Design of a Novel Spectrum Sequential Display with a Wide Color Gamut and Reduced Color Breakup

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Abstract

The advantage of RGB color sequential displays is that they have no color filters, but the disadvantage is that they need to run at high refresh rates (>>180 Hz) to prevent flicker and color breakup. At Philips we have developed an alternative color sequential display, which can operate at relatively low refresh rates (~100 Hz) without disturbing color breakup or flicker. The display has two color filters per pixel (cyan and magenta) on the LCD panel and the backlight can generate two types of spectra (blue-green and green-red), which results in a wide gamut four primary display effectively. One part of the paper describes the color reproduction, including color filter design, gamut mapping and multi-primary conversion. The other part deals with the reduced perception of color breakup on the novel spectrum sequential display compared to conventional color sequential displays. A working prototype of the display has been build for demonstration purposes.

Introduction

Currently, most LCD displays have a (continuous) white backlight and an LCD panel with red, green, and blue color filters. Such a display uses 3 subpixels to make an image pixel and absorbs two-third of the light in the color filters.

Color sequential displays,[1-3] on the other hand, do not need color filters to make a color image, because they can flash the backlight sequentially to red, green, and blue. Hence, in theory they can be three times as efficient as a conventional LCD display and can display the same resolution with only one-third of the number of (sub)pixels. However, these displays also have some drawbacks.[4-7] In order to avoid flicker they need to run at refresh rates as high as 180 Hz. Yet, at this frequency the observer will still see an annoying color breakup (color flash) when moving his eyes across the screen. Extremely high refresh rates of well above 600 Hz are needed to avoid this color breakup.

With today's direct view LCDs, such refresh rates are not possible, due to the slow response of the LC molecules. In fact, even a refresh rate of 180 Hz is quite difficult to achieve with current LCDs; the pixel response, especially from black to white, is still too slow and the high update frequency generates high current to each subpixel, which requires a large TFT in each subpixel. These effects will limit the aperture of the subpixel and counteract the brightness advantage of a color sequential display.

Therefore we developed an alternative type of display, which combines the best of conventional LCDs and color sequential LCDs.[8] The principle of a similar display design was also described in another recent paper.[9] In order to gain more brightness we use two types of broadband color filters (cyan and magenta) instead of three types of narrow band color filters (red, green, and blue). This also improves the resolution because there are only two instead of three subpixels per pixel. Further, it seems that the panel can operate at about 100 Hz, without having flicker and with much less color breakup than a 180 Hz color sequential display. This lower frame rate allows for a smaller TFT and hence a larger pixel aperture.

The aim of this paper is to describe the display design and to discuss its implications for the perceived image quality. The display design section will focus on the gamut design of color filters and backlight spectra. The discussion of the perceived image quality will focus on the perception of color breakup.

Display Design

The spectrum sequential display has two color filters per pixel and generates two different backlight spectra time sequentially (see Figures 1 and 3). The backlight spectra are made with three standard LEDs for backlighting purposes; red, green, and blue. The peak brightness of the LEDs are at 469, 525, and 612 nm. In field 1 the blue and green LED are on, in field 2 the green and red one.

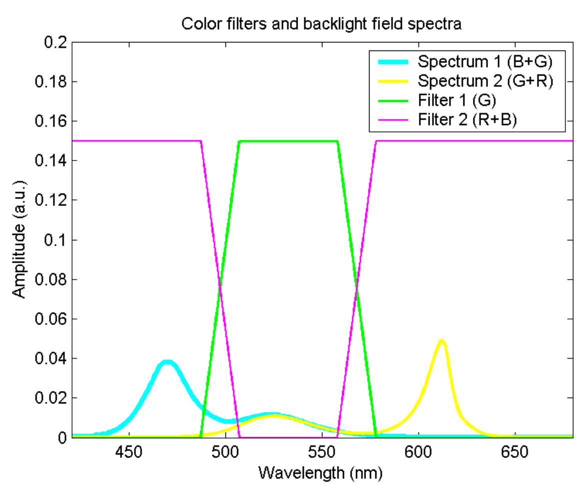

Figure 1. Lamp spectra of field 1 and 2 and the transmission spectra of the two color filters in the first design. Note that the lamp spectra are made with standard RGB LEDs in which the green LED is turned on in both fields.

Color Filter Design 1

In a first design, the color filters had their cutoff wavelengths exactly midway between the spectral peaks of the LEDs. That is, a green filter that passes the light with wavelengths between 497 and 569 nm and a magenta filter that blocks the light between those wavelengths. The color filter and the field spectra are illustrated in Figure 1. Such a color filter design results effectively in a display with three primaries of which the chromaticity coordinates of the red, green, and blue primary coincide with those of the red, green, and blue LEDs, respectively. Unfortunately, the red and blue color points of the LEDs were not saturated enough to cover the EBU color gamut (=the gamut defined in both the PAL and NTSC television standards). This is illustrated in Figure 2, which shows the chromaticity coordinates of the primaries in this first design.

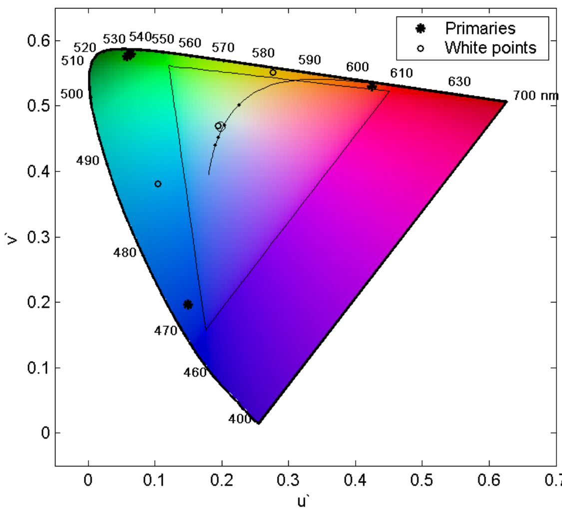

Figure 2. Chromaticity coordinates (CIE 1976) of the four primaries (*) and of the "white" points (o) of field 1 and 2 (in cyan and yellow area respectively) and of the two fields combined (near D65; larger white circle) of color filter design 1. The thin black triangle and the curved black line represent the EBU gamut and the black body curve, respectively.

Color Filter Design 2

In a second color filter design, we tried to cover at least the EBU color gamut and tried to obtain as much brightness as possible out of the display for the predefined white point (D65). The first step in this color filter design is to tune the blue and red primary by changing the low and high cutoff wavelengths of the magenta filter, respectively. If the lower cutoff wavelength is decreased, the blue primary shifts to a color point corresponding to blue with a shorter wavelength. Oppositely, the red primary shifts to a color point corresponding to red with a larger wavelength if the higher cutoff wavelength is increased.

The second step in the color filter design is to tune the green primary. It could be kept the same as in the first design giving a much wider gamut for green and cyan colors than the EBU gamut, but that is at the expense of the brightness of the display. Alternatively, we took a cyan instead of a green color filter, which passes not only the light from the green LED, but also a large part of the spectrum of the blue LED and a small part of the red LED spectrum. This is illustrated in Figure 3.

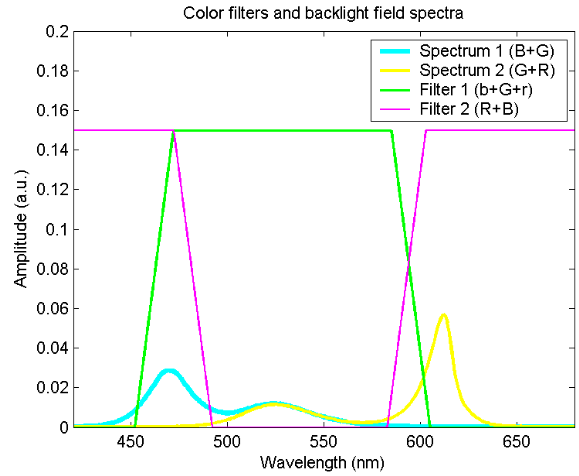

Figure 3. Same as Figure 2, but for the second color filter design.

This new color filter design has a very interesting side effect. In field 2, which has the red and green LEDs on, the resulting red and green primaries match with the corresponding EBU primaries. In field 1, however, the resulting blue primary matches with EBU, but the resulting "green" primary is actually a cyan primary, because the cyan color filter passes all the light of the green LED and part of the light of the blue LED.

Figure 4 shows the four primaries in the second color filter design, indicated with an asterisk (*). The quadrangle spanned by the four primaries corresponds to the color gamut of the display. It covers the entire EBU gamut (thin black triangle) and for cyan colors it is even much wider. The small circles (o) in the cyan and yellow area of the figure indicate the "white" point of field 1 and 2, respectively. The actual display white point corresponds to the average of the white points of the two fields and matches with D65. The tuning of the white point was carried out after the color filter design by choosing the correct ration of the intensities of the individual red, green, and blue LEDs.

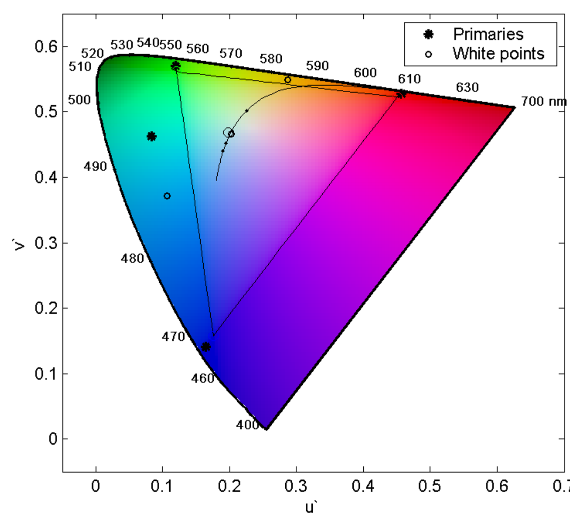

Figure 4. Same as Figure 2, but for color filter design 2.

The panel we build has a striped pixel configuration. Figure 5 illustrates how the combination of the two color filters and the two backlight spectra generate a spatial color distribution per field. It also shows the integrated color that the eye sees. When the viewing distance to the panel is large enough, the eye will integrate colors of neighboring subpixels as well and in this example a white display will be seen.

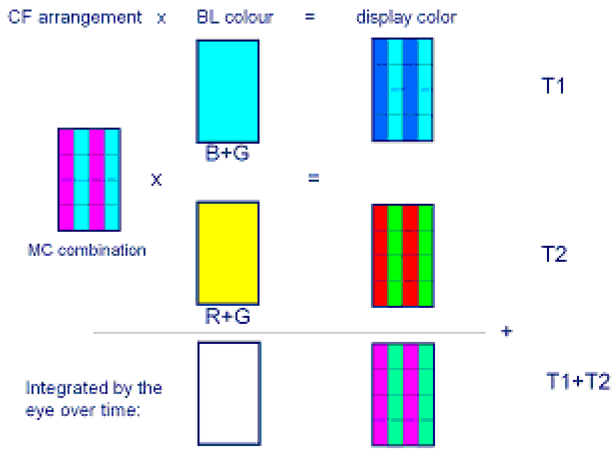

Figure 5. Illustration of how the combination of spatial color filters and the different backlight spectra in the two fields generate a color per field and the integrated color by the eye. Note that 16 subpixels are shown in a striped pattern.

Robustness

Apart from matching the color points of the primaries in a color filter design it is also very important to investigate how robust it is for color filter variations. Especially, because color filters for LCD displays are made with a dye, which means that one cannot make any arbitrary color filter transmission spectrum. There are two important design aspects; 1) the cutoff wavelengths and 2) the slope of the filter. The cutoff wavelength has a large impact on the color points of the primaries, but when choosing it on the safe side it will only make the gamut larger with little impact on the brightness of the display. Fortunately, the slope of the filter has little effect on the color points of the primaries; doubling the width of the color filter slope from 20 to 40 nm gives a marginal shift in the color point of the primaries of less than 0.025 in CIE 1976 u'v' color space.

Comparing the second with the first design, we can conclude that we have created a somewhat smaller gamut in the green, but a larger gamut for red and blue without loosing in cyan. The second color filter design also has a 10% higher display luminance. For those reasons we decided to build the actual spectrum sequential display based on the second color filter design.

Signal Processing

In order to obtain correct color reproduction, the driving signal for each of the two fields must be calculated and send to the panels at the correct time. This requires a tight control between updating the panel and flashing the backlight. This time control was accomplished with a custom made driver board.

The calculation of the drive signals for the two fields requires a multi-primary color mapping technique. We used a so-called matrix mixing technique based on that described in Ref. [10].

In order to illustrate the front-of-screen performance of the display we simulated it in Figure 6. The left and middle panels show the images of the first and second field, respectively. Note that the image of field 1 contains only cyan-blue colors and the image of field 2 only red and green colors, which correspond to the primaries of the display in the respective fields. The right image shows that the eye sees a full color image with the correct colors when the images are played sequentially at a refresh rate of 120 Hz. The inset in the upper left corner is a zoomed image of a part of the forehead. It clearly illustrates the different colors that are made in a single subpixel.

Figure 6. Illustration of the two fields in the case of an actual image of a girls face and the resulting image as seen by the eye when presented at a refresh rate of 120 Hz. The left corner shows a zoomed image of the forehead. One can clearly see the striped pattern and the difference in the color of the pattern in each field and the resulting field.

Visibility of Color Breakup Artifacts

As already indicated in the introduction, color sequential displays suffer from color breakup. In order to estimate the expected amount of color breakup (or the absence thereof) in the new display, we emulated the front-of-screen performance of this display on a CRT and compared it to an emulation of an RGB-color sequential display on another CRT. The CRTs were Philips Brilliance 201P, which we operated at frequencies up to 180 Hz using a Radeon 9000 video board.

In a first test, both CRTs were set to a refresh rate of 180 Hz, which results in a frame rate of 180/2=90 Hz for the spectrum sequential display and 180/3=60 Hz for the color sequential one. Viewers were asked to scale the amount of flicker and color breakup in both displays. Preliminary results show that the amount of flicker was judged rather low in both displays and not significantly different. Yet, the amount of color breakup was judged significantly higher in the color sequential displays than in the spectrum sequential display.

In a second test, the simulated color sequential display remained at 180 Hz refresh rate, but the spectrum sequential display was lowered in refresh rate until it was equal in preference to the 180 Hz color sequential one. Preliminary results show that this happened at refresh rates of 90-100 Hz. The main reason was that viewers reported to see flicker in the spectrum sequential display at those low refresh rates. Yet, they also indicated that visibility of color breakup was still rather low and much less than on the 180 Hz color sequential one.

In order to test at which frequency the spectrum sequential and color sequential displays are judged equal in the amount of color breakup we have to setup the experiment in a different way. We should set the spectrum sequential one at 120 Hz (no flicker, little color breakup) and increase the refresh rate of the color sequential display to refresh rates well above 180 Hz. With our current experimental setup such an experiment is not possible. Yet, from the literature[2,4] it is already known that even at refresh rates of 540 Hz color breakup can be annoying in color sequential displays and we notice that it is not very annoying in the spectrum sequential one at 120 Hz.

Conclusions

This paper describes a spectrum sequential display technique that combines the best properties of conventional LCD displays and color sequential displays. The new display technique can be readily made with existing LCD fabs and backlight components and does not require new material development. We showed that it outperforms the conventional LCD display with respect to luminance and resolution. The color sequential display is outperformed on visibility of color breakup and flicker, which means that much lower refresh rates are needed and thus a smaller TFT (=more aperture) resulting in more brightness. Altogether this means that we can now make a display with a much higher perceived resolution than is possible with conventional mobile LCD displays, with sufficient brightness (=low power), and no annoying flicker or color breakup.

Acknowledgements

We would like to acknowledge our colleagues in Philips MDS Kobe, Philips Research Redhill, and Philips Research Eindhoven for their contributions to make a prototype of the spectrum sequential display.

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Author Biography

Erno Langendijk received his M.S. degree in Physics from Nijmegen University (1994; The Netherlands) and a Ph.D. in Physics from Delft University (2002; The Netherlands). During his Ph.D. he worked at TNO Human Factors (Soesterberg, The Netherlands) and at the University of Wisconsin (US). Since 2000 he has worked at Philips Research Laboratories Eindhoven (The Netherlands), where his work has focused on visual perception, and on architectures, of display systems.