Performance of High-Power LED Illuminators in Projection Displays

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Abstract

A new type of Light Emitting Diode - called Luxeon™ - has been introduced that has a much larger luminance than conventional LEDs. In fact, Luxeon luminance is such that they are getting attractive for projection displays. Various architectures for Luxeon based projection are discussed with respect to system efficiencies and throughput. Critical parameters for describing the projector performance are the collected étendue and luminance of the Luxeon Emitters. We will show that the throughput of Luxeon based projector is limited by the luminance of the emitters, but that for smaller screen sizes they are becoming attractive alternatives to High Intensity Discharge Lamps.

1. Introduction

For display illumination applications—in specific for micro display projection—light is required in its red, green, and blue components. In a three micro display system, a white high intensity discharge lamp is typically used; the light is split into red, green, and blue channels by using dichroic mirrors, and sent to the corresponding display by the use of a mirror system. In the case of a DLP™ projector, a color wheel is used to get the red, green, and blue components and the display is synchronized with the illuminator color. Starting with white light, both approaches have disadvantages: In the three panel configuration the illumination system is bulky and has losses, while in the single color sequential DLP™ case the color wheel is absorbing 2/3 of the light.

Light emitting diodes (LEDs) are available in red, green, and blue, and have turn-on times well below 1 microsecond. Until recently, luminance and light output of LEDs were not sufficient to obtain reasonable screen performances with standard microdisplays. With the introduction of Luxeon by Lumileds[1], this has changed. This new type of LED, Luxeon, is available in a 1 Watt and 5 Watt power package, and has a high efficiency. Both the power capabilities of Luxeon, as well as the efficiency performances, contribute to a high luminance[4].

The throughput of a projector is determined by the étendue or optical extent of the microdisplay, and the luminance of the source[2]. For a microdisplay the étendue (E_d) is given by the area (A_d) of the display, and the F-number (F) of the projection lens used:

$$E_d = \frac{\pi}{4}\frac{A_d}{F^2} \qquad (1)$$

For a well designed system, the projection lens and microdisplay are matched to obtain best luminous output and contrast. For example, in case of DLP™, the mirrors can tilt over an angle of 24°. In order to obtain best contrast, the acceptance cone of the projection lens should be 24° as well. The corresponding F number is given in that case by: $F = 1/(2\sin(\theta/2))$, where θ =24°.

The maximum luminous flux (ϕ) of a projector for a lambertian source with luminance L is given by [3]:

$$\phi = \eta L E_d \qquad (2)$$

where η is the optical efficiency of the system. This efficiency is determined by the losses associated with the optical components used which include: light collection losses (collimator), integration losses (integrating rod or lenslet array), color separation losses (dichroic mirrors used to split the light in red, green and blue components), polarization losses (in case of a liquid crystal based microdisplay), reflection or transmission losses at the microdisplay itself, color combination losses (X-cube losses), and the losses in the projection lens (reflection losses at the lens surfaces)[2]. Eq. (2) can be used for non-lambertian sources, if we use the luminance averaged over the étendue of the system.

In practice the étendue of a light source is determined by the area of the light source (A_s), and the collection angle of the optics used. In a properly designed system, the étendue of the light source and collector (E_c, the collected étendue) is larger

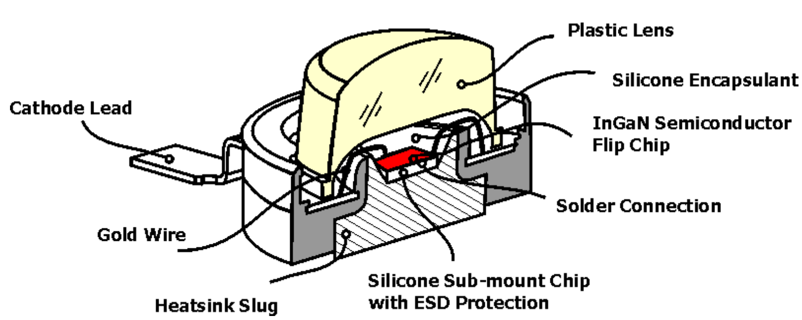

Figure 1. Luxeon Emitter Structure

	Dominant Wavelength *nm*	Current *mA*	Power *W*	Flux *lm*	Étendue $mm^2\,sr$	Luminance Mcd/m^2
Red	627	350	1	44	14	3.1
Green	530	350	1.2	35	10	3.5
		700	4.8	140	34	4.1
Blue	470	350	1.2	5	10	0.5
		700	4.8	19	34	0.6

Table 1 Typical Performance Data for Luxeon Lambertian Emitters

than the étendue of the microdisplay. The collected étendue is given by:

$$E_c = \pi A_s \sin^2 \theta_{½} \qquad (3)$$

where $\theta_{½}$ is the collection half angle. In eq. 3 it is assumed that the emitting surface is emitting in air. If this is not the case, for example in the case in LEDs where the LED-chip sits in an encapsulant (either epoxy or silicone-gel), the refractive index (n) of this medium must be taken into account:

$$E_c = n^2 \pi A_s \sin^2 \theta_{½} \qquad (4)$$

2. Étendue and Luminance for Luxeon Emitters

A cross section of a Luxeon Emitter is shown in Fig. 1. Key elements for high power, (long) lifetime, and high efficiency operations are the LED chip itself, the soft silicone gel (which is used as an encapsulant), the metal slug directly below the actual LED chip (to provide a very low thermal resistance path for heat conduction), and a high temperature resistant plastic lens [4].

For the purpose of étendue calculations the size of the LED chip is important. Chip sizes for the Luxeon Emitters differ with color, and power. A 1 Watt Luxeon green or blue emitter has an LED-chip size of 1 mm x 1 mm and the height of the chip is 0.1 mm. For the 5 Watt Luxeon blue or green part, the size is 2 mm x 2 mm and a height of 0.1 mm. The 1 Watt red Luxeon part has a size of 0.5 mm x 0.5 mm, and has a height of approximately 0.25 mm. The surfaces of the LED chip behave simalarly to lambertian emitters, and light is emitted through the top, and through the sides of the chip. Assuming all the light from the surfaces is collected $(\theta_{½} = 90^\circ)$, we can use eq. 4 to calculate the étendue of the chip, as shown in Table 1.

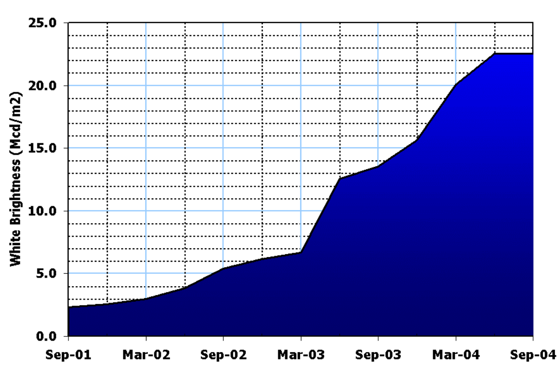

Fig 2 Luminance Performance of Luxeon Emitters: history and outlook

Given the total Luxeon étendue (E_l), average luminance (L_l) is given by:

$$L_l = \frac{\phi}{E_l} \qquad (5)$$

where ϕ is the flux out of the device. This flux is determined by current density and internal quantum efficiency of the LED chip, and the extraction efficiency of the package. Typical performances for the red, green, and blue devices in terms of wavelength, étendue and luminance are summarized in Table 1.

For projector performance calculations, it is convenient to work with the effective white luminance, where the white is obtained by mixing of red, green, and blue using dichroic mirrors. To obtain a white point with a correlated color temperature (CCT) of 9000K the luminous flux fractions of red, green, and blue are: 23%, 71%, and 6%. If dichroic mirrors are used to combine the light from the red, green, and blue emitters, an effective white luminance can be obtained by adding the brightness according to these lumen fractions: for a color temperature of 9000K we obtain a white luminance of 5.2 Mcd/m^2.

It is important to note that the numbers in Table 1 are typical numbers, at nominal operating conditions, for a lifetime of 50,000 hours. Actual performance (both color points and flux) varies in production and depends on temperature and current. Data sheets and application notes for the Luxeon Emitters can be found on the Web[5].

Due to continuous advancements in LED-materials technology, the performance of Luxeon Emitters with regard to efficiency and current density have improved over the last decades at a rate of approximately a factor of 2x every 3 year , and this is expected to continue for at least the next decade. Both efficacy as well as current density result in a higher luminance. The (effective) white luminance improvements over the last several years, and expected improvements over the next 2 years are shown in Fig 2.

3. Illuminator Architectures for Luxeon Emitters

If we compare the étendue numbers for the Luxeon Emitters with those of actual microdisplays, it becomes clear that in many cases one 5 Watt Luxeon Emitter per color is the maximum that is allowed. Étendue of a 0.7" DLP™ is 21 mm2sr (with an F2.4 lens), and 0.9" HTP-LCD is 34 mm2sr (same F), while a 0.7" LCOS with an F2.8 lens has an étendue of 15mm2sr. If the source behaves lambertian, which means that the luminance is independent of position and or angle of the source, adding more LEDs would overfill the microdisplay either in space, or in angle, and would not contribute to improved throughput. In the event the display allows for more than one Luxeon Emitter, or that the 1 Watt Luxeon Emitters are being used, they can be combined in a configuration as shown Fig 3. This would be the case if a big LCD were used (4" ~ 5"). The drawing shows an array of three but this approach can easily extended and in all dimensions (Luxeon arrays in a hexagonal structure).

The illuminator architectures depend on the number and type of microdisplays used. In this paper we discuss three architectures: a three panel spatial separated illuminator, an angular separated illuminator, and a color combination illuminator. In the following we assume that each color channel is using one Luxeon (in most cases the 5 Watt version), but all color channels can be used with a Luxeon array as shown in Fig 3.

(A) Spatial Separated (X) illuminator

This basic architecture is shown in Fig 4A. In this case three microdisplays are used: one display for the red, one for the green, and one display for the blue channel. Typically the different colored images are combined using an X-cube.

The Luxeon illuminators in this case would in most cases consist of one 5 Watt Luxeon with a single collimator and a polarizer. An array of Luxeon Emitters can be used as well (see Fig 4B) for displays with a large étendue, or if 1 Watt Luxeon Emitters are preferred. The polarizer is preferably a

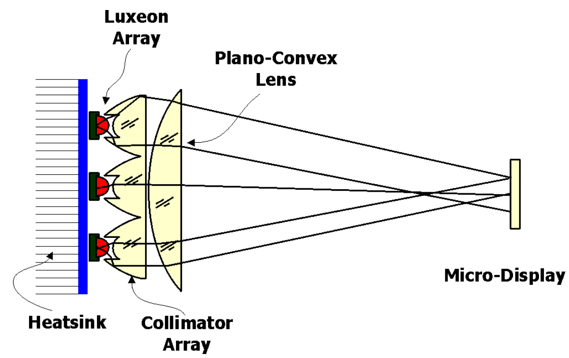

Fig 3 Clusters of Luxeon Emitters for Micro Display illumination

wire grid polarizer, so that some light can be recycled.

(B) Angular Separated (AS) illuminator

In this case the Luxeon Emitters illuminate the panel in parallel, separated in angular space (Fig 4B). The available étendue from the display must be divided over the étendue of the different light sources. It looks very similar to the array configuration as shown in Fig 2; the difference in this case is that each Luxeon (array) has a different color. This approach is most favorable from an efficiency and cost perspective. This architecture would be well suited for a LCD with a linear micro-lens structure that illuminates the LCD columns with spatially alternating red, green, and blue light.

(C) Color Separated (CS) illuminator

In this case, the light from the red, green, and blue Luxeon Emitters is combined first using dichroic mirrors or an X-cube, such that the emitters, when viewed from the display side, would be superimposed on each other (Fig 6). In this approach the effective étendue would be determined by the color cluster which has the biggest étendue. This architecture is best suited for microdisplays that are operated in color sequential mode such as DLP™.

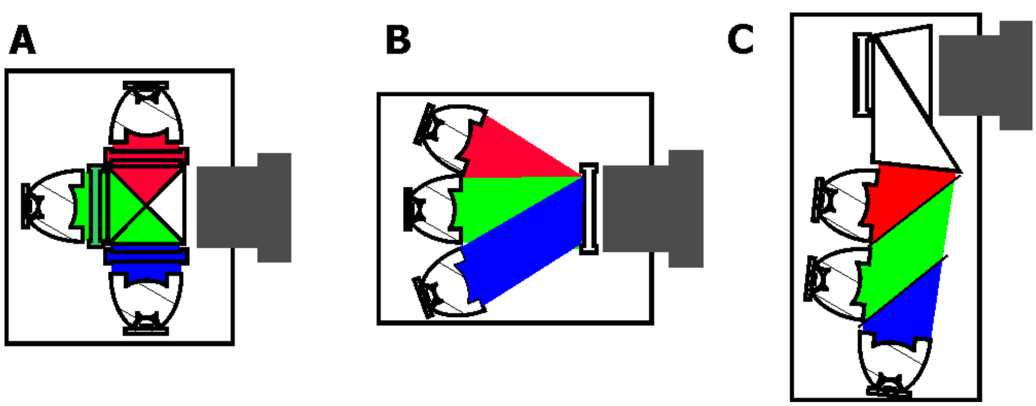

Fig 4: Examples of Illumination Architectures for LED based projectors

A) Spatially Separated Illumination, B) Angular Separated Illumination, and C) Color Separated Illumination

Micro Display(s)		X-LCD	AS-LCD	DLP
Number of Panels		3	1.3	1
Diagonal	*inch*	0.9	1.1	0.7
Aspectratio		4:3	4:3	4:3
Area	*mm^2*	251	375	152
Projection Lens				
F-number	-	2.4	2.4	2.4
Angle	°	12	12	12
Étendue	***$mm^2 sr$***	**34**	**17**	**21**
Optical Efficiency				
Collection	-	85%	85%	85%
Color Combination	-			85%
Polarization	-	40%	40%	
Overfill	-	90%	90%	90%
Display	-	60%	50%	65%
Color Combination	-	85%		
Projection Lens	-	85%	85%	85%
Total	-	**13%**	**13%**	**36%**

Table 2. Parameters for Performance Comparison

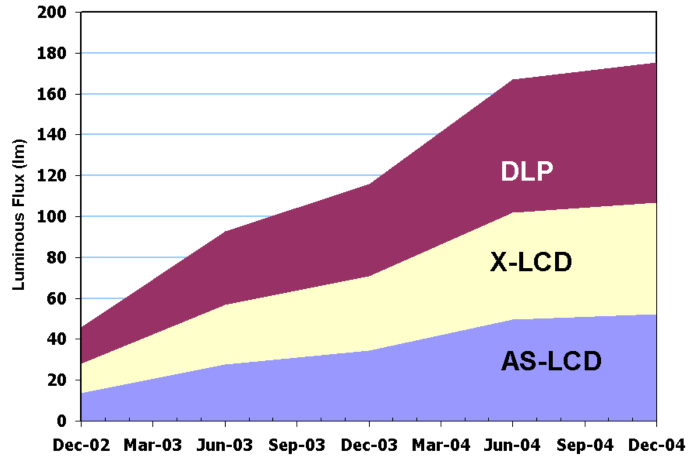

Fig 5. Performance of Luxeon based Projectors

5. Performance of Luxeon based Projectors

For each of the illuminator configurations, examples of projector performance in terms of luminous flux are shown in Fig 5, where the system performance calculations are based on the brightness roadmap (Fig 2) and the system parameters and efficiencies (Table 2). We have taken the Luxeon luminance roadmap (Fig 3) as the basis for LED performance. The total system performance was calculated using Eq 2. It is important to note that for the DLP™ it is assumed that the luminous flux loss by duty cycling the LEDs is compensated for by driving the LEDs at higher current densities.

6. Discussion and Conclusions

Projectors for business presentations have fluxes in the range of 1000 to 2000 ANSI lm. The luminous flux requirement in this application is driven by contrast and screen size, where contrast is largely determined by the level of ambient light at the projection screen. As Fig 5 shows, the performance of Luxeon based projectors is still much lower than this: Lumileds expects to reach a 200 lm output level within 2 years.

What is important to notice about the performance in Fig 5 is that it is limited by the étendue of the Luxeon Emitters: the performance is obtained using single LEDs. This makes that LED based projectors have a low power consumption (in the range of 7 to 15 Watts), and can be driven by batteries. Related to the low power is the low heat generation, which is (in addition) not generated in the form of IR-radiation but in the form of temperature rise of the heat sink, which can be lead away by conduction (and eventually by convection outside the case). This and the fact that LEDs don't produce UV makes it possible to use plastic optics, reducing the cost and weight of a Luxeon based projector.

A Luxeon based projector seems a good fit for very small, ultra portable projectors, to be used for images of the size of a letter or standard monitor screen. This is illustrated in Fig 6, which shows the brightness of a screen as a function of image size and for various flux levels of an Luxeon based projector in a rear projection configuration (screen gain 3x, screen transmission 50%). As a reference, monitors typically have a brightness of 150 to 200 nits while TV's are in the range of 400 to 600 nits. If we take 200 nits as a minimum performance for such a small projector, the performance of the Luxeon based projectors is good for displays up to a size of 20-30 inch now, while they will enter the 30-40 inch range within 2 years from now .

References

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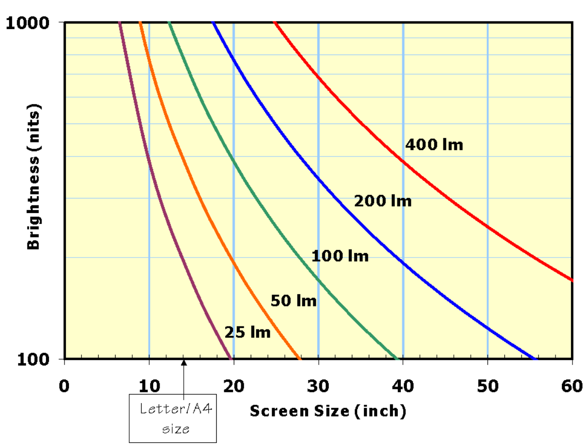

Fig 6. Screen brightness as function of luminous flux and screen size.