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LED Product Evaluation Final Report

Introduction

This report for Project 2.3 LED Low Profile Fixtures provides a summary of the performance of current LED products obtained from major LED manufactures. The report focuses on attributes such as efficacy, color rendering, color consistency, distribution, lumen maintenance, thermal controllability, cost, and reliability.

The research team for this Project includes Nadarajah Narendran and Ramesh Raghavan, both with the Lighting Research Center (LRC). The information in this report has been gathered to assist the LRC in developing a specification for an optimized solid-state light source for the low-profile LED luminaires that will be designed in this PIER Project.

Available LED Packages

LEDs have evolved from light sources primarily used in indicator applications to become suitable for some general illumination application. Indicator LEDs usually have relatively small lumen packages (less than 1 lm per device for white light) and are typically operated at 20 milliamps (mA). The 5 millimeter (mm) LED “through hole” and surface mount device (SMD) packages mainly used in indicator LEDs are shown in **Figure 1**, below. Other packages such as 3mm/4mm LEDs and chip LED modules also fall under the category of indicator LEDs.



5mm Through Hole LEDs

Surface Mount LEDs

Figure 1: Single Indicator LED Packages ^[A]

Illuminator LEDs (**Figures 2 and 3**), have larger lumen packages (greater than 5 lumens per device for white light), and are operated at significantly higher drive currents (a few hundred mA) than indicator LEDs. The higher drive currents and increased power consumption of these devices also lead them to generate significantly more heat than indicator LEDs. Due to this increased heat production, illuminator LEDs are typically assembled with thermal controls, such as heat sinks, to lower the junction temperature of the LED.

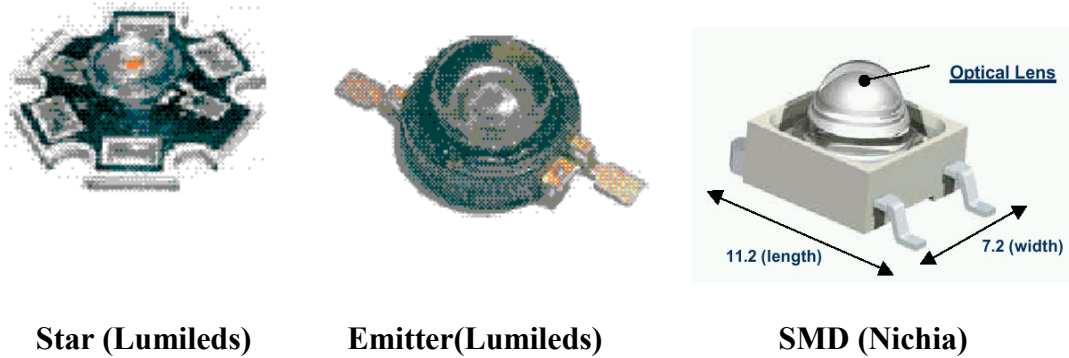


Figure 2: Single Illuminator LED Packages^[B]



Figure 3: Pre-engineered Illuminator LED Packages^[C]

Color Properties

LEDs are generally grouped into two categories: the Gallium Arsenide/Gallium Phosphide type, which is typically referred to as GaAs/GaP LEDs, and the Gallium Nitride type, which is typically referred to as GaN LEDs. The GaAs/GaP LEDs operate in the visible portion of spectrum between 540 and 670 nanometers (nm) with a peak efficacy at 611nm. Orange, amber, yellow and red LEDs are normally made from GaAs/GaP. GaN devices emit from the ultraviolet portion of the spectrum up to 550nm with their current peak efficiency at 420nm. Blue and green LEDs are made from these GaN devices. There are two approaches for creating white light with LEDs. The first approach is to mix multiple colored LEDs (red, green, blue, or any number of colors) in suitable proportions, thus producing white light. The second approach is to combine a blue LED with a down-conversion phosphor (yttrium aluminum garnet, YAG), which then emits white light.

Since monochromatic LEDs are very saturated in color appearance, dominant wavelength is often used to describe their color, while white LEDs are typically described by referring to their correlative color temperature (CCT) and color-rendering index (CRI).

The CRI of the current phosphor white LEDs is about 70-80 with a CCT range from 4500 Kelvin (K) to 6500K. White light that is produced by mixing various colored LEDs can have a CRI up to 90 with nearly any CCT value desired. **Table 1** summarizes the pros and cons of the two types of white LEDs.

The LRC's study of some of the high power LEDs rings indicated that these white LEDs had excellent color consistency between devices after 100 hours seasoning. The chromaticity coordinates of the six LEDs evaluated were within four Macadam Eclipses.

Phosphor white LED	Mixed color white LED
Single integrated package	Need external optical elements to mix colors well
Lower luminous efficacy due to conversion efficiency losses of the phosphor	Higher luminous efficacy compared to phosphor white LEDs
High color temperatures, >4000 K	Any color temperature
Maintains color properties fairly well.	Difficult to maintain color, since each color LED degrades at a different rate
Flux varies with temperature	Flux varies with temperature
Color properties are fairly stable with ambient temperature change	Color properties change significantly with ambient temperature change

Table 1: The Pros and Cons of the Two Types of White LED^[4]

Lumen output and efficacy

Normally, indicator LEDs require less than 0.1 watt of power and produce less than 1 lumen per device, while illuminator LEDs require 1-5 watts of power and produce up to 20 lumens per device. Lumileds has introduced higher-power LEDs with a larger LED die size. This larger die size results in a minor loss in efficacy but allows for a major gain in luminous flux per device (over 100 lumens). These high-power LEDs are available in white, green and blue. **Table 2** summarizes the typical characteristics of the state-of-the-art white LEDs.

LED Type	Wattage (W)	Flux/device (lm)	Efficacy (lm/W)	CCT (K)	CRI
5mm	~0.1W	1	10-12	>5500	70-80
High Power	1W	22	15-20	>4500	70-80
High Power	5W	120	~24	>4500	70-80

Table 2: The Typical Characteristics of the State-of-the-art White LEDs

Thermal Management

LEDs are temperature sensitive devices. A rise in an LED's junction temperature will decrease its light output, cause a shift in the LED's color, and reduce its life. The red, red-orange and amber LEDs based on Aluminum Indium Gallium Phosphide (AlInGaP) technology are more sensitive to increases in junction temperature than LEDs that produce other colors. Manufacturers generally recommend a maximum LED junction temperature of 120 °Celsius (C) during operation. Higher junction temperatures will result in a significant decrease in the life of the LED. Therefore, proper thermal design is imperative to keep the LED package at or below its rated operating temperature.

Heat sinks (often made of flat or finned aluminum) are generally used to alleviate the rise in LED temperature. **Figure 5** illustrates some typical heat sinks for the high power LED devices. One of the primary mathematical tools used in thermal management design is thermal resistance ($R\theta$). Thermal resistance is defined as the ratio of temperature difference to the corresponding power dissipation, $R\theta_{\text{junction-Ambient}} (^{\circ}\text{C}/\text{W}) = \Delta T_{\text{junction-Ambient}} / \text{Power dissipation}$. **Table 3**, shown on page 11, shows the thermal resistance of some LED packages.

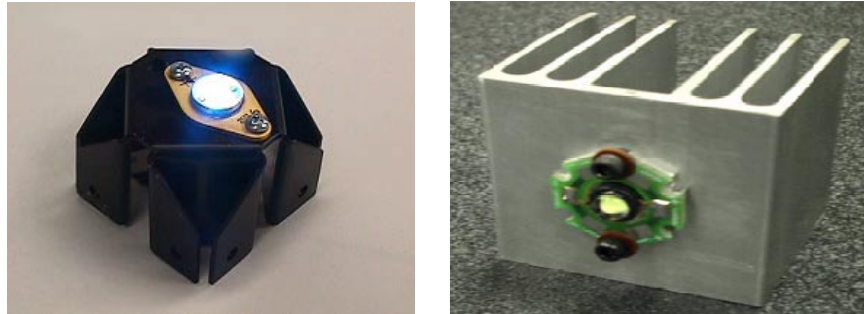


Figure 5: Heat Sinks for High Power LEDs ^[D]

Light Distribution

The radiation pattern of indicator LEDs are described in $\theta_{1/2}$, which is the off axis angle from lamp centerline where the luminous intensity is $1/2$ of the peak value. The illuminator LEDs light distribution is often categorized in the following four patterns: the lambertian pattern, the batwing pattern, the side-emitting pattern and the collimating optics radiation pattern. Typical graphs are shown as **Figure 6** ^[2].

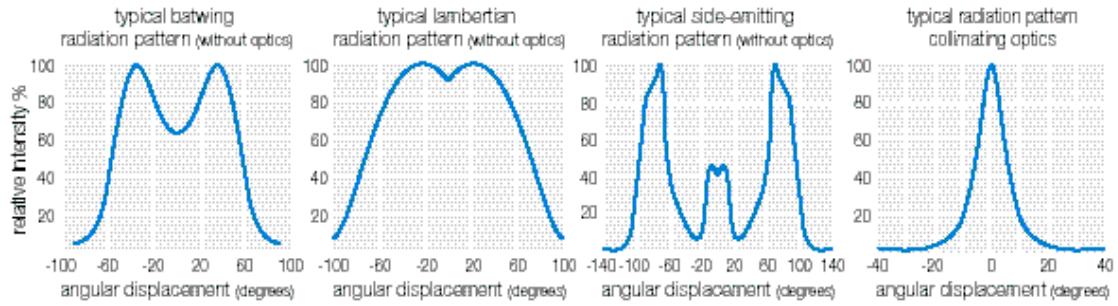


Figure 6: The Illuminator LED Light Distribution Pattern^[E]

Life and Lumen Maintenance

Five mm white LEDs reach 50 percent of their initial light output at around 10,000 hours of operation at rated drive current under laboratory conditions. The high degradation rate in these devices is mainly due to packaging. The newer high-power white LEDs have significantly improved lumen maintenance (**Figure 7**), and therefore they could have much longer lamp life (greater than 25,000 hours). **Figure 8** illustrates monochromatic LEDs life and lumen maintenance.

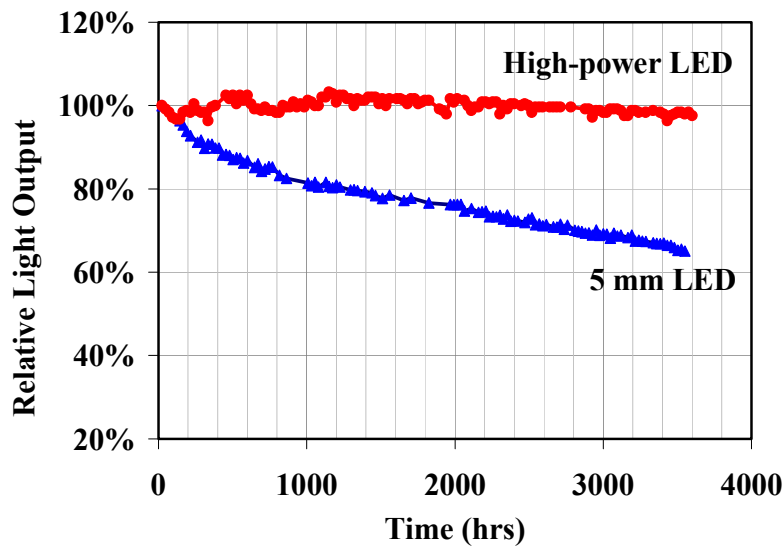


Figure 7: Relative light output from 5-mm indicator lamps and from high-power illuminator LEDs, as a function of operating time (Narendran and Bullough, 2001).^[1]

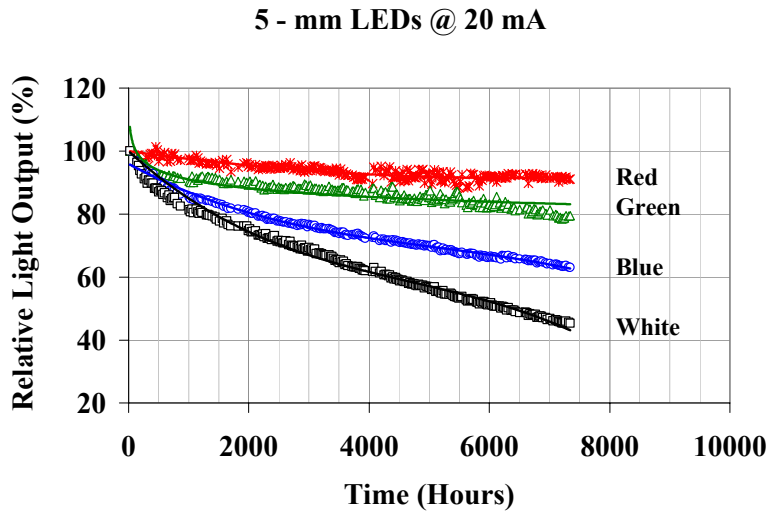


Figure 8. Relative light output of red, green, blue and white indicator LEDs operated at nominal forward current. ^[2]

Controllability

LEDs generally offer more flexible controllability than other available light sources. Increasing or decreasing the current through the device easily controls its light intensity. Another important benefit is that the energy efficiency of the device is maintained or improved as the device is dimmed (**Figure 9**). Lower operating currents have a positive affect on the life of the device and if temperature is stabilized there is no change in color at different current loadings. Color can also be controlled over the entire color space by varying the intensity of three or more different colored LEDs. Another possibility given the low voltage of these devices and their package configurations, is that it is very feasible that LEDs will be addressable, allowing a very high degree of control in future lighting applications.

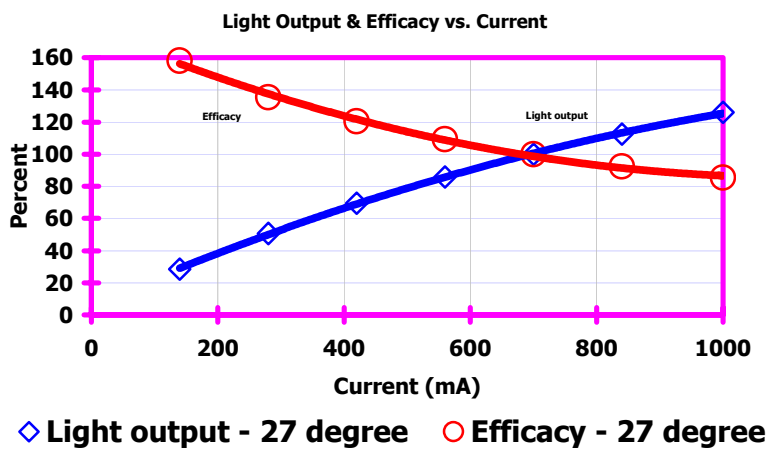


Figure 9: High Power LED Light Output and Efficacy Vs. Dimming Current ^[3]

Conclusions

Based on an evaluation of the attributes discussed above, (i.e., efficacy, color rendering, color consistency, distribution, lumen maintenance, and thermal controllability), the LRC has concluded that high power illuminator LEDs will be the most appropriate source for the low profile luminaire applications. It is yet to be determined whether the LRC will select the phosphor coated white LED or a combination of colored LEDs as the white light source for the low profile LED luminaires that will be developed in this project. These determinations will be made in the next project phase.

Results of the LRC's evaluation of the attributes of several types of LEDs are summarized in **Table 3** on the following page.

Overview of the LED Performance

Table 3: Below is an overview of the LED performance from the survey of 16 LED product manufacturers.

Type	Wattage (W)	Color	I _F (mA)	Technology	Package	Lumen output/device (lm)	Efficacy (lm/W)	Dominant wavelength or CCT & CRI	Radiation pattern (or 2θ _{1/2}) (Degree)	θ (C/W)	Manufacture
Indicator	0.06-0.5	W	2-55	InGaN, GaN+phosphor	3mm, 5mm, SMD, backlight, coinlight, linearlight	0.54-4	12	5000-6500K 70-80	13, 15, 20, 25, 30, 50, 90, 120	205-450	Gelcore, Gilway, Ledtronics, Lumileds, Nichia, Roithner, Osram
		R	2-150	AlInGaP, GaAlAs, GaAsP, GaAlP, GaP	2mm, 3mm, 4mm, 5mm, 10mm, SMD, backlight, coinlight, linearlight module	0.003-6	NA	605-660nm	4, 6, 9, 12, 15, 20, 23, 30, 45, 50, 60, 70, 85, 90, 100, 120, 25*68, 50*100, 60*120, 35*70	200-480	Agilent, Gelcore, Gilway, Lumileds, Nichia, Osram, Roithner, Vishay, Toyoda Gosei
		G	2-55	InGaN, GaP, GaN, GaAlP, GaAsP	2mm, 3mm, 4mm, 5mm, 10mm, SMD, chip, subminiature, backlight, coinlight, linearlight	0.3-4.5	8	500-570nm	4, 9, 12, 15, 20, 30, 45, 50, 60, 70, 90, 100, 120, 140, 35*70, 60*120	200-480	Agilent, Gelcore, Gilway, Lumileds, Nichia, Osram, Roithner, Vishay, Toyoda Gosei
		B	20-55	InGaN, GaN,	3mm, 4mm, 5mm, subminiature, SMD, chip, backlight, coinlight, linearlight	0.080-2	2	430-470nm	4, 6, 9, 10, 12, 15, 16, 20, 30, 40, 50, 60, 90, 110, 120, 37*70, 60*120	200-480	Agilent, Gelcore, Gilway, Lumileds, Nichia, Osram, Roithner, Vishay, Toyoda Gosei
Illuminator	1-25	W	160-1050	InGaN	Star, emitter, line, ring, flood, TO66, SMD, HEX	16-325	NA	2700-6000K 70	Batwing, Lambertian, Side emitting, 54	1-65	Lumileds, Norlux, Nichia, Optotech
		R	100-1050	AlInGaP, AlGaAs	Star, emitter, line, ring, flood, TO66, 5mm, HEX, module	2.9-790	NA	611-660 nm	Batwing, Lambertian, Side emitting, 20, 40, 54, 60, 120	1-35.5	Lumileds, Norlux, Roithner
		G	160-1050	InGaN	Star, emitter, line, ring, flood, TO66, SMD, HEX	23-450	NA	525-530 nm	Batwing, Lambertian, Side emitting, 10, 54, 60	1-65	Lumileds, optotech, Roithner, Norlux, Nichia
		B	160-1050	InGaN	Star, emitter, line, ring, flood, TO66, SMD, HEX	5-90	NA	460-470 nm	Batwing, Lambertian, Side emitting, 10, 54, 60	1-65	Lumileds, optotech, Roithner, Norlux, Nichia
	5	W	700	InGaN	Emitter, Star	105-120	NA	5500K 70	Lambertian, Side emitting	8-12	Lumileds
		G	700	InGaN	Emitter, Star	110-120	NA	530-550 nm	Lambertian, Side emitting	8-12	Lumileds
		B	700	InGaN	Emitter, Star	25-30	NA	460-490 nm	Lambertian, Side emitting	8-12	Lumileds

References

1. Narendran, N. and J. D. Bullough. 2001. Light emitting diodes as light sources. 9th International Symposium on the Science and Technology of Light Sources, Ithaca, NY, August 12-16.
2. Narendran, N., N, Maliyagoda, L. Deng and R. Pysar. 2001. Characterizing LEDs for general illumination applications: Mixed-color and phosphor-based white sources. *SPIE 46th Annual Meeting*, July 29-August 3, San Diego, CA.
3. Report submitted to the Department Of Energy (contract no. DE-FC26-01NT41203)
4. Narendran, N, Notes for the LED Institute, September 2002, Lighting Research Center, Troy, NY

Image References

Images referenced in this document are listed below with the web site source. The images were downloaded from the web sites in December 2002.

- Images A – www.nichia.com
- Images B, C, D, and E – www.lumileds.com and www.nichia.com

Additional Resources

Additional information on LED light sources is available from the following web sites.

- www.osram-os.com
- www.agilent.com
- www.gelcore.com
- www.optotech.com
- www.lrc.rpi.edu/solidstate/leds.htm