46.3: An Efficient Illumination System for Single-Pane LCD Projector

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Abstract
A novel illumination system for single-panel type LCD projector that employs angular color separation for synthesis of full color images is described. The optical design of the illumination system is optimized to give maximum optical efficiency and minimum color mixing.

Background and Objectives
Projection type image display has become the leading technology for providing high quality large-area images for conference and presentation applications. However, the use of projectors is still mostly limited to business occasions due to their high costs. Whether projectors will find their way into home applications will depend largely on if their prices can be lowered to a level acceptable to average consumers.

Due to the simplicity of its optical system design, single-panel LCD projection promises to be the most affordable approach for home applications such as home theater and rear projection TV. There are at least four methods to project full color image from one single LCD panel: 1) on-panel color filter, 2) field sequential, 3) scrolling, and 4) angular color separation.

In the first two approaches, color filters are used to create red, green, and blue images that can be multiplexed spatially or sequentially to produce full color images. The main drawback of these color filter methods is low optical efficiency due to absorption of complementary color components when the white light is transmitted through the color filters.

The scrolling method uses dichroic mirrors and rotating prisms to generate horizontal red, green, and blue stripes that scroll rapidly across LCD panel in vertical direction. This approach has the advantage of high optical efficiency, but suffers from system complexity.

A simpler yet light-efficient approach is the angular color separation. This method places a micro-lens over each set of three sub-pixels to focus the incident red, green, or blue light onto their respective sub-pixel. The micro-lens is designed in such a way that when a color beam is incident upon the display at a predetermined angle, it will focus the light onto the appropriate sub-pixels to pass just that color. Synthesis of full color images is accomplished on screen by the projection lens.

In modern display applications such as computer graphics and HDTV, it is often desirable to have square pixels. When a square pixel is divided into three (or more) sub-pixels, the transmitting aperture of sub-pixels has an elongated shape, as illustrated in Fig. 1.

Conventional illumination system for single panel projectors based on angular color separation method uses a condenser lens to collimate the white lights emitted from an arc lamp. The collimated beam then illuminates a dichroic-mirror assembly or a diffraction grating to generate red, green, and blue light beams with appropriate angles of incidence to the LCD panel. The micro-lens array on LCD panel focuses the color beams onto apertures of their respective sub-pixels. Images of the arc source are formed on sub-pixels by the micro-lens array.

When the illumination optics is designed to have a small enough arc image on the sub-pixel to prevent light leaking into adjacent sub-pixels, some portion of the open aperture will be wasted, as illustrated in Fig. 1(a). This causes lower system efficiency. On the other hand, if the arc image is designed to be large enough to more effectively utilize the open aperture, some of the light may leak across the black matrix into the adjacent sub-pixels and deteriorates the color purity of the images, as illustrated in Fig. 1(b).

Other drawbacks of conventional illumination system described above include poor uniformity and low optical efficiency due to the mismatch.
between the shapes of illuminating light beam and active area of the LCD panel.

It is to be noted that integrator rod approach has also been used to build illumination system for single panel LCD projector. This approach eliminates the problems of shape mismatch and inefficient usage of sub-pixels' open aperture. But polarization conversion cannot be easily implemented to improve the system efficiency.

(a)      (b)   (c)

Fig. 1 Sub-pixel structure and light distribution on the center sub-pixel for (a) inefficient, (b) efficient but color mixing, and (c) optimum use of sub-pixel aperture.

Brightness and saturated color are two of the major metrics for evaluation of performances of a projector. It is important for modern projectors to have maximum optical efficiency and good color performances. Even for rear projection applications, high brightness is desired to alleviate the requirements on the projection screen. In this paper, we describe an illumination system that is tailored to give maximum optical throughput without color mixing on a single panel LCD projector that use angular color separation for synthesis of full color images.

Design of the Illumination System

The optical layout of the illumination system is illustrated in Fig. 2. The design of illumination system is essentially the same as that of three-panel type LCD projectors with two distinct modifications.

The illumination system consists of an arc lamp with parabolic reflector, a first and a second integrator lens array, a pair of recycle reflectors, a PS-converter, a condenser lens, a collimating lens, and a three-filter dichroic mirror assembly.

The elements of the first lens array divide the light beam from the lamp and image the arc into the apertures of the second lens array. The second lens array and the condenser together form superimposed images of the elements of the first integrator lens array on the display. This allows the system to transform the circular beam from the lamp to the display’s rectangular shape and to homogenize the intensity distribution across the illuminated area. The collimator lens makes the lights telecentric before entering the dichroic mirror assembly.

The dichroic mirror assembly produces red, green, and blue light beams with appropriate angles of incidence to the LCD panel. After entering the panel, the micro-lens array focuses the color beams onto their respective sub-pixels.
The micro-lens re-images the arc images formed by the first lens array onto the open aperture of each sub-pixel, as illustrated in Fig. 1(c) for the green beam. The width and height of the arc-image cluster is a function of the focal length of micro-lens and the f-number of the telecentric light beam illuminating the display.

For no color mixing, the width of the image cluster should be at least smaller than p+b, and to obtain maximum optical efficiency, w should be less than a. Due to the unavailability of very short arc lamp, compromise usually needs to be made on optical efficiency.

The first distinct feature of the illumination system is that the two integrator lens arrays have an elongated shape similar to that of sub-pixels to provide an illumination beam with appropriate f-numbers in the width and height direction. With such an integrator lens design, the f-number in the width direction of panel’s sub-pixel is sacrificed for angular color separation. But in the height direction, small f-number is preserved for optical efficiency.

Because the light beam emerging from the lamp has a cross section wider than the elongated lens array, the first lens array can not collect all the lights emitted from the source unit. The second distinct feature of the illumination system is that reflectors are placed on both side of the first lens array to redirect the lights missed by the lens array back into the lamp unit. A fraction of these lights will have proper angles to pass through the arc and emerge within the region covered by the first lens plate and become useful to the system, as illustrated by one of the possible the ray path in the lamp unit in Figs. 2.

**Computer Simulation**

Computer simulation of the illumination system using ASAP is performed to evaluate the optical throughput efficiency. A 1.6” SVGA panel is used in the simulation. The panel has a pixel size of 40.5µm, which corresponds to a sub-pixel pitch of 13.5µm. The width of the black matrix is assumed to be 5µm (p=13.5µm, a=8.5µm, b=5µm in Fig. 2). Focal length of the aspheric micro-lens array is approximately 140µm in air, which place the focal plane slightly after the pixel electrode. The geometric structure of the panel is shown in Fig. 3.

The integrator lens array consists of 4x12 rectangular elements. A dummy PS-converter is placed between the second integrator lens array and the condenser lens to simulate the geometric effects of the PS-converter. To match with the micro-lens’ f-number and sub-pixel pitch, the dichroic mirrors are adjusted to have an angle of 3.5 degree between each other. In this simulation, the green light is allowed to incident on the panel normally.

The lamp used in the simulation is modeled with ASAP based on lamp data for a Matsushita 150W ultra-high pressure mercury lamp. The arc gap is ~1.1mm and the reflector size is 70x65mm. The arc is modeled with a nest of ellipsoid volume emitters. Fig. 4 shows the quartz bulb, electrodes, and the shape of the arc in the lamp model.
The computed light distribution after the pixel electrode is shown in Fig. 5. The sharp vertical edges indicate that the arc image cluster is wider than the open aperture of each sub-pixel. However, no color mixing is observed in the simulation result. Note that real dichroic mirrors and micro-lens were assumed in the simulation.

![Fig. 5 Computed light distribution on a plan right after the pixel electrode.](image)

The computed geometrical efficiency after the pixel electrode is about 0.3 without the recycle reflectors. With recycle reflectors, the efficiency increases to 0.34. Assuming efficiencies of 0.7 for polarization effect, 0.7 for interfaces and dichroic mirrors, and 0.85 transmittance for the LCD panel and projection lens, the total system efficiency should be more than 10%.

### Experimental Results

A commercially acquired single panel projector (Lightware’s Scout) was modified to implement the illumination system. Only the dichroic mirror assembly, LCD panel, and the projection lens of Scout were retained for the experiment. The rest of the optics were from other sources and the specs of these optics were not optimized for this application. The brightness and uniformity data are summarized in the following table.

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<th>Brightness</th>
<th>Uniformity</th>
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<tr>
<td>W/o recycle reflector</td>
<td>545 ANSI lm</td>
<td>87%</td>
</tr>
<tr>
<td>With recycle reflector</td>
<td>590 ANSI lm</td>
<td>85%</td>
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### Discussion

We have presented a single panel LCD projector design that is capable of high efficiency, good uniformity and saturated color performance. One drawback of angular color separation method is the panel’s pixel count has to be three times the resolution of the panel. It may not be very cost effective to produce such panels with resolution higher than SVGA using HTPS process. However, with LTPS process such as CGS, it may become economically feasible to produce larger-sized panels to accommodate the higher pixel count. We believe that high resolution LPTS panels used with the illumination system described in this paper has the potential to be the most affordable solution for high quality home and business projection applications.

### Acknowledgements

The authors acknowledge Drs. J. C. Yoo, S. Wei and others at Q200 of OES/ITRI for their help with the experiment.

### References