The Luminance Resolution Characteristics of Multi-Primary Color Display

多原色表示装置における輝度解像度特性の解析

Yasuhiro Yoshida ∗[1] Shinji Nakagawa ∗[1] Akiko Yoshida ∗[2] Kazuyoshi Yoshiyama ∗[1]
Hiroyuki Furukawa ∗[3]

In this paper, we analyze the resolution characteristics of multi-primary color (MPC) display systems. We demonstrate that four-primary (4PC) displays can increase the effective resolution for achromatic images in the luminance domain by a factor of two as compared to conventional RGB-based displays with MPC-specialized sub-pixel rendering, which we propose in this paper. Five- and six-primary color (5PC and 6PC) display system can reproduce denser luminance data than conventional RGB-based display systems and solve a problem of MPC displays, viz. increase of production costs and decrease of the aperture ratio caused by increasing the number of sub-pixels in one pixel. This is an essential advantage of MPC display systems, which is related to the combination of our proposed color filter architecture and image processing: so, we propose a completely new advantage of MPC display systems in addition to their well-known capabilities of color reproduction and power-saving.

本論文では多原色表示装置における解像度の解析を行う。本論文に示す多原色表示装置特有のサブピクセルレンダリング方法を用いることで，４原色表示装置は一般的な３原色表示装置と比べて２倍の実効的な輝度解像度を持つことができる。５原色や６原色の表示装置では，一般的な３原色表示装置よりも高い輝度解像度を持つことができるとともに，１画素当たりの原色数が増えることによる製造コストの増加や開口率の低下を解決できる。解像度の向上は，色域の拡大や省電力と並び，多原色表示装置の全く新しい本質的な優位点である。

1. Introduction

Multi-primary color (MPC) display systems and their related technologies can be considered as one of the fastest emerging research areas in recent years (1-8). Traditionally, wide color gamut displays have been required for visually superior image reproduction and/or for accurate color reproduction of existing materials. Visually sufficient images are commonly needed for entertainment use while the accurate color reproduction is demanded for professional use such as digital archives, designs, simulations, and medical systems. MPC display systems, which are well-known for their wide color gamut, are not only suitable for achieving wider color gamut but also suitable for achieving a specific color gamut accurately and efficiently, e.g., the gamut of nature colors. This is the biggest difference from conventional display devices which simply expand the color gamut with three primary colors (red, green, and blue: RGB).

Besides their wide and accurate color reproduction, there are additional advantages of MPC display systems. One of their well-known strength is their flexibility for color reproduction, so-called color reproduction redundancy. This characteristic leads to a number of applications for MPC display systems such as higher luminance reproduction (9), wide viewing-angles (10), high light-use efficiency (i.e., low power consumption as consequence) (11, 12) and minimization of color variation caused by the individual characteristics of viewers (13).

In addition to these advantages based on MPC's color reproduction redundancy, its potential of high resolution representation in luminance domain is also well-known. The sub-pixel rendering approach is usually employed for increasing effective resolution for both MPC systems and conventional RGB-based systems; however, there is a severe trade-off to co-reproduce pseudo-colors by sub-pixel rendering.

In this paper, we introduce an essential advantage of

∗[1] A1288 Project Team
∗[2] Advanced Display Systems Development Center, Digital Information Appliance Division
∗[3] Telecommunication & Image Technology Laboratories, Corporate Research and Development Division

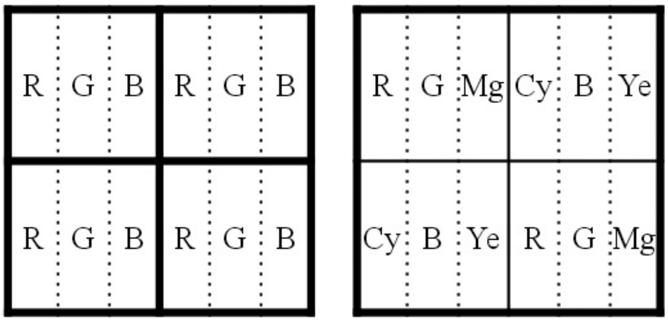
MPC display systems in terms of the luminance resolution characteristics. In Section 2, the characteristic of color reproduction redundancy in MPC systems is briefly reviewed with application examples. Section 3 deals with one of the MPC systems, four-primary color (4PC), and describes resolution properties. In Section 4, we propose a 4PC-specialized sub-pixel rendering for both increasing effective luminance resolution and moderating pseudo-color display. Computational simulation and results of three types of 4PC displays such as RGB + Yellow (RGBYe), RGB + Cyan (RGBCy) and RGB + White (RGBW) are described in Sections 5 and 6. In addition, we improve this rendering method to apply to five or more primary color systems. We compare the luminance resolution characteristics of several kinds of MPC displays such as RGBRCyYe and RGBCyMgYe. For these cases, we check the potential to reproduce three effective pixels on each pixel.

Finally, we show that 4PC systems are potentially capable of representing effective resolution as twice as conventional RGB-based systems and also moderating the problem of pseudo-colors by applying 4PC-specialized sub-pixel rendering. Additionally, five-primary color (5PC) or six-primary color (6PC) systems are capable of reproducing the same luminance resolution as RGB-based display systems even if MPC display systems have only a half of pixels in horizontal direction compared with RGB-based display.

2. Background

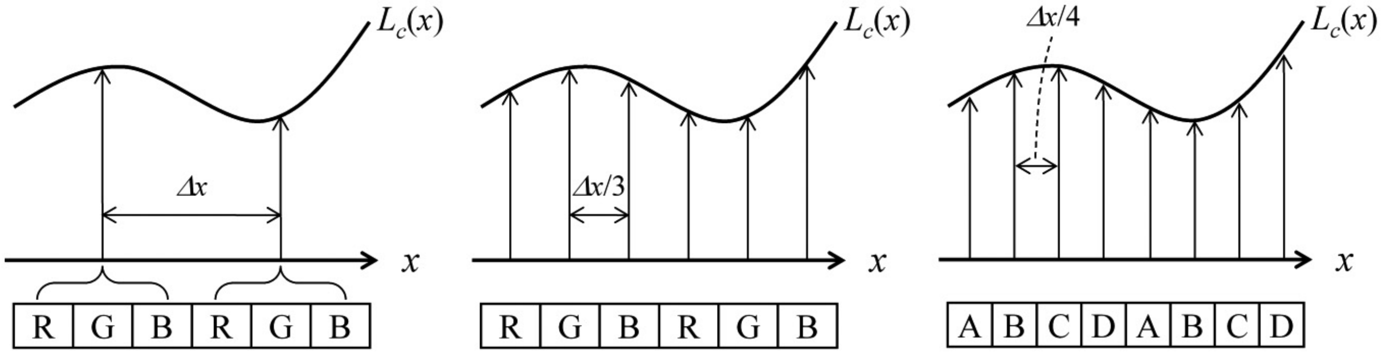
Resolution is one of the most important display specifications for image quality of a display device. However, by increasing the number of pixels and/or sub-pixels, the production cost of a display also increases. 6PC systems especially have a severe problem related to this kind of disadvantage. Typical 6PC (exactly 6 sub-pixels) displays are constructed as 3PC displays with changing primary colors; e.g. changing from RGBRGB (two pixels at 3PC) to RGBCyMgYe (one pixel at 6PC) (10, 14). It is because that there are several advantages such as avoiding the increase of the production cost and decreasing the aperture ratio of the display. On the other hand, the numbers of pixels of 6PC displays becomes half both horizontally and vertically compared to 3PC displays as shown in **Fig. 1**.

Sub-pixel rendering has been commonly used to increase effective resolution without increasing the actual number of pixels of a display. **Fig. 2** illustrates pixel-rendering and sub-pixel rendering. When sampling a continuous function Lc (x), let us define the sampling interval as Δx for pixel-rendering. It becomes Δx/3 for sub-pixel rendering in



(a) 3PC display (b) 6PC display

Fig. 1 3PC (RGB) display and 6PC (RGBCyMgYe) display. Most imaging systems assume displays have square-shaped pixels. A pixel of 6PC displays consists of 12 sub-pixels to keep their pixels square, although that of 3PC displays consists of only 3 sub-pixels.



(a) 3PC pixel rendering

(b) 3PC sub-pixel rendering (x3 sampling)

(c) 4PC sub-pixel rendering (x4 sampling)

Fig. 2 A comparison of pixel rendering and sub-pixel rendering. 4PC systems with sub-pixel rendering are essentially capable of higher effective luminance resolution due to their denser sampling intervals.

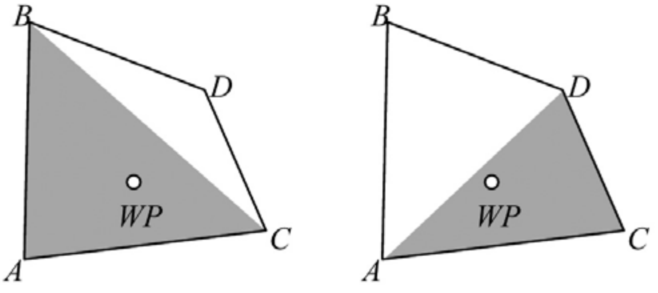
3PC systems, Δx/4 in 4PC systems, and so on. This means that MPC systems are essentially capable of higher-resolution representation than conventional 3PC display systems because of the possibility of denser sub-pixel sampling (15). The most primitive sub-pixel rendering is the decimation filter (down-sampler). It works well only when an input image is band-limited at the half of the output sampling rate. Another example of sub-pixel rendering is a series of box-filters (mean-filters) for anti-aliasing. As one of more sophisticated sub-pixel renderings, Daly introduced spatio-chromatic visual models to improve perceived horizontal resolution in 3PC (16).

MPC display systems, which consist of RGB and additional primary color(s), potentially have an advantage of high-resolution image representation because of the increased number of sub-pixels. A number of results of sub-pixel architecture and/or sub-pixel rendering in MPC display systems have been presented (8, 17-19). Den Engelsen et al. discussed how to achieve cost-effective MPC for four- and five-primary colors in CRTs and concluded that one of the proposed 4PC-CRT reproduces relatively high luminance without lowering perceived sharpness (8). In (17), Elliott et al. firstly presented two types of sub-pixel arrangements for 3PC systems. One aligns sub-pixels in rectilinear array, and the other arranges sub-pixels in a five-pixel array. A sub-pixel rendering is applied as a combination of a two-dimensional tent filter for red and green sub-pixels and a box-filter for blue sub-pixels. Their PenTile technology was extended for MPC systems with RGB and White primaries in (18), and also employed in (19).

Sub-pixel rendering increases effective resolution in luminance domain; however, there is a severe problem in displaying pseudo-colors. Compared to the conventional pixel-rendering, the increase of sampling density also increases the possibility of pseudo-color display. For example, in 3PC, it may happen that dense sampling intervals lead to pseudo-colors in sub-pixel rendering or rough sampling intervals do not display pseudo-colors in pixel rendering. No other choice is left so that big improvement for luminance resolution by sub-pixel rendering cannot be expected in 3PC (20, 21). Even for MPC display systems, conventional sub-pixel rendering algorithms lead to pseudo-color display. (14).

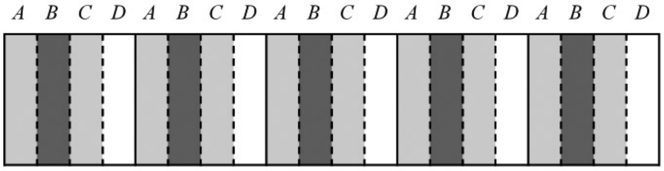
3. Resolution Properties In MPC

Let us consider the 4PC case in this section as one of the examples of MPC systems. As shown in **Fig. 3**, there are at least two combinations of primary colors for reproducing white. This means that two different luminance reproductions are possible at the different parts in one pixel as seen in **Fig. 4**. This can be formulated as follows.

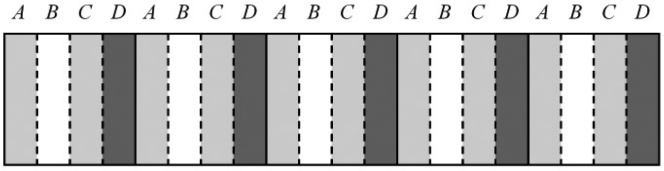


(a) Reproducing white by ABC (b) Reproducing white by CDA

Fig. 3 There are at least two combinations of primaries to reproduce white in 4PC display systems due to their color reproduction redundancy.



(a) Reproducing black by ABC and white by CDA



(b) Reproducing white by ABC and black by CDA

Fig. 4 4PC display systems are enable to reproduce two different luminance data onto one pixel without the issue of pseudo-colors.

The tristimulus values (X, Y, Z) of an expected color can be written as

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_A & X_B & X_C & X_D \\ Y_A & Y_B & Y_C & Y_D \\ Z_A & Z_B & Z_C & Z_D \end{bmatrix} \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} \tag{1}$$

where (A, B, C, D) are the indices of primary colors, ($X_{\{A, B, C, D\}}$, $Y_{\{A, B, C, D\}}$, $Z_{\{A, B, C, D\}}$) are the tristimulus values of each primary, and (a, b, c, d) are the digital code values of each sub-pixel. When $a=b=c=d=v_{\max}$ where $v_{\max}$ is the maximum digital code value, the output tristimulus values represent white point at (X_W, Y_W, Z_W). Here, we assume that the white-balance correction is already applied in this system.

When reproducing white, for example, two sets of the digital code values for each sub-pixel are calculated as

$$\begin{bmatrix} X_A & X_B & X_C & X_D \\ Y_A & Y_B & Y_C & Y_D \\ Z_A & Z_B & Z_C & Z_D \end{bmatrix}\begin{bmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \end{bmatrix} = \begin{bmatrix} X_A & X_B & X_C & X_D \\ Y_A & Y_B & Y_C & Y_D \\ Z_A & Z_B & Z_C & Z_D \end{bmatrix}\begin{bmatrix} a_2 \\ b_2 \\ c_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} X_W/2 \\ Y_W/2 \\ Z_W/2 \end{bmatrix} \tag{2}$$

where (a_1, b_1, c_1, d_1) and (a_2, b_2, c_2, d_2) are the sets of digital code values for two different luminance reproductions. Due to the property of color reproduction redundancy in MPC, the digital code values of each sub-pixel are mathematically underspecified. If each reproduction employs three of four primaries (see **Fig. 3** as an example), they can be specified as

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} X_A & X_B & X_C \\ Y_A & Y_B & Y_C \\ Z_A & Z_B & Z_C \end{bmatrix}^{-1}\begin{bmatrix} X_W/2 \\ Y_W/2 \\ Z_W/2 \end{bmatrix} \tag{3}$$

and

$$\begin{bmatrix} a_2 \\ c_2 \\ d_2 \end{bmatrix} = \begin{bmatrix} X_A & X_C & X_D \\ Y_A & Y_C & Y_D \\ Z_A & Z_C & Z_D \end{bmatrix}^{-1}\begin{bmatrix} X_W/2 \\ Y_W/2 \\ Z_W/2 \end{bmatrix} \tag{4}$$

However, it is highly unlikely to be ($a_1 + a_2$, b_1, $c_1 + c_2$, d_2) = ($v_{\max}$, $v_{\max}$, $v_{\max}$, $v_{\max}$) but one or more of the elements may exceed $v_{\max}$. To correctly keep the maximum luminance reproduction, the digital code values need to be optimized by a simple normalization step such as

$$\begin{bmatrix} a_1' \\ b_1' \\ c_1' \\ d_1' \end{bmatrix} = \begin{bmatrix} a_1/(a_1+a_2) \\ b_1/(b_1+b_2) \\ c_1/(c_1+c_2) \\ d_1/(d_1+d_2) \end{bmatrix}\cdot v_{\max}, \quad \begin{bmatrix} a_2' \\ b_2' \\ c_2' \\ d_2' \end{bmatrix} = \begin{bmatrix} a_2/(a_1+a_2) \\ b_2/(b_1+b_2) \\ c_2/(c_1+c_2) \\ d_2/(d_1+d_2) \end{bmatrix}\cdot v_{\max} \tag{5}$$

where (a_1', b_1', c_1', d_1') and (a_2', b_2', c_2', d_2') are optimized digital code values. In this case, b_1' and d_2' are always $v_{\max}$ and d_1' and b_2' are always 0, respectively. Another optimization method, which is to keep the minimum pseudo-color display, is achieved by the following normalization step:

$$\begin{bmatrix} a_1' \\ b_1' \\ c_1' \\ d_1' \end{bmatrix} = \begin{bmatrix} a_1/M \\ b_1/M \\ c_1/M \\ d_1/M \end{bmatrix}\cdot v_{\max}, \quad \begin{bmatrix} a_2' \\ b_2' \\ c_2' \\ d_2' \end{bmatrix} = \begin{bmatrix} a_2/M \\ b_2/M \\ c_2/M \\ d_2/M \end{bmatrix}\cdot v_{\max} \tag{6}$$

where M = max ($a_1 + a_2$, $\mathrm{b}_1 + b_2$, $c_1 + c_2$, $d_1 + d_2$). In this case, d_1' and b_2' are always 0, respectively. An ideal solution is to optimize color coordinates of primary colors. It is easier for LCDs to design tristimulus values of primary colors to be ($a_1 + a_2$, b_1, $c_1 + c_2$, d_2) = ($v_{\max}$, $v_{\max}$, $v_{\max}$, $v_{\max}$) compared to PDPs. This optimization allows both maximum luminance reproduction and minimum pseudo-color display. In addition, alignment of primary colors is important for this optimization. To achieve two luminance reproductions shown in **Fig. 3**, primaries B and D have relatively high luminance as compared to primaries A and C. Because of using additional primary(ies) such as yellow and cyan, digital code values of effective pixels are asymmetric (on the other hand, effective pixels of RGBG 4PC display are symmetric). It means that this primary design is significantly important for our method.

Let us name the digital code values of effective sub-pixels as (a_1L_1, b_1L_1, c_1L_1, 0) and (a_2L_2, 0, c_2L_2, d_2L_2) after optimization. The output tristimulus values (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) by them are computed as

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} X_A & X_B & X_C & X_D \\ Y_A & Y_B & Y_C & Y_D \\ Z_A & Z_B & Z_C & Z_D \end{bmatrix}\begin{bmatrix} a_1L_1 \\ b_1L_1 \\ c_1L_1 \\ 0 \end{bmatrix} \tag{7}$$

and

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_A & X_B & X_C & X_D \\ Y_A & Y_B & Y_C & Y_D \\ Z_A & Z_B & Z_C & Z_D \end{bmatrix}\begin{bmatrix} a_2L_2 \\ 0 \\ c_2L_2 \\ d_2L_2 \end{bmatrix} \tag{8}$$

Note that the effective pixel produced by the primaries *C*, *D*, and A consists of the sub-pixels in different pixels (see **Fig. 4**). Finally, the digital code (*a*, *b*, *c*, *d*) for two luminance reproduction are calculated as

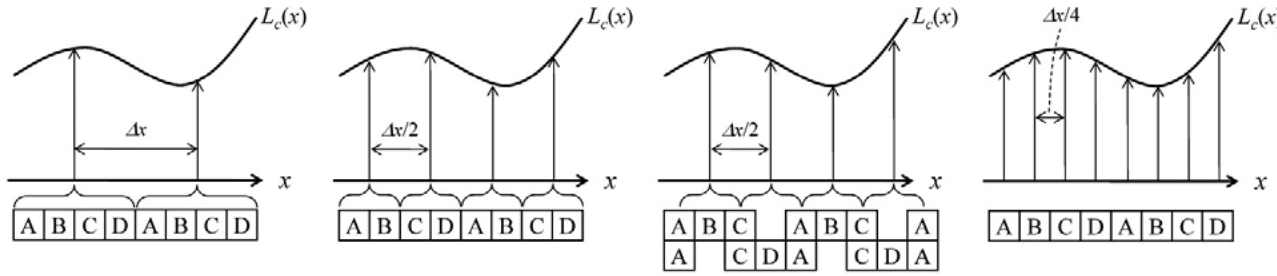
$$\begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} a_1L_1 \\ b_1L_1 \\ c_1L_1 \\ 0 \end{bmatrix} + \begin{bmatrix} a_2L_0 \\ 0 \\ c_2L_2 \\ d_2L_2 \end{bmatrix} \tag{9}$$

where L_0, L_1 and L_2 are luminance sampled continuously. This equation shows how one pixel can represent two different luminance values for an average luminance. This leads to a luminance reproduction that is two time larger than the number of actual pixels when displaying achromatic images. Additionally, this concept can be applied to not only 4PC systems but also other MPC systems. In the next section, we present how to balance increasing effective resolution and moderating pseudo-colors by MPC sub-pixel rendering.

4. Sub-Pixel Rendering For MPC Display System

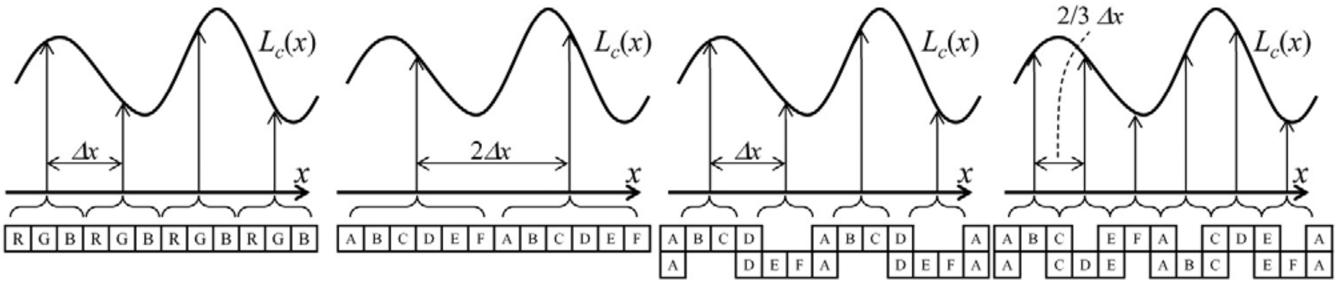
Fig. 5 shows our sub-pixel rendering for 4PC display systems. **Fig. 5 (a)** represents the case of pixel-rendering which moderates pseudo-color display, and **Fig. 5 (d)** is the sub-pixel rendering which increases the sampling density. We propose an MPC-specialized sub-pixel rendering as shown in **Fig. 5 (c)**. In this algorithm, the sampling interval is the half of the pixel-rendering because of the two different luminance reproductions on one pixel based on Equations (7) and (8). This indicates that MPC-specialized sub-pixel rendering can provide the interval choices which exist neither in 3PC pixel rendering nor in sub-pixel rendering approaches. This advantage may balance increasing the density of sampling intervals and moderating pseudo-color display. **Fig. 5 (b)** shows another case of MPC sub-pixel rendering when its sampling interval is half of that in pixel rendering.

This method can be applied not only to 4PC displays but also to other MPC systems which have five or more primary colors. **Fig. 6** shows our sub-pixel rendering for 6PC display systems compared to 3PC (RGB) pixel rendering. Typical 6PC systems need six sub-pixels along horizontal direction as shown in **Fig. 6 (b)**. The sampling interval of 6PC systems is twice and resolution is halved compared with traditional 3PC systems shown in **Fig. 6 (a)**. On the other hand, sub-pixel rendering can divide one pixel into two effective pixels in the horizontal direction. In the case



(a) Pixel rendering in 4PC
(b) Sub-pixel rendering (x2 sampling) in 4PC
(c) 4PC-specialized sub-pixel rendering (x2 sampling)
(d) Sub-pixel rendering (x4 sampling) in 4PC

Fig. 5 Pixel and sub-pixel renderings on 4PC display systems.



(a) 3PC pixel rendering (x1 sampling)
(b) 6PC pixel rendering (x1/2 sampling)
(c) 6PC-specialized sub-pixel rendering (x1 sampling)
(d) 6PC-specialized sub-pixel rendering (x3/2 sampling)

Fig. 6 Pixel and 6PC-specialized sub-pixel renderings on 6PC display systems.

shown in **Fig. 6 (c)**, effective pixels are composed of sub-pixels ABCD and DEFG, respectively. This means that the luminance resolution of 6PC-based display systems with specialized sub-pixel rendering is the same as that of 3PC systems. Moreover, three luminance values can be reproduced on one pixel. In the case shown in **Fig. 6 (d)**, effective pixels are composed of sub-pixels ABC, CDE and EFA, respectively. Horizontal luminance resolution of 6PC-based display systems is higher than that of traditional RGB-based display systems with reduced pseudo-color display.

5. Computational Simulation

In this section, we describe the simulations for both pixel rendering and sub-pixel rendering approaches on RGB-based and MPC displays. There are various patterns of primary color combinations for MPC display systems. For our simulation, three types of the 4PC systems (RGBYe, RGBCy and RGBW), one type of 5PC system (RGBRCyYe), and one type of 6PC system (RGBCyMgYe), are chosen as examples of MPC systems. An additional colored sub-pixel is employed to widen the color gamut (e.g., RGBYe) while a white sub-pixel is commonly introduced to increase luminance reproduction. Here, we assume that these two systems are linearly related in order to simplify the conditions in our simulation, as same as in the reference (20).

5.1 RGBYe and RGBCy

A continuous function, the circular zone plate (CZP), is used as an input signal. Since CZP consists of only luminance information, it can be the ideal input signal for sampling simulations. YUV is employed for the output of luminance and chromaticity signals in our simulation so that aliasing and pseudo-colors are calculated based on YUV. First, the luminance data of an input signal are sampled and applied onto each sub-pixel. Then, YUV values are computed on each sub-pixel. In this simulation, the conversions from RGB, RGBYe and RGBCy to YUV are processed as

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2126 & 0.7152 & 0.0722 \\ -0.1146 & -0.3854 & 0.5000 \\ 0.5000 & -0.4542 & -0.0458 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2126 & 0.3081 & 0.0722 & 0.4071 \\ -0.1146 & -0.1391 & 0.5000 & -0.2463 \\ 0.5000 & -0.3544 & -0.0458 & -0.0998 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ Ye \end{bmatrix} \tag{11}$$

and

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2551 & 0.3576 & 0.0505 & 0.3367 \\ -0.1375 & -0.1927 & 0.3500 & -0.0198 \\ 0.6000 & -0.2271 & -0.0321 & -0.3408 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ Cy \end{bmatrix} \tag{12}$$

Note that the 3-by-3 matrix in Equation (10) is defined in BT. 709 (22). Equations (11) and (12) come from an assumed set of color coordinates of RGBYe and RGBCy primaries defined as a linear combination of RGB in Equation (10). The sets of RGBYe and RGBCy coordinates are derived from

$$\begin{bmatrix} \mathbf{R}_4 \\ \mathbf{G}_4 \\ \mathbf{B}_4 \\ \mathbf{Ye}_4 \end{bmatrix}^T = \begin{bmatrix} \mathbf{R}_3 \\ \mathbf{G}_3 \\ \mathbf{B}_3 \end{bmatrix}^T \begin{bmatrix} 1 & -r_{Ye} & 0 & r_{Ye} \\ 0 & 1-g_{Ye} & 0 & g_{Ye} \\ 0 & -b_{Ye} & 1 & b_{Ye} \end{bmatrix} \tag{13}$$

and

$$\begin{bmatrix} \mathbf{R}_4 \\ \mathbf{G}_4 \\ \mathbf{B}_4 \\ \mathbf{Cy}_4 \end{bmatrix}^T = \begin{bmatrix} \mathbf{R}_3 \\ \mathbf{G}_3 \\ \mathbf{B}_3 \end{bmatrix}^T \begin{bmatrix} \bar{r}_{Cy} & 0 & 0 & r_{Cy} \\ 0 & \bar{g}_{Cy} & 0 & g_{Cy} \\ 0 & 0 & \bar{b}_{Cy} & b_{Cy} \end{bmatrix} \tag{14}$$

where $\{R_3, G_3, B_3\}$, $\{R_4, G_4, B_4, Ye_4\}$ and $\{R_4, G_4, B_4, Cy_4\}$ are the sets of 3×1 YUV color vectors for RGB primaries in Equation (10), RGBYe primaries in Equation (11) and RGBCy primaries in Equation (12), respectively, and (r_{Ye}, g_{Ye}, b_{Ye}) and (r_{Cy}, g_{Cy}, b_{Cy}) are the combination parameters (set as $(r_{Ye}, g_{Ye}, b_{Ye}) = (0.25, 0.50, -0.05)$ in Equation (13) and $(r_{Cy}, g_{Cy}, b_{Cy}) = (-0.20, 0.50, 0.30)$ in Equation (14), respectively) and $(\bar{r}_{Cy}, \bar{g}_{Cy}, \bar{b}_{Cy}) = (1-r_{Cy}, 1-g_{Cy}, 1-b_{Cy})$. Because of the reason described in Section 3, optimizing YUV values of primary colors is necessary for the best performance of our method. In this simulation, YUV values of primary colors are ideally optimized by using these equations and their parameters.

5.2 RGBW

Since the white primary only consists of luminance information, YUV values of white can be formulated as $Y = wY_W$ and $U=V=0$ where Y_W is the part of tristimulus value (i.e., Y of XYZ) and w is the digital code value of the white primary. The relationship between all primaries in RGBW can be given as $Y_R + Y_G + Y_B + Y_W = 1$. According to these rules, the conversion from RGBW to YUV is presented as

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2126\overline{Y}_W & 0.7152\overline{Y}_W & 0.0722\overline{Y}_W & Y_W \\ -0.1146 & -0.3854 & 0.5000 & 0 \\ 0.5000 & -0.4542 & -0.0458 & 0 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ W \end{bmatrix} \tag{15}$$

where $\overline{Y}_W = 1 - Y_W$. In this simulation, we examine three types of RGBW display where $Y_W = 0.25$, $Y_W = 0.50$ and $Y_W = 0.75$. Note that effective pixels of RGBW system depend on Y_W as shown in **Fig. 7(b)(c)(d)** and they are definitely different from those of other 4PC systems to which a chromatic primary is added such as the case of RGBYe shown in **Fig. 7(a)**. As clearly seen in the figure, $Y_W = 0.5$ is mandatory for MPC-specialized sub-pixel rendering. When $Y_W = 0.5$, the effective pixel introduces its luminance distribution in either square or Gaussian shape. However, for both cases of increasing and decreasing Y_W from 0.5, the luminance distribution becomes asymmetric in shape. This leads to decreasing the effect of luminance driven resolution improvement.

5.3 RGBRCyYe and RGBCyMgYe

In this simulation, both 5PC and 6PC systems have six sub-pixels in each pixel. Note that a pixel of 5PC system consists of one sub-pixel for each G, B, Cy and Ye and two for R. The conversion from RGBW to YUV is presented as

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.0744 & 0.2146 & 0.0469 & 0.0744 & 0.2009 & 0.3888 \\ -0.0401 & -0.1156 & 0.3250 & -0.0401 & 0.1073 & -0.2365 \\ 0.1750 & -0.1363 & -0.0298 & 0.1750 & -0.2546 & 0.0706 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ R \\ Cy \\ Ye \end{bmatrix} \tag{16}$$

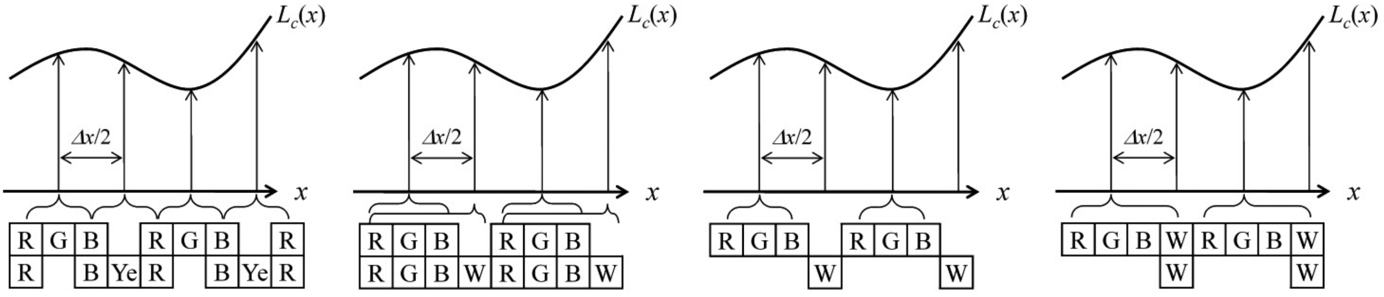
and

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.0850 & 0.2503 & 0.0397 & 0.2077 & 0.0603 & 0.3569 \\ -0.0458 & -0.1349 & 0.2750 & -0.0042 & 0.1292 & -0.2193 \\ 0.2000 & -0.1590 & -0.0252 & -0.1954 & 0.1840 & -0.0044 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \\ Cy \\ Mg \\ Ye \end{bmatrix} \tag{17}$$

The sets of RGBRCyYe and RGBCyMgYe coordinates are derived from

$$\begin{bmatrix} \mathbf{R}_5 \\ \mathbf{G}_5 \\ \mathbf{B}_5 \\ \mathbf{R}_5 \\ \mathbf{Cy}_5 \\ \mathbf{Ye}_5 \end{bmatrix}^T = \begin{bmatrix} \mathbf{R}_3 \\ \mathbf{G}_3 \\ \mathbf{B}_3 \end{bmatrix}^T \begin{bmatrix} \overline{r}_5/2 & 0 & 0 & \overline{r}_5/2 & r_{Cy} & r_{Ye} \\ 0 & \overline{g}_5 & 0 & 0 & g_{Cy} & g_{Ye} \\ 0 & 0 & \overline{b}_5 & 0 & b_{Cy} & b_{Ye} \end{bmatrix} \tag{18}$$

and



(a) RGBYe (b) RGBW ($Y_W < 0.5$) (c) RGBW ($Y_W = 0.5$) (d) RGBW ($Y_W > 0.5$)

Fig. 7 A comparison between RGBYe and RGBW systems when applying our MPC-specialized sub-pixel rendering.

$$\begin{bmatrix} \mathbf{R}_6 \\ \mathbf{G}_6 \\ \mathbf{B}_6 \\ \mathbf{Cy}_6 \\ \mathbf{Mg}_6 \\ \mathbf{Ye}_6 \end{bmatrix}^T = \begin{bmatrix} \mathbf{R}_3 \\ \mathbf{G}_3 \\ \mathbf{B}_3 \end{bmatrix}^T \begin{bmatrix} \bar{r}_6 & 0 & 0 & r_{Cy} & r_{Mg} & r_{Ye} \\ 0 & \bar{g}_6 & 0 & g_{Cy} & g_{Mg} & g_{Ye} \\ 0 & 0 & \bar{b}_6 & b_{Cy} & b_{Mg} & b_{Ye} \end{bmatrix} \tag{19}$$

where $(\bar{r}_5, \bar{g}_5, \bar{b}_5) = (1-r_{Cy}-r_{Ye}, 1-g_{Cy}-g_{Ye}, 1-b_{Cy}-b_{Ye})$, $(\bar{r}_6, \bar{g}_6, \bar{b}_6) = (1-r_{Cy}-r_{Mg}-r_{Ye}, 1-g_{Cy}-g_{Mg}-g_{Ye}, 1-b_{Cy}-b_{Mg}-b_{Ye})$ and the combination of the parameters are as follows; $(r_{Cy}, g_{Cy}, b_{Cy}, r_{Ye}, g_{Ye}, b_{Ye}) = (-0.20, 0.30, 0.40, 0.50, 0.40, -0.05)$ in Equation (18) and (rCy, gCy, bCy, rMg, gMg, bMg, rYe, gYe, bYe) = (−0.10, 0.30, 0.20, 0.35, −0.05, 0.30, 0.35, 0.40, −0.05) in Equation (19), respectively.

6. Results

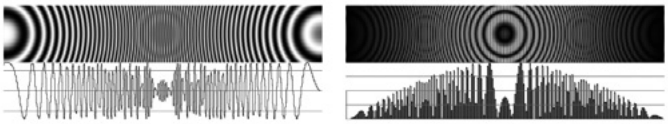
Table 1 summarizes the rendering methods and simulation results. In this table, sampling intervals are shown in **Fig. 2, 5, 6** and **7**. Δx is based on pixel interval of RGB-based system shown in **Fig. 2 (a)**. Pixel intervals of 5PC and 6PC systems are set to 2Δx as shown in **Fig. 6 (b)** because of the reason discussed in Section 2.

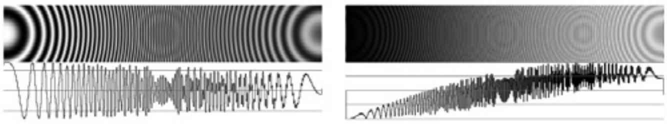
Table 1　Rendering methods for our simulation.

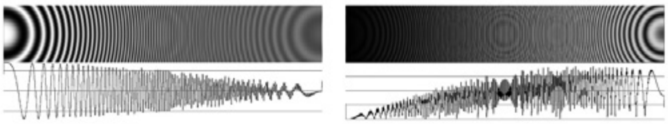
Primary colors		Rendering method	Smpl. interval	Figure
3PC	RGB	Pixel rendering	Δx	8 (a) (b)
		Sub-pixel rendering	1/3 Δx	8 (c) (d)
4PC	RGBYe	Sub-pixel rendering	1/4 Δx	8 (e) (f)
			1/2 Δx	8 (g) (h)
		MPC-specialized SPR	1/2 Δx	8 (i) (j)
	RGBCy	MPC-specialized SPR	1/2 Δx	8 (k) (l)
	RGBW (Y_W=0.25)	MPC-specialized SPR	1/2 Δx	9 (a) (b)
	RGBW (Y_W=0.50)			9 (c) (d)
	RGBW (Y_W=0.75)			9 (e) (f)
5PC	RGBRCyYe	MPC-specialized SPR	Δx	10 (a) (b)
			2/3 Δx	10 (e) (f)
6PC	RGCyMgYe	MPC-specialized SPR	Δx	10 (c) (d)
			2/3 Δx	10 (g) (h)

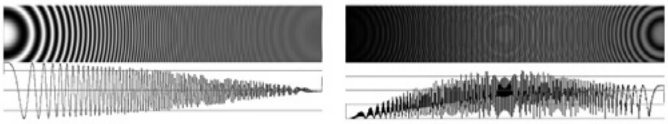
6.1　RGBYe and RGBCy

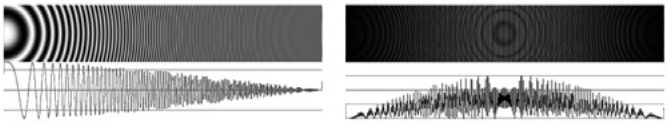
Simulated values of luminance (Y) and pseudo-colors (UV = $(U^2 + V^2)^{0.5}$) are presented in **Fig. 8**. The plots represent the simulated output signals at vertical spatial frequency $f_y = 0$. In the left-side column, the plots show luminance (Y) values with the horizontal lines at the center and 3dB decrease from the maximum. In the right-side column, the plots show chromaticity (UV) values with horizontal lines at 0, 25, 50, 75, and 100%. The leftmost and rightmost ends of the plots represent $f_x/f_s = 0$ and $f_x/f_s = 1$, respectively, where f_x is horizontal spatial frequency and f_s is sampling frequency of 3PC pixel rendering system shown in **Fig. 2 (a)**. **Fig. 8 (a) (b)** and **(c) (d)** show the results of pixel rendering and sub-pixel rendering applied to 3PC systems, respectively. Pixel rendering is not able to reproduce high-frequent signals and sub-pixel rendering reproduces strong pseudo-colors. The cases of RGBYe systems, two kinds of sub-pixel rendering also reproduce pseudo-colors shown in **Fig. 8 (e) (f)** and **(g) (h)** although luminance aliasing are moderated.


(a) Y: RGB pixel rendering　(b) UV: RGB pixel rendering


(c) Y: RGB sub-pixel rendering (x3 sampling)　(d) UV: RGB sub-pixel rendering (x3 sampling)


(e) Y: RGBYe sub-pixel rendering (x4 sampling)　(f) UV: RGBYe sub-pixel rendering (x4 sampling)


(g) Y: RGBYe sub-pixel rendering (x2 sampling)　(h) UV: RGBYe sub-pixel rendering (x2 sampling)


(i) Y: RGBYe 4PC-specialized sub-pixel rendering (x2 sampling)　(j) UV: RGBYe 4PC-specialized sub-pixel rendering (x2 sampling)

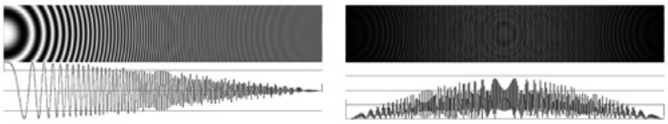

(k) Y: RGBCy 4PC-specialized sub-pixel rendering (x2 sampling)　(l) UV: RGBCy 4PC-specialized sub-pixel rendering (x2 sampling)

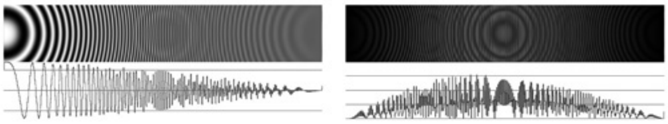
Fig. 8　Results for CZP input signals by pixel and sub-pixel renderings on RGB, RGBYe and RGBCy display systems.

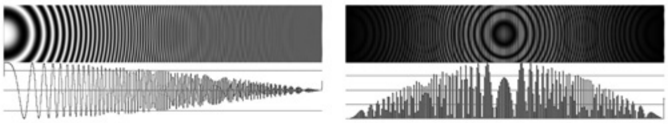
Fig. 8 (i) (j) shows the results of our MPC-specialized sub-pixel rendering applied to RGBYe systems. It is clearly seen that both aliasing and pseudo-color display are moderated by using MPC-specific sub-pixel rendering. This result is explained as follows: our MPC-specialized sub-pixel rendering is exactly positioned on the most effective point for luminance resolution improvement regarding the trade-off between sampling intervals and pseudo-color display. In addition, RGBCy system has the same potential to moderate aliasing and pseudo-color display as shown in **Fig. 8 (k) (l)**.

6.2 RGB + White

Fig. 9 compares the results of RGBW for CZP input signals. In the ideal cases of RGBW in **Fig. 9 (c) (d)**, both aliasing and pseudo-color display are moderated very well. As described in Section 5.2, Y_W of RGBW is strictly limited to be 0.5.

The other cases are shown in **Fig. 9 (a) (b)** and **(e) (f)**, clearly, strong aliasing occurs in those cases. This indicates that the improvement by our MPC-specialized sub-pixel rendering is highly limited for RGBW display systems.


(a) Y: RGBW ($Y_W = 0.25$) (b) UV: RGBW ($Y_W = 0.25$)


(c) Y: RGBW ($Y_W = 0.50$) (b) UV: RGBW ($Y_W = 0.50$)

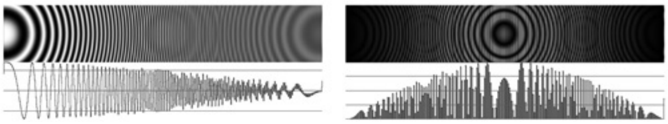
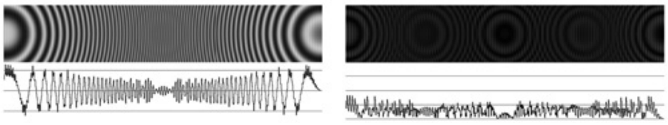

(e) Y: RGBW ($Y_W = 0.75$) (f) UV: RGBW ($Y_W = 0.75$)

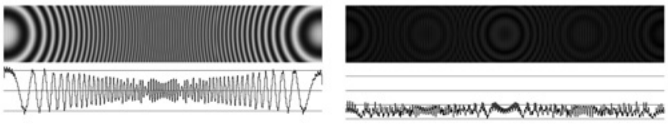
Fig. 9 Results for CZP input signals on RGBW systems.

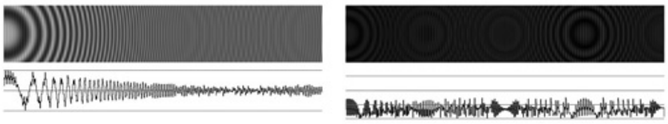
6.3 RGBRCyYe and RGBCyMgYe

The results of RGBRCyYe and RGBCyMgYe are shown in **Fig. 10**. The results with sampling interval of Δx shown in **Fig. 10 (a) (b)** and **(e) (f)** are similar to that of traditional RGB-based displays with the pixel rendering shown in **Fig. 8 (a) (b)**. In addition, these displays can reproduce three luminance resolutions on each pixel shown in **Fig. 10 (c) (d)** and **(g) (h)** although the contrast of rendering results decreases.

As a result, although the number of pixels of RGBRCyYe- and RGBCyMgYe-based displays is half as that of RGB-based displays in the horizontal direction, the resolution characteristics of MPC displays with our rendering method is not inferior to that of RGB-based displays. It means that MPC displays which have six sub-pixels not only can reproduce wide color gamut images but also have the same or higher luminance resolution as RGB-based displays which have the same sub-pixel interval.


(a) Y: RGBRCyYe (x1 sampling) (b) UV: RGBRCyYe (x1 sampling)


(c) Y: RGBCyMgYe (x1 sampling) (d) UV: RGBCyMgYe (x1 sampling)


(e) Y: RGBRCyYe (x3/2 sampling) (f) UV: RGBRCyYe (x3/2 sampling)

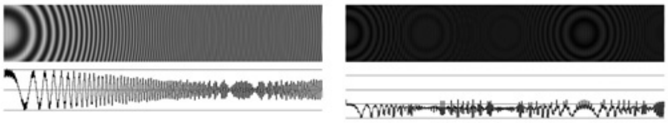

(g) Y: RGBCyMgYe (x3/2 sampling) (h) UV: RGBCyMgYe (x3/2 sampling)

Fig. 10 Results for CZP input signals on RGBRCyYe and RGBCyMgYe systems.

7. Conclusions

In this paper, we present that MPC display systems are essentially capable of reproducing higher luminance resolution compared to the conventional RGB-based display systems. The color reproduction redundancy of 4PC systems allows us to reproduce white by using three of four primary colors. This leads to at least two possibilities of primary combinations for white reproduction; therefore, it is possible to reproduce multiple luminance information on one pixel. As a result, 4PC display systems are capable to have luminance resolution that is two times larger than RGB-based systems even when they are designed with the same pixel resolution.

5PC and 6PC systems are capable of reproducing the same luminance resolution as RGB-based display systems even if MPC display systems have only a half of pixels in horizontal direction compared with RGB-based display. In addition, five or six primary display systems can reproduce three luminance values on one pixel. Each MPC system can reproduce denser luminance data than conventional RGB-based display systems and solve a problem of MPC displays, viz. increase of production costs and decrease of the aperture ratio caused by increasing the number of sub-pixels in one pixel.

Sub-pixel rendering commonly produces the issue of pseudo-color display although it is highly useful to increase effective luminance resolution. In this paper, we introduce MPC-specialized sub-pixel rendering both to increase luminance resolution and to moderate pseudo-color display. Our computational simulation shows that the MPC systems with RGB and additional chromatic primary (RGBYe and RGBCy in this paper) are more suitable for our 4PC-specialized sub-pixel rendering than RGBW systems.

This paper only deals with achromatic images and evaluates luminance resolution characteristics. As future work, we shall apply chromatic images and evaluate the resolution properties of colorful pictures. We expect that our MPC-specialized sub-pixel rendering will work well if we apply appropriate filtering based on the perception model of the human eye, which indicates that our eyes are more sensitive to luminance than to colors (23).

References:

[1] Y.-C. Yang, K. Song, S. Rho, N.-S. Rho, S. Hong, K. B. Deul, M. Hong, K. Chung, W. Choe, S. Lee, C. Y. Kim, S.-H. Lee, and H.-R. Kim, “Development of six primary-color LCD,” SID2005 Digest, pp. 1210-1213 (2005).

[2] 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,” SID2006 Digest, pp. 1221-1224 (2006).

[3] S. Roth, N. Weiss, M. B. Chorin, I. B. David, and C. H. Chen, “Multi-primary LCD for TV applications,” SID2007 Digest, pp. 34-37 (2007).

[4] Y. Yoshida, T.Mori, S.Ueki, K.Nakamura, and K.Tomizawa, “Novel wide color gamut liquid crystal display with five-primary color,” Proceedings of the 28th International Display Research Conference (IDRC), pp. 115-118 (2008).

[5] T. Ajito, T.Obi, M.Yamaguchi, and N.Ohyama, “Expanded color gamut reproduced by six-primary projection display”, Projection Displays 2000, Proceedings of SPIE, vol. 3954, pp. 130-137 (2000).

[6] T. K. Hatwar, J. P. Spindler, M. J. Ricks, R. H. Young, L. Cosimbescu, W. J. Begley, and S. A. van Slyke, “White OLED Structures Optimized for RGB and RGBW Formats”, Proceedings of Asia Display, (2004).

[7] A. D. Arnold, P. E. Castro, T. K. Hatwar, M. V. Hettel, P. J. Kane, J. E. Ludwicki, M. E. Miller, M. J. Murdoch, J. P. Spindler, S. A. Van Slyke, K. Mameno, R. Nishikawa, T. Omura, and S. Matsumoto, “Full-Color AMOLED with RGBW Pixel Pattern”, Journal of the SID, 13 (6), pp. 525-535 (2005).

[8] D. den Engelsen, I. Heynderickx, and S. Sluyterman, “Color-gamut expansion in CRTs”, Journal of the SID, 12 (3), pp. 241-250 (2004).

[9] A. Arkhipov, K. Park, B.-W. Lee, C. Kim, “Adaptive White Extension for Peak Luminance Increase in RGBW AMOLED”, SID 2009 Digest, pp. 931-934, (2009).

[10] S. Ueki, K. Nakamura, Y. Yoshida, T. Mori, K. Tomizawa, Y. Narutaki, Y. Itoh, and K. Okamoto, “Five-primary-color 60-in. LCD with novel wide color gamut and wide viewing angle”, Proceedings of SID (2009).

[11] B. H. You, J. S. Bae, J. H. Koh, D. W. Park, H. D. Kim, K. H. Ahn, J.-S. Kim, S. Y. Lee, S.-W. Jung, Y. J. Kim, S. T. Shin, “The Most Power-Efficient 11.6" Full HD LCD Using PenTile Technology for Notebook Application”, SID 2010 Digest, pp.265-268, (2010).

[12] K. Yoshiyama, M. Teragawa, A. Yoshida, K. Tomizawa, K. Nakamura, and Y. Yoshida, “Power-Saving: A New Advantage of Multi-Primary Color Displays Derived by Numerical Analysis”, SID 2010 Digest, pp. 416-419, (2010).

[13] G. Demos, “Minimizing Color Variation”, Proceedings of sixteenth Color Imaging Conference, pp. 30-37, (2008).

[14] K. Hinnen, M. Klompenhouwer, Y. Xie, Ruben Rajagopalan, “Multi-Primary Displays From a Systems Perspective”, Proceedings of the 29th International Display Research Conference (IDRC), 20.2, (2009).

[15] K. Yoshiyama, H. Furukawa, N. Kondo, S. Nakagawa, and Y.Yoshida, “A New Advantage of Multi-Primary-Color Displays”, SID 2010 Digest, pp. 281-282, (2010).

[16] S. Daly, “Analysis of Subtriad Addressing Algorithms by Visual System Models”, Proceedings of SID DIGEST (2001).

[17] C. H. Brown Elliott, T. L. Credelle, S. Han, M. H. Im, M. F. Higgins, and P. Higgins, “Development of the PenTile Matrix color AMLCD sub-pixel architecture and rendering algorithms”, Journal of the SID, 11 (1), pp. 89-98 (2003).

[18] C. H. B. Elliott and T. L. Credelle, “PenTile Matrix Displays and Drivers”, Proceedings of ADEAC, pp. 87-90 (2005).

[19] H. J. Yoon, J. H. Lee, K. P. Hong, J. Y. Chun, B. Y. Ryu, J. M. Jun, and J. Y. Lee, “Development of the RGBW TFT-LCD with Data Rendering Innovation Matrix (DRIM)”, Proceedings of SID DIGEST, pp. 244-247 (2005).

[20] M. A. Klompenhouwer and G. de Haan, “Sub-pixel image scaling for color matrix displays”, Journal of SID, vol. 11 (11), pp. 99-108 (2003).

[21] M. A. Klompenhouwer and E. H. A. Langendijk, “Comparison the Effective Resolution of Various RGB Sub-pixel Layouts”, Proceeding of SID 2008 symposium (2008).

[22] International Communication Union (ITU), “Rec. ITU-R BT.709-5: Parameter values for the HDTV standards for production and international programme exchange,” (2002).

[23] B. A. Wandell, “Foundations of Vision”, Sinauer Associates, Inc. (1995).