

# P-188: Single-Panel Spatial-Color and Sequential-Color LCOS Projectors Using LED Lamps

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## Abstract

We present and compare two single-panel LCOS projectors using LED lamps. The 0.59" sequential-color LCOS microdisplay with integrated frame buffers can deliver 10.5 lm by a 4W red, green and blue LED. The 0.59" spatial-color LCOS microdisplay with white sub-pixels can deliver 14 lm by a 6W white LED.

## 1. Introduction

Liquid-crystal-on-silicon (LCOS) microdisplay has been developed for more than 10 years [1, 2]. There are three kinds of LCOS microdisplays, arranged in different manners for various applications. The first one was a monochrome and high-resolution microdisplay developed in early 1990, and arranged in three-panel architectures for rear projection television (RPTV) applications [3, 4]. The second one was a color-sequential microdisplay developed in late 1990, and arranged in single-panel architectures for near-to-eye and RPTV applications [5~7]. The third one was a spatial-color microdisplay developed in early 2000, and arranged in single-panel architectures for near-to-eye and mini-projector applications [8]. These three kinds of LCOS microdisplays and projectors were not designed for use with light emitting diodes (LEDs). But as the fast development of power LEDs, the prospect of using LEDs as light sources for these three LCOS projectors has been greatly increased [9~11].

A Corner of 3M applied red, green and blue (RGB) LED lamps to a three-panel LCOS projector, which used three 0.61" SVGA panels, and obtained 267 lm [10]. H Zou of Philips Research replaced the scrolling prism in a single-panel sequential-color projector, which used a 1.3" progressive-scan SXGA panel, by sequential RGB LED lamps and obtained 44 lm [9]. It was expected that the output could be improved to 135 lm if the progressive-scan LCOS panel was replaced by a frame-loading one. H S Lo of ITRI proposed optical designs for very compact mini-projectors using 0.38" color-filter LCOS panels [11]. But the output was low due to the light absorption by RGB color filters.

In this paper, we present our works on single-panel spatial-color and sequential-color LCOS projectors using LED lamps. We added white sub-pixels to the color-filter LCOS panel to increase the panel reflectivity from typically 20% to 32%. The output of the spatial-color LCOS projector was correspondingly improved. We integrated frame buffers to the sequential-color LCOS panel to eliminate the frame loading time. As a result, the optical efficiency of the sequential-color LCOS projector was greatly improved. Moreover, the sequential-color LCOS projector had

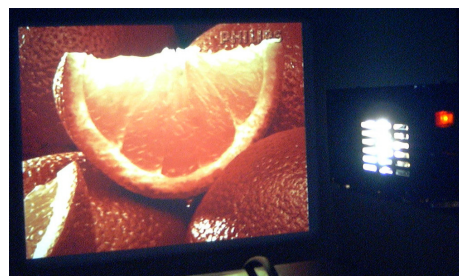
enough time budgets for RGB and white (RGBW) color sequence for more optical output.

## 2. Spatial-Color LCOS Projector

The color-filter LCOS microdisplays were designed to be used with low-cost halogen lamps for low-cost video projectors. Figure 1 shows a palm-size spatial-color LCOS projector using a 50W halogen lamp in a MR11 package. The projector could produce 20 lumen output from a 0.47" VGA panel with a color gamut of 35% NTSC level, which was limited by low color temperature of the halogen lamp.



(a)



(b)

Figure 1 (a) Spatial-color LCOS projector using halogen lamp and (b) its projection

In an attempt to use LED lamps for this spatial-color LCOS projector, we designed a compound parabolic concentrator (CPC) of the MR11 size and assembled with a 2x3 white LED array. Where the LED array were flip-chip bonded with 1.15mm pitch and 0.15mm space to a highly conductive substrate. The CPC was a shallow disk with free-form surfaces to concentrate the light to the 0.47" panel in 45 mm away. The surface of the CPC was

pasted with a quarter-wave plate and a reflective polarizer for 65% polarization utilization as shown in Figure 2.

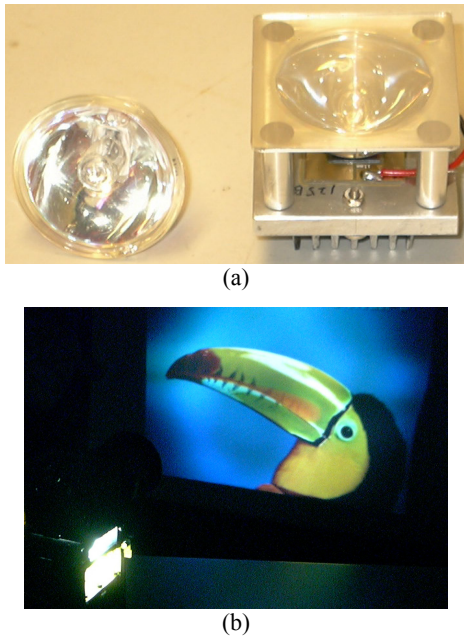


Figure 2 (a) MR11 halogen and CPC LED lamps, and (b) projection of the spatial-color LCOS projector with the LED lamp

Figure 2 also shows a projection image of this spatial-color projector with a 6W white LED lamp as the light source. The color gamut was improved to 45% NTSC level due to a higher color temperature of the LED lamp compared with that of a halogen lamp. But the output was reduced to only 3 lm due to a lower illumination and optical efficiency.

Most of the light was lost at the disk-like CPC, which focused 40% of the light from the LED array to the 0.47" VGA panel. But only 50% of the light was within the cone of F#2, which could be collected by the projection lens, and 65% was converted to the right polarization through the simple polarization converter. As a result, the disk-like CPC only coupled 13% useful and polarized light to the 0.47" panel. The panel reflected 20% of the light to the projection lens, which transmitted 60% of the light to the screen. We therefore obtained 1.6% optical efficiency from the LED array to the projection image. The LED array could emit 210 lm or 35 lm per LED and hence, the projector could deliver 3 lm output.

By applying the same LED illumination to a larger 0.62" SVGA panel, the output was increased proportionally by area to 5 lm. Where, the disk-like CPC coupled 20% useful and polarized light to the 0.62" panel. A 60mm-long conventional rod-like CPC could improve the coupling efficiency of useful and polarized light on the panel to 32%, and then the projector could deliver 8.5 lm output. But this 60mm-long rod like CPC might be considered too bulky for a compact LCOS projector with LED lamp. An efficient and compact secondary optics for the LED lamp is required in order to improve the optical efficiency and keep the compactness.

In addition to the improvements in the LED and the projection optics, another improvement of the optical efficiency can be done

by adding white sub-pixels to the LCOS panel. In this approach, the panel reflectivity was increased from 20% of RGB pixels to 33% of RGBW pixels. We designed a new 0.59" SVGA panel with RGBW pixels of 15µm pitch and assembled to a projector with the previous setup. The light efficiency of this new spatial-color LCOS projector with RGBW pixels was improved to 6.5% or for a 14 lm projection with 6W LED lamp. But the color gamut was slightly reduced to 42% due to color mixing by the RGBW sub-pixels as compared and illustrated with previous RGB pixels in Figure 3.

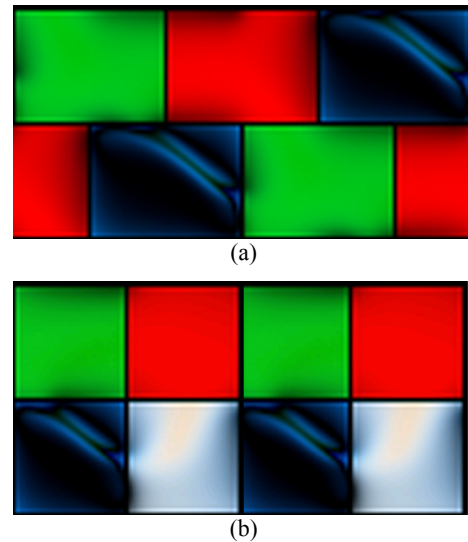


Figure 3 Simulated (a) RGB and (b) RGBW pixels of color-filter LCOS microdisplays.

Table 1 summarizes the improvements of the optical efficiency and output of the earlier and the new spatial-color LCOS projectors. Where, the earlier projector used a disk CPC and a 0.62" panel with RGB pixels, while the new projector used a rod CPC and a 0.59" panel with RGBW pixels.

Table 1 Optical efficiency of two spatial-color LCOS projectors

	0.62" RGB panel	0.59" RGBW panel
2x3 LED array	210 lm	210 lm
CPC	30% by disk CPC on panel	50% by rod CPC on panel
Polarization utilization	65%	65%
LCOS reflectivity	20% by RGB pixels	33% by RGBW pixels
Projection lens	60%	60%
Output	2.4% or 5 lm	6.5% or 14 lm

### 3. Sequential-Color LCOS Projector

Another single-panel LCOS projector can be realized by color sequential illumination of a monochrome LCOS panel. This sequential-color LCOS projector requires a dedicated data

processor to convert the parallel video data to serial ones and illuminate RGB light accordingly as shown in Figure 4.

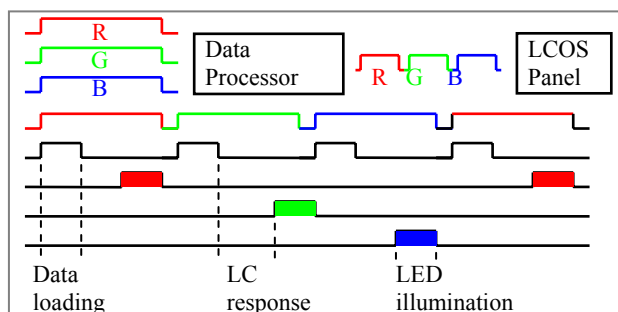


Figure 4 Sequential-color driving scheme

In order to improve the light efficiency of this projector, the data loading and LC response times should be minimized. We used five transistors and three capacitors to implement the pixel as shown in Figure 5. Two pairs of two transistors and one capacitor form two dynamic random access memories, where one drives LC and the other loads the next frame through the complementary  $\phi 1$  and  $\phi 2$  signals. The fifth transistor and the third capacitor form a conventional pixel, where the transistor was used to reset the pixel before loading the next frame. Through this reset, the LC response time could be reduced to 2ms for a highly reflective MTN mode [12].

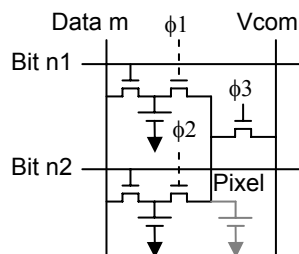


Figure 5 The pixel structure of five transistors and 3 capacitors

We designed a 0.59" SVGA panel with this pixel structure of five transistors and three capacitors. Small low-voltage transistors were used to squeeze the pixel pitch to 15 $\mu$ m and the LC had to be driven by common voltage (Vcom) modulation. With the elimination of data loading time, the light efficiency of this sequential-color LCOS projector was greatly improved. In our early study of RGB color illumination of this frame-loading panel, we allocated 30% of the frame time for LC response and 70% for LED illumination. The LC response time of each sub-frame was 1.7ms, which was not adequate but close enough to the 2ms response time of the panel.

For the 70% LED illumination by one red, two green and one blue (RGGGB) LED, we allocated 25% for red, 25% for green and 20% for blue LED. In this study, we used the same disk-like CPC to couple the RGGGB LED illumination to the 0.59" panel, and the LED was over driven by 50% in pulses. The coupling efficiency of useful and polarized light from the LED array to the panel was slightly increased to 36% due to a smaller 2x2 LED array. The panel reflectivity was improved to 70% by the monochrome panel. After the 60% transmission of the projection lens, the red, green and blue LED contributed roughly 1.4, 2.8 and 0.4 lm to the projection image for a combined optical output of 4.5 lm, which

corresponded to 3.6% optical efficiency of the RGGGB LED of 125 lm in continuous use.

In a later study of RGBW illumination of this 0.59" SVGA panel with the rod-like CPC, we allocated 40% of the frame time for LC response and 60% for LED illumination. The LC response time of each sub-frame was kept at the same of 1.7ms as before. For the 60% LED illumination, 15% was for red, 15% for green, 10% for blue and 20% for white. In this study, we also changed the secondary optics of LED to the rod CPC, which coupled 40% useful and polarized light to the panel. With 70% panel reflectivity and 60% transmission of the projection lens, this RGBW sequential-color projector could deliver 10.5 lm, which corresponded to 8.4% optical efficiency of the RGGGB LED of 125 lm..

Table 2 summarizes the improvements of the optical efficiency and output of these two sequential-color LCOS projectors with different color sequences. The first one used a disk CPC and RGB sequence, while the second used a rod CPC and RGBW sequence.

Table 1 Optical efficiency of the sequential-color LCOS projector with different color sequences

		RGB sequence	RGBW sequence
RGGGB LED on time	R	25%, 14 lm	35%, 19.5 lm
	G	25%, 28 lm	35%, 39 lm
	B	20%, 4 lm	30%, 5.5 lm
LED output		46 lm	64 lm
CPC		36% by disk CPC on panel	60% by rod CPC on panel
Polarization utilization		65%	65%
LCOS reflectivity		70%	70%
Projection lens		60%	60%
Output		4.5 lm	10.5 lm

## 4. Comparisons

### 4.1 Optical Efficiency

We have demonstrated both the single-panel spatial-color and sequential-color LCOS projectors with common projection lens and LED optics. For the spatial-color LCOS projector, white LED lamps were used since color was already available on the panel. We have obtained 14 lm out of a 0.59" RGBW spatial-color LCOS panel with a 6W white LED lamp. The white LED was operated continuously and consumed 6W. In terms of optical efficiency, this spatial-color projector produced 2.3 lm per LED, or 2.3 lm per optical wattage.

For the sequential-color LCOS projector, color LED lamps were used to produce color. With a true sequential-color 0.59" LCOS panel that has internal frame buffer to eliminate the data loading time, we were able to apply RGBW color sequence to the panel. We obtained 10.5 lm out of this RGBW sequential-color LCOS projector which employed the same optics as that was used in the

previous spatial-color LCOS projector. The color LED was operated in pulses and consumed 2W. In terms of optical efficiency, this sequential-color projector produced 2.6 lm per LED, or 5.2 lm per optical wattage.

## 4.2 Electronic System

Light leakage and thermal leakage were not a concern for the LCOS panel with LED lamps since the temperature on the panel was always below 40°C. The spatial-color LCOS projector can run at 90Hz without flicker. At this frame rate, the 0.59" spatial-color LCOS panel consumed 200mW. It was natural to run the RGBW sequential-color LCOS projector at 60 Hz frame rate or 240 Hz sub frame rate. At this frame rate, the 0.59" sequential-color LCOS panel consumed 400mW.

In addition to common video chips to drive the display, the sequential-color projector required a dedicated data processors and to convert the parallel video data to serial ones for color sequence. In our study, we used a FPGA to implement this data processor, and the power consumption of this data processor and the associated memory bank was over 1.5W. This might be a fair comparison, but it was expected that the sequential-color projector would probably consume 1.5W more in electronics than the spatial-color projector.

## 4.3 Color

Color and brightness have to be compromised in the projector. In these two low-power projectors with low brightness, we tried to maximize the output at the expense of color. The RGBW spatial-color projector could exhibit a color of 42% NTSC level. We believed we could improve the color of the RGBW sequential-color projector 60% NTSC level according to our simulation [13]. But it was difficult to further improve the color of the spatial-color projector. The limitations were on the fringing effect among smaller sub-pixels. The spectrum of the white LED does not match the spectrum of color filters on the LCOS, either.

The sequential-color projector could exhibit much better color if the LC response time was increased to allow for full LC response. This would minimize the color mixing between adjacent sub frames and illuminations. We expected the color could exceed 80% NTSC level, thought we have not demonstrated yet.

## 5. Conclusion

In summary, we have demonstrated and compared both the single-panel spatial-color and sequential-color LCOS projectors with common projection lens and LED lamps. Optimizations were applied to the LCOS panels to improve their optical efficiencies

through white sub-pixels and frame buffers, respectively. Further optimizations in the projection lens and LED optics would certainly improve these two compact projectors for mobile display applications. The spatial-color projector has cost and compactness advantages, while the sequential-color projector has better color and the potential to produce more output through 3 RGB LED arrays and an x-cube [9].

## 6. Acknowledgements

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