

Low Power Consumption and Wide Color Gamut AMOLED Display with Four Primary Colors†

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Abstract

First four primary-color (RGBY) AMOLED display was demonstrated by a 4.65" panel with HD resolution (1280 x 720, 317 ppi). The RGBY display possessed superior NTSC ratio of 112% and low power consumption, which is 16% lower than conventional three color AMOLED panel under same panel size and pixel density. The introduction of yellow color significantly improved image quality and panel power consumption, and therefore made it a favorable display for mobile apparatus.

Author Keywords

AMOLED; four primary colors; power consumption; wide color gamut; sub-pixel rendering; mobile display.

1. Introduction

Due to continuous demand of superior display quality, active-matrix organic light emitting diodes (AMOLED) has emerged as a strong candidate for display technology in portable device recently [1]. In addition to high pixel density, wide color gamut and lower power consumption are both crucial to high quality display and pleasure user experience. Four-primary-color technology had been adopted to enhance color performance in conventional liquid crystal displays (LCD) [1-3]. For OLED, the additional yellow emission would also provide an unprecedented wide range in graduations to deliver colors just as they are in nature, such as natural gold or light-yellow. Moreover, yellow was the most sensitive color for human eye, and this implied that yellow emission could enhanced panel to reach same brightness with lower input current, i.e. realized lower power consumption. Therefore, RGBY AMOLED panel possessed potential to save power and would be suitable for mobile apparatus.

However, inserting extra yellow sub-pixel in AMOLED panel was challenging, especially for high pixel-density (>300 ppi) applications based on real RGBY pixels arrangement. White OLED (WOLED) with color filter was a simple way to realize it because no fine metal mask (FMM) was required in the fabrication process. However, additional new yellow emission layer (or dopant) would complicate manufacturing process, especially for tandem WOLED device. Furthermore, WOLED with color filter generally produced lower efficiency than isolated RGBY OLED. This would sacrifice the intrinsic power saving advantage of the four primary-color AMOLED.

The technology of sub-pixel rendering (SPR) has been widely utilized to realize high ppi AMOLED display through a 2/3 (RG1BY2/ RGB1RGB2) sampling ratio or higher ones [4] [5]. It reduced half sub-pixels of red and blue color but kept the green color in actual resolution to retain the most of original image luminance. Here we adopted the SPR concept with 2/3 sampling ratio while replaced one of the green sub-pixel of RGBG pixel with yellow. Therefore, the fabrication difficulty was greatly relieved and a 4.65", HD resolution (1280 x 720, 317 ppi) panel with superior image quality and low power consumption was delivered successfully.

2. Methods

(a) The 2/3 SPR of RGBG and RGBY configuration

Currently, the PenTile-RGBG performed the distortion of R/B sub-pixel to augment layout area but remained the same number of green sub-pixel as conventional stripe panel for luminance and resolution consideration. Since the R/B distortion was delineated in individual 2 pixel types, the SPR algorithm could program which pixel to emit its own B/R sub-pixel.

Table 1. showed the configuration of conventional PenTile-RGBG and the proposed RGBY. The RGBY sub-pixel arrangement utilized the same sampling ratio as PenTile-RGBG but replaced a slot pose of green sub-pixel with yellow. The software simulation results of the Pentile-RGBG and proposed RGBY macro-pixel configuration were shown in Fig. 1(a) and Fig. 1(b), respectively.

For driving algorithm design purpose, we divided the RGBY sub-pixels into two sub-groups. The first group included red and green sub-pixels as the main-type pixel. Blue and yellow sub-pixels were combined to form the second-type of pixel. Through the amplification of both pixel types, a color deficiency in either pixel type could be implicitly resolved.

Compared to real-stripe pixel arrangement, the adoption of SPR can ease the layout design and relieve FMM evaporation difficulty. Thus the panel resolution, production yield, and cost can be significantly improved.

Table 1. The SPR Configuration with RGBG and RGBY

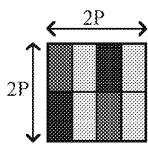
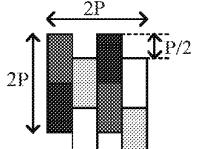
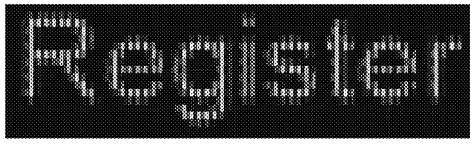
PenTile-RGBG Configuration	Proposed RGBY Configuration	Descriptions
		Sample ratio: 3:2 Display resolution: 720x3x1280 Sub-pixel area: 1/2PxP
		
		

Figure 1. The macro-pixels of software simulation from (a) RGBG (b) RGBY configuration

(b) Gamma correction of RGBY colors

Since the R/B and G/Y sub-pixels were connected along a single data line, digital gamma mapping was required to achieve individual voltage correction of RGB colors. The reduction of data line would spare more area for desired layout. Through normal gamma correction, the driving voltage of red and blue color could be measured to discern. In general, the red OLED sub-pixel consumed lower driving voltage than blue one. A look-up table (LUT) was then established to map the driving voltage of red OLED into the voltage range of blue OLED by software processing. When the red grayscale was input, the LUT grayscale would replace the original input with corresponding output to rebuild the image correctly.

In the same manner, the data voltage of Y-OLED could be corrected to perform specified display perception. The brightness of Y sub-pixel should be determined based on its chromaticity and the set white point CIE_{xy} coordinates.

(c) Driving of RGBY Panel

The source IC, the circuit design of gate on array (GOA) and external FPGA (Field Programmable Gate Array) of the TCON (timing controller) board were combined to drive the 4.65" RGBY HD (1280 x 720) panel. The schematic view of panel driving was described in Fig. 2. The source IC was utilized to provide driving voltage of row data by input image and the gate TFTs were switched with the GOA circuit. Each source IC was responsible to drive 720 dots of panel row. The FPGA of the TCON board was presented to initialize individual RGB curve of gamma voltage and provide video signal for source IC. The algorithm design was also performed in the FPGA. Through the register transfer language (RTL) coding, the proposed SPR algorithm was implemented.

(d) RTL coding in FPGA

The FPGA was adopted to provide digital data and control signals. It included the adjustment of gamma voltage, the transmission of PpM signal, the clocking of GOA signal, and the provision of specific power voltage. This TCON board could also draw specific test patterns to emphasize possible display defects. The proposed SPR algorithm was implemented in the FPGA board to facilitate step-by-step improvement in display deficiencies. The RTL of the PE function included the edge detection, edge transcriber, edge code comparator, and dual multiplier of R/B color diffusion. Since the proposed SPR configuration used only 2/3 of data lines and the output sequence of the source IC still presented as a RGB stripe, a data merge was requested to combine several pixels of input image data for target format presentation.

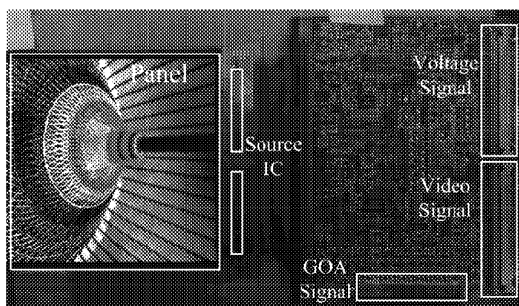


Figure 2. The architecture of driving board

In order to fit the proposed RGBY arrangement, two formats of R0G0B1Y1 and B0Y0R1G1 were fetched along sequential order of input pixel data. Through the two pairs of PpM submission, the both bit-streams could be aligned in individual source output. Since the R/B and G/Y sub-pixels were connected on a single data line, the R/B and G/Y LUT of digital gamma was required to map the voltage range of red color into the one of blue color. The LUT file for R/B gamma adjustment was generated by practical measurement and data interpolation of software processing.

(e) Power-consumption calculation and comparison for RGBG and RGBY panel

To estimate how the yellow emission could improve power saving, we calculated the power consumption of RGBY and RGB-composed panels under identical test conditions (including same resolution, same pixel density and same panel brightness). The CIE_{xy} coordinates and corresponding efficiencies of R, G, B and Y OLED were showed in Fig. 3(a). The 27 kinds of color points for power consumption evaluation were also marked in the diagram.

We calculated the power consumption of each color with 300 nits panel brightness, then averaged them for comparison. Compared to RGB-composing panel, the power-saving percentage of RGBY panel were 6.7, 15.9, 17.2 and 19.8 % when the YOLED efficiency were 60, 80, 100 and 120 cd/A, respectively. (Fig. 3(b)) The result indicated that additional yellow emission possessed great potential to save power and was worthy to be realized in AMOLED panel.

3. Results

(a) Panel Fabrication

The RGBY and RGB panels were both evaporated on low temperature poly-silicon (LTPS) substrates including TFT circuits and pre-patterned electrodes, respectively. LTPS possessed higher mobility than amorphous Si thus being a great substrate choice for OLED device [6]. The schematic view of electrode and OLED configuration of the full-color AMOLED were illustrated in Fig. 4(a). The organic layers were evaporated in sequence and a thin metal was deposited at last as the cathode with a capping layer above it. The capping layer can modify the device optical properties such as improving light extraction, reducing color variation, etc [7]. The separate red, yellow, green, and blue emission was produced by different optical cavity conditions (different organic hole-transporting layer thickness).

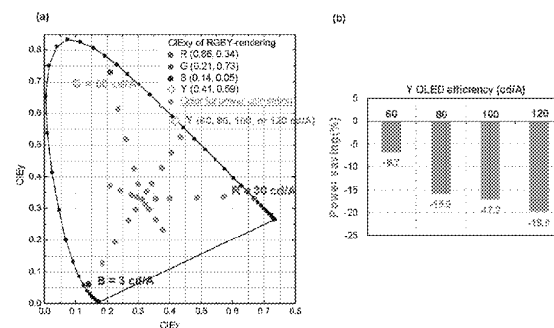


Figure 3. (a) The CIE_{xy} coordinates, corresponding efficiencies of R, G, B and Y OLED, and the color points for power consumption calculation. (b) The power-saving of RGBY panel with various yellow OLED efficiencies

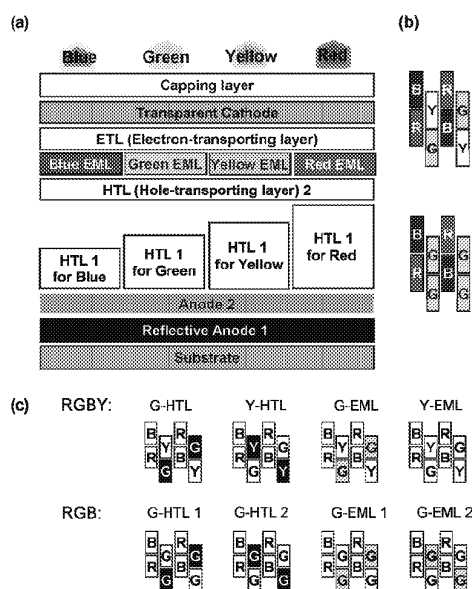


Figure 4. (a) Device structure of red, green, blue and yellow OLED. (b) Pixel arrangement of RGBY and RGB panel. (c) The deposition steps of HTL and EML of green and yellow sub-pixels in RGBY and RGB panels.

Moreover, the pixel-arrangement of panel were showed in Fig. 4(b), and the sub-pixel number ratio is 1 to 1 to 1 to 1 for RGBY-composed panel or 1 to 2 to 1 for RGB-composed panel. It was worthy mentioning that the OLED deposition steps for RGBY and RGB panel were identical (assuming same single slot-type FMM was adopted in the evaporation process), indicating the RGBY design would not complicate the panel manufacturing process.

(b) Power consumption measurement

The panel specifications were summarized in Table 2. Based on micro-cavity effect, the panel achieved high color purity for RGBY sub-pixels of (0.66, 0.33), (0.21, 0.73), (0.14, 0.05) and (0.40, 0.60), respectively. The RGBY panel possessed a superior high NTSC ratio of 112%, which was better than the 105% ratio of traditional RGB panel. The RGBY sub-pixels under microscope and the real panel picture were shown in Fig. 5.

The power consumption of this RGBY panel was only 261 mW under a peak brightness of 300 cd/m² and a white point of (0.30, 0.32) with 30% image loading. In the same time, the traditional RGB panel consumed 311 mW under identical condition. This indicated that the power saving percentage was about 16.4%, which was very similar to the calculation result, i.e. between 15.9 and 17.2%, as shown in figure 1b.

Table 2. Panel performance of RGBY and RGB panel

Panel type	RGBY				RGB		
Sub-pixel	R	G	B	Y	R	G	B
CIExy	(0.66, 0.33)	(0.21, 0.73)	(0.14, 0.05)	(0.40, 0.60)	(0.66, 0.33)	(0.21, 0.73)	(0.14, 0.05)
NTSC (%)	112				105		
Power consumption (mW)*	261				311		

* 30% of 300nits white loading

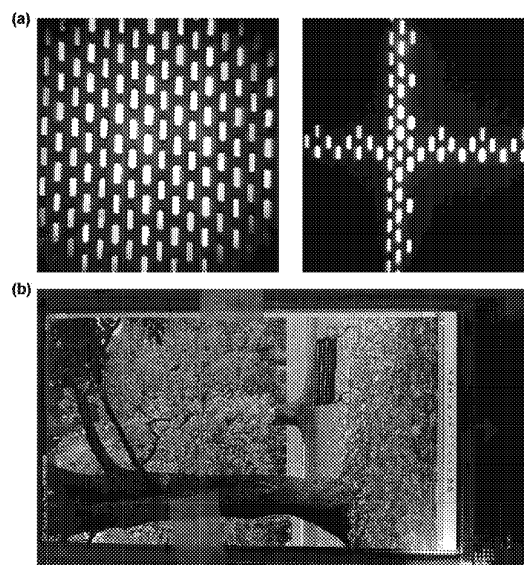


Figure 5. Photos of (a) RGBY sub-pixels under microscope and (b) real panel displaying image

The power consumption of full-color AMOLED panel was highly dependent on the display image content. Therefore, we further measured the power consumption with 19 different display images and then averaged them for comparison. The results were shown in Table 3. The averaged power was 438 mW for RGB panel and 357 mW for RGBY panel, which was 16.7% power-saving. The power-saving percentages of white point with 30% loading and 19 random display images were almost identical, implying the additional yellow emission indeed could improve the power consumption of AMOLED display.

(c) SPR algorithm examination

Some problems were usually observed in panel adopted SPR concept. For example, dot resource management was an important consideration for data processing in corresponding SPR algorithm. When the first and second pixel types were grouped in alternate patterns, the cyan and magenta color would be visible around respective image edges and thus would downgrade the display quality. In order to avoid these issues, the actual representations under different contents of RGBY panel were observed to verify the algorithm design of RTL coding, the data merge and digital gamma correction.

The proposed 2/3 sampled delta configuration utilized the overlapping area to eliminate the grid effect of current design. Through the characters/fonts of the test pattern, the one-side of color diffusion effectively resolved most color leakage on the edge of R/B sub-pixel.

In practice, the diffusion coefficients of defined 9 edge codes were optimized through optical measurement case by case. Since the 2/3 sampled delta possessed a vertical shift of 1/2 pitch, superior color appearance could be experienced. The panel also verified that the distance of 40 um would be unperceivable to human eye, thus it could be a reference of tolerance to develop SPR technology. The adaptability of pattern estimation could be useful to develop advanced SPR technology with different definition of edge coding.

Table 3. Panel performance of RGBY and RGB panel

Item																	Avg.			
Power consumption (mW)	RGB	171	180	279	270	270	270	342	324	432	459	414	441	459	522	594	675	864	900	438
	RGBY	117	135	180	189	189	207	243	288	297	306	333	351	378	396	468	513	612	774	801

4. Summary

In this paper, we demonstrated first four-primary color AMOLED display with RGBY sub-pixels. A SPR algorithm of 2/3-sampled delta triad was introduced to implement a 4.65" HD (1280 x 720) AMOLED panel with 317 ppi. Compared to traditional RGB panel, the RGBY panel could save 16% power consumption by introducing yellow OLED with efficiency of 90 cd/A. If we further improve the efficiency to 120 cd/A, 20% power saving would be achievable. Moreover, the additional yellow emission also provided an unprecedented wide range in graduations to deliver colors just as they are in nature. The SPR technology was developed to achieve AMOLED panel with high pixel density. The panel lifetime could also be extended through OLED devices utilizing larger aperture ratio. The RGBY and SPR technologies could be keys to superior quality AMOLED display for mobile apparatus.

5. References

- [1] K. Yoshiyama, H. Furukawa, N. Kondo, S. Nakagawa and Y. Yoshida, "Late News Paper: A New Advantage of Multi Primary Color Displays", SID Symposium Digest of Technical Papers, 41, 281-282 (2010).
- [2] S. H. Han, Y. H. Kim, J. M. Yoon, I. C. Park, M. C. Jun and I. J. Jung "Luminance Enhancement by Four-Primary-Color (RGBY)" SID Symposium Digest of Technical Papers, 41, 1682-1684 (2010).
- [3] C. K. Hui, S. W. Cheng, W. C. Sun and J. S. Yu, "Optimization of Sub-pixel Area for Multi-primary Displays Based on Preferred Image Performance", SID Symposium Digest of Technical Papers, 42, 1249-1252 (2011).
- [4] M. A. Klompenhouwer and G. de Haan, "Subpixel image scaling for color matrix displays," J. Soc. Info. Disp., vol. 11, no. 1, 99-108 (2003).
- [5] L. J. Kerofsky and D. S. Messing, "Optimal rendering for colour matrix displays," ADEAC, (2005).
- [6] T. Urabe, T. Sasaoka, K. Tatsuki, and J. Takaki, "Technological Evolution for Large Screen Size Active Matrix OLED Display," SID Symposium Digest of Technical Papers 38, 161-164 (2007).
- [7] H. Riel, S. Kargo, T. Beierlein, W. Rie ß, K. Neyts, "Tuning the emission characteristics of top-emitting organic light-emitting devices by means of a dielectric capping layer: An experimental and theoretical study," J. Appl. Phys. 94, 5290-5296 (2003).