High-Pixel-Density PenTile Matrix™ RGBW Displays for Mobile Applications

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Abstract

High-pixel-density displays are now under development to meet the needs of next-generation mobile devices; methods to more efficiently build such displays are described. Displays based on subpixel rendering and RGBW technologies, known as PenTile Matrix™ RGBW, are shown to offer the best approach to meeting the demanding requirements of low manufacturing cost, high brightness, and low power.

1. Introduction

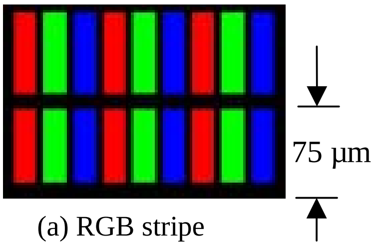
The advent of wideband services for mobile phones is creating new demands from customers to improve all aspects of the color display. No longer is qVGA (240x320) resolution sufficient; resolution should be at least VGA, brightness should be >300 cd/m^2, viewing angle should widen, and color gamut should expand. These requirements are putting real stress on display manufacturers; the traditional RGB stripe format is creating manufacturing challenges that increase costs, increase power, and increase electrical noise.

For example, a 2.4” VGA RGB stripe display has subpixels that are only 25 µm wide; given the manufacturing tolerances achieved today, these narrow subpixels have reduced aperture ratio, increased stray capacitance, and reduced contrast ratio. Given the quality level set by lower-pixel-density displays e.g. 2.2” qVGA, the traditional way of building displays must change in order to achieve broad customer acceptance. And manufacturing cost must be kept low in order to meet handset manufacturer’s expectations.

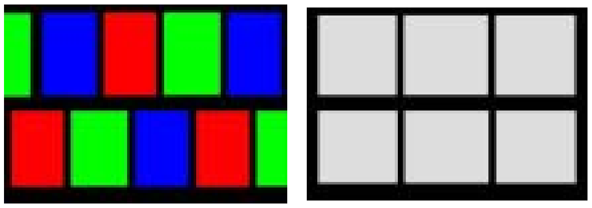
To meet these needs, there are several alternatives to traditional RGB stripe that are under development for high-pixel-density displays, each of which has its advantages and disadvantages. In this paper, the alternatives to RGB stripe will be outlined and the operating characteristics will be described. In particular the concepts of subpixel rendering combined with the addition of a white subpixel will be shown to be perhaps the best way to meet customer demands for higher performance and lower cost.

2. Approaches to High-Pixel-Density Displays

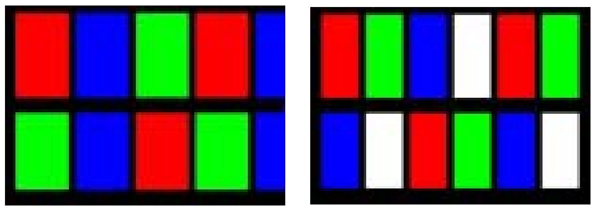
There are three basic approaches to building high-pixel-density displays: traditional RGB-stripe or RGB-delta displays, frame-sequential displays, and subpixel-rendering displays. In addition, white subpixels can be added to improve brightness or cut power consumption. Figure 1 illustrates the main approaches for a 2.4” VGA.



(a) RGB stripe



(b) Delta Triad (c) Frame sequential



(d) PenTile RGB (e) PenTile RGBW

Figure 1. Various layouts for pixelated displays

Table 1. Comparison of various pixel formats for 2.4" VGA (330 ppi)

	TFT Array	Color Filter	Cell Assembly	Electronics
RGB Stripe	25 µm wide subpixels	Standard	Standard	Standard
Delta Triad	50 µm offset pixels with zig-zag electrodes	Offset pixels	Standard	Requires processing to remove aliasing
Frame sequential	75 µm wide subpixels	No color filter	~1.5 µm cell gap	2x-3x frame rate + high-speed memory
PenTile RGB	50 µm wide subpixels	Checker pattern	Standard	Requires extra rendering logic (~25K gates)
PenTile RGBW	38 µm wide subpixels	Checker pattern + white	Standard	Requires extra rendering and white pixel logic (~50K gates)

Note that subpixel size varies from 25 µm wide (RGB stripe) to 75 µm wide (frame sequential); in comparison, today's 2.2" qVGA RGB stripe displays have approximately 47 µm wide subpixels. Most challenging design is the traditional RGB stripe; maintaining high aperture ratio and high yield is problematic, even with LTPS TFT arrays. While prototypes have been produced, there is no volume manufacturing of this size and resolution to date. Delta designs, Figure 1(b), have larger aperture and use fewer TFTs and drivers, but text performance is inferior. Color fringing is also an issue for most delta designs. Frame sequential designs, Figure 1(c), have the potential for lower TFT manufacturing costs and increased aperture, but require extremely narrow cell gaps to achieve good performance and have reduced color range at low temperatures due to slower LC response time. Subpixel rendering designs, Figure 1(d) and (e), have larger subpixels and have been shown to yield excellent text quality and increase brightness, but additional processing logic is required.

A summary of the key features for these various approaches is shown in Table 1. As can be seen, there are significant challenges to achieving the goal of high pixel density without increasing manufacturing difficulties or power. Recently developed subpixel rendering techniques may offer the most cost and power effective means to build these displays, especially when combined with RGBW pixel layouts. The remainder of this paper will be devoted to describing this new technology: how it works, its properties, and its implementation.

3. Subpixel Rendering

An historical review serves as a good introduction to the development of subpixel rendering algorithms and color subpixel architectures optimized for them. The earliest form of subpixel rendering on color subpixelated LCDs is simple decimation, in which the red, green, and blue color component planes are instantaneously sampled [1]. This method allowed the use of the color subpixels to reconstruct the luminance field at a higher reconstruction frequency, which reduced moiré, but introduced chromatic aliasing, color fringing and banding of spatial frequencies greater than the Modulation Transfer Function Limit (MTFL), which is the highest monochromatic spatial frequency that can be reconstructed without chromatic aliasing. A basic limitation of the decimation technique is that to prevent chromatic aliasing, images must be restricted to band-limited images (e.g. photo & video) where the Nyquist Limit matches that of the MTFL. This explains the popularity of decimation algorithms on the Delta Triad architecture for digital and video camera viewfinders, which display mostly band limited images.

To overcome the problem of chromatic aliasing in RGB Stripe displays, simple filtering was introduced by IBM [2]. This algorithm consists of a simple displaced box filter (average of adjacent pixel values) of each color component plane of an over-sampled image in order to filter out some of the spatial frequencies above the MTFL. This technique was later commercialized for improved text quality on the

RGB Stripe architecture [3] for ClearType™ (trademark: Microsoft Corp.). Investigators at Sharp approached the problem differently in that they first converted the over-sampled image from RGB color space to L*ab color space, and then the chromatic aliasing components were filtered to allow only those aliasing components outside the visible range of the chromatic contrast sensitivity function of the human eye [4, 5 ,6]. These improved subpixel rendering algorithms allow non-band-limited images to be reconstructed with reduced luminance and chromatic aliasing and moiré on the RGB Stripe architecture, improving the appearance of text.

To further increase the MTFL of subpixel architectures that allow reconstruction of non-band-limited as well as band-limited images with fewer subpixels, novel subpixel architectures with matching subpixel rendering algorithms were introduced by Clairvoyante [7-14]. The family of layouts, known as PenTile Matrix™ layouts, has subpixel utilization efficiencies, defined as the number of subpixels required per pixel to achieve a given MTFL, ranging from two subpixels down to one and a quarter subpixels per pixel compared to three subpixels per pixel for the RGB Stripe layout. The increased subpixel efficiency of the PenTile layouts with subpixel rendering means that at a given resolution, the aperture ratio will be higher, allowing higher resolution displays at both lower cost and lower power.

4. Subpixel Rendering with RGBW

One effective way to increase brightness in displays is to add a white subpixel; this technique has been used for years in avionic displays. The usual way to add white is to increase the subpixel count to four subpixels per pixel in either a quad or stripe format. The questions often asked are “will the color saturation be affected and will natural images still look correct?”

To understand the impact of RGBW systems it is helpful to analyze “real world” imagery. The natural images of the real world are typically made up of rich, saturated colors, which are hardly ever very bright, as well as extremely bright unsaturated objects, such as reflections from smooth objects. Unfortunately, the real world is a subtractive color system and electronic displays are additive color systems, and under traditional design standards, require display designers to make tradeoffs in brightness, color saturation, and power consumption.

Optimally, electronic displays would render natural scenes by creating very bright non-saturated colors and darker highly saturated colors; however, the conventional three primary color RGB system’s non-saturated color brightness is limited to adding partially-saturated color primaries. If the saturated colors in natural images are mapped to the partially-saturated RGB primaries, then the system is unable to map the bright non-saturated colors from images. Conversely, if the brightest non-saturated colors in natural images are mapped to the brightest non-saturated RGB colors, then the RGB primaries are unnecessarily bright and insufficiently saturated.

This means there is a tradeoff between the brightness of the non-saturated colors and the color saturation gamut of an RGB display. The more saturated the color primaries, the lower the non-saturated brightness, since white = red + green + blue. This creates a luminance/saturation compression in which the non-saturated colors are reduced in brightness, and saturated colors are compressed, or desaturated, to fit within the limitations of the compromise system. Achieving both high brightness and wide color gamut requires higher brightness backlights to compensate for the lower transmissivity of highly saturated color primaries. A color formation system that adds a non-saturated “primary” such as white can better display natural images without making the same tradeoffs.

Clairvoyante’s PenTile Matrix™ RGBW LCD adds this additional white primary – without increasing subpixel count. The white subpixels are much brighter than the red, green, and blue subpixels since the white is formed using a transparent filter that allows most of the light through, while the other three colors are formed by filtering out all but a narrow band of the spectrum. Since such color filters are not ideal bandpass filters, the transmissivity is less than 100% even in the desired bandpass wavelengths, which further darkens the subpixel. Since the white subpixel has higher light transmission, the RGBW system significantly increases the brightness of the panel when displaying non-saturated colors indicative of natural images, and in turn allows the use of more highly saturated color primaries in a display without significantly reducing the total display brightness.

Because fewer subpixels are required for a given resolution, Clairvoyante's PenTile Matrix also offers increased aperture ratio, enabling increased saturated color brightness compared to RGB stripe, especially at high pixel densities.

5. Comparisons

For any given manufacturing process, whether it be aSi, LTPS, OLED, or plasma, there will be a usable pixel area within the pixel overall area. This is often called aperture ratio or fill factor. As pixel density increases, the process design rules must be tightened or brightness will decrease and power will increase. A simple plot of white light output vs. pixel density in pixels/inch (ppi) is shown in Figure 2. Here it is assumed that LTPS has a higher inherent aperture ratio than aSi due to smaller TFT, although recent reports are that the two technologies can have quite similar aperture ratios due to improvement in aSi tooling. A standard color filter with ~50% NTSC ratio is assumed for all versions. Note that the Pentile Matrix RGBW displays can have significantly higher white transmission owing to the white subpixel. Typical improvement for a 2.4" VGA display is 2x or more, depending on design rules and color filter coordinates. If more saturated color filters are used, then the benefit of PenTile RGBW will be even greater.

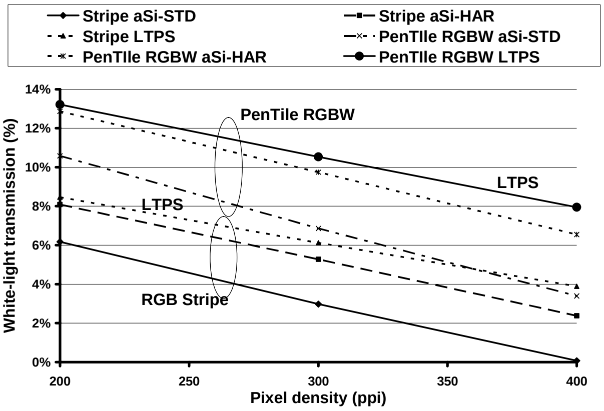


Figure 2. White-light transmission vs. pixel density (STD=standard aSi processing; HAR= High Aperture Ratio aSi processing)

6. Implementation

All of the methods described in this report require some changes in manufacturing and electronics. Some of the key changes are detailed below.

6.1 RGB stripe

For RGB stripe to be competitive at densities above 250 ppi, black matrix widths and TFT size must decrease. To achieve thinner vertical black matrix, improvements in tolerances of alignment (top to bottom glass) are necessary; this can lead to increased cost or decreased yield.

6.2 Frame/field sequential

Frame sequential systems require changes to both manufacturing processes and electronics. To achieve fast response, new liquid crystal materials may be necessary; in addition, the cell gap should be decreased to 1.0-1.5 µm in order to achieve fast response. This can have negative impact on yield. Electronics must also be changed to include fast memory and higher refresh rates, which impacts cost, power, and EMI. Additionally, a three-LED sequencing backlight circuit is required. Finally, heaters may be needed to achieve fast response at low temperatures.

6.3 PenTile RGBW

PenTile RGBW displays require only minor changes to manufacturing processes. First of all, the TFT array and black matrix can actually have relaxed tolerances because the subpixels are 33% wider than for an equivalent RGB stripe. No other changes are needed to TFT processing. The color filter requires a white, or clear, subpixel and this can be accomplished via either a fourth patterning step or a clear overcoat that "fills in" the clear pixel. The only change required in the electronics is to add the PenTile Processing logic (approximately 50K gates) and two extra lines of memory. Note that the bandwidth of data to the display is actually reduced by 33%, which decreases EMI. A block diagram of the processing required in a PenTile RGBW display is shown in Figure 3.

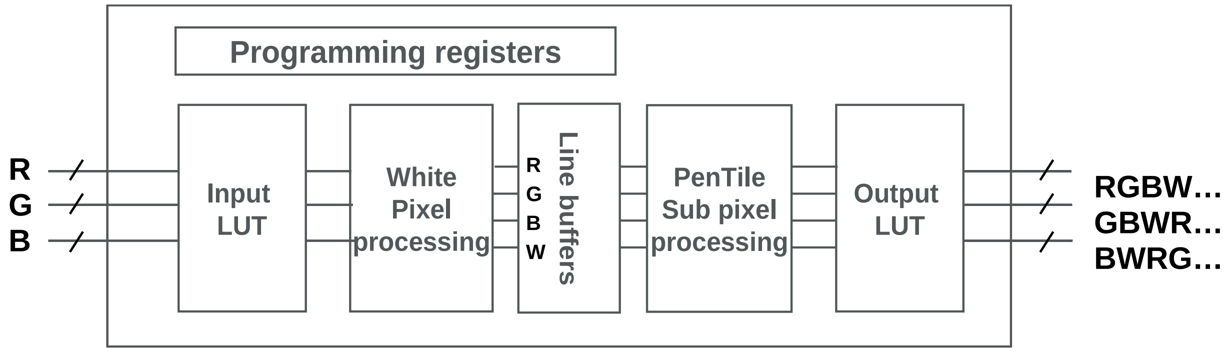


Figure 3. Block diagram of PenTile Processing. Total logic gates is approximately 50K; 2 dual-port RAM line buffers and input and output gamma tables are also included.

An example of a 2" VGA PenTile RGBW using a 1.5 subpixel/pixel design (also known as "L1W") that represents the highest pixel density achieved to date is shown in Figure 4.

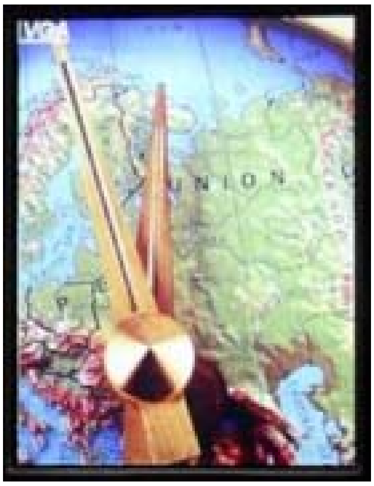


Figure 4. 2" VGA PenTile RGBW display with 400 ppi (Courtesy: Samsung AMLCD Div.)

An example of an image from a 1.8" qVGA PenTile RGBW display using a two subpixel/pixel design (also known as "L6W") is shown in Figure 5. White-light transmissivity of the aSi TFT LCD is ~10% and contrast ratio is 450:1 [15]. Specifications for two qVGA sizes developed by BOE are shown in Table 2. An equivalent RGB stripe panel would only be 150 cd/m^2 brightness for same backlight power. [15]

Figure 5. 1.8" qVGA PenTile RGBW (Courtesy: BOE Hydis)

Table 2. Specifications of 1.8" and 2.0" qVGA PenTile RGBW

	1.8"	2.0"
Display Mode	TN	TN
Pixel Pitch	0.057 mm x 0.114 mm	0.645 mm x 0.129 mm
Pixel density	221 ppi	200 ppi
Aperture ratio	35%	42.5%
Transmittance	9.9%	10.6%
Brightness (cd/m^2)	280	300
Contrast ratio	450:1	500:1
Color Gamut	42%	42%
Interface	6-6-6	6-6-6
Backlight (cd/m^2)	3000	3000

Backlight Power	150 mW	150 mW

7. Conclusion

Several technologies that address the needs of high-pixel-density displays for mobile applications are under development. Traditional RGB stripe may no longer be the best approach due to the manufacturing and power impact. The PenTile Matrix RGBW display may be the most optimum approach to meeting the needs of next-generation displays for mobile devices. Not only are manufacturing costs reduced, but brightness is dramatically increased. This technology is now being applied to qVGA and VGA LCDs for mobile phones and can also be applied to emissive displays such as OLED or PDP.

8. Acknowledgements

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