64.4: Four Primary Color Projection Display

Shmuel Roth
Genoa Color Technologies, Herzelia, Israel
Walt Caldwell
Advanced Digital Optics, Westlake Village, CA

Abstract
We have developed a four primary front projector prototype in a multi HTPS panels configuration. The projector is based on modifications of the optical platform of an off-the-shelf high quality brand product. Standard 720p input signal is converted to the required multiprimary input using the ColorPeak™ algorithm implemented in the KESHET ™ chip. The result is a substantial increase in color gamut and brightness.

1. Introduction

Digital projection displays were introduced into the market a few years ago, and captured a large share of the business and home cinema front projection market. Single panel sequential projection engines, either in DLP™ or LCOS technologies, as well as three-panel HTPS or LCOS engines are used extensively. Multiprimary technology (more than three primary colors) enhances the performance of displays, by allowing wider color gamut [1,2] and higher brightness [2]. Recently, we have applied multiprimary technology to single panel displays. In this paper, we describe an application of multiprimary technology to transmissive HTPS panels display.

In a three panel RGB display wider color gamut is achieved by narrowing the spectral pass band of each of the primaries. This, in turn, reduces the amount of transmitted light, resulting in a decrease of the display brightness. This is especially true for projectors, which use a high pressure mercury lamp, since the high intensity "yellow peak" that has substantial brightness content is filtered out. By adding more primaries, multiprimary technology can use the rejected light to increase brightness, and thus allowing the other primaries to be more saturated.

In this paper we describe the development of four panels four primary projectors based on patent pending Genoa proprietary technologies. The projectors are based on modification of existing high quality RGB HTPS projectors (Sony, "Cineza" VPL-HS20). The modified four primary projectors have enhanced color gamut, substantially larger than the NTSC gamut, and their brightness is higher by approximately 40% than that of the RGB projector, at a color corrected white point of D65. Simple analysis shows that by proper design (and not just a modification of an existing design) a brightness improvement by a factor of ~2 can be achieved.

2. Design and Performance

In order to decrease the development time and costs, we decided to modify the existing design of the RGB projector rather than to design and build the four primary projectors from scratch. This also allowed us to make use of the existing components of the original projector. Also, when we had to use new optical components (like a new projection lens and X-cube), we made efforts to use existing products and minimized the number of specially developed components. This approach enabled us to achieve our goal of minimizing development time and costs; however it results in a less than optimal design. Nevertheless, a major improvement in performance over the RGB projector is achieved. Evidently, a less restrictive design would yield an even better performance boost. In the following sections the original projector optical platform and its performance are described, followed by a detailed description of the modifications made in the multiprimary prototype, and the resulting color gamut and brightness enhancement.

2.1. Original Projector

Figure 1 depicts a schematic configuration of the optical engine of the original projector with three HTPS transmissive panels. The light from the lamp passes through an IR/UV cutoff filter, an integrator and polarizing conversion system, and then collimated by a lens to produce s-polarized white light. This beam is split into three color channels using two dichroic mirrors, one reflecting the red while passing the blue and green parts of the spectrum, and a second one that separates the green from the blue.

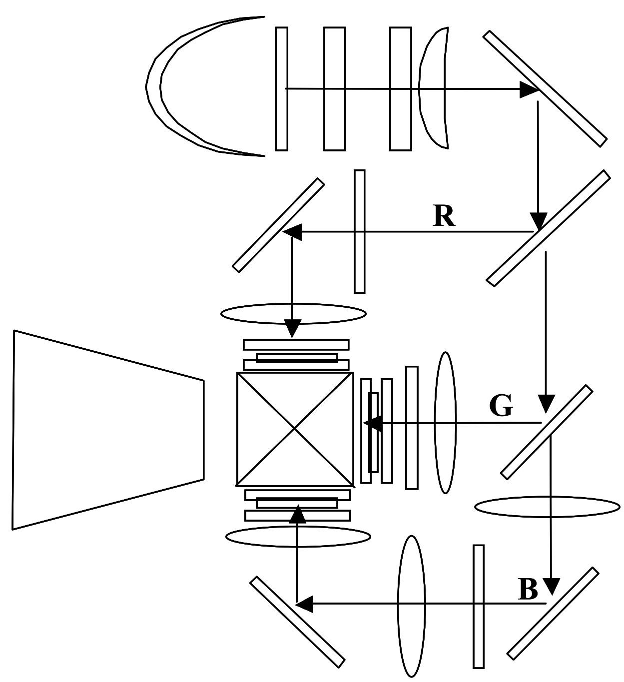

Figure 1. Structure of the original projector optical bench.

Each of the colored beams passes through additional filtering to obtain a better definition of its color. Then, each of the beams is imaged on its LC spatial light modulator, which modulates the brightness profile to create the primary color image. The three modulated primary images are then combined using a standard X cube. The cube is designed to reflect red and blue s-polarization and to transmit green at p-polarization. The polarizations of the primary colors are matched to the X cube characteristics by appropriate polarization rotators. The combined images are then projected on a screen by a projection lens.

The measured spectral bands of the three channels at 50% transmission points and the corresponding chromaticity of primaries are given in table 1.

Primary Color	Spectral band	Chromaticity
Red	High pass, 602 nm	x = 0.657 y = 0.330
Green	Band pass, 521 – 567 nm	x = 0.268 y = 0.669
Blue	Band pass, 428 – 498nm	x = 0.146 y = 0.065

Table 1: Measured spectral bands and chromaticity coordinates of the RGB projector primaries

The color coordinates of the natural white point with all the primaries set at maximum was (0.284, 0.352). In order to correct for a balanced white point, the blue and green primaries gains are reduced.

From the table, it is clear that the "spectral windows" of 498 – 521 nm and 567 – 602 nm are not used. Note that one of those rejected windows covers the “yellow peak” of the lamp, which has high brightness efficiency.

2.2. Modified Projector

The modified four primary projection optical engines have an advantage over the three-color engine in terms of brightness and gamut. In particular, the fourth primary (yellow) uses the unused "yellow part" of the lamp spectrum. However, the layout of the four primary engines is more complicated and presents several problems, especially regarding the color-combining path. As it was based on off-the-shelf projectors and elements, it was subject to many constraints, which could be removed if the engine were designed from scratch.

2.2.1. Optical Platform

Figure 2 depicts the structure of the modified four primary HTPS projection optical engine that we have constructed. The illumination path is quite similar to that of the original RGB engine, with a few modifications. We wanted to maximize the blue throughput in order to use more of the yellow light, so we swapped the red and the blue color paths. Thus, the first dichroic reflects the blue part of the spectrum and the second reflects the green part of the spectrum. Originally we had a third dichroic element reflecting the red part of the spectrum and allowing the remaining yellow light to be transmitted through. However, since the existing projector optics placed this element (plain mirroe in the original projector) inside a non-telecentric space, there was significant color non-uniformity across the red and yellow fields. In order to eliminate the non-uniformity, we used a polarizing arrangement. The polarized red-yellow light is passed through a ColorSelect® selective polarization rotator (obtained from ColorLink, Boulder, Colorado), which rotates the yellow light to p-polarization while the red light is kept in its s-polarization. The s-polarized red light is separated from the p-polarized yellow light by a wire grid polarizing beam splitter (from Moxtek, Inc.), which reflects the red and transmits the yellow. The color non-uniformity is thus solved since the selective polarization rotator and wire grid PBS are rather spectrally uniform.

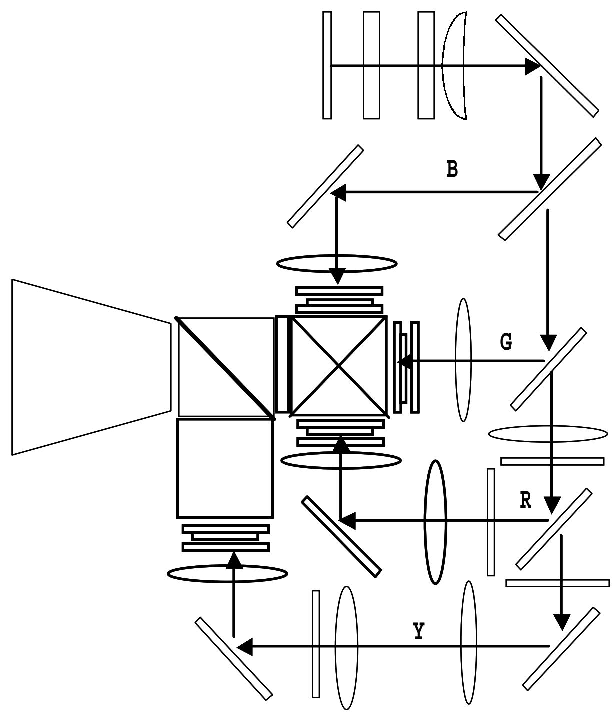

Figure 2. Structure of the modified projectors optical bench.

The color combination arrangement is also modified. A first combination step on the red, green and blue channels is done by means of a standard “X cube”, combining s-polarized red and blue light with p-polarized green light. The combination of the red, green, and blue light with the yellow light is difficult to do using only dichroics. Therefore, this combination is done using a polarizing beam splitter cube, which reflects the s-polarized yellow light, while transmitting p-polarized red, green and blue light. In order to obtain p-polarized light coming out from the X-cube, a selective green-magenta ColorSelect® rotator is placed between it and the PBS cube to rotate the polarization of the blue and red light from s to p polarization, while maintaining the polarization of the p-polarized green light. Finally, a glass cube is placed between the PBS and the yellow panel in order to keep the optical path equal for all panels. An "off the shelf" projection lens was used, which had a longer back focal distance and similar F# as the original projection lens.

2.2.2. Color Conversion Algorithm and Electronics

The video input signal in RGB or YC_BC_R format is converted to multi-primary signals driven to the four panels using the KESHET™ chip. The KESHET™ chip accepts three-color input (8 or 10 bits per channel including control and timing signals), at standard video resolutions in the range up to 1080p (alternatively computer standard resolutions up to UXGA). In the current application a 720p HD source has been used. The KESHET™ converts the input signals to multi-primary signals, 8 bits per signal, 4 to 6 primaries, retaining the same input clock and control signals. The chip was installed on a KESHET™ evaluation board that allows the use of DVI interfaces for the input and output. The four primary signals were carried on two DVI output connections from the board, each carrying the data of the RGB channels and yellow channel respectively. This was necessary, since the existing projector electronics only support three channels of color. In order to drive the fourth panel, a second complete set of electronics was incorporated into the projector. The yellow panel was connected to the green channel of the second DVI connection. The RGB primaries are controlled through one control panel from the first projector and the Y is controlled through the G control of the second control panel.

2.2.3. Performance

Our goal was to optimize the natural white point to D65. Since the natural white point was slightly shifted to the green, we inserted trim filters that rejected a small wavelength region and further increased color gamut. For evaluation purposes, we built two units, and used different trim filters in each of them, resulting in different green and yellow color points. The blue and red color coordinates were also slightly different due to different contrast in the two units and dichroics element's tolerances.

The resulting color chromaticity coordinates for the two projectors are shown in table 2, and drawn in figure 3.

Primary Color	Spectral band		Chromaticity	
	#1	# 2	# 1	# 2
Red	High pass, 605 nm		x = 0.661 y = 0.312	x = 0.677 y = 0.315
Yellow	Band pass, 557–600nm	Band pass, 552–600nm	x = 0.498 y = 0.493	x = 0.456 y = 0.535
Green	Band pass, 502–550nm	Band pass, 502–542nm	x = 0.230 y = 0.707	x = 0.154 y = 0.773
Blue	Band pass, 428 – 494nm		x = 0.145 y = 0.046	x = 0.147 y = 0.045

Table 2: Spectral bands and chromaticity coordinates of the two multiprimary projectors

The original projector had a 87% NTSC gamut. The four primary projectors have a 105% NTSC and 126% NTSC color gamuts respectively. At D65 color temperature, the maximum brightness was ~40% higher than the maximum brightness of the original projector at D65 color temperature. Thus, a very significant gamut and brightness improvement was achieved by modifying the projectors to four primaries.

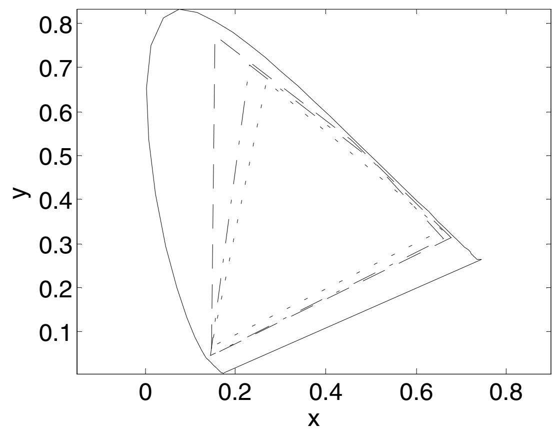

Figure 3: The color gamut of the original projector (dotted line) and the first (dash-dotted line) and the second (dashed line) four primary projectors.

2.2.4. Perception

The increase of color gamut can be easily computed from the known chromaticity coordinates of primaries. However, the important question is whether this increase is meaningful from the perceptual point of view. In particular, it is important to understand whether the additional colors have an impact on image quality.

Although we did not test the issue scientifically, a comparison between the multi-primary and the RGB projector clearly demonstrated that there is a major perceptual impact of the increase in color gamut. Images and movies seen on the modified projector appear significantly more vivid, with more natural colors. The color improvement is visible in all regions: very bright and saturated yellow and orange colors, saturated blue, magenta, green and red colors, and display of cyan colors that are neither present in the original display nor in virtually all the existing RGB displays. Furthermore, projector No. 2 was demonstrated at the 2005 International CES in Las Vegas, side by side with the original projector and was appreciated by all viewers for its excellent picture quality.

We are currently investigating what would be the optimal color coordinates of the primaries, taking into account both the two-dimensional gamut and the brightness distribution. For this investigation we use both the two projectors described above and additional multiprimary platforms we have developed. We will use the results of this investigation in the design of future commercial multiprimary displays.

3. Achievable Performance

As we have discussed above, the projectors that we produced were based on an existing projector design, and thus, given the constraints imposed by that design, did not have optimum configuration and performance. A proper design will enable improved performance.

We measured the spectrum of the original projector illumination unit – lamp, UV/IR filter and polarization conversion device. The color coordinates of this light were 0.296, 0.323. These color coordinates represent a white point of ~7500K, close to the black body curve.

Actual color coordinates of the output light of a projector will depend on the spectrum of the illumination unit multiplied by the spectral transmission of the optical engine and panels for each primary.

Since, as presented above, the four primaries projector "can use" all the available spectral output of the lamp and still allow a very large color gamut, proper design of optical engine taking into account panels transmission may enable to "fine tune" the output of the projector to a desired white point in a very efficient way.

We illustrate the achievable performance gain of a multiprimary over an RGB projector by spectral analysis of the original RGB and one of the multiprimary projectors we built (projector 2 above). We adjusted the individual gains of the panels to get maximum output at D65. For the RGB projector, in order to get D65 white color temperature, the red primary was driven to maximum intensity; the green and blue primary intensities were significantly reduced. For the multiprimary projectors all the primaries were driven at maximum intensity.

We than measured the spectrum of both projectors and adjusted the intensity scales, so that the spectral intensity in the red (above 600nm) was similar – see figure 4. This simulates possible performance if we assume identical lamps and engine optical transmission. Using these assumptions, we would get a brightness ratio of 2.1 between the multiprimary and the RGB projector outputs at D65.

Thus, we estimate that by proper design of a projector using four primaries, a brightness increase of up to a factor of ~2 above the "useful brightness" of an RGB projector is achievable, while maintaining a very large (higher than NTSC) color gamut.

4. Summary

To summarize we have developed two four primaries HTPS projectors on the modification of existing high performance RGB projectors. The performance of the four primary projectors was substantially improved over that of the original RGB projectors both in brightness and color gamut. Overall appearance of the picture of the four primary projectors was

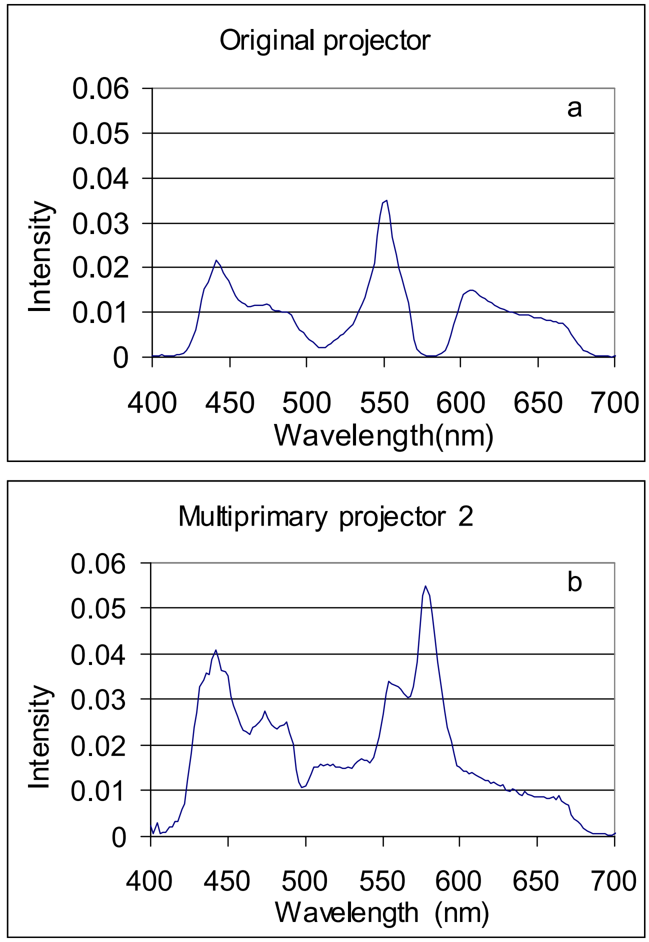

Figure 4. Spectral output of the original and the multiprimary projectors at D65 white point.

judged by many observers as superior to that of the original high quality RGB projectors.

Analysis shows that the use of four primaries enables efficient usage of the available lamp spectrum and brightness gain by a factor of ~2 above the brightness of an RGB projector is achievable, while getting a color gamut larger than NTSC.

5. References

[1] T. Ajito, et al. Expanding color gamut reproduced by six-primary projection display, Proc. SPIE, Vol. 3954, pp. 130-137, 2000.

[2] S. Roth, et al. Wide gamut, high brightness multiple primaries single panel projection displays, 2003 SID Int. Symp. Tech. Digest of Papers, p118-121 (2003).