

P-46: Optimization of Subpixel Color Tiles for Mobile Displays

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Abstract

A key issue for the optimization of subpixel color tiles for mobile displays is to maximize the image quality, often defined in terms of brightness or reflectance, and color saturation, while minimizing display power consumption. For the mirasol™ display based on MEMS technology, the RGBY quad is found to be a structure that achieves a balance between reflectance and color saturation. Simulation results based upon demonstration devices are presented with discussions about proper image quality metrics for mobile displays.

Keywords

subpixel color tiles, image quality metric, color brightness, reflective displays, interference, MEMS.

1. Introduction

For mobile displays two subpixel color tile structures are commonly used. The classic RGB stripe mosaic dominates cellphones, PDAs and other mobile devices which evolved from text based applications. Meanwhile the RGB triad is used for digital cameras and camcorders, which target photographic applications. Subpixel structure with quad color tiles, such as RGBW, have been proposed for many years but are still struggling to gain manufacturers' acceptance in mobile displays [1, 2]. These, in addition to a RGBY quad pixel mosaic are the focus of this discussion and are shown in Figure 1.

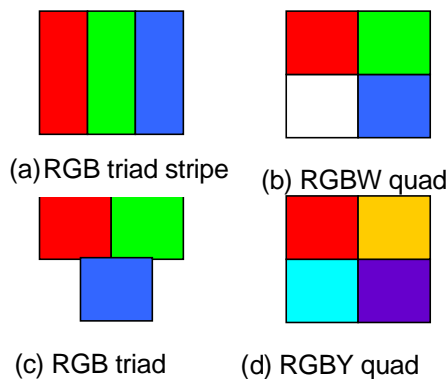


Figure 1. Four subpixel color tiles

The mirasol display, developed by Qualcomm™, is a reflective display based on MEMS (micro-electro-mechanical systems) technology and interference optics. mirasol displays are suitable for direct view mobile applications with their excellent sunlight viewability, high reflectance, good contrast, vivid colors, low power consumption and fast switching speed for video applications.[3, 4] Colors in mirasol displays are selected by interference in an optical cavity with an air gap controlled by applied electric voltage.

Several means are available for the optimization of display performance for any given technology. mirasol displays are no different in this regard. Other work has described the benefits of using primary color specific optical cavity designs [4]. These pixel structures can also enhance white reflectance and color gamut by balancing alternative manufacturing tradeoffs. Similarly, peripheral component improvements also affect the balance between reflectance and color gamut in reflective displays. For example, holographic front diffuser films enhance brightness, allowing for increased brightness with equivalent color gamut. This discussion focuses on the design choices within the subpixel color tiles.

Unlike LCD, the interference nature of a mirasol display lends naturally to color selection from an incident neutral white light with an IMOD (Interferometric Modulator) element. Reflecting back that broad neutral white incident light is possible, but involves alternative designs of the optical cavity.

Therefore, as an alternative to RGBW, a RGBY quad color tile can be easily implemented within mirasol displays. We find that RGBY has as many merits as a RGBW quad, plus some unique advantages over the RGBW or RGB tiles. Many of the benefits for RGBY are not specific to mirasol displays but apply to other reflective, transmissive or emissive displays. Spectral plots for RGB and RGBY color tiles for two feasible Mirasol displays are shown in Fig. 2a and 2b, respectively, for comparison.

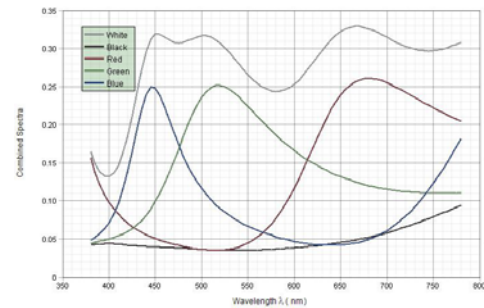


Figure 2a Simulated spectra for a mirasol display with RGB triad color tile.

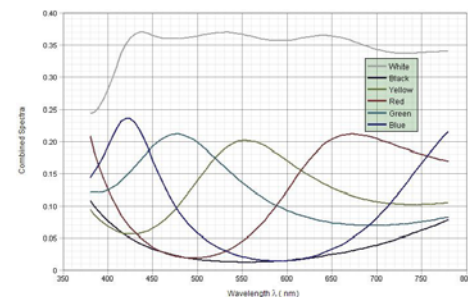


Figure 2b Simulated spectra for a mirasol display with RGBY quad color tile.

In of this article, we first introduce the mirasol display color spectra and color tile optimization considerations. Then mirasol displays will be used as an example to compare the RGBY quad color tile to the RGB triad stripes to show the advantages of the quad design. We then compare the RGBY quad with RGBW to illustrate their similarities and differences. The results from demonstration devices will be presented, followed by a section to discuss suitable color metric for mobile displays.

2. mirasol Display Color Tiles and Optimization

The mirasol display selects colors by interference, with each of the red, green and blue color tiles consisting of an optical stack made of a thin absorber layer, dielectric layers, an air gap and a reflective mirror. The mirror is actuated by electro-mechanical forces to operate between bistable states, with the black state produced by the low air gap and color state by the high air gap. The air gaps for the RGB color tiles are pre-determined by the thicknesses of the sacrificial layers in the MEMS structure.

The spectral curves for R, G, B and Y pixels, as well as the black state, of a color mirasol display are shown in Fig. 2b. The spectral peaks of the color tiles are selected in order to maximize the color gamut, and to achieve a white balance of D65 when all the tiles are switched on. The luminance of the white state of the device, in case of RGBY quad color tile, can be calculated by the following formula:

$$I = \sum_{i=1}^4 \int S(\lambda)P(\lambda)R_i(\lambda)d\lambda$$

where $i=1, 2, 3, 4$ represents the R, G, B, and Y color tiles with $R_i(\lambda)$ as their corresponding spectral reflectance, $S(\lambda)$ the illuminating source spectrum and $P(\lambda)$ the photopic response curve of the human visual system. Maximization of the brightness, usually with a light source of D65 for ambient lighting or with a white LED spectrum for LED illumination under dark ambient, is achieved by choosing the peak positions of the color tiles. For each of the color tiles, the peak width can be chosen from either the 1st order interference peak or the 2nd order one. An example of 1st order green is compared with the 2nd order green in Figure 3. It is obvious that the 2nd order color offers better color saturation at the expense of device reflectance.

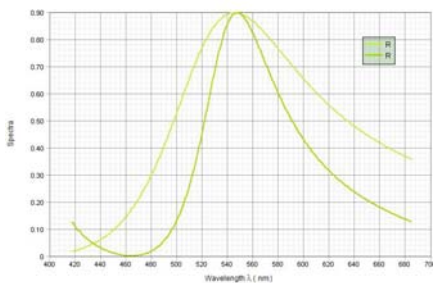


Figure 3. Simulated spectra for a 1st order Green and a 2nd order Green color tile.

Unlike color filter based LCD display, the peaks of the color tiles of a mirasol display can be tuned on a continuum by tuning the air gaps for the color tiles. All achievable color coordinates of the tiles forms a spiral in a color space, as a function of air gap, and this trajectory is therefore called the color spiral. A design choice of RGBY color tiles is illustrated in Fig. 4a, with the color gamut

calculated from the area of the quadrilaterals formed by the apex points of the RGBY color tiles. Now the optimization of the RGBY color tiles is reduced to optimization of a merit function with weights from both brightness and color gamut, by choosing the positions of four color tiles along the color spiral. The problem has four degrees of freedom with four constraints, two for D65 white color, one for reflectance and one for color gamut. We have assumed in this article that the color tiles are all equal in size, for simplicity of discussion as well as manufacturing.

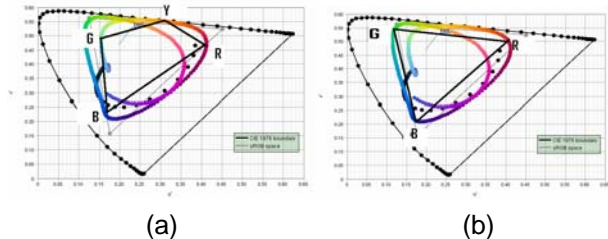


Figure 4 Simulated color for a mirasol display with (a) RGBY quad color tiles, (b) RGB triad color tiles

3. Comparison of RGBY Quad and RGB Triad Stripe

In the optical design of a display, the choice between RGBY quad and RGB triad stripe, shown in Fig. 4a and 4b, involves far more considerations than optimization of a merit function with brightness and color gamut. Other important factors include image quality for text and graphic content, driver functionality and cost, as well as manufacturing capability and cost [4].

The image content input to a display module is usually in sRGB format. For an RGBY panel, the display driver must have the functionality to map the data from sRGB into the RGBY format. For high volume production, this added driver cost is usually minor, compared to the benefits. The power consumption for the added data conversion is also low enough to be negligible.

For optimization of brightness and color gamut, the RGBY quad tiles offer more advantages over the RGB triad. First the quad has one more degree of freedom in optimizing variables. The triad G can be treated as a special case of quad, with the quad Y and G, usually cyan-like green, color tiles combined into one. Imposing the constraint of white balance, the RGBY quad has two more degrees of freedom left to optimize reflectance and color gamut, while the RGB triad has only one. This extra degree of freedom allows the optimization of both color gamut and reflectance for RGBY.

For the RGB triad, the way to maximize the color gamut is to push the RGB color tiles to be more saturated, with increasingly narrower spectral peaks, which has the effect of reducing panel brightness. For RGBY quad with its quadrilateral-shaped gamut, shown in Fig. 4a, the same gamut value can be achieved by less saturated RGB, with wider spectral peaks, a clear benefit for brightness enhancement.

In transmissive and emissive mobile display applications the uncontrolled, high ambient illumination conditions dilute the perceivable color saturation due to unavoidable front surface reflections. Though text and graphic content do not typically require highly saturated colors, the ambient illumination can completely overpower the display, rendering it illegible. Conversely such a dramatic variation in performance does not occur in reflective displays. Colors remain equivalently saturated, independent of the

ambient illumination levels. Given a fixed color gamut level, sufficient for typical text and graphic content, additional performance capability can be directed towards the reflectance of the individual color tiles. The high brightness in R, Y and G tiles offers the viewer more value in the perceived color quality or richness. Fig. 5a and 5b give a visual illustration of a simulated a RGB triad stripe and a RGBY quad. The color is more vivid for the quad.



(a)



(b)

Figure 5 Visual simulation for

(a) an RGB triad stripe and (b) an RGBY quad

There is an increasing drive towards ever higher display resolutions in mobile displays. 1.8" QCIF+ displays are giving way to 2.2" QVGA and even 2.4" VGA displays with corresponding increases in resolution from 156 ppi, to 182 ppi and 333 ppi respectively. MEMS elements are often simpler to manufacture if their aspect ratios are close to 1. Therefore the RGBY quad with square tiles provides a straightforward path to these and higher resolutions.

4. Comparison of RGBY and RGBW Quads

For the mirasol display the interference color is usually of limited spectral width, making it difficult to achieve a neutral white tile for RGBW. Therefore RGBY is an easy way to achieve quad color tiles.

For LCD or other color filter based displays, the choice between RGBW and RGBY may be more subtle and involves more considerations of manufacturing process and cost for a white tile against a yellow tile. In the following we will limit our discussions to color gamut and brightness considerations only.

The RGBW quad offers little improvement in color gamut compared with a RGB triad since the additional white tile is equivalent to the sum of the remaining RGB tiles. There is an increase in brightness/reflectance for an RGBW quad relative to a RGB triad, due to the increase in area devoted to bright color tiles (50% is G or W vs. 33% G). However, our estimates indicate that the brightness for the RGBW tiles and RGBY tiles is about the same for the white state.

When displaying colors along the periphery of the color gamut, RGBW color tiles fare much worse, relative to the RGB triad case since an individual color tile has decreased in area from 33% to 25%. The white tile contributes to the brightness of colors along the periphery only marginally. The RGBY color tiles, from the discussions in the previous sections, can achieve roughly the same white state color point and greater color gamut value, with higher reflectance though less saturated R and G colors. A graphical representation of the two is shown in Fig. 6. As we discussed in the previous section, the less saturated but brighter R, G, and Y colors for the RGBY is a better choice for mobile applications where saturated colors are rarely viewable under bright ambient lighting conditions, especially for transmissive and emissive displays, like LCD and OLED.

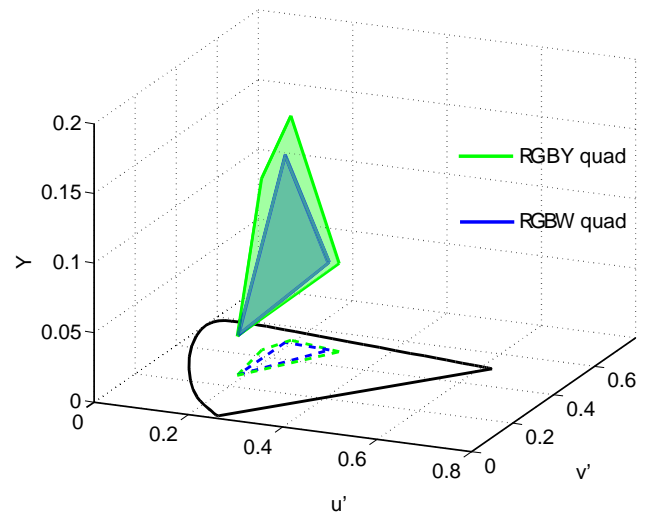


Figure 6 Brightness vs. primary colors for an RGBW and an RGBY quad

5. A New Color Metric for Mobile Display

As discussed in the previous sections the single value of color gamut is not adequate for image quality. It does not indicate the saturation of color tiles, as can be seen, in Fig. 4a and 4b, by comparing the triangle of RGB triad and the quadrilateral of a RGBY quad. Both gave the same gamut value meanwhile the individual color tiles for RGBY are less saturated. Gamut also fails to measure the perceived richness of the colors. There is a need for a better metric that indicates brightness and perceived richness of the colors for a display device. This holds especially for mobile displays which are viewed under widely varying illumination conditions, which are not favorable for viewing saturated RGB colors with low brightness.

We propose a 'color brightness index' metric defined as the sum of the brightness of the primary colors located along the periphery of the limiting color polygon shown in Fig. 6. In these examples

the ‘color brightness index’ equals 37.6% for RGBY while for RGBW the index equals 22.6%. In combination with the size of the addressable color gamut it can be used as a figure of merit, comparing alternative subpixel color tile designs. This metric differentiates RGBY from RGBW, showing the difference in brightness for the most saturated colors displayed by the display device. For both RGB and RGBY designs the color brightness index is equal to the white state brightness. This is true for all designs where each color tile forms a corner of the color polygon.

6. mirasol Display with RGBY Color Tiles

mirasol display demonstration units of both RGB triad and RGBY quad color tiles have been fabricated by QMT. However, designs for both demonstration devices were not selected purely for color and brightness optimization which would allow for a one-to-one comparison of the RGB triad with RGBY quad. In order to make a one to one comparison simulated designs were used. These simulations however were calibrated by these demonstration devices.

Figure 7 shows the overlapped designs of a RGB triad and a RGBY quad with the same design, such as air gaps within optical cavities. For both cases, the white point was set close to D65. The simulated optical performances are compared in Table I. From the result, we see that for a color gamut of 27% in both designs, the reflectance, and the contrast, of the RGBY quad is about 16% higher relative to the RGB triad.

Table I Performance simulation of RGB triad and RGBY quad designs for a color mirasol display

| | RGB triad | RGBY quad |
|-----------|-----------|-----------|
| Gamut (%) | 27.5 | 27.4 |
| Y (%) | 30.5 | 35.4 |
| Contrast | 19:1 | 23:1 |

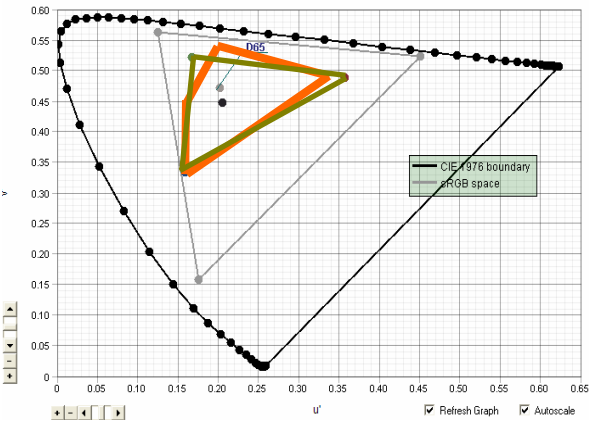


Figure 7 Color Gamut Comparison of RGB triad and RGBY quad designs for a color mirasol display

A photograph from a manufactured RGB unit is shown in figure 8. Two photographs from a manufactured RGBY demonstration unit are shown in Figure 9.



Figure 8. A photograph from a manufactured mirasol display with a RGB triad color tile



Figure 9 Two photographs taken of a mirasol display with a RGBY quad color tile

7. Conclusions

The mirasol display with RGBY quad color tile has been made and tested at QMT and compared to that with RGB triad stripe. The measurement result and analysis showed that the RGBY quad tile structure offers some advantages over RGB triad and RGBW, many of which are also applicable to other types of mobile displays. We also illustrated the limit of color gamut as the color metric and proposed a complementary metric, color brightness index, as an indicator for display image quality.

8. References

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