# XLamp® XD16 Premium White Color-Tunable LED Arrays Reference Design

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Cree LED / 4001 E. Hwy. 54, Suite 2000 / Durham, NC 27709 USA / +1.919.313.5330 / www.cree-led.com

## INTRODUCTION

The new XLamp® XD16 Premium White (PW) LED improves on the original XD16 LED design by giving better optical control, less crosstalk and more uniform color over angle while maintaining extremely high lumen density in a 1.6 mm by 1.6 mm ceramic package. To take advantage of this high lumen density, small color-tunable arrays can be designed for indoor directional applications such as architectural lighting, retail show room lighting and art gallery spot lighting.

However, tightly packing these LEDs has tradeoffs which must be carefully considered in any new design. Generally, smaller LED-to-LED spacing will increase temperature, decrease lumen output and cause a color shift away from the binned color point.

When mixing LED colors or CCTs, the arrangement of each type should also be optimized based on several factors to achieve good color mixing and the best thermal dissipation. Mixing with two colors vs. three colors also has several tradeoffs which are discussed below.

## DESCRIPTION OF COLOR-TUNABLE ARRAY USED FOR TESTING

For these tests, a 12-mm diameter circular LES was defined to encompass all 28 LEDs on the board. The average edge-to-edge gap between LEDs varies but was typically 200-300 µm. Four total arrays were built.

- 2-channel: XD16 Standard LED (14x 5000 K 90 CRI and 14x 2700 K 90 CRI)
- 2-channel: XD16 Premium White LED (14x 5000 K 90 CRI and 14x 2700 K 90 CRI)
- 3-channel: XD16 Standard LED (8x 5700 K 90 CRI, 8x 4000 K 90 CRI and 12x 2200 K 90 CRI)
- 3-channel: XD16 Premium White LED (8x 5700 K 90 CRI, 8x 4000 K 90 CRI and 12x 2200 K CRI)

The available optics for a 12-mm diameter array are typically designed for chip-on-board (COB) LEDs. These were repurposed for this array of discrete components. The optics used in testing were:

1. LEDiL YASMEEN-70-S
    a. The YASMEEN family is designed for COBs up to 14.5-mm LES size. They are intended for track lighting in high-contrast retail without spill light. The Spot “S” is a 70 mm diameter optic designed with a 15° wide beam (LES 10 mm).

2. LEDiL YASMEEN-70-M
    a. The Medium “M” is a 70 mm diameter optic designed with a 26° wide beam.

3. LEDiL AMY-70-WW
    a. The AMY product family is designed for low profile track and downlights and this 70 mm diameter ultra-wide version is intended to have an ~60° wide beam.

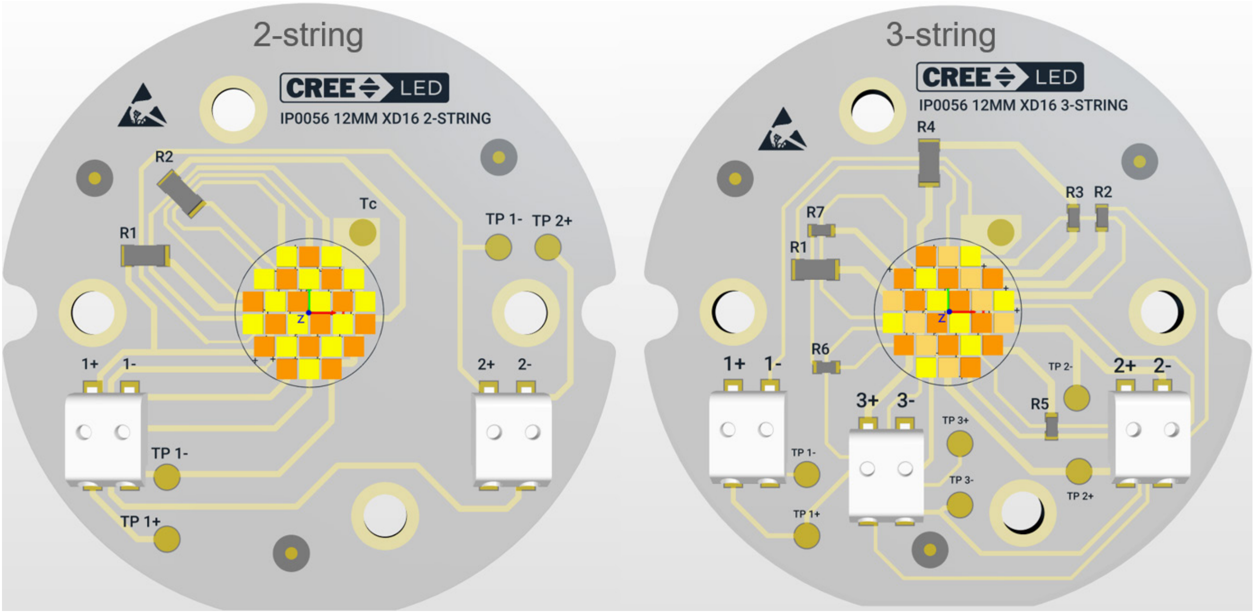


**Figure 1: Test boards used for this study, showing the 2-string arrangement at left and the 3-string arrangement at right. The average gap between LEDs was 200-300 µm.**

The arrays were mounted to a thermoelectric controller (TEC) set to 25 °C and measured after a steady-state temperature was reached. A total luminous flux output of 1000-lumens was targeted at each CCT for a consistent user experience. The dependent electrical power input, substrate temperature and LES temperature were recorded.

## CHOOSING BETWEEN 2-CHANNEL AND 3-CHANNEL CCT MIXING

The first decision to be made is between 2-channel and 3-channel CCT mixing. Below are the primary considerations when choosing:

- 2-channel reduces the complexity of the circuitry, connectors and controls.
- 2-channel can achieve a higher lumen density and higher efficacy at the warmest and coolest CCTs because half of the LEDs are used instead of one third.
- 3-channel can achieve a wider CCT range without falling far below the black body line (BBL) due to the extra anchoring point in neutral white.
- 3-channel is more likely to have splotches or dark spots in the projected beam due to larger gaps between energized LEDs.

### Luminous Efficacy and Color Rendering Performance of 2-Channel and 3-Channel Arrays

The testing below was carried out at a nominal 1000-lumen output without secondary optics, corresponding to a lumen density of 8.84 lumens/mm$^2$. Figure 2 shows that using all three strings simultaneously gives a small efficacy advantage in neutral white (4000 K) because all the LEDs can be equally energized. At the extremes of CCT, only one or two strings can be active, so the differences are minimal.

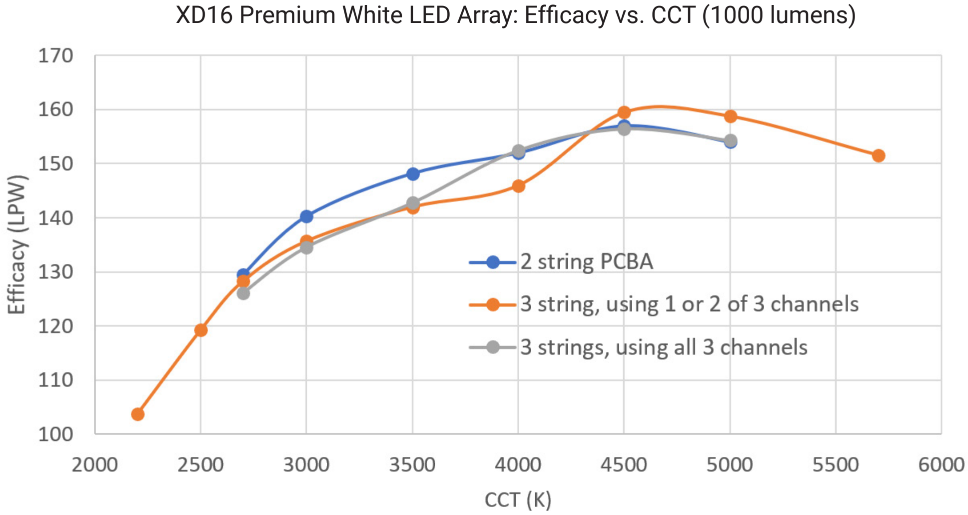


**Figure 2: Efficacy vs. CCT of the 12-mm XD16 Premium White LED arrays on a 25 °C TEC without an optic, operating at nominally 1000 lumens. The lines compare the differences between the 2-string and 3-string boards and the operation of the 3-string board in a 2-string mode.**

In Figure 3 below, the conclusion is that CRI and CRI R9 will tend to be higher when a variety of LEDs are mixed which creates a fuller spectrum. For the highest possible color rendering, select cool white, neutral white and warm white LEDs for a CCT-tunable array and use all three strings whenever possible.

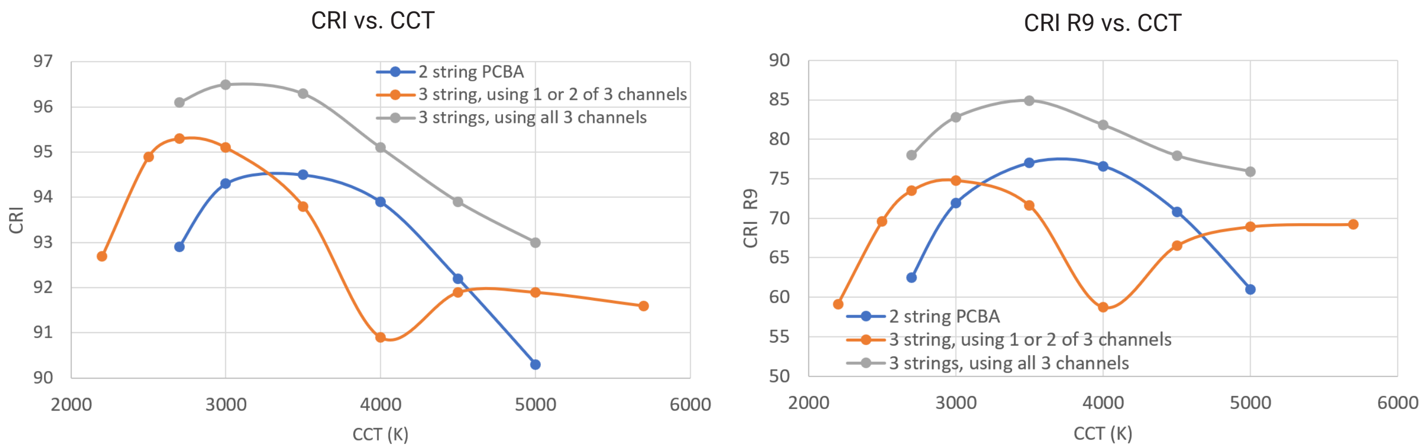


**Figure 3: Color rendering performance of the XD16 Premium White LED array across the CCT range. The lines compare the differences between the 2-string and 3-string boards and the operation of the 3-string board in a 2-string mode.**

The reflector and first diffuser were necessary for good color mixing. The secondary diffuser showed a further marginal improvement and was used during data collection. More details will be shared in a later section.

## COLOR TUNING CONSIDERATIONS ACROSS THE CCT RANGE

When choosing the LEDs for these boards, it was important to consider the line of interpolation in the color space between them. When tuning between two black-body color points over a large range of CCT (2000 K or more), starting with LEDs slightly above the black body line will help to compensate for the curve shown below in Figure 4 and prevent the mixed color point from being far below the black body line.

Furthermore, using 3 strings provides a center anchoring point which constrains the hue to a narrow range near the black body line. However, if energizing all three strings in mixing to achieve neutral white, the cool white and warm white strings can pull the neutral white color point downward from the anchoring point to below the black body line. For this reason, we chose a neutral white bin slightly above the black body line to compensate. This allowed us to maximize efficacy at 4000 K.

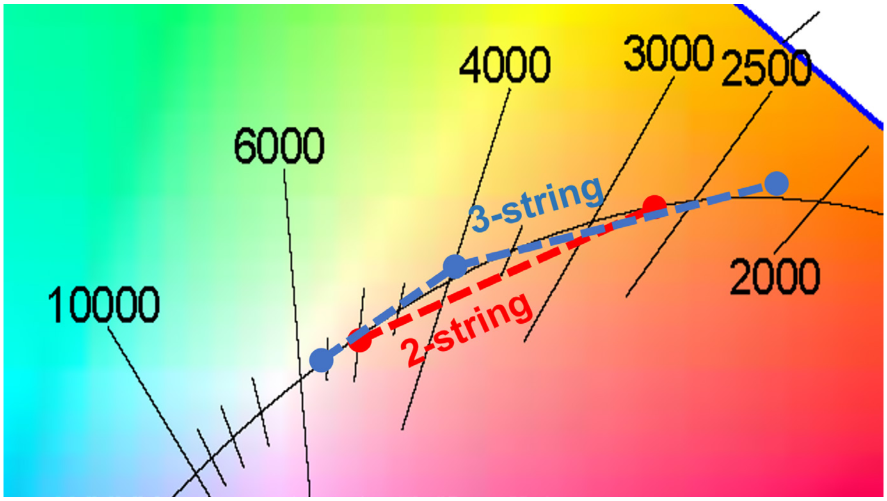


**Figure 4: Comparison of color output near the black-body line when using 2-channel vs. 3-channel white mixing solutions, as was done in this reference design. Note that the 2-channel approach falls well below the black body line at middle CCTs.**

## IN-OPTIC PERFORMANCE COMPARISON OF XD16 PREMIUM WHITE AND XD16 STANDARD LEDS

### Light Intensity Distribution in Spot, Medium and Wide Optics

The improved directionality and reduced crosstalk of XD16 Premium White LEDs should result in better optical efficiency in most optics. Before testing in secondary optics, each array was tuned to 3000 K at 1000 lumen output in an integrating sphere without the optics. These power inputs were held for the in-optic goniometer testing shown below in Figure 5. The data clearly show that with the same total lumen output from the LEDs, the Premium White version delivered higher intensity in the spot, medium and wide optics.

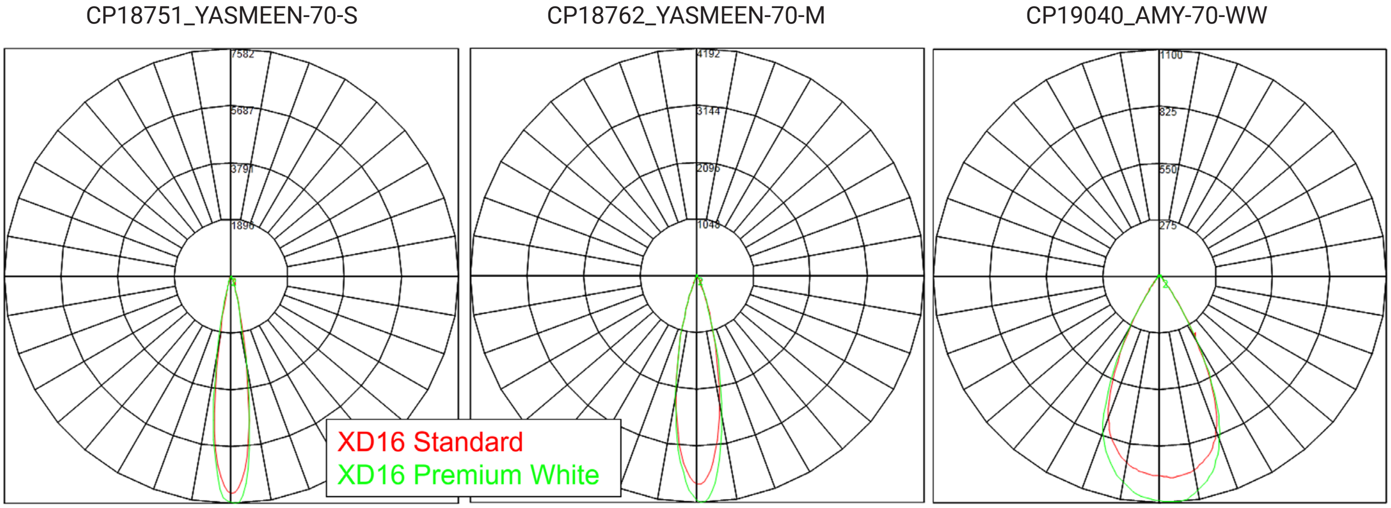


**Figure 5: Polar plots from goniophotometer measurements of the 12-mm 2-string arrays measured with secondary optics at 3000 K color tuning. In all cases, the XD16 Premium White LED outperforms the Standard in intensity due to reduced crosstalk light absorption and reduced spill light.**

Furthermore, Table 1 shows that the total lumen output from the Premium White version was higher in all cases, leading to an average increase in optical efficiency of 4% and about 10% higher LPW of the final luminaire. The beam angle and field angles were narrowed slightly in the medium and wide optics, while they were nearly identical in the spot optic.

**Table 1: In-optic performance quantitative comparison between XD16 Standard and XD16 Premium White 2-string LED arrays. In all cases, Premium White has higher max candela, higher optical efficiency and higher efficacy. Power inputs were normalized to 1000 lumens on a bare board in an integrating sphere before testing in-optic.**

| | YASMEEN-70-S | | YASMEEN-70-M | | AMY-70-WW | |
|---|---|---|---|---|---|---|
| | Standard | Prem. White | Standard | Prem. White | Standard | Prem. White |
| Max Candela | 7242 | 7577 | 3848 | 4186 | 978 | 1099 |
| Total Lumens | 755 | 802 | 718 | 763 | 744 | 793 |
| Optical Eff. | 76% | 80% | 72% | 76% | 74% | 79% |
| Beam Angle | 17.1 | 17.2 | 23.4 | 22.9 | 52.7 | 51.7 |
| Field Angle | 29.7 | 29.9 | 41.3 | 40.9 | 73.6 | 73.0 |
| LPW | 98 | 107 | 93 | 102 | 96 | 106 |

## Maximum Output of the 12-mm Array in Spot Optic

The Premium White 2-string array was further pushed to its upper limits with active heat sinking to test the lumen density and candela. At 55 W input power mixed to 4000 K, it produced 6076 lumens (at 110 LPW), corresponding to about 54 lumens/mm$^2$. This lumen output is roughly double what can typically be expected from a COB of a similar size. It also achieved over 42,000 maximum candela in the YASMEEN-70-S optic.

## Color Mixing in Projected Beam of 2-Channel Arrays with Secondary Optics

The color uniformity over angle was measured in the goniometer to compare XD16 Standard and Premium White LED arrays in each secondary optic. In general, the XD16 Premium White LED has improved color over angle as a single LED measured in far-field. The in-optic color uniformity will depend on how each optic extracts and mixes light from the different LED types.

Figure 6 below shows that in the Spot optic, they have similar color uniformity. In the Medium optic, the XD16 Premium White LED has nearly flawless color uniformity while the XD16 Standard LED has a strong shift starting at 10 degrees. In the Wide optic, both have similar shapes but the XD16 Premium White LED has a larger amplitude of color shift in the outer portions of the beam.

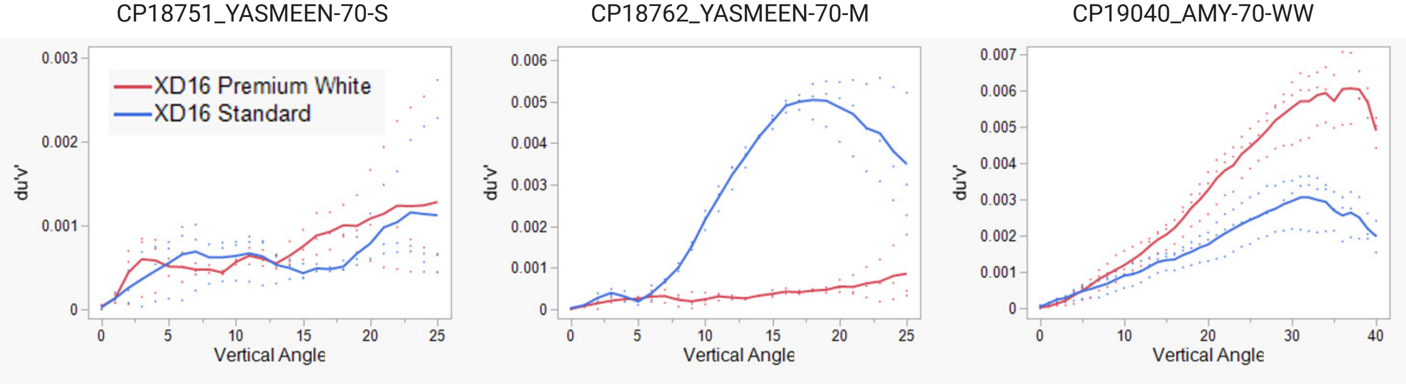


**Figure 6: In-optic color uniformity performance of the 2-string 12-mm arrays tuned to 3000 K. The data points shown are from the 0-, 45- and 90-degree horizontal sweeps.**

## COLOR POINT SHIFT BY ARRAY PITCH IN XD16 STANDARD AND XD16 PREMIUM WHITE LEDS

Tightly packed LEDs will have a natural color shift in the +CCx and +CCy direction due to blue light from one LED exciting the phosphor of a neighboring LED. This decreases the natural blue peak intensity and increases the green/yellow/red peak intensity (depending on LED color selection). This effect can be stronger in LEDs with thicker phosphor layers (warmer CCTs). Limiting this light recirculation will minimize the magnitude of the color shift. The XD16 Premium White LED reduces this light circulation compared to the XD16 Standard LED using an innovative internal reflector and phosphor design.

This time-zero color shift should be expected and designed for using the data below, especially for the XD16 Standard LED. Note that these are 3x3 arrays, and larger arrays may have a larger color shift. This can be compensated for by ordering color bins in the -CCx and -CCy direction of the intended final color target, also accounting for color shifts caused by operating temperature and secondary optics or diffusers.

### Varying Pitch Array Measurement Method

The data below were collected in an integrating sphere, without a secondary optic. In each array, 1 LED was placed in the center position and measured by itself (Figure 7A). Then, 8 more LEDs were populated around it on electrically dead pads, and the center LED was measured again (Figure 7B). This test shows the nearest-neighbor effects acting on each LED as a function of array spacing.

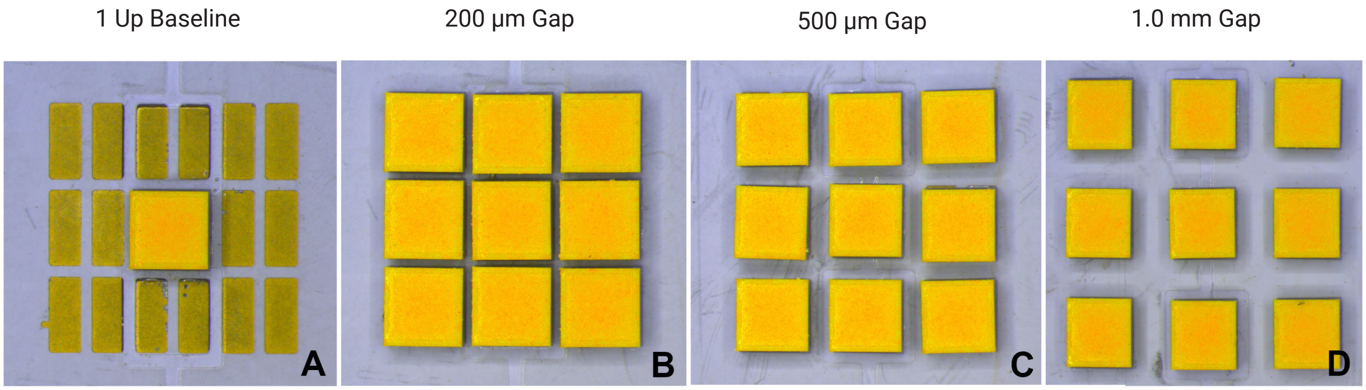


**Figure 7: Build sequence for measuring the color differences of a single LED, versus that same LED surrounded by others at varying distances.**

### Results by Array Pitch and LED Choice

In Figure 8, it is clear that the XD16 Premium White LED has a drastically reduced color shift compared to the XD16 Standard LED when built into tightly packed arrays. For example, a 3x3 array of XD16 Standard LEDs with a 500 µm gap between LEDs shifts by almost the full length of a 4-step ellipse. A 200 µm gap array of the same components shifts by a full ANSI bin.

By contrast, the XD16 Premium White LED has a negligible shift of <0.001 CCx and <0.001 CCy in all array spacings. The reduction in light recirculation of the XD16 Premium White LED is evident in the top-down light-up images in Figure 8.

When the gap between LEDs is over 1 mm, the difference between the color shift of the two products is negligible.

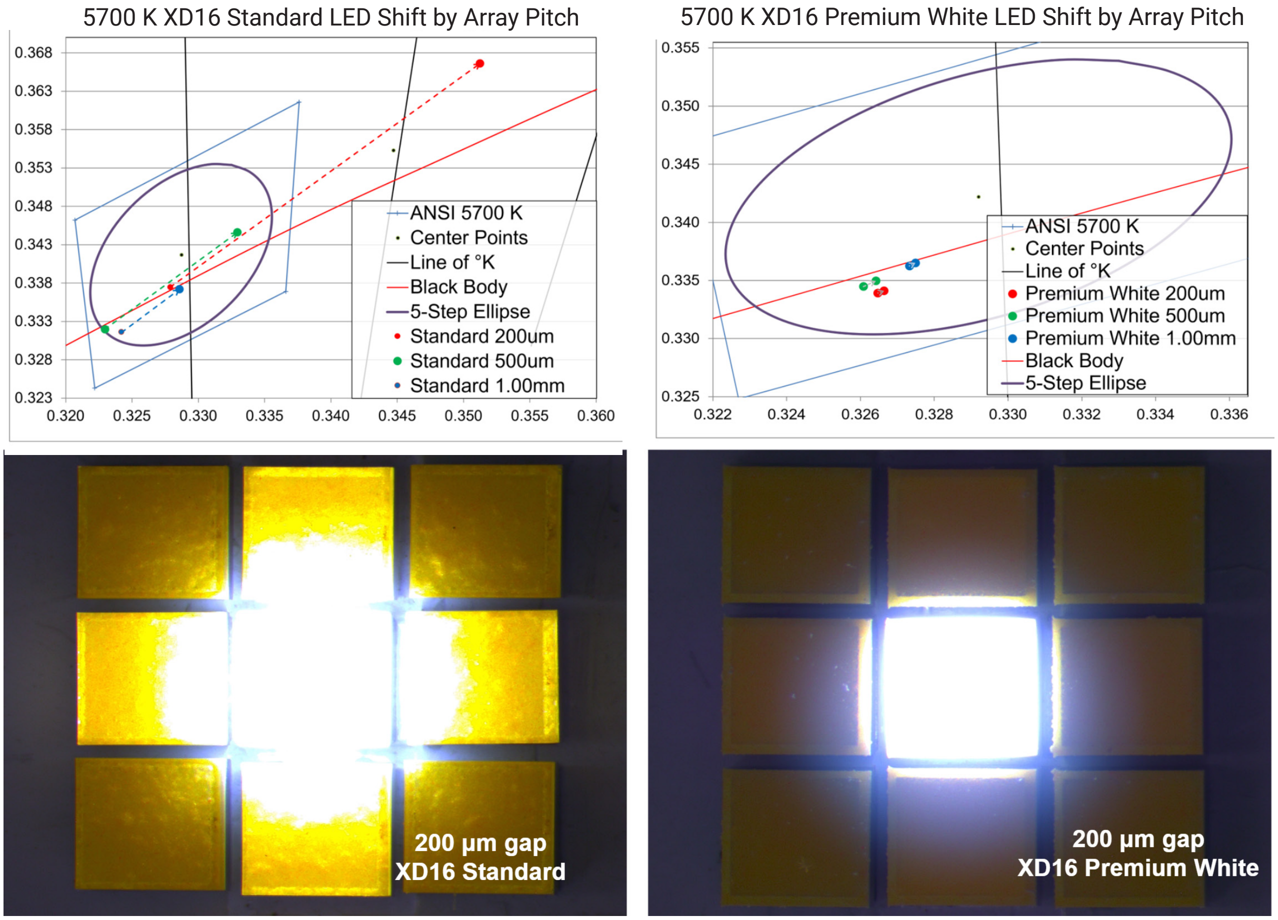


**Figure 8: Color shift of nominally 5700 K LEDs before and after adding neighboring LEDs of the same CCT. The XD16 Standard LED is shown in the left column to have a large shift, while the XD16 Premium White LED in the right column has only a small shift.**

Testing at 2700 K by the same method shows similar results. Figure 9 compares the XD16 Standard LED to the XD16 Premium White LED.

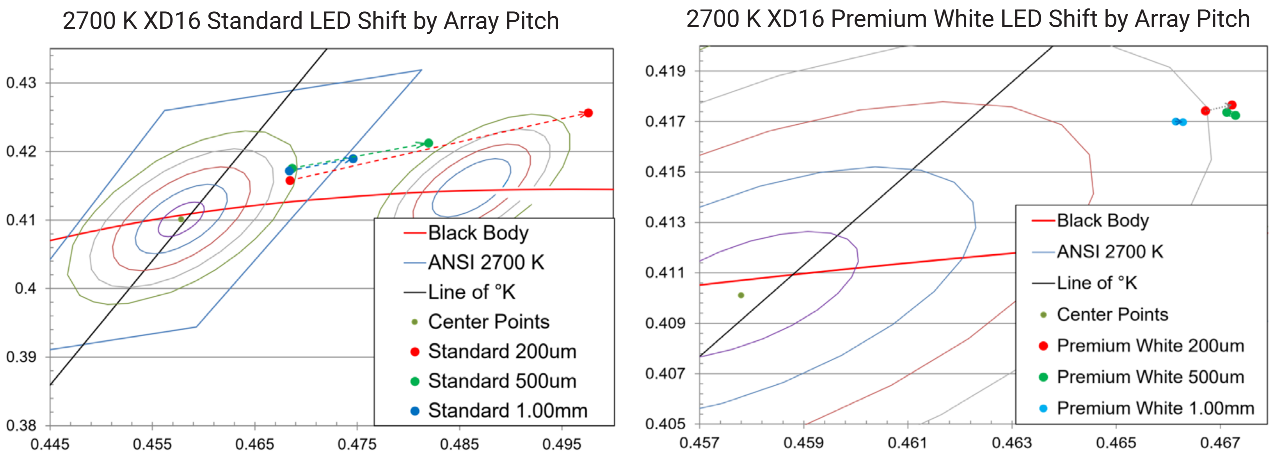


**Figure 9: Color shift of nominally 2700 K LEDs before and after adding neighboring LEDs of the same CCT. The XD16 Standard LED is shown at left to have a large shift, while the XD16 Premium White LED shown on the right has only a small shift.**

## SUMMARY OF GUIDELINES FOR DESIGNING 2-CHANNEL AND 3-CHANNEL ARRAYS WITH THE XD16 PREMIUM WHITE LED

Many design tradeoffs are covered above in detail. Below are the most important takeaways to consider when designing color tunable arrays with the XD16 Premium White LED:

- If a hue shift above or below the black body line can be tolerated, a 2-channel design will have less complexity, higher efficacy (on average), but lower color rendering.
- For the best CCT range, color accuracy, color rendering and hue control, use a 3-channel design.
- In all cases, the bookend CCTs should use LEDs above the black body line to minimize the dip below the black body line during mixing.
- When an array pitch of 1 mm or less is used, use the XD16 Premium White LED to prevent time-zero color shifts from nearest neighbor effects. If using the XD16 Standard LED, select LED color bins to compensate for the expected shift.
- When the highest optical efficiency and max candela is required, the XD16 Premium White LED delivers a higher percentage of light to the target in most secondary optics.