61.5: LED-Based Light-Recycling Light Sources for Projection Displays

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Abstract

LED-based light sources utilizing novel light-recycling cavities have been developed that have small output etendue. A portion of the light emitted by the LED source is recycled back to the LEDs to enhance both the average brightness of the source and the brightness of the cavity output. Experimentally, we have achieved brightness enhancement factors of approximately 1.3x-2.0x.

1. Introduction

Large format front and rear projection displays currently use UHP arc lamps in order to achieve sufficient on-screen brightness. Arc lamps, however, have several drawbacks for display applications. An arc lamp has a relatively short lifetime, (a few thousand hours), and must be replaced periodically. In addition, arc lamps have relatively long turn-on times, cannot be pulsed for color sequential operation, use the toxic element mercury and emit large amounts of UV and IR light that must be removed from the optical system.

LED-based projection systems have recently been developed [1-4] that have several significant advantages compared to systems based on arc lamps. LEDs have longer lifetimes than arc lamps and can be pulsed for color sequential imaging. An LED display can have a larger color gamut than an arc lamp display and, in addition, the wavelengths of the emitted LED light and the display color temperature can be modified if desired. These attributes are strong motivations for eliminating traditional arc lamp sources from projection display products.

Projection display optical systems can be designed using microdisplay panels based on digital light processors (DLP^{TM}), liquid crystal on silicon (LCOS) devices or liquid crystal display (LCD) devices. A schematic diagram of a DLP-based projection system that uses LEDs is illustrated in Fig. 1.

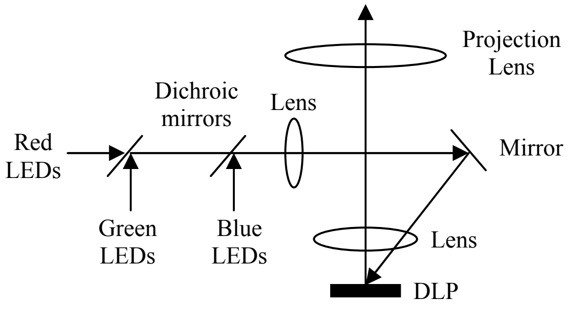

Figure 1. Schematic diagram of a DLP projection display.

Projection display optical systems are constrained by the system etendue. Etendue is defined at a source plane or image plane as

$$\text{Etendue} = (\text{area of the source or image})(\pi)(\sin^2 \theta), \quad (1)$$

where θ is the half-angle of the light cone at the source or image plane. In order to maximize the utilization of the source light flux, the etendue of the source must be less than or equal to the etendue of the remainder of the projection system. The projection system etendue is normally restricted by the etendue of the incorporated microdisplay panel, (DLP, LCOS or LCD). Specifications and etendue values for two example DLP microdisplay panels are shown in Table 1.

Table 1. Example DLP microdisplay specifications

DLP Specifications	xHD4	HD3
Diagonal (inches)	0.85	0.55
Resolution	1920x1080p	1280x720p
Area (mm^2)	199	83
Half-angle (degrees)	12	12
Etendue (mm^2-sr)	27	11.3
Equivalent source area (mm^2) (if the source is Lambertian)	8.6	3.6

The xHD4 is a 0.85”-diagonal DLP device having an etendue of 27 mm^2-sr when operated at F/2.4 with a 12° light cone. Although the xHD4 can accept 15° or an F/2 light cone (at least in one axis), an F/2 projection lens will then be required, resulting in increased optical system cost. When operated at F/2.4, the maximum number of 1-mm^2 LEDs that can be used as a planar light source for the xHD4 is eight. This assumes the LEDs are Lambertian emitters.

The HD3 is a smaller, lower-resolution, 0.55”-diagonal DLP device having an etendue of 11.3 mm^2-sr when operated at F/2.4. The maximum number of Lambertian-emitting, 1-mm^2 LEDs that can be used as a planar light source for the HD3 is three at F/2.4.

Due to the etendue restrictions, it is very difficult to achieve a high-brightness projection display using a planar array of LEDs as the source. However, LEDs can reflect incident light, in sharp contrast to blackbody light sources such as arc lamps and filament lamps that do not reflect significant amounts of light. We utilize the inherent reflectivity of LEDs to enhance the average brightness of LED light sources. We have developed LED-based, light-recycling cavities that have reduced output etendue and enhanced output brightness relative to conventional LED sources

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[5-6]. The resulting sources will produce significantly brighter projection displays.

2. Overview of Light-Recycling Cavities

An LED can both emit light and reflect light as illustrated schematically in Fig. 2. The LED shown on the left in Fig. 2 emits light. The same LED can also reflect light as shown on the right in Fig. 2. The light directed at the LED can come from other LEDs or can come from emitted light that is recycled back to the same LED. The reflected light adds to the emitted light, increasing the effective brightness of the LED.

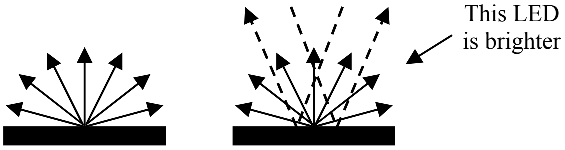

Figure 2. An LED can both emit and reflect light.

The brightness and brightness enhancement of LEDs in this example and the following examples refer, respectively, to the average brightness and the average brightness enhancement of the LEDs. The emission and reflecting properties of an LED are not uniform across the LED output surface. Some parts of the LED will be brighter than other parts. However, when assembling an array of LEDs, one cannot choose to use only the brighter sections of the LED output surface. One must use the entire LED surface. From a practical standpoint, the most important brightness values to consider are the average brightness of the LED and the average brightness enhancement.

The reflectivity of different LED designs varies. Although an LED reflects light, only part of the light that is directed to an LED will be reflected. The overall LED reflectivity depends on several design factors including the reflectivity of any top metal contacts, the reflectivity of the mirror surface on the backside of the LED, the absorption of light by the intervening semiconductor layers and the number and type of light extracting elements incorporated in the LED design.

The concept of a light-recycling cavity is illustrated using the simplified schematic diagram shown in Fig. 3. The cavity in Fig. 3 has a single LED at one end of the cavity and an output aperture at the other end. The LED has total area A, reflectivity R=100% and emits N photons/sec. The output aperture has area A/2, which is one-half the area of the LED. The cavity, including the portions of the output end that surround the output aperture, has specular reflecting surfaces with reflectivity R=100%. Light is emitted from the LED at relatively small angles, (e.g. ±20°). The cavity has length L and the transit time for light to travel the length of the cavity is time T.

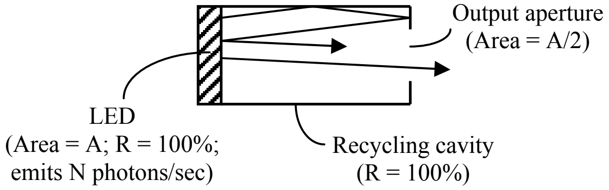

Figure 3. Simplified illustration of light recycling.

Fig. 4 shows how the light-recycling cavity functions. At zero time, the LED is turned "on" and begins to emit N photons/s toward the output end of the cavity. The light first reaches the output end at time T. Beginning at time T, one-half the light (or N/2 photons/sec) will exit the cavity through the output aperture without being recycled and one-half of the light, (or N/2 photons/sec), will be reflected and recycled a first time back to the LED. The light that is recycled a first time will return to the LED at time 2T. Starting at time 2T, the light recycled a first time will be reflected by the LED and add to new light concurrently being emitted by the LED. The total brightness of the LED will then increase to 1.5 times the initial brightness.

The light that is recycled a first time and subsequently reflected by the LED reaches the output end of the cavity at time 3T. Starting at time 3T, one-half, (or N/4 photons/sec), of the light recycled a first time will exit the cavity through the output aperture and one-half, (or N/4 photons/sec), of the light recycled a first time will be recycled a second time back to the LED.

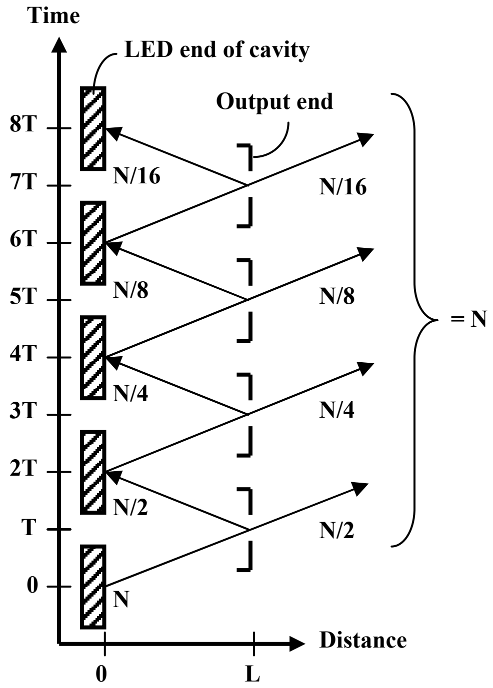

Figure 4. Illustration of a light-recycling cavity.

Starting at time 4T, the light recycled a second time will be reflected by the LED and add to the first recycled light and to the new light concurrently being emitted by the LED. The total brightness of the LED will then increase to 1.75 times the initial brightness.

The light recycled a second time and subsequently reflected by the LED reaches the output end of the cavity at time 5T. This sequence of steps continues for light recycled a third time starting at time 5T, for light recycled a fourth time starting at time 7T and so forth.

When the system reaches equilibrium at long times, a total of N photons/sec will be exiting the output aperture. The N photons/sec exiting the output aperture equals the N photons/sec newly emitted by the LED, so that the number of photons in the system is conserved.

However, the N photons/sec emitted through the output aperture are emitted through the smaller area A/2. The photon density, (in photons/sec per unit area), at the output aperture is 2N/A, or double the photon density of the LED in the absence of a cavity. The output brightness of the cavity is enhanced by a factor of two.

When the system reaches equilibrium for long times, the LED emits N photon/sec and reflects N photons/sec in area A. The photon density coming from the LED is 2N/A. The average brightness of the LED is thereby enhanced and is equal to twice the average brightness of an LED in the absence of a cavity. At equilibrium, the photon density measured at the LED is equal to the photon density measured at the output aperture. The enhanced cavity output brightness is equal to the enhanced average LED brightness.

Brightness enhancement at the output aperture of the light-recycling cavity can occur if the area of the output aperture is less than the total area of the LEDs in the cavity. In the example illustrated in Fig. 3 and Fig. 4, the output aperture area is equal to one-half of the area of the one LED and the brightness enhancement is 2x. In general, if the LED and cavity reflectivity is 100% and there are no absorption losses, the maximum possible brightness enhancement is given by

Maximum brightness enhancement =
(LED area)/(Output aperture area). (2)

Realistic cavities will have absorption losses, however. The actual brightness enhancement is the product of the maximum brightness enhancement times the cavity output efficiency.

Brightness enhancement =
(Maximum brightness enhancement)(Cavity efficiency) (3)

3. Recycling Cavity With 8 mm^2 Output

3.1 Experimental Cavity Design

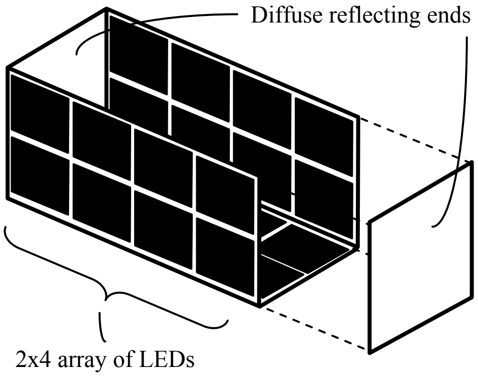

Figure 5. Diagram of experimental design.

Light recycling cavities were constructed with three 2x4 arrays of eight 1mm^2 LED dies. Separate cavities were made for blue, green and red LED light sources. The dies were commercial production items made by a major LED manufacturer.

The arrangement of the arrays is illustrated in Fig. 5. The inside dimensions of the cavity are 2 mm by 4 mm by 2 mm. One 2-mm by 4-mm array of 8 LEDs is on the bottom of the cavity and the other two 2-mm by 4-mm arrays make up two sides of the cavity. The two ends of the cavity are closed by highly reflective diffuse reflective material. The 2-mm by 4-mm top is open and forms the output aperture. For cavities having a Lambertian output, which is the typical light output distribution for a recycling cavity, the resulting etendue is 25 mm^2-sr. This etendue value is slightly smaller than the etendue for the xHD4 DLP operating at F/2.4.

3.2 Theoretical Calculations

By utilizing a non-sequential, ray-tracing program, one can model the efficiency and the brightness enhancement for the cavity illustrated in Fig. 5 as a function of the LED reflectivity. The LEDs are assumed to be Lambertian emitters and diffuse Lambertian reflectors. The diffuse reflective ends of the cavity are assumed to have a reflectivity of 98%. A graph of the results is shown in Fig. 6.

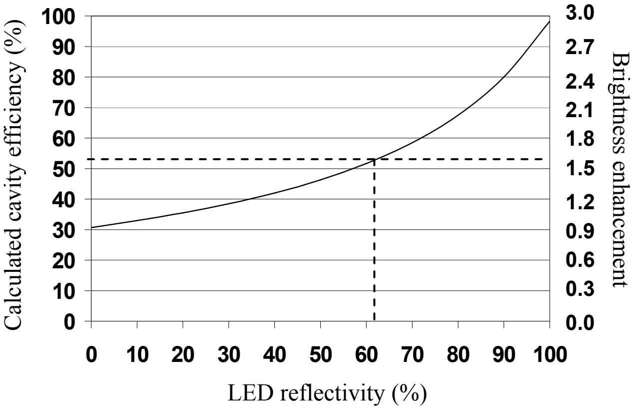

Figure 6. Calculated cavity efficiency and brightness enhancement versus LED reflectivity.

3.3 Experimental Results

Experimental values for cavity efficiency and output brightness enhancement were measured for blue, green and red cavities that had 2-mm by 4-mm output apertures. The results were compared to individual 2-mm by 4-mm arrays of eight LEDs not enclosed in a recycling cavity. Measurements were done using an integrating sphere. Brightness enhancement occurred for all blue, green or red light-recycling cavities and the enhancement factors ranged from about 1.3 to 1.6 (see Table 2). The green cavity efficiency of 53% and the brightness enhancement factor of 1.6 correspond to an LED reflectivity of 62% in Fig. 6 (see dashed lines). This reflectivity value is consistent with experimental measurements.

Table 2. Results for red, green and blue cavities.

Cavity Output Color	Cavity Efficiency (%)	Brightness Enhancement
Red	46	1.4
Green	53	1.6
Blue	46	1.3

Red, green and blue cavity light outputs were measured as a function of the applied electrical current per die. Green and blue dies had a maximum rated current of 0.50 amperes. The red dies had a maximum rated current of 0.75 amperes. The experimental measurements extended to 0.42 amperes per die, which is less than the rated maximum values for each die. The green cavity, which had an 8-mm^2 output aperture and an etendue of 25 mm^2-sr, emitted approximately 530 lumens of light. The results are shown in Fig. 7.

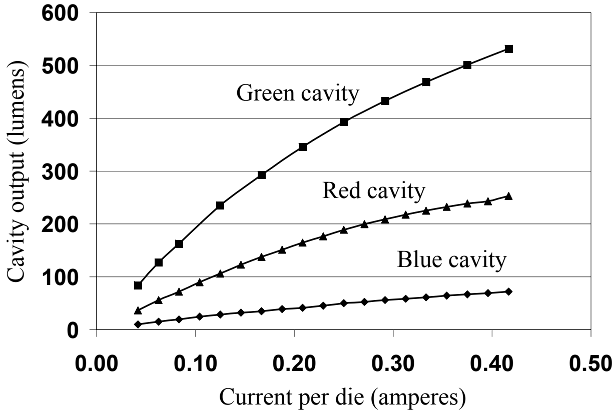

Figure 7. Light emission from cavities with 8 mm^2 outputs.

4. Recycling Cavity With 4 mm^2 Output

4.1 Theoretical Calculations

The cavity design shown in Fig. 5 was then modified to restrict the output aperture area. A reflecting cover was placed over the 2-mm x 4-mm output aperture, restricting the output area to 4 mm^2. The resulting cavity output etendue is 12.5 mm^2-sr, which is only slightly larger than the etendue of the small HD3 DLP device. This modified design was also modeled using the non-sequential, ray-tracing program. The LEDs were again assumed to be Lambertian emitters and diffuse Lambertian reflectors. The two ends of the cavity and the top reflecting cover that surrounds the output aperture were assumed to have a diffuse reflectivity of 98%. A graph of the calculated results is shown in Fig. 8.

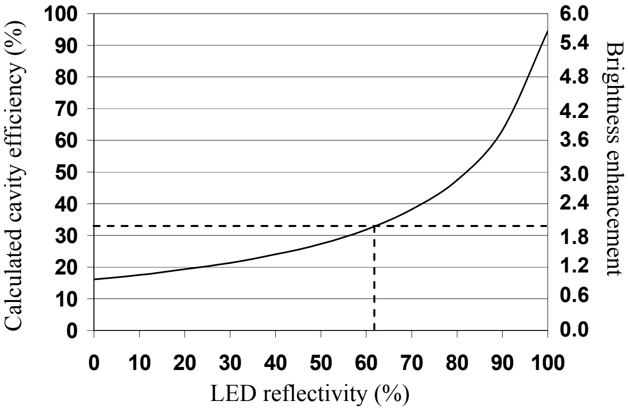

Figure 8. Calculated cavity efficiency and brightness enhancement versus LED reflectivity.

4.2 Experimental Results

Cavity efficiency and output brightness enhancement were measured for the modified green cavity. Although the output aperture area (4 mm^2) decreased to 50% of the original value (8mm^2), the cavity light output only dropped to 63% of the original output. The brightness enhancement increased to 2.0x (from 1.6x) as shown in Table 3. The measured efficiency of 33% and the brightness enhancement factor of 2.0 again correspond to a reflectivity of 62% as shown by the dashed lines in Fig. 8.

Table 3. Result for a green cavity with a restricted output.

Cavity Output Color	Cavity Efficiency (%)	Brightness Enhancement
Green	33	2.0

5. Conclusions and Discussion

We have modeled and experimentally demonstrated LED-based light-recycling cavities that have significantly enhanced, (1.3x to 2.0x), output brightness compared to LED light sources based on planar LED arrays. The resulting light-recycling cavities are ideal light sources for front and rear projection displays.

The experimental results were obtained using standard production LED dies. As the light output of conventional LEDs (i.e. LEDs having approximately a Lambertian light output distribution) is improved in the future, we expect that LED reflectivity will also continue to improve. Figures 6 and 8 illustrate how the cavity efficiency and the brightness enhancement will increase as LED reflectivity improves.

Other factors are necessary in addition to brightness enhancement in order to achieve recycling cavity light outputs that are sufficient for projection display applications. For example, LEDs with the high external quantum efficiency are also required. LEDs with low external quantum efficiency and low light output will not produce a practical light source even if the LEDs are highly reflective. Furthermore, thermal management of the heat generated by the LEDs is important since higher LED operating temperatures result in lower light output.

This paper has focused on the enhanced brightness that can be achieved using recycling cavities. However, brightness enhancement is not the only reason for using light-recycling cavities in projection display applications. The recycling cavity also serves to homogenize and mix the light from the LED dies. The mixing results in greater uniformity of color and brightness. This reduces, if not eliminates, the necessity of using LEDs that come from the same brightness or wavelength "bin."

Finally, the availability of an enhanced brightness light source allows the projection display designer the opportunity to trade off a portion of the brightness enhancement for reduced LED drive currents. Operating LEDs at reduced currents increases their working lifetimes.

6. References

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