hybrid four-primary LCD can be an attractive candidate to solve this problem.

The hybrid four-primary display still partially depends on the FSC technique. Color breakup (CBU) [22] is the most disturbing artifact that degrades the image quality in FSC. It manifests itself in the appearance of multiple color images of stationary objects during saccadic eye motion, or along the edges of moving objects when tracking the objects with the eye. Several methods have been proposed to suppress the CBU, including increasing the frame rate [22], inserting another color or black fields [23], four-color fields arrangement [24], and Stencil-FSC method [10]. However, most of these methods put stringent requirement on LC response time and some of them may sacrifice the display brightness.

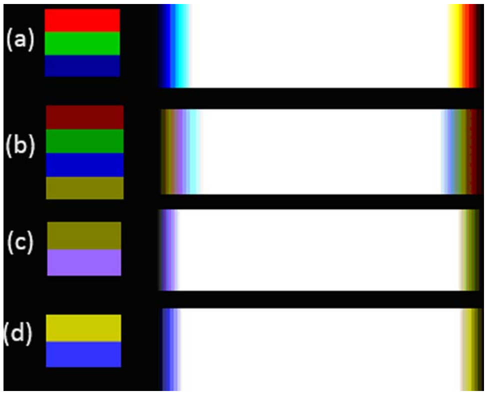

Fig. 6. Simulated color breakup for: (a) RGB 3-primary FSC; (b) RGBY 4-primary FSC; (c) Hybrid four-primary color; and (d) Hybrid four-primary color with optimized color weighting ratios.

To evaluate the CBU of the hybrid method, we simulate the CBU when displaying a typical white color with different color sequential methods. The white object has a width of 250×75 pixels, and the object moves in the horizontal direction with a speed of 30 pixels/frame. As shown in Fig. 6, the rainbow-like CBU patterns can be clearly observed in a RGB color sequential display [Fig. 6(a)] and even more pronounced in a RGBY color sequential display [Fig. 6(b)]. But the hybrid four-primary display [Fig. 6(c)] exhibits much less CBU due to reduced frame number. Moreover, we can take advantage of the color-reproduction redundancy and optimize the color ratio to further suppress CBU. For example, we can use high-brightness yellow and low-brightness blue when mixing a white color. As our eyes tend to feel that the bright yellow merges into the white object and weak blue merges into dark background, an even less CBU is observed (Fig. 6(d)).

Finally, we evaluate the LC response time requirement. For a typical 120-Hz frame rate, the period of each frame is 8.33 ms. Our hybrid four-primary requires two subframes, so the period of each subframe is 4.16 ms. Currently, commerical MVA LCDs, e.g., Sharp's Aquos HDTV, can achieve 4 ms response time. So our hybrid four-primary approach can be readily integrated into commerical LCD products. On the contrary, FSC with three and four subframes require response time of 2.77 and 2.08 ms, respectively. They can only be realized by some fast-response nematic cells [11], [25], [26] or blue phase [27]–[29].

Table I compares the performance of our hybrid four-primary LCD with three-primary using RGB color filters. The hrybrid four-primary LCD outperforms its three-primary conuterpart in following aspects: 1) It requires fewer subpixels so that it can boost the spatial resolution by 1.5× under the same fabrication precision; 2) it provides another degree of color reproduction redundancy' 3) QD allows us to optimize the input light SPD to match the transmission spectra of color filters. By combining these advantages, the four-primary LCD is expected to heve 2X higher light efficiency. 4) The four-primary LCD can achieve color gamut over 130% NTSC in CIE 1931 color space and 155% NTSC in CIE 1976 color space. It can reproduce yellow and cyan with much higher fidelity. The only drawback is it requires 2× higher frame rate. But compared to conventional FSC technique, the hybrid four-primary display does not put too stringent burden on the LC response time and it is readied by existing commercial products. Overall speaking, the hybrid four-primary LCD have advantages in spatial resolution, color gamut, light efficiency, and less demanding LC response time.

TABLE I
COMPARISION OF THREE-PRIMARY AND HYBRID FOUR-PRIMARY LCDs

	Three-primary	Hybrid four-primary
Color synthesis	RGB CFs	two CFs and two sub-frames
Spatial resolution	1	1.5
Light efficiency	1	~2
Color gamut (CIE 1931)	At most 120%	120%~130%
Frame rate	1	2 (affordable)

IV. SUMMARY

We propose a hybrid spatiotemporal four-primary LCD with quantum dots. The four-primary colors are generated partly by spatial filtering and partly by time sequential signal. Moreover, we propose to use quantum dots to reduce the LED number and optimize the emission spectrum. This approach has several advantages: 1) 1.5X spatial resolution; 1) 2X light efficiency; 3) wide color gamut; and 4) less demanding LC response time. This approach can be readily integrated with existing fast-response commercial products.

REFERENCES

[1] S. Kobayashi, S. Mikoshiba, and S. Lim, *LCD Backlights*. Hobokem, NJ, USA: Wiley, 2009.
[2] M. Anandan, "Progress of LED backlights for LCDs," *J. Soc. Inf. Display*, vol. 16, pp. 287–310, 2008.
[3] K. Tomizawa, K. Nakamura, S. Ueki, Y. Yoshida, T. Mori, M. Hasegawa, A. Yoshida, Y. Narutaki, Y. Itoh, Y. Yoshida, and M. Teragawa, "Multi-primary-color LCD: Its characteristics and extended applications," *J. Soc. Inf. Display*, vol. 19, no. 5, pp. 369–379, 2011.
[4] E. Chino, K. Tajiri, H. Kawakami, H. Ohira, K. Kamijo, H. Kaneko, S. Kato, Y. Ozawa, T. Kurumisawa, K. Inoue, K. Endo, H. Moriya, T. Aragaki, and K. Murai, "Development of wide-color-gamut mobile displays with four-primary-color LCDs," in *SID Dig. Tech. Papers*, 2006, vol. 37, no. 1, pp. 1221–1224.
[5] S. Wen, "Design of relative primary luminances for four-primary displays," *Displays*, vol. 26, no. 4, pp. 171–176, 2005.
[6] H. C. Cheng, I. Ben-David, and S. T. Wu, "Five-primary-color LCDs," *J. Display Technol.*, vol. 6, no. 1, pp. 3–7, Jan. 2010.
[7] H. C. Cheng, L. H. Rao, and S. T. Wu, "Color breakup suppression in field-sequential five-primary-color LCDs," *J. Display Technol.*, vol. 6, no. 6, pp. 229–234, Jun. 2010.
[8] S. Ueki, K. Nakamura, Y. Yoshida, T. Mori, K. Tomizawa, Y. Narutaki, Y. Itoh, and K. Okamoto, "Five-primary-color 60-inch LCD with novel wide color gamut and wide viewing angle," in *SID Dig. Tech. Papers*, 2009, vol. 40, no. 1, pp. 927–930.
[9] Y.-C. Yang, K. Song, S. Rho, N.-S. Rho, S. J. Hong, K. B. Deul, M. Hong, K. Chung, W. H. Choe, S. Lee, C. Y. Kim, S. H. Lee, and H. R. Kim, "Development of six primary-color LCD," in *SID Dig. Tech. Papers*, 2005, vol. 36, no. 1, pp. 1210–1213.
[10] F. C. Lin, Y. P. Huang, C. M. Wei, and H. P. D. Shieh, "Color-breakup suppression and low-power consumption by using the stencil-FSC method in field-sequential LCDs," *J. Soc. Inf. Display*, vol. 17, no. 3, pp. 221–228, 2009.
[11] T. Ishinabe, K. Wako, K. Sekiya, T. Kishimoto, T. Miyashita, and T. Uchida, "High-performance OCB-mode field-sequential-color LCD," *J. Soc. Inf. Display*, vol. 16, no. 2, pp. 251–256, 2008.
[12] S. Gauza, X. Zhu, S. T. Wu, W. Piecek, and R. Dabrowski, "Fast-switching liquid crystals for color-sequential LCDs," *J. Display Technol.*, vol. 3, no. 3, pp. 250–252, Sep. 2007.

[13] Z. Luo, Y. Chen, and S.-T. Wu, "Wide color gamut LCD with a quantum dot backlight," *Opt. Express*, vol. 21, no. 22, pp. 26269–26284, 2013.
[14] J. Chen, V. Hardev, J. Hartlove, J. Hofler, and E. Lee, "A high-efficiency wide-color-gamut solid-state backlight system for LCDs using quantum dot enhancement film," in *SID Dig. Tech. Papers*, 2012, vol. 43, no. 1, pp. 895–896.
[15] S. Coe-Sullivan, "Quantum dot developments," *Nat. Photon.*, vol. 3, no. 6, pp. 315–316, 2009.
[16] J. S. Steckel, R. Colby, W. Liu, K. Hutchinson, C. Breen, J. Ritter, and S. Coe-Sullivan, "Quantum dot manufacturing requirements for the high volume LCD market," in *SID Dig. Tech. Papers*, 2013, vol. 44, no. 1, pp. 943–945.
[17] E. H. A. Langendijk, "A novel spectrum-sequential display design with a wide color gamut and reduced color breakup," *J. Soc. Inf. Display*, vol. 15, no. 4, pp. 261–266, 2007.
[18] E. H. A. Langendijk, G. Cennini, and O. Belik, "Color-breakup evaluation of spatio-temporal color displays with two-and three-color fields," *J. Soc. Inf. Display*, vol. 17, no. 11, pp. 933–940, 2009.
[19] R. Lu, X. Zhu, S. T. Wu, Q. Hong, and T. X. Wu, "Ultrawide-view liquid crystal displays," *J. Display Technol.*, vol. 1, no. 1, pp. 3–14, Sep. 2005.
[20] J. H. Lee, D. N. Liu, and S. T. Wu, *Introduction to Flat Panel Displays*. oboken, NJ, USA: Wiley, 2008.
[21] M. Reyes-Sierra and C. A. C. Coello, "Multi-Objective particle swarm optimizers: A survey of the state-of-the-art," *Int. J. Comput. Intell. Res.*, vol. 2, pp. 287–308, 2006.
[22] M. Mori, T. Hatada, K. Ishikawa, T. Saishouji, O. Wada, J. Nakamura, and N. Terashima, "Mechanism of color breakup in field-sequential-color projectors," *J. Soc. Inf. Display*, vol. 7, no. 4, pp. 257–259, 1999.
[23] K. Sekiya, T. Miyashita, and T. Uchida, "A simple and practical way to cope with color breakup on field sequential color LCDs," in *SID Dig. Tech. Papers*, 2006, vol. 37, no. 1, pp. 1661–1664.
[24] C. H. Chen, F. C. Lin, Y. T. Hsu, Y. P. Huang, and H. P. D. Shieh, "A field sequential color LCD based on color fields arrangement for color breakup and flicker reduction," *J. Display Technol.*, vol. 5, no. 1, pp. 34–39, Jan. 2009.
[25] F. Yamada, H. Nakamura, Y. Sakaguchi, and Y. Taira, "Sequential-color LCD based on OCB with an LED backlight," *J. Soc. Inf. Displays*, vol. 10, no. 1, pp. 81–85, 2002.
[26] D. Xu, L. Rao, C. D. Tu, and S. T. Wu, "Nematic liquid crystal display with submillisecond grayscale response time," *J. Display Technol.*, vol. 9, no. 2, pp. 67–70, Feb. 2013.
[27] 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.
[28] K. M. Chen, S. Gauza, H. Q. Xianyu, and S. T. Wu, "Submillisecond gray-Level response time of a polymer-stabilized blue-phase liquid crystal," *J. Display Technol.*, vol. 6, no. 2, pp. 49–51, Feb. 2010.
[29] 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 crystals," *Appl. Phys. Lett.*, vol. 99, p. 201105, 2011.

Zhenyue Luo received the B.S. and M.S. degrees in optics from Zhejiang University, Hangzhou, China, in 2007 and 2010, respectively, and is presently working toward the Ph.D. degree from the College of Optics and Photonics, University of Central Florida, Orlando, FL, USA. His current research focuses on backlight design and quantum-dots-enhanced liquid crystal display devices.

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

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

Dr. Wu is the recipient of OSA Esther Hoffman Beller medal (2014), SID Slottow-Owaki prize (2011), OSA Joseph Fraunhofer award (2010), SPIE G. G. Stokes award (2008), and SID Jan Rajchman prize (2008). He was the founding Editor-in-Chief of IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY. He is a Charter Fellow of the National Academy of Inventors, a Fellow of the Society of Information Display (SID), Optical Society of America (OSA), and SPIE.