White LED and Remote Phosphor Comparison

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Abstract

There are various approached to making white light with LEDs. Early “white LED” efforts had been concentrated at integrating phosphor into the package. Making white LEDs by physically separating the phosphor and blue LED pump source is commonly known as remote-phosphor systems; this idea has existed for more than 10 years. But recent claims of 30 percent efficacy gains through remote-phosphor activities have sparked new interest in the debate over which process is best.

The objective of this work is to study and compare integrated white LED packages with remote-phosphor systems in different geometric configurations. Our analysis found that in downlight and bulb configurations, light output gains are approximately 20 percent with remote-phosphor systems; however, the cost of phosphor and coating far exceeded the option of additional white LEDs. System integrators must carefully consider different LED technologies for their lighting applications by balancing cost and performance.

Experiment

In order to run an “apples-to-apples” comparison, we have to consider the LED chip, phosphor, and final system configuration since most elements are the same except for the phosphor location.

To obtain the same LED baseline, White LEDs and Royal Blue LEDs are built using the same LED wafer, matching wavelength and radiant flux power. They are packaged with the same package dimensions as the Cree® XLamp® XT-E LED family. The LEDs are made into 9 x 9 high-density LED modules as basic light engines to be used in different applications tests. For the remote-phosphor portion, we made a phosphor disc and a phosphor bulb using the same warm white phosphor targeting a CCT of 3000K as in the XT-E warm white. These remote-phosphor parts are integrated into the LED modules and compared with white LED counterparts. Commercially available remote-phosphor parts were also obtained for comparison.

The disc and bulb configurations are used to investigate whether or not the geometric configuration plays a role in efficacy improvements. The disc system is to be tested in a downlight application, while the bulb configuration is to be tested in an omni-directional application.

We also want to test the system as closely as possible to its actual application environment: high flux and high temperature. Thus, the LED module is mounted on a heat stage at 85°C at a steady state condition (30 minutes stabilization time). The LEDs are operated at 700mA, giving a system level light output of approximately 1400 lumens.

Downlight

For the downlight test, we built a 4-inch white LED downlight with the warm white LED module described earlier, using a plastic reflective cone and a 4-inch polycarbonate diffuser. On the remote phosphor version, we used the royal blue LED module with a white plastic reflective cone and a 4-inch phosphor coated glass. Schematics of the two systems are illustrated in Fig. 1 below. The remote phosphor glass disc is made with the same phosphor as the XT-E warm white LED in a silicone matrix, coating it on a piece of glass. Both systems are tuned to the same color temperature of 3000K. The two downlight modules are mounted on an 85°C heat stage in a 0.5M sphere for 30 minutes before measurement, as shown on Fig. 2.

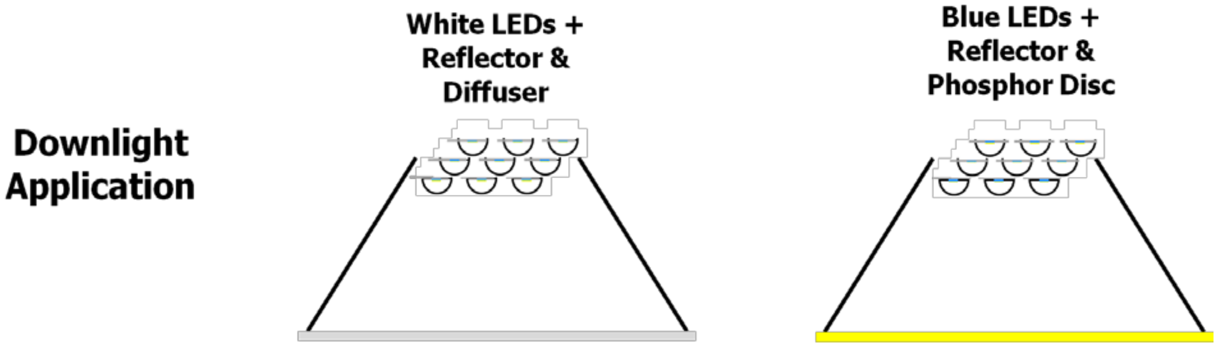

Fig. 1. Schematics of white LED and Remote-Phosphor System in a downlight test set up

XT-E warm white baseline

XT-E + Ref Cone (97% reflective)

XT-E + Ref Cone & Diffuser (overall lost ~5%)

XT-E-RB baseline build with same chip as XT-E warm white above (Dom λ ~457nm)

XT-E-RB + Ref Cone (97% reflective)

XT-E-RB + Ref Cone & RemPhos Disc (large & small)

Fig. 2. Photographs of white LED and Remote Phosphor downlight test setup

<u>Bulb</u>

For the bulb test, we used nine Cree XLamp XP-E high efficiency warm white LEDs to build a bulb module with a 35mm diameter glass globe with a diffuser coating (most bulbs have a diffuser coating to hide the hot spot of the LED). On the remote-phosphor version, we used nine Cree XT-E royal blue LEDs to build a module with a glass bulb coated with phosphor-embedded silicone. Schematics of the two systems are illustrated in Fig. 3. Again, the phosphor used is the same in the X-PE LED and is targeted at 3000K for comparison. The two bulb modules are mounted on an 85°C heat stage in a 0.5M sphere for 30 minutes before measurement, as shown in Fig. 4. To understand the temperature effects, 25°C steady state measurement data were also collected.

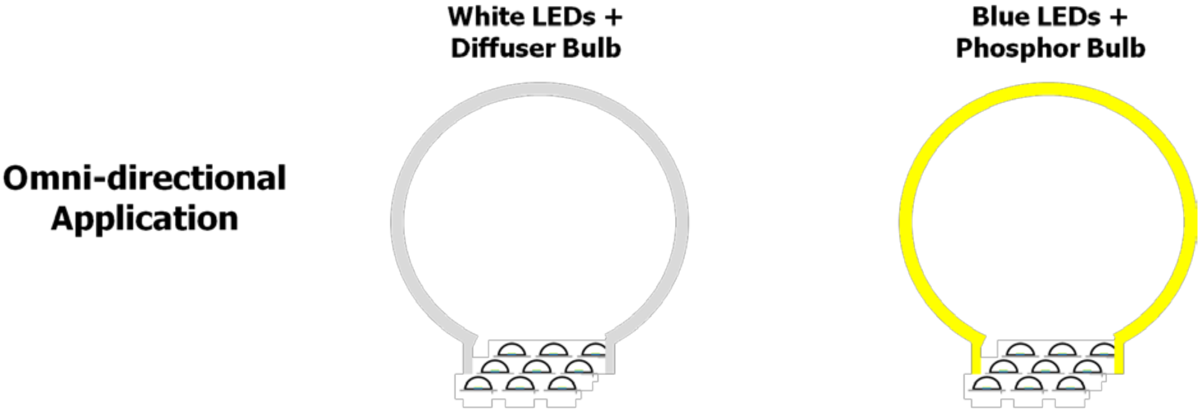

Fig. 3. Schematics of white LED and Remote-Phosphor System in bulb test

XT-E warm white baseline

XT-E + Light Diffuser Globe
LEDs inside can be seen

XT-E + Heavy Diffuser Globe

XT-E-RB baseline build with same chip as XTE-HEW above

XT-E-RB + Cree WW Globe

XT-E-RB + Company X WW Globe

Fig. 4. Photographs of white LED and Remote Phosphor bulb test setups

Results and Analysis

The steady state sphere measurements are outlined in Table 1 below:

Downlight Application

LED	Description	25C Lum	85C Lum	% of Hot baseline	Note	% of Hot Lum Lost
XT-E WW	9 XT-E warm white	1471	1234	/	Hot baseline = 1234lm @ 85C	16.1%↓
XT-E WW	9 XT-E + Cone	1416	1187	3.8%↓		16.4%↓
XT-E WW	9 XT-E + Cone + Diffuser	1358	1146	7.2%↓	Cone Reflector + Diffuser lost from 7% to 15%, cone efficiency ~96.5%	15.6%↓
XT-E-RB	9 XT-E-RB	7.74W	6.66W			14%↓
XT-E-RB	9 XT-E-RB + Cone	7.32W	6.29W		Cone efficiency ~ 94% for blue	14%↓
XT-E-RB	9 XT-E-RB + Cone + L Cree Phos Disc	1541	1324	7.3%↑	15% ↑ from XT-E WW + Ref Cone & Diffuser	14%↓
XT-E-RB	9 XT-E-RB + Cone + L Company X Phos Disc	1589	1363	10.5%↑	19% ↑ from XT-E WW + Ref Cone & Diffuser	14.2%↓
XT-E-RB	9 XT-E-RB + Cone + S Company X Phos Disc	1542	1322	7.1%↑	15% ↑ from XT-E WW + Ref Cone & Diffuser	14.3%↓

Table 1: Light output summary for different LED downlight configurations, for white LED and remote phosphor system comparison.

Table 1 lists different test configurations and light output measurements for the downlight application. The baseline light output from the nine white LEDs at 85°C steady state condition (30 minutes on-time) is 1234 lumens. In order to compare the remote-phosphor disc system, we need to put the white LEDs in a white reflector and diffuser disc to simulate a downlight application; this is comparable to how most customers would use the white LEDs. The light output for this white LEDs configuration at 85°C steady state is 1146 lumens. This should be the baseline used to compare the remote-phosphor system.

Additionally, we have measured three remote-phosphor discs: one with the same phosphor as the white LEDs in the base line, and two with a commercially available phosphor disc (large and small discs at different distances from the LEDs). With the Cree phosphor disc, the light output is 1324 lumens at 85°C steady state, a 15 percent increase over the baseline. For the commercially available phosphor discs, the light output is 1363 lumens (19% increase), and 1322 lumens (15% increase) for the large and small discs respectively.

Thermal degradation from 25°C to 85°C is averaged at 16% for white LEDs, and 14% for the remote-phosphor system. The remote-phosphor system has a slightly better lumen maintenance / hot-cold factor.

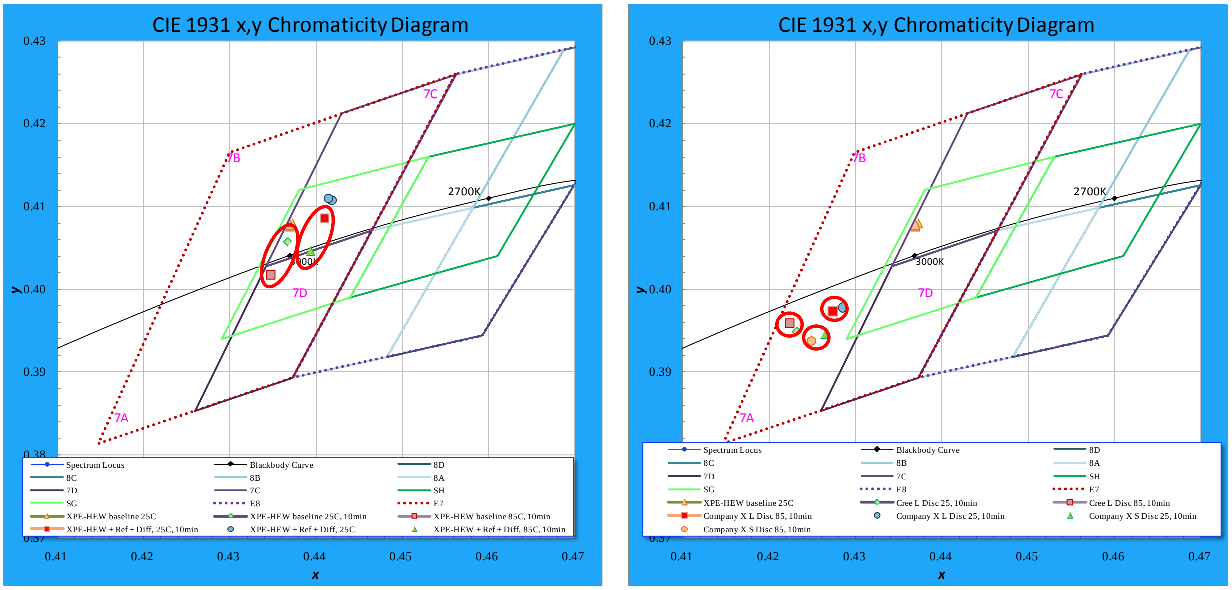

Fig. 5a (left) and Fig. 5b (right): Color point shift due to temperature change comparison for white LEDs and remote-phosphor disc system

Next we looked at the color maintenance for the white LED and remote phosphor system. In Figure 5a above (left), the color points of the bare white LED and the white LED configured with a reflector cone and diffuser at 25°C and 85°C are plotted. The shift at high temperature is to the lower left, toward the blue corner of the CIE diagram. For the white LEDs, the phosphor is placed on the LED chip and the phosphor temperature can be very close to the junction temperature of the LED (approximately 90°C) when the stage is 85°C. The conversion efficiency of the phosphor can drop with increasing temperature, thus there will be less yellow light from the phosphor and the overall LED color will shift toward blue. In Figure 5b (right), the color points of the three remote-phosphor discs at 25°C and 85°C are shown. The shift is smaller with the phosphor discs far from the LED and heat stage, the phosphor temperature is much lower and the efficiency can be maintained, keeping a relative stable color point.

Bulb Application

LED	Description	25C Lum	85C Lum	% of Hot baseline	Note	Hot Lum Lost
XT-E WW	9 XT-E warm white	1471	1234	/	Hot baseline = 1234lm @ 85C	16.1%↓
XT-E WW	9 XT-E + Diffuser Globe	1314	1099	10.9%↓	Other diffuser range from 92% to 85% depends on the type of coating	16.4%↓
XT-E-RB	9 XT-E-RB	7.74W	6.66W			14%↓
XT-E-RB	9 XT-E-RB + Cree WW Globe	1551	1326	7.5%↑	20.6% ↑ from XT-E WW + Diffuser Globe	14.5%↓
XT-E-RB	9 XT-E-RB + Company X WW Globe	1315	1127	8.7%↓	2.5% ↑ from XT-E WW + Diffuser Globe	14.3%↓

Table 2: Light output summary for different LED bulb configurations

The table above lists different test configurations and light output results for the bulb application. The baseline light output from the nine white LEDs at 85°C steady state condition (30 minutes on-time) is 1234 lumens, the same as downlight result. For the bulb comparison, we used a glass bulb with diffuser particle coating to hide the hot spots of the LEDs similar to an acutal bulb application. The light output for this bulb configuration at 85°C steady state is 1099 lumens (the light coating and higher diffuser loading can lead to a lower light output). This should be the baseline used to compare the remote-phosphor system.

Two phosphor bulbs utilizing XT-E Royal Blue LEDs were also measured: one with same phosphor as the white LED, and one commercially available plastic bulb with embedded phosphor. The Cree phosphor bulb has a measured light output of 1326 lumens at 85°C steady state, a 20.6 percent increase over the baseline, while the commercial phosphor bulb has a light output of 1127 lumens at 85°C steady state, a 2.5 percent increase over baseline.

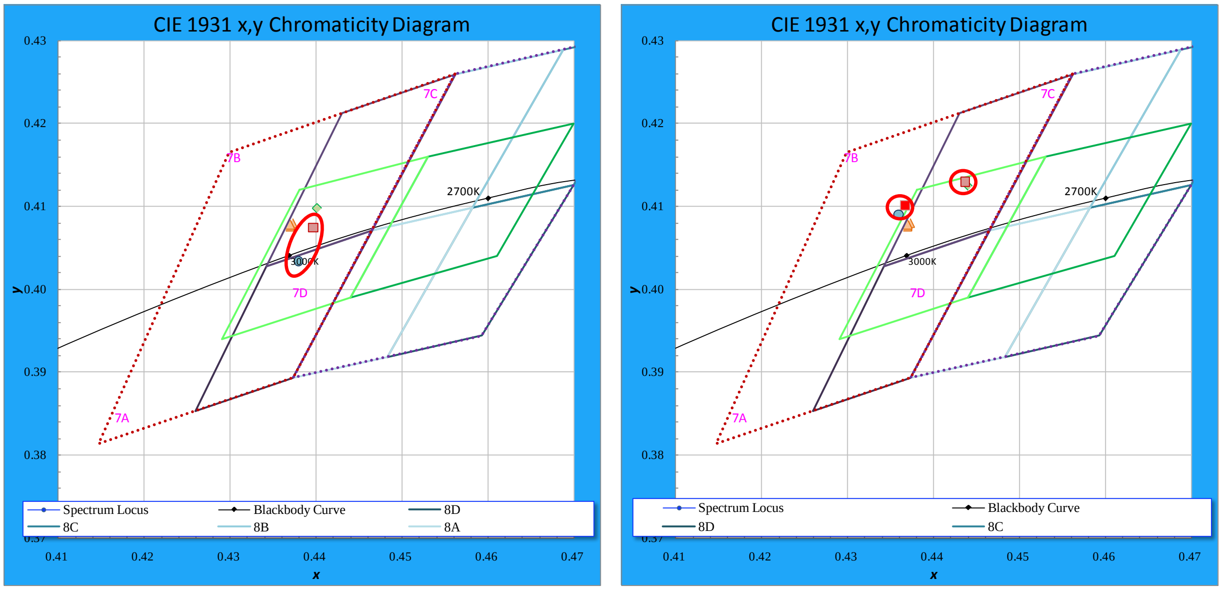

Fig. 6a (left) and 6b (right): Color point shift due to temperature change comparison for white LEDs and remote phosphor bulb system

We also looked at the color point temperature stability for the bulb application. Similar to the color point plot on the downlight comparison, Fig. 6a shows the white LED with diffuse bulb shifting toward blue, while the remote-phosphor bulb had a relative stable color point from 25°C to 85°C (Fig. 6b). This further verified that remote phosphor can maintain a more stable color with increasing temperature.

Our test of remote-phosphor systems in different configurations, both downlight and bulb (omni-directional), have shown increased light output when comparing final user configuration—as with a reflector and diffuser or with a diffuser bulb only to enclose the LED—by as much as a 20 percent more lumens. The conditions are comparable to actual applications such as a recessed downlight, bulb in a pendent, or wall scones. Also, we have shown that the remote-phosphor system has a better color point stability over temperature; this could be important depending on the specific lighting application requirement.

How it works

In this experiment, we have shown that remote-phosphor systems can be more efficient than integrated white LEDs and have a better color point stability with temperature increases. Here we will discuss some of the proposed mechanisms of the remote phosphor and try to understand its efficiency gain.

An integrated white LED has phosphor very close to the chip, either as a thin coating or embedded in a silicone encapsulant matrix. The blue light generated by the LED chip emits in all directions, some of this light rays will interact with the phosphor on the LED chip and convert into light of different wavelengths, but mostly yellow light. These yellow lights are also emitted in all directions and some of them will head back to the LED chip and be absorbed, loosing efficiency (illustrated in Fig. 7a). In comparison, in a remote-phosphor system, the phosphor is placed far from the LED chip. As the blue light reaches the phosphor and the excitation-emission process occurs, the yellow light from the phosphor emits in all direction as in the white LED; but since the LED chip is far away, the chances of the yellow light hitting the chip and being absorbed is significantly lower (illustrated in Fig. 7b). As long as the remote-phosphor system is well designed with a high-efficiency reflector for the yellow light to be recycled, the overall efficiency in a remote phosphor system will be higher than the white LED.

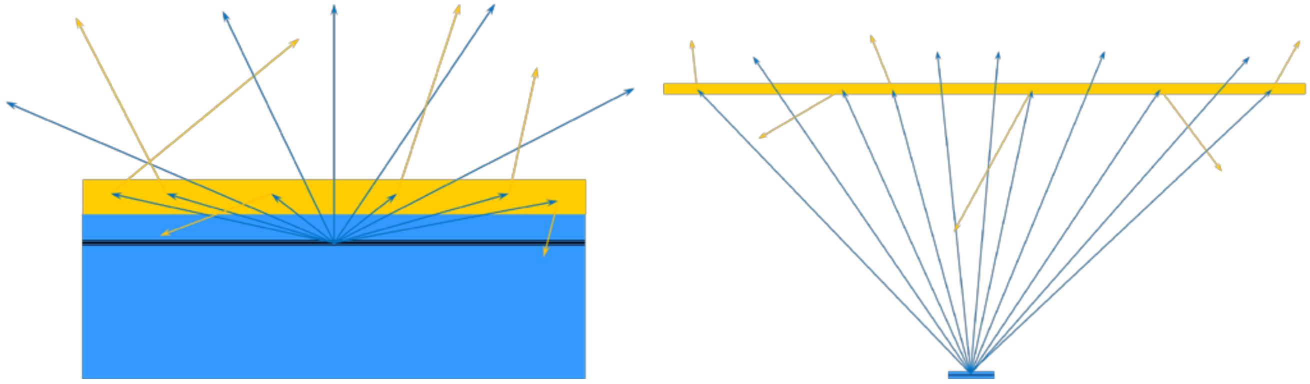

Fig. 7a (left) and 7b (right): phosphor conversion process in a white LED and remote phosphor system

Also, we can see that in the white LED, since the phosphor is in direct contact with the LED chip, it can get very hot and lower its conversion efficiency, changing the overall blue-to-yellow light ratio and causing a color shift as demonstrated previously in Figures 5 and 6. In contrast, the phosphor in the remote-phosphor system is not affected by the LED temperature and thus can maintain a consistent conversion rate and overall color point.

Price to Pay

One aspect we have not touched on in the comparison is cost. We have shown that remote-phosphor systems can increase system light output by 20 percent; but we also need to factor in the cost trade off for final comparison. This shall be illustrated in the following example:

A typical 1000 lumen downlight can be built with 10 LEDs at an approximate cost of $17.00 (assuming an LED cost of approximately $1.70 each). If we would like a gain of 20 percent in light output, we can either add two additional LEDs at an incremental cost of $3.40, or use a remote-phosphor disc for an additional cost of $8.00 (at high volume; individual price of $15.00). Lighting system designers and integrators will have to evaluate if their application requires this additional cost and make the choice.

Conclusion

We have demonstrated an actual usage comparison of integrated white LEDs vs. remote-phosphor systems in both downlight and omni-directional bulb applications. Our results show that remote-phosphor systems can provide light output gains of 20 percent in a high flux, high temperature environment with a more stable system color point compared to white LEDs; however, these gains in performance come at a very high cost as the cost of phosphor—especially in the warm white color region—is extremely expensive, even surpassing the cost of additional white LEDs to make up the light output gain. Additionally, these costs do not take into consideration other major concerns such as IP issues and LM-80 testing for Royal Blue LEDs.

Remote-phosphor systems may have advantages in particular applications; but until the cost of remote phosphor comes down, or when remote-phosphor overall system cost is less than white LED cost in a particular lighting system, white LEDs should still be the choice for general lighting.