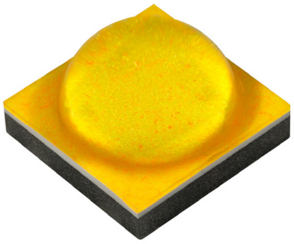
# XLamp® XP-G4 LED Design Guide



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## INTRODUCTION

Ceramic high-power LEDs, such as the XLamp® XP-G2, XP-G3 and XP-G4 LEDs, are commonly used for many directional lighting applications in a one-to-one configuration with optics specialized for each application. Advances in LED technology that improve the LED's light output, light directionality, efficiency and reliability can change the interactions with these secondary optics. The XLamp XP-G4 LED includes many performance improvements over the previous XP-G2 and XP-G3 LEDs, including higher maximum drive current, more CCT and CRI options and lower thermal resistance.

While it is impossible to fully predict how LED changes will affect all types of optics, this application note aims to document optical similarities and differences of the new XLamp XP-G4 LED to the previous generation XP-G2 and XP-G3 LEDs across a wide range of applications.

All mentions of the XP-G2 LED in this document refer to the pre-PCN version, meaning that the XP-G2 LEDs tested were manufactured before the changes stated in CreeLED-PCN-5146, issued April 13, 2021. While pre-PCN XP-G2 LEDs are no longer available, this application note serves as a guide for how XP-G4 LEDs behave in optical systems that were developed before the change in 2021.

## OPTICAL ADVANTAGES OF XP-G4 OVER XP-G2 & XP-G3

The narrowed emission, reduced spill light and well-defined LES of the XP-G4 LED makes it ideal for directional lighting applications such as spotlights, premium torch, and sports lighting. Our extensive testing with compatible optics below shows the XP-G4 LED is a drop-in upgrade for the XP-G2 LED in most applications for the following reasons.

### Matched Color Over Angle Compared to XP-G2

The XP-G2 LED was well-received by customers for its excellent color-over-angle, or low color shift (du'v') from the center to the outer beam. The XP-G4 LED is designed with a flat and smooth phosphor layer to closely match the color-over-angle profile of the XP-G2 LED. Our data show this similarity in every optic tested, like the sports lighting optic projections shown below in Figure 1.

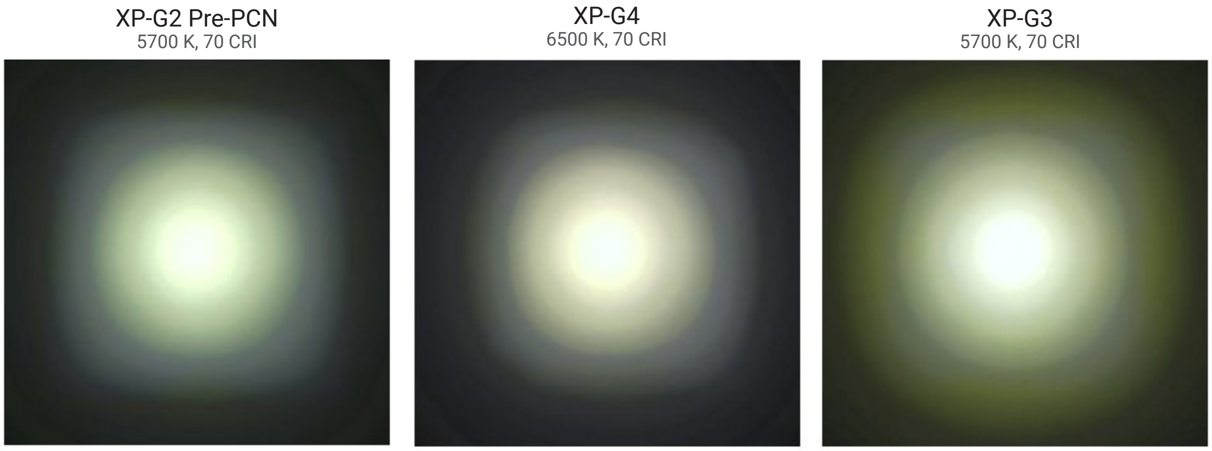



**Figure 1: Spotlight projections showing the similarities in color and beam cutoff between the XP-G4 and XP-G2 LEDs**

### Narrowed 120° Emission Profile With Improved High-Angle Cutoff

The XP-G4 LED uses new technologies to direct the emitted light into a narrower, more uniform cone, resulting in a view angle (FWHM) of 120° in neutral white to closely match the XP-G2 LED, shown in the data from this narrow-beam spotlight optic in Figure 2 below. This is accomplished without changes to the overall dimensions so it can drop in without mechanical interference.

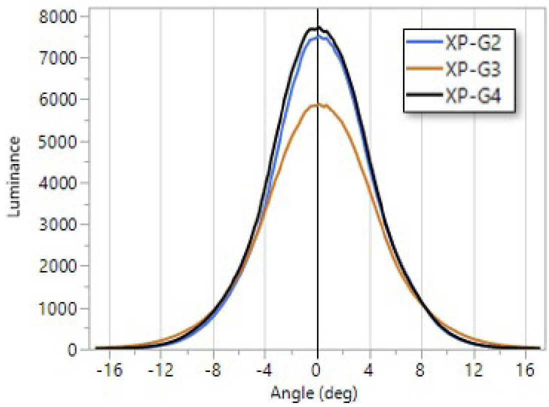



**Figure 2: Luminance over angle of a narrow beam spot optic projection, showing the similarities in beam shape and intensity between the XP-G4 and XP-G2 LEDs**

### Radically Enhanced Efficiency and Thermal Conductivity

The XP-G4 LED is more efficient than the XP-G2 LED, and with a higher maximum rating of 3 A it can deliver 75% more lumens than the XP-G2 LED running at 1.5 A, with proper heat sinking. In addition, the lower thermal resistance of the XP-G4 LED keeps the LED cooler than the XP-G2 LED under the same operating conditions, which will improve the long-term reliability of the LED.

## OPTICAL TESTING

Data sheet values report on total lumens in an integrating sphere, but Cree LED understands the importance of delivering the lumens to the target. The XP-G4 LED not only maintains industry-leading lumens on the data sheet, it also allows unparalleled optical control for this power class. The data below show several examples of this performance. Contact your Cree LED Sales Representative for more details on optical performance and recommendations.

### Methods

Test data with secondary optics was collected using a ProMetric® IC-PMI16-ND3 Radiant Vision Systems camera. The optics were mounted to the LEDs following manufacturer instructions and the device was aligned to the same axis as the camera with a 2-way projection screen in between. Intensity in this test is labeled as luminance in the tables below.

All testing was performed at 350 mA DC constant current, running at steady state on an actively cooled heat sink at 41 °C.

### Sports Lighting Optical Analysis

One of the applications best-suited for the XP-G4 LED is stadium or arena lighting. The combination of high efficacy, long lifetimes, high luminous intensity and excellent color uniformity make the XP-G4 LED the best LED on the market for precisely illuminating playing fields without wasting lumens.

**LEDiL C17991 SPORT-2X2-S1**

The LEDiL C17991 SPORT-2X2-S1 optic is labeled as their “narrowest, most powerful sport beam”, so using this optic provides a great opportunity to test the boundaries of the XP-G4 LED performance. The XP-G4 LED showed 2.7% higher peak luminance and closely matched view angle versus the XP-G2 LED. The XP-G3 LED has a wider emission profile, better suited for wide-beam applications, and did not show high peak luminance in this optic.

**Table 1: Performance comparison using LEDiL C17991 SPORT-2X2-S1 optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 8.1 | 16.7 | 7507.5 | -2.7% |
| XP-G3 | 9.2 | 18.8 | 5881.3 | -23.8% |
| XP-G4 | 8.3 | 17.0 | 7716.4 | --- |

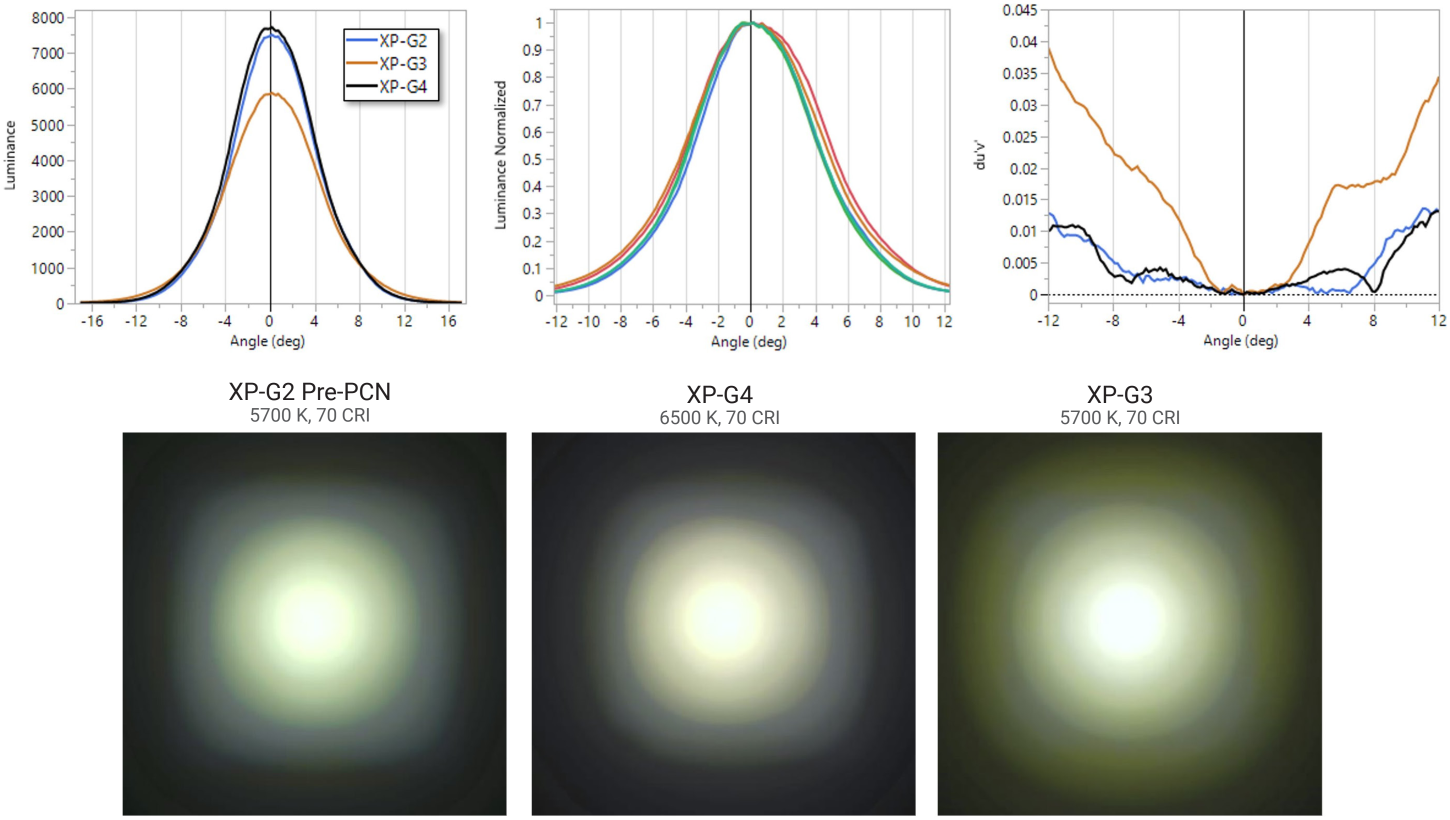



**Figure 3: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL C17991 SPORT-2X2-S1 optic**

**LEDiL C17411 SPORT-2X2-S2**

The LEDiL C17411 SPORT-2X2-S2 is listed as a “slightly asymmetric ~20° spot beam with minimum spill light”. Spill light, in this case, refers to unwanted light at the top of the beam that spectators would perceive as glare. This aspect of the distribution is just as important as the maximum intensity. This optic type illustrates an important test case with an asymmetric beam that requires a well-defined cutoff. Again, the XP-G4 LED is the top performer with 10-12% higher peak luminance than both the XP-G2 and XP-G3 LEDs.

Additionally, the secondary optic demonstrates a higher degree of control with the XP-G4 LED, shown by the steeper slope from peak to cutoff at 20°. This is further quantified by the narrower view angle. The true-color beam projection images below show just how similar the XP-G4 LED color uniformity is to the XP-G2 LED.

**Table 2: Performance comparison using LEDiL C17411 SPORT-2X2-S2 optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 15.7 | 33.7 | 7753.3 | -10.2% |
| XP-G3 | 15.4 | 33.3 | 7580.5 | -12.2% |
| XP-G4 | 14.7 | 33.6 | 8637.3 | --- |

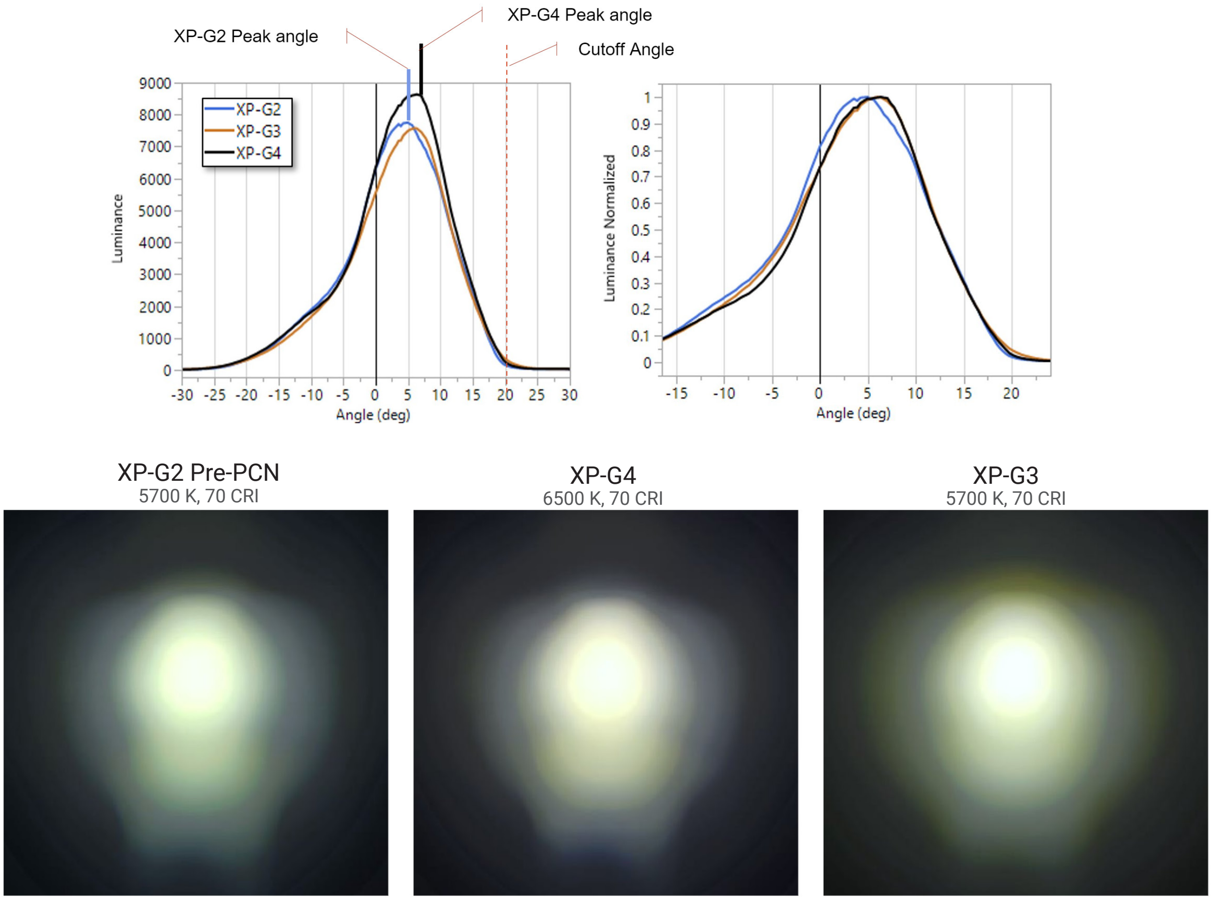



**Figure 4: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL C17411 SPORT-2X2-S2 optic**

### LEDiL C17414 SPORT-2X2-S6

This wider 60° optic is the exception to the improved peak luminance examples shown above in narrower optics. Described as a “slightly asymmetric ~60° spot beam with minimum spill light”, this optic is more compatible with a wider-emission LED like the XP-G3 LED, which had 10.6% greater peak luminance than the XP-G4 LED.

In this case, the greater optical control that the XP-G4 LED provides becomes a disadvantage as it has a narrower primary peak with additional light redirected toward a strong wide-throw shoulder where a smooth transition is more desirable.

**Table 3: Performance comparison using LEDiL C17414 SPORT-2X2-S6 optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 20.8 | 45.0 | 6821.1 | 4.2% |
| XP-G3 | 22.1 | 44.6 | 7244.8 | 10.6% |
| XP-G4 | 16.9 | 47.0 | 6548.4 | --- |

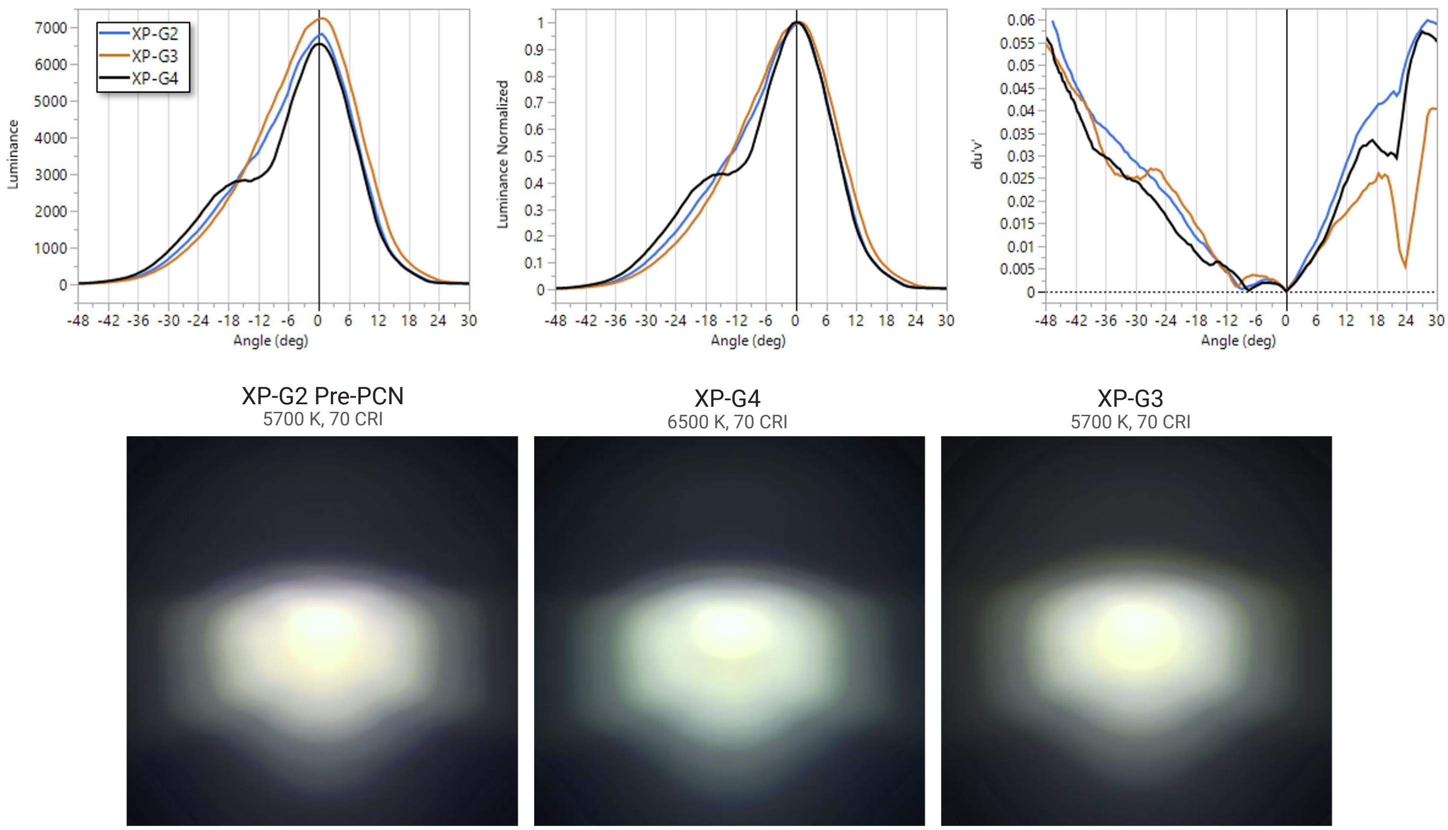



**Figure 5: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL C17414 SPORT-2X2-S6 optic**

## Indoor Spotlight Optical Analysis

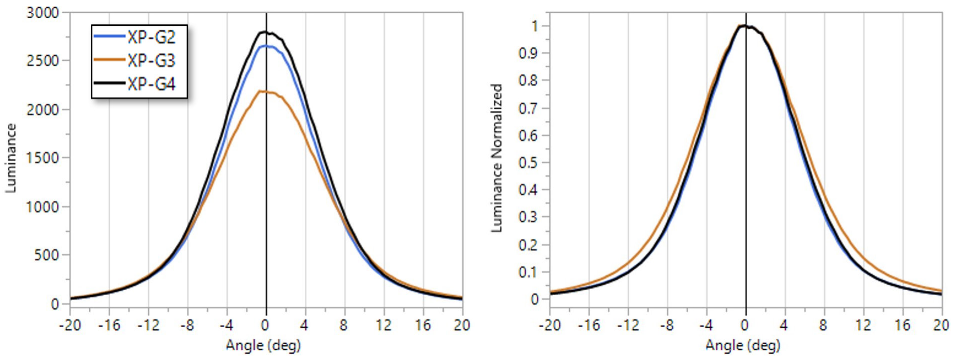
With indoor-type optics, the XP-G4 LED replicates the excellent color uniformity and tight beam angles of the the XP-G2 LED while delivering even greater intensity to the target. The XP-G4 LED is also available in a much wider range of CCT and CRI options, including the Pro9™ version for maximum efficacy at 90- and 95-CRI minimums.

### LEDiL CA11264 HEIDI-D

This is a ~10° diffused spot beam optic that could easily be used for indoor spot and architectural applications where color and emission uniformity is critical. In this case, the XP-G4 LED had a 5.1% higher peak luminance than the XP-G2 LED with a matched cutoff angle.

**Table 4: Performance comparison using LEDiL CA11264 HEIDI-D optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 11.1 | 23.6 | 2653.9 | -5.1% |
| XP-G3 | 12.4 | 26.4 | 2184.3 | -21.9% |
| XP-G4 | 11.7 | 23.6 | 2795.1 | --- |




XP-G2 Pre-PCN
5700 K, 70 CRI

XP-G4
6500 K, 70 CRI

XP-G3
5700 K, 70 CRI

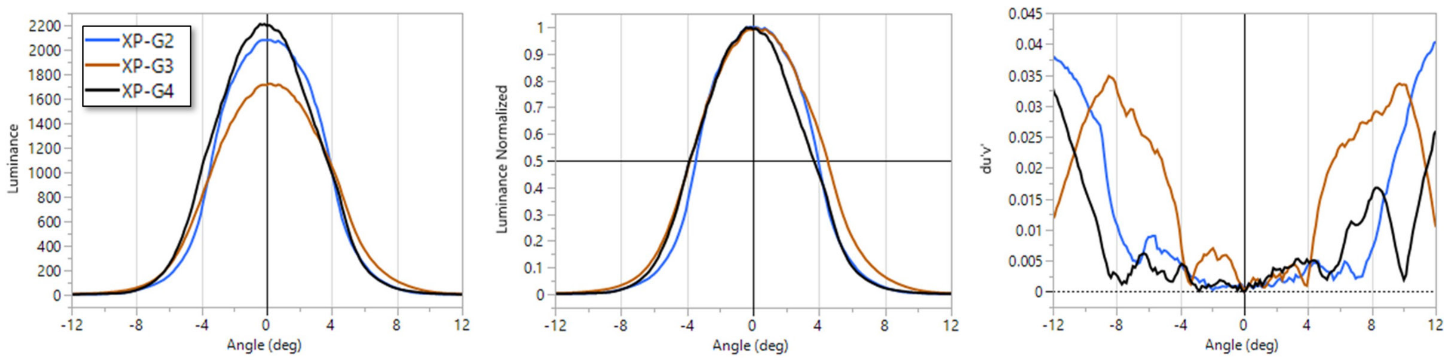
**Figure 6: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL CA11264 HEIDI-D optic**

## LEDiL CA16206 SURI-RS

This optic "is designed for surgery and other technical lighting requirements with a tight 6° beam." In a life-saving application like this, color fidelity and optical control is critical. The XP-G4 LED once again delivers the highest peak luminance, 6.0% more than the XP-G2 LED and 21.8% more than the XP-G3 LED while maintaining a similar color uniformity, beam angle and field angle to the XP-G2 LED. In addition, one of the main criteria for surgical lighting is the ratio between beam and field angle, which should be 0.50 or higher. The XP-G4 LED has a ratio of 0.62, which is considered excellent.

**Table 5: Performance comparison using LEDiL CA16206 SURI-RS optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 7.3 | 11.7 | 2081.3 | -6.0% |
| XP-G3 | 8.3 | 13.7 | 1731.6 | -21.8% |
| XP-G4 | 7.4 | 12.0 | 2213.7 | --- |



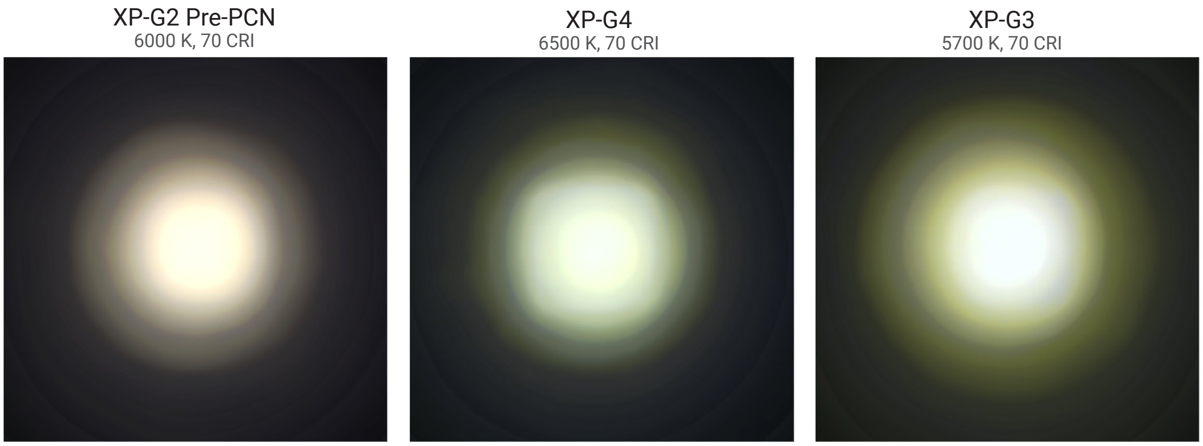




**Figure 7: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL CA16206 SURI-RS optic**

### Carclo Narrow Spot Optics Analysis

Carclo Optics offers a line of small TIR lenses described as "Narrow Spot Plain TIR" that are common off-the-shelf solutions for a range of spotlight applications. Using the available XP-G4 LED ray trace files, Carclo Optics simulated performance using this line of optics for comparison against the XP-G3 LED, which was already available on their website. Table 6 below summarizes these results.

In all cases, the XP-G4 LED narrows the FWHM and drastically improves the candela per lumen (cd/lm) over the XP-G3 LED by 19-46%. This is also illustrated in the beam images shown in Figure 8.

**Table 6: Simulated comparison of XP-G3 and XP-G4 LEDs in Narrow Spot Plain TIR optics made by Carclo Optics**

| Optic Diameter | Carclo Part Number | XP-G3 | | XP-G4 | |
|---|---|---|---|---|---|
| | | FWHM (°) | cd/lm | FWHM (°) | cd/lm |
| 10 mm | 10412 | 26.0 | 3.1 | 23.5 | 4.5 |
| 20 mm | 10003 | 12.8 | 11.4 | 12.0 | 14.2 |
| 26.5 mm | 10048 | 9.6 | 20.7 | 8.4 | 27.0 |
| 30 mm | 10755 | 8.8 | 24.4 | 7.8 | 35.7 |
| 30 mm | 10756 | 12.1 | 12.9 | 11.5 | 15.1 |

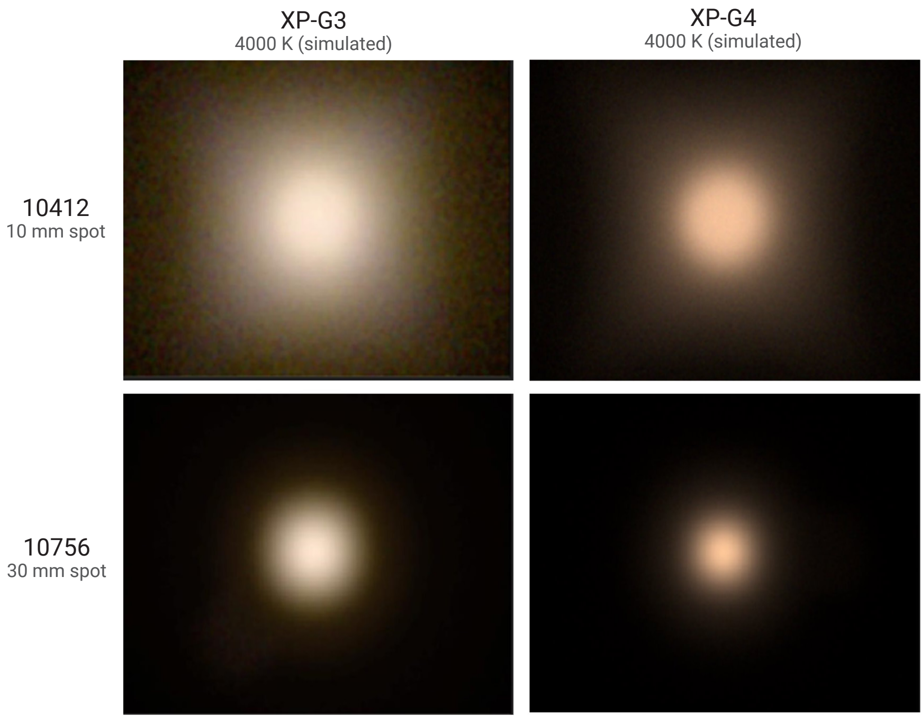



**Figure 8: Simulated true color spot projections from two select Narrow Spot Plain TIR optics. Images provided by Carclo Optics.**

**Khatod ARENA Reflector Stadium Optics Analysis**

Many applications are well suited to reflector optics rather than transparent TIR optics, and the Khatod ARENA Reflector KCLP4801CRSM is a great case study of the improvements the XP-G4 LED can give in stadium lighting.

Khatod Optoelectronic carried out the following simulations using provided ray trace files with equal total luminous flux and found that the XP-G4 LED gives a 47% max candela improvement over the XP-G3 LED while narrowing the beam angle by 1.1 degrees. Furthermore, the XP-G4 High Intensity (HI) LED gives an additional 13% max candela improvement over the XP-G4 High Density (HD) LED and narrows the beam angle by another 3.3 degrees

**Table 7: Simulated peak intensity, beam angle, and field angle values of XP-G3 and XP-G4 LEDs in an ARENA reflector KCLP4801CRSM**

| Parameter | XP-G3 HD | XP-G4 HD | G4/G3 HD Change | XP-G4 HI | Change |
|---|---|---|---|---|---|
| Maximum Candela | 166,631 | 244,189 | +47% | 319,040 | +13% |
| Maximum Cd/lm | 16.0 | 23.4 | +47% | 30.5 | +13% |
| Beam Angle | 9.7° | 8.6° | -1.1° | 5.3° | -3.3° |
| Field Angle | 27.2° | 22.0° | -5.2° | 22.7° | +0.7° |

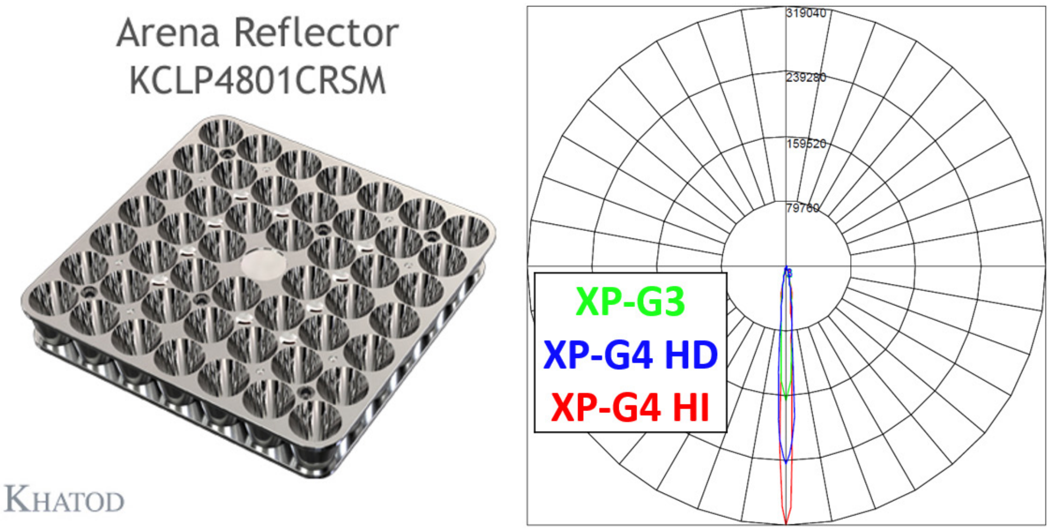



**Figure 9: Simulated polar plot of XP-G3, XP-G4 HD and XP-G4 HI LED emission in an Arena Reflector KCLP4801CRSM from Khatod Optoelectronic, showing a 47% peak intensity improvement using the XP-G4 HD LED and an additional 13% improvement from the XP-G4 HI LED.**

## Roadway and Streetlight Optical Analysis

Roadway applications tend to bend light away from the normal axis of the LED to throw it at wide angles over a roadway or parking lot. These optics usually work best with LEDs that have wider view angles like the XP-G3 S Line LED. LEDs with high intensity in the normal axis like the XP-G4 LED tend to throw light at a narrower angle than what the optic may have been designed for. Although the XP-G4 LED is better-suited to narrow-beam applications, its excellent color uniformity, high-angle cutoff, and high LPW may still make it a leading performer in some roadway applications.

### LEDiL C13301 STRADA-2X2-T3

This is a Type 3 roadway optic, typically situated at the side of a highway and throwing light across several lanes of traffic. The polar plot on the left of Figure 10 shows that both the XP-G2 and XP-G3 S Line LEDs have excellent peak candela at about 70 degrees from normal, and the XP-G3 S Line LED tends to add more street-side light in the angles between 10 and 60 degrees. The XP-G3 LED also has a smoother intensity distribution as seen in the Bird's Eye View on the right in Figure 10. Because the XP-G4 LED is designed for high intensity in the normal direction, it has the highest illuminance directly below the pole and lowest peak candela at 70 degrees, both of which are generally detrimental to performance in Type 3 optics.

In Type 2 (not shown) and Type 3 Roadway Optics, theXP-G3 S Line LED continues to deliver excellent peak candela and the widest peak angle, allowing for greater pole-to-pole spacing, resulting in cost savings.

C13301 STRADA-2X2-T3

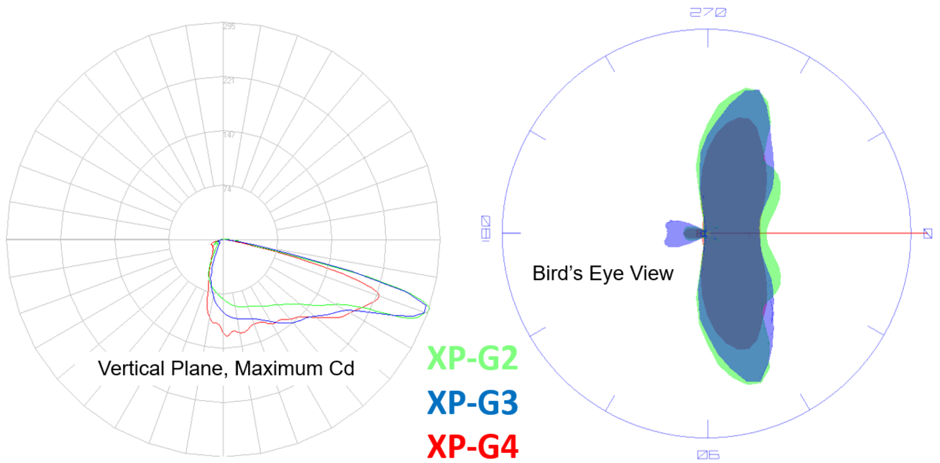



**Figure 10: Polar plots of XP-G2, XP-G3 S Line, and XP-G4 LED performance in a Type 3 C13301 STRADA 2X2 T3 roadway optic, normalized for total lumens**

### LEDiL C14680 STRADA-2x2-VSM

This is a Type 5 square optic commonly used for parking lots. In this case, the XP-G2 LED has the highest peak intensity, followed closely by the XP-G3 S Line LED, and the peak occurs at the largest angle from normal. The XP-G4 LED throws more light downward directly below the fixture rather than outward. Any of these three generations could be designed-in depending on the unique illumination and spacing requirements of the project. For example, higher illuminance levels and shorter pole-to-pole spacing would favor the XP-G4 LED, while lower levels and further spacing would favor the XP-G3 S Line and XP-G2 LEDs.

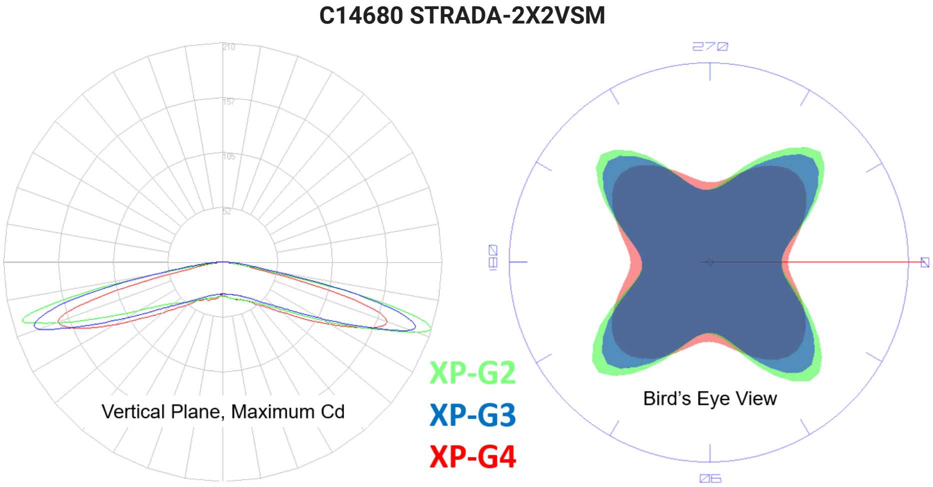



**Figure 11: Polar plots of XP-G2, XP-G3, and XP-G4 LED performance in a Type 5 C14680 STRADA 2X2 VSM streetlight optic, normalized for total lumens**

## Torch and Portable Lighting Optical Analysis

The XP-G2 LED has a long history of use in portable torch applications, and the XP-G4 LED builds on that success with even higher peak intensity than the XP-G2 LED while matching color over angle.

### LEDiL CA18102 TINA-Y-RS

This is a 14° spot optic designed for compact torches and headlamps and is compatible with LEDs up to a 3535 package. The XP-G4 LED had about 1% greater peak luminance than the XP-G2 LED at identical operating conditions. Because the XP-G4 LED has doubled the maximum drive current from the XP-G2 LED, it could deliver significantly more light to the center of the beam if designed to operate at a higher drive current.

**Table 8: Performance comparison in LEDiL CA18102 TINA-Y-RS optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 14.2 | 25.1 | 2231 | -0.9% |
| XP-G4 | 14.9 | 25.7 | 2253 | --- |

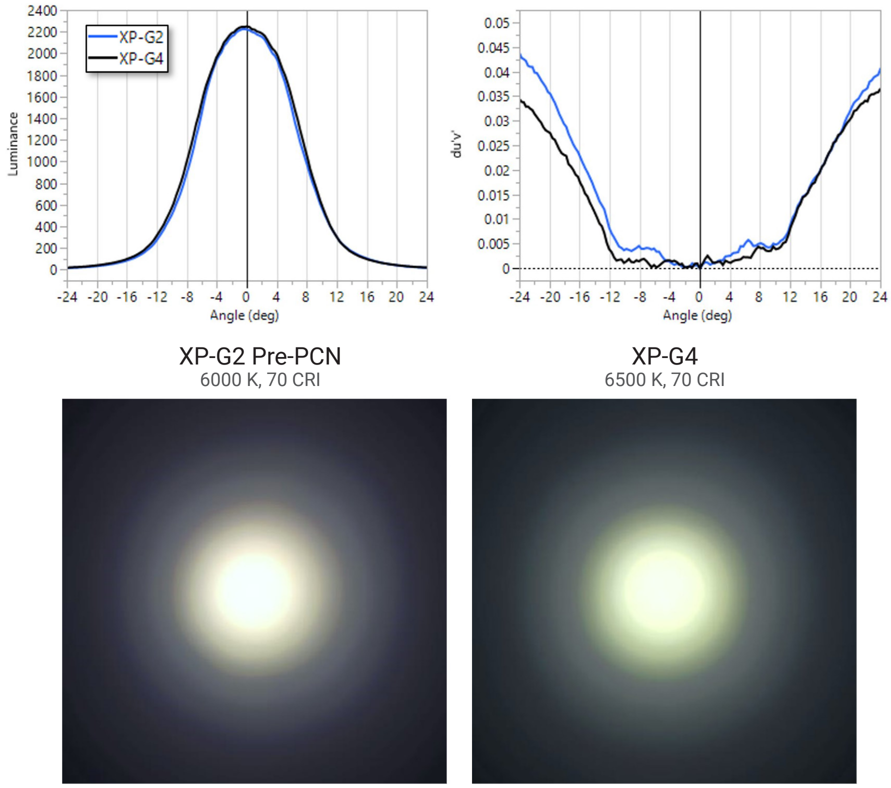



**Figure 12: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL CA18102 TINA-Y-RS optic**

### LEDiL CA18106 TINA-Y-WW

This is a small 55° wide-beam optic also designed for compact torch, headlamps, and some specialty indoor architectural applications. The XP-G4 LED maintains a 16% intensity advantage over the XP-G2 LED while keeping a nearly identical view angle and field angle. The color over angle is also similar.

**Table 9: Performance comparison using LEDiL CA18106 TINA-Y-WW optic**

| LED | View Angle (°) | Field Angle (°) | Peak Luminance (lm) | % Change From XP-G4 |
|---|---|---|---|---|
| XP-G2 (Pre-PCN) | 22.8 | 41.9 | 1009 | -16.4% |
| XP-G4 | 23.3 | 42.3 | 1207 | --- |

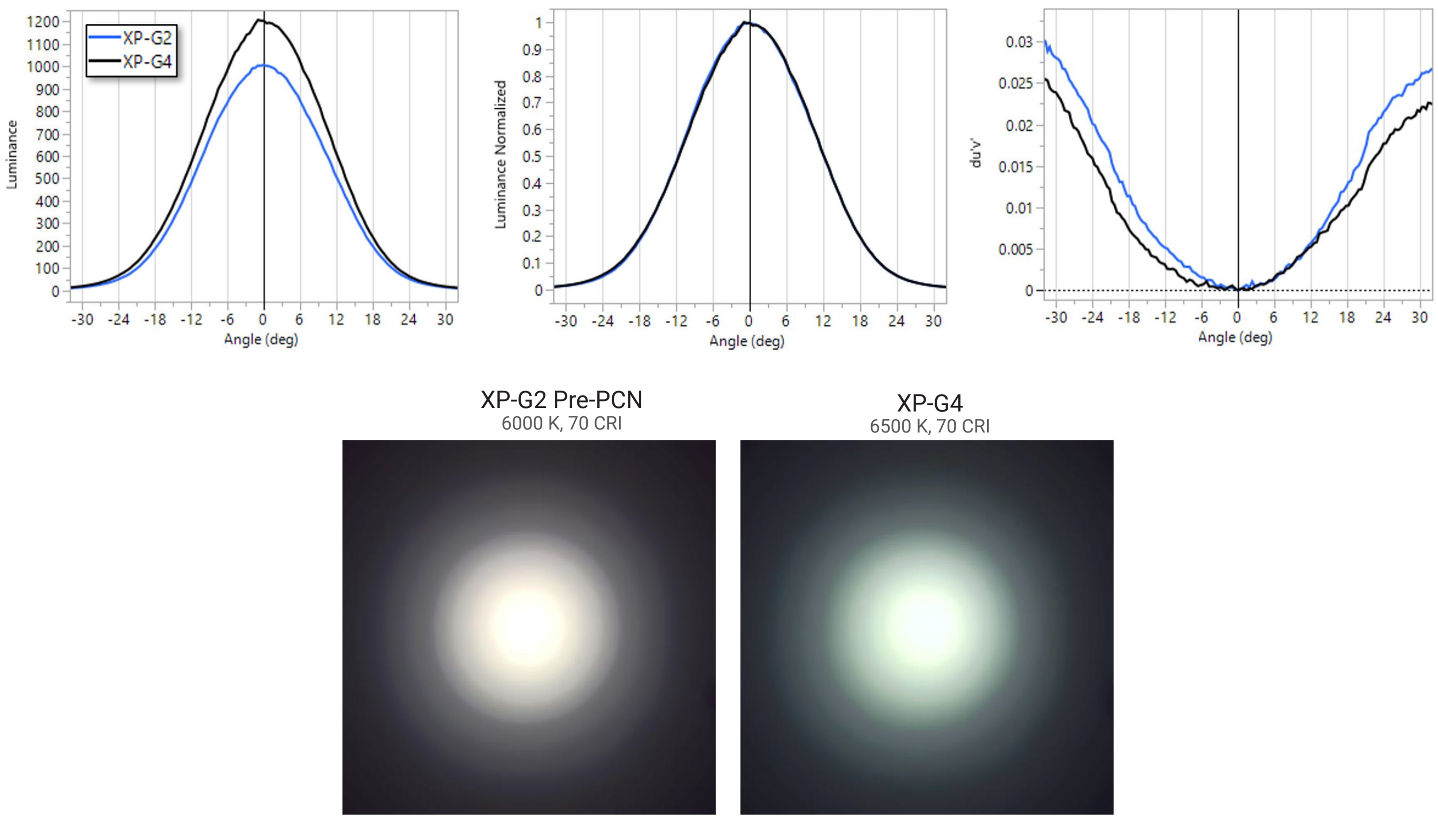



**Figure 13: Luminance and color over angle data (top) with corresponding true color beam projection images (bottom) from the LEDiL CA18106 TINA-Y-WW optic**

## THERMAL TESTING

### Advantages of Direct Thermal Path PCB on Output and LES Temperature

The XP-G4 LED design enables the use of a new PCB technology often referred to as "Direct Thermal Path" (DTP) or "Copper-pedestal" that allows direct thermal connection between the LED thermal pad and the base copper layer of the PCB. Figure 14 below illustrates the DTP technology in cross-section with an XP-G4 LED soldered onto a Rayben MHE®301 starboard.

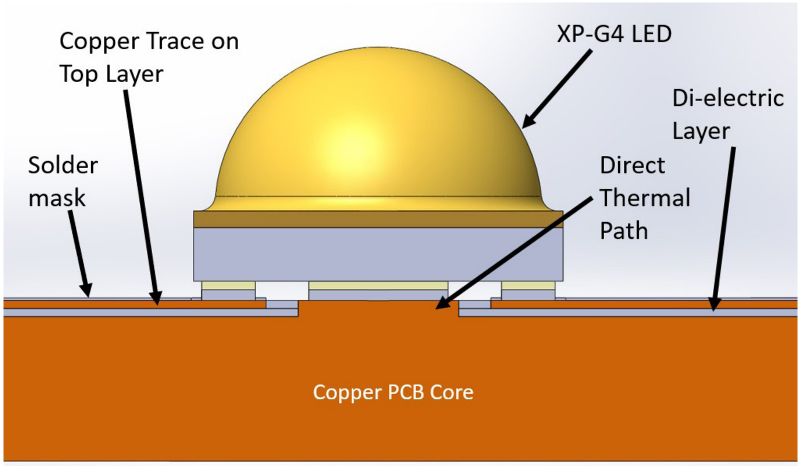



**Figure 14: Cross-section illustration of an XP-G4 LED soldered onto a direct thermal path (DTP) copper core board such as MHE® 301 from Rayben**

The copper core of the board extends up through the solder mask layer in a continuous piece, allowing the large neutral thermal pad of the XP-G4 LED to directly solder onto the copper core for maximum heat dissipation. The anode and cathode are soldered onto 2-ounce copper traces that are electrically isolated from the copper core by the dielectric layer. In testing, Cree LED has found that Rayben's MHE®301 DTP PCB technology outperforms standard aluminum-core MCPCBs in both light output and thermal management for higher-current (> 2 Amp) applications.

## Steady-State (30-second) Thermal and Flux Measurements

### Test Methods

Cree LED has conducted extensive testing on Rayben's MHE®301 technology and the advantages are demonstrated in the following sections. These data in the following sections were collected by fixing the PCBs onto a thermoelectric cooler (TEC) set to 20 °C mounted in a 2-meter sphere. The LEDs were energized at the specified current for 30 seconds before recording measurements, to help inform on ANSI FL-1 Standard Testing. LED encapsulant temperature data was captured using a FLIR E64501 thermal imaging camera. The PCB temperature (Tc) was measured with a thermocouple about 1 mm from the LED base on an exposed metal pad. This temperature floated above 20 °C to a new equilibrium as power to the LEDs was increased.

The following tests were carried out on the following two board types:

1. 62 mm x 39 mm PCBs
2. 20 mm starboards

These board types used two different PCB materials for direct comparison:

- 1.5 mm thick copper core board and 1-oz copper foil traces ("DTP Copper")
- 1.5 mm thick aluminum core board (2 W/m-K) and 1-oz copper foil traces ("Al Core")

These boards were mounted to a TEC as mentioned above. Note that these tests use extremely effective heat sinking and active cooling to show the fundamental capabilities of the LED. Performance will decrease with smaller PCBs or passive heat sinking. A size comparison is shown in Figure 16.

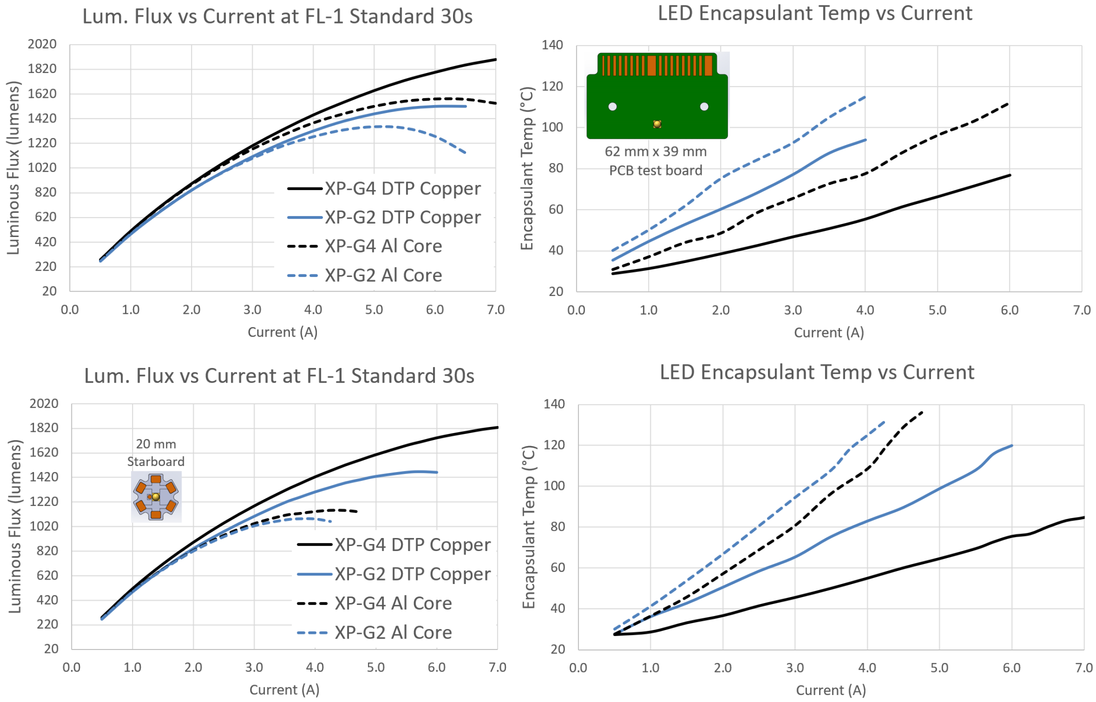



**Figure 15: Monitoring the LED encapsulant temperature and total luminous flux output of the XP-G2 and XP-G4 LEDs over current, using different PCB materials, different board sizes, and an actively cooled heat sink. The top row reflects using a larger 62 mm x 39 mm PCB, while the bottom row reflects using a standard 20 mm starboard.**

### Thermal Design Guidelines for XP-G4 LEDs

Cree LED's general recommendations for thermal management of XP-G4 LEDs are:

1. When operating at or above 2.0 A drive current per LED, or close-packing a large array of LEDs, use a direct thermal path PCB design to improve flux output and maximize lifetime.
2. When a DTP design is not being used, use at least 2-ounce copper foil and 2 W/m-k materials. Carefully measure the junction temperature in your system at operating conditions to prove that better heat dissipation is not needed.

## SUMMARY OF XP-G4 LED DESIGN GUIDELINES

The data above show that XP-G4 LED truly gives a "best of both worlds" combination: taking the excellent color over angle and peak intensity from the XP-G2 LED, while keeping the extremely high efficacy and reliability of the XP-G3 LED.

1. The XP-G4 LED excels in applications using narrow-beam optics such as sports lighting, indoor spot lighting, and torch or portable lighting.
2. Users can expect nearly identical color over angle and peak intensity to XP-G2 in most narrow-beam applications.
3. Using roadway optics, the XP-G4 LED will likely perform differently than the XP-G2 or XP-G3 LEDs, so Cree LED recommends further analysis to determine which LED is the best fit for the given optic and target illuminance requirements.
4. Total luminous flux output, efficiency, and reliability are similar to the XP-G3 LED in most applications.
5. The XP-G4 LED thermal performance is significantly improved compared to the XP-G2 LED, and will further benefit from using a DTP PCB when the drive current is at or above 2.0 A.

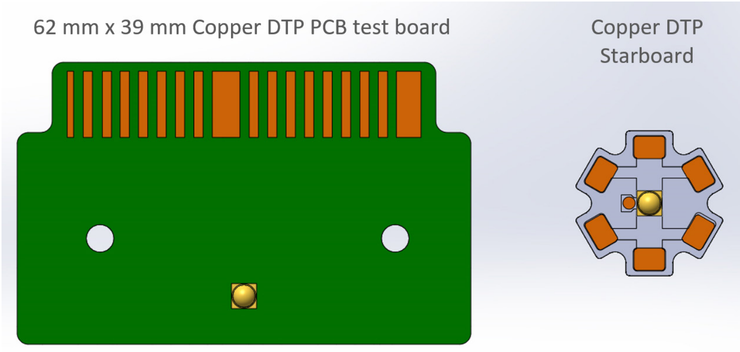



**Figure 16: Renderings of the test board used (left) with an XP-G4 LED compared to a regular DTP starboard size (right). The larger PCB on the left gives a thermal advantage and allows the LED to be pushed to extreme performance without thermal limitation from the substrate.**

**Improvements Provided By XP-G4 LEDs**

The thermal improvement of the DTP approach is shown clearly by Figure 15. The DTP starboard keeps the encapsulant at the top of the LED about 21 °C cooler at 2 A and 35 °C cooler at 3 A (the maximum current rating) compared to the Al-core starboard. At 3 A, the DTP starboard gives the XP-G4 LED an additional 13.6% luminous flux boost over the Al-core board.

Comparing the XP-G4 LED to the pre-PCN version of the XP-G2 LED, the significant improvement in thermal efficiency and luminous flux output can be seen. At 3 A on an Al-core, large PCB, the XP-G4 LED runs 27 °C cooler. (See the top right graph of Figure 15.) The 5% flux advantage of the XP-G4 LED at 0.5 A becomes an 18% flux advantage at 6 A (the maximum overdrive current) due to the improved droop and thermal efficiency of the the XP-G4 LED.

Pushing the XP-G4 LED to its limits with excellent heat sinking on the larger DTP PCB, we were able to reach 7.0 A of drive current at steady-state for over 30 seconds, and the LED flux continued increasing until 8.0 A (not shown). The “roll-over” point of the XP-G4 LED depends heavily on the heat sinking; it is over 8.0 A with excellent heat sinking, but drops to 4.25 A when using a smaller Al-core starboard with active heat sinking.

Cree LED recommends using a DTP PCB when designing a system with the XP-G4 LED to run at or above 2.0 A per LED to realize these flux gains and maximize LED lifetime.