3-Channel White Tunable 1000 lm 4" Downlight Reference Design

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DESCRIPTION OF REFERENCE DESIGN BUILD

Two 3-channel boards with an identical 35-mm LES size were built into a basic wall-mounted downlight. They are refered to as Board 1 and Board 2 below.

1. Using three discrete bins of J Series® Pro9™ 90 CRI White LEDs: 6500 K, 4000 K and 2700 K.
   a. Channel 1: 14x 2835 3-V G Class Pro9 6500 K 90 CRI White
   b. Channel 2: 12x 2835 3-V G Class Pro9 4000 K 90 CRI White
   c. Channel 3: 12x 2835 3-V G Class Pro9 2700 K 90 CRI White

2. Using seven colors of J Series Color LEDs, split among the 3 channels based on color space:
   a. Channel 1: 6x 2835 3-V N Class PC Amber, 6x 2835 3-V N Class Red (two parallel strings)
   b. Channel 2: 2x 2835 3-V N Class Royal Blue, 4x 2835 3-V G Class Pro9 6500 K 90 CRI White (one string)
   c. Channel 3: 9x 2835 3-V N Class PC Lime, 6x 2835 3-V N Class PC Mint, 3x 2835 3-V N Class Green (three parallel strings)

6500 K, 4000 K and 2700 K
J Series Pro9 90 CRI White

J Series Color LEDs
6 Colors + 6500 K Pro9 90 CRI White

Figure 1: Comparison of Boards 1 (left) and 2 (right). Board 1 uses only 90 CRI White LEDs; Board 2 uses 6 different colors plus 6500 K 90 CRI LEDs for the highest CCT range of 90+ CRI.

Optics and Housing Used

The boards were built into an inexpensive ASD Lighting 4” diameter wall-mounted downlight housing. For enhanced color mixing, three optical elements were chosen as shown in Figure 2.

1. LEDiL C12598_LENINA-M reflector

2. LEDiL C12606_LENINA-DL diffuser

3. BrightView C-HE55-PE07-S-M01 secondary diffuser

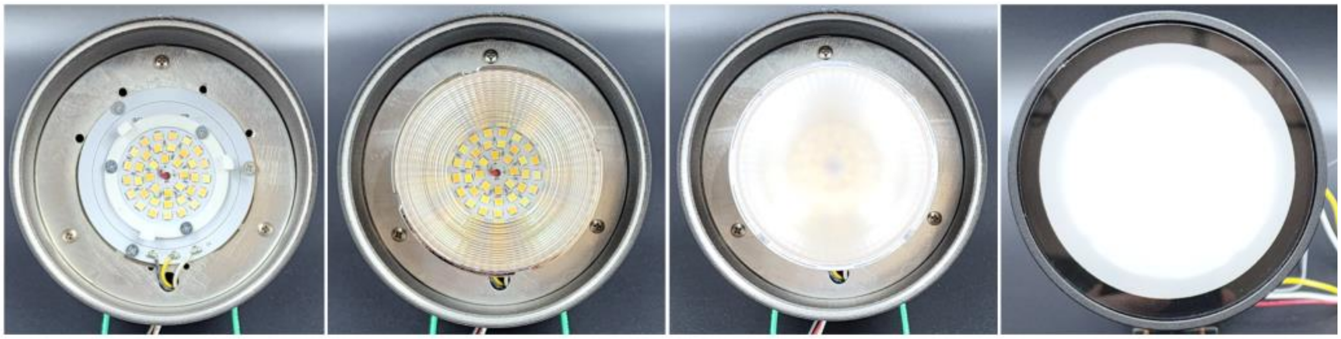

Figure 2: Build sequence (left to right) showing each optical diffusing element added.

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

PCB Substrate and Thermal Management Used

There were two clear options available for the PCB substrate: FR4 or aluminum-core PCB. The benefit of a FR4 board would be having 2 signal layers of copper for the circuit design. This would allow a complicated circuit design without jumper resistors and easier trace routing. However, the disadvantage of FR4 PCB material is poor thermal conductivity (0.25 W/mK).

On the other hand, the aluminum-core PCB would allow a higher thermal conductivity (1 to 3 W/mK) but only has a single signal layer to work with.

A single layer 2 W/mK aluminum-core PCB was selected because a single signal-layer design was feasible with the use of "jumper" zero-ohm resistors and the increased thermal conductivity would be beneficial. After the fixture was assembled and tested at the relevant currents across the CCT range, the maximum steady-state Tc temperature was recorded at 43.7 °C which is within the acceptable range for these LEDs. The determination was that the performance is limited by the maximum current of the LEDs, and not by the thermal management of the system.

OPTICAL CONSIDERATIONS FOR TUNABLE WHITE

White LED Selection

The J Series Pro9 board (Board 1) was built with 6500 K, 4000 K, and 2700 K White LEDs to enable a wide range of color temperatures. This range could be achieved with 6500 K and 2700 K only, but the neutral White tuning would fall well below the black body line (BBL).

When the user needs 4000 K lighting, it would be easiest to turn on only the 4000 K channel. However, this uses only one third of the available LEDs and sacrifices efficiency. If the 6500 K and 2700 K channels are mixed with the 4000 K channel, the full board can be used to achieve the highest LPW and/or total lumen output. This effect is shown in Figure 3.

Note that there is a penalty of dropping below the BBL when adding the 6500 K and 2700 K channels. To compensate for the curvature of the black body, it is best to select the cool White and warm White LEDs to be above the BBL, while the neutral White LEDs are centered on the BBL, as was done for this study.

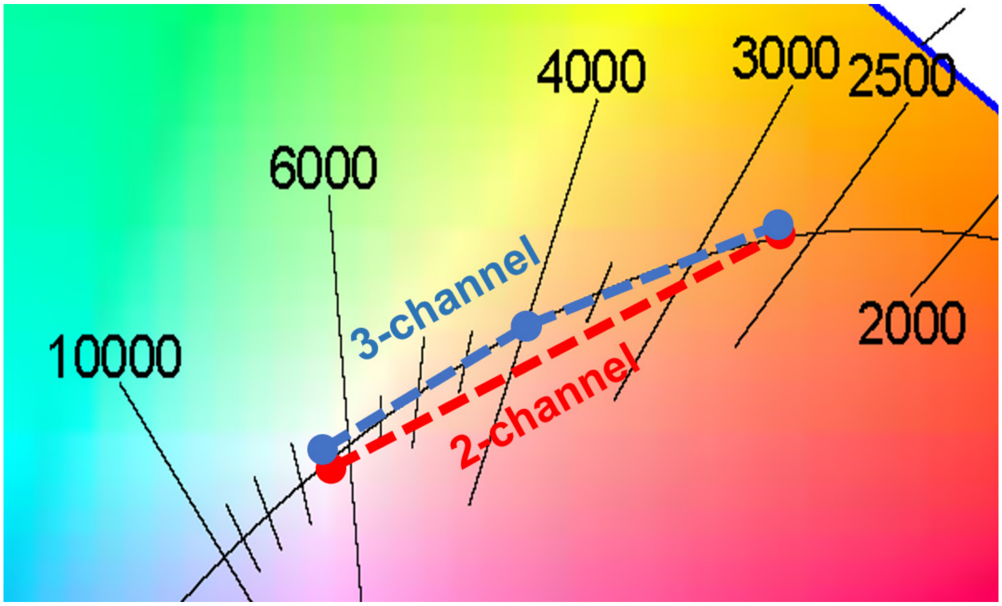

Figure 3: Comparison of color output near the black body line when using 2-channel vs. 3-channel White mixing solutions, as was done in this reference design. Note that the 2-channel approach falls well below the black body line at middle CCTs.

Color LED Selection

The J Series Color board (Board 2) went through several iterations of color LED selection until the widest CCT range of >90 CRI was achieved. The simplest 3-channel build would be three desaturated colors surrounding the White color space like a 6500 K 90 CRI White, a PC Mint/Lime, and a PC Amber.

However, mixing these three colors only yielded a narrow range of CCTs >90 CRI. By mixing neighboring color points in each channel, e.g. PC Amber + Red, the spectral range was widened for each channel and the CRI was increased.

The following guidelines should be considered when choosing LED colors for a color-mixing application:

- For the highest range of CRI, mix adjacent colors in each string to broaden the spectral contribution.
- For the highest efficacy, use narrower spectral ranges like Royal Blue, PC Mint and Red-Orange.
- For the widest gamut, use only saturated colors like Royal Blue, PC Lime and Red.

PERFORMANCE COMPARISON

Comparison of 2-Channel and 3-Channel Tuning Modes in White Board 1

Before exploring the data, it is important to note that the 3-channel White Board 1 could easily be operated across the CCT range using only 2 channels at a time. Figure 4 shows the improvement in LPW that can be gained by using all 3 channels by CCT at a fixed 1000 lm total output. The LPW advantage is greatest near Neutral White when all LEDs can be nearly equally mixed, culminating in a 10% LPW improvement at 4000 K compared to using only the 4000 K channel. There is no improvement near the starting and ending CCTs. The 3-channel mode also had a nominal 1-2 point CRI advantage and a 3-10 point CRI R9 advantage.

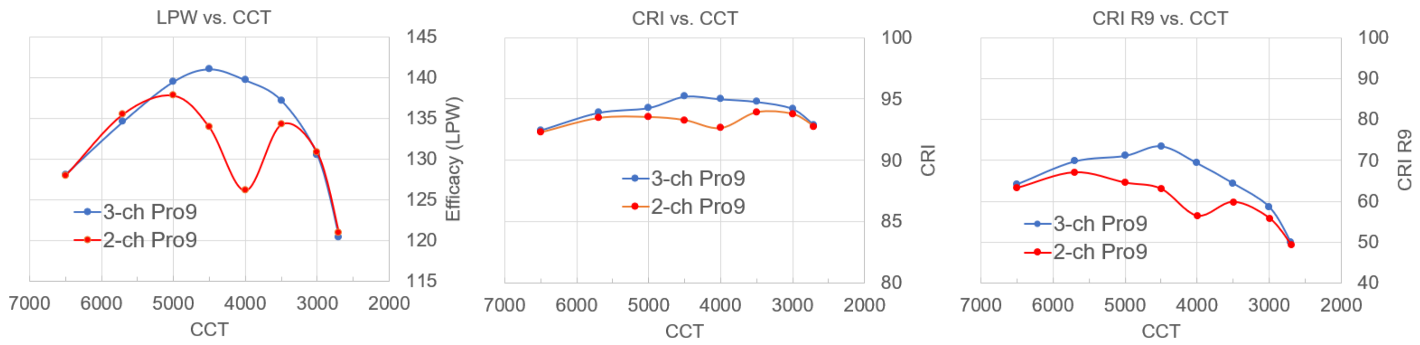

Figure 4: Comparison of LPW, CRI and CRI R9 across the CCT range of a single J Series Pro9 White downlight (with optics), operated in both 2-channel and 3-channel modes. The board's channels were 2700 K, 4000 K and 6500 K White.

Comparison Using All 3 Channels Simultaneously

Efficiency, CRI and CRI R9 data are shown over the full CCT range in Figure 5 below. Overall, the Pro9 board (Board 1) achieved a higher LPW at all color temperatures. This was impacted slightly by the two additional 6500 K LEDs on the board, but removing those would not be enough to close this gap.

Furthermore, the Pro9 board held >90 CRI at all CCTs because the three LED bins used were already >90 CRI. The color-mixing board was only able to hold >90 CRI starting from 4000 K and warmer because the CCT constrained the LEDs that could be used to fill the spectrum. Less-optimized iterations of the color-mixing board only had 90 CRI from 3000 K and warmer.

The color mixing board had an advantage in CRI R9 in warm White due to the highly saturated red content that was possible. It also will have a wider range of available hues away from the black body line.

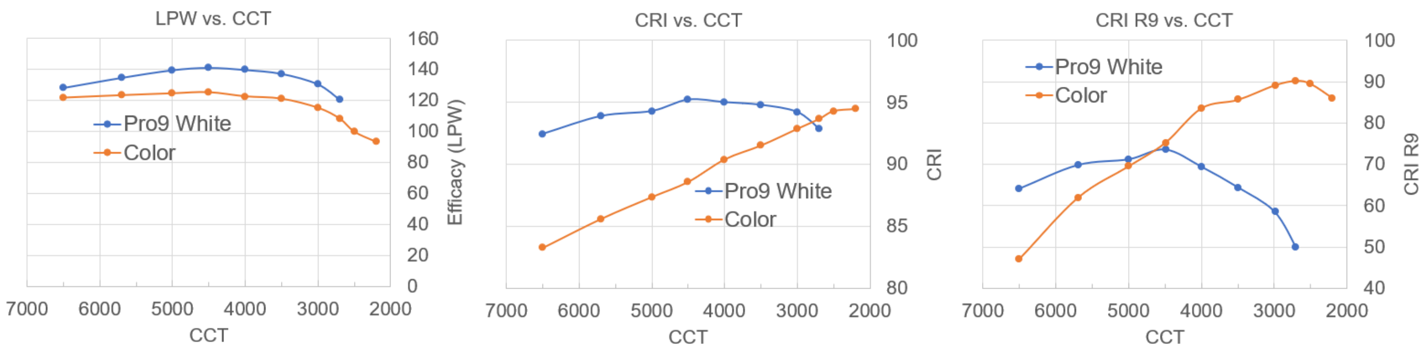

Figure 5: Comparison of the Pro9-based 3-channel White module vs. a 3-channel J Series Color module utilizing 7 different color LEDs. All conditions were measured at nominally 1000 lumen total luminaire output.

Maximum Output Comparison

The above data were taken at a fixed 1000 lm output. Tests were also performed to compare the maximum lumen output of each board at each CCT in the completed luminaire. The maximum output was defined by the maximum rated conditions of the LEDs used and the mixing needed to achieve each CCT. Results are shown in Figure 6 below. The Pro9 Board 1 holds a maximum output advantage at the CCTs between the channels present on the board because it can use all of the LEDs more evenly. For the same reason, the color-mixed Board 2 shows peak output in neutral White. The Pro9 Board 1 also holds a clear LPW advantage across the CCT range.

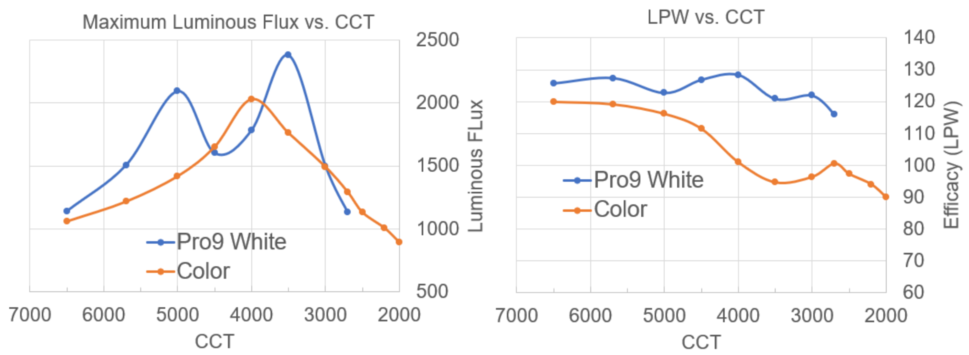

Figure 6: Maximum lumen output and resulting LPW at each CCT of the Pro9 Board 1 and color-mixed Board 2.

Light Intensity Distribution

The two luminaires had identical emission profiles even though they had different LED counts and arrangements. The LES size, reflector, diffusers and housing were all consistent and were the driving factors in these similarities. The polar plot overlay from goniometer testing is shown in Figure 7. The resulting beam angles (FWHM) were 100° and field angles (FWTM) were 149°.

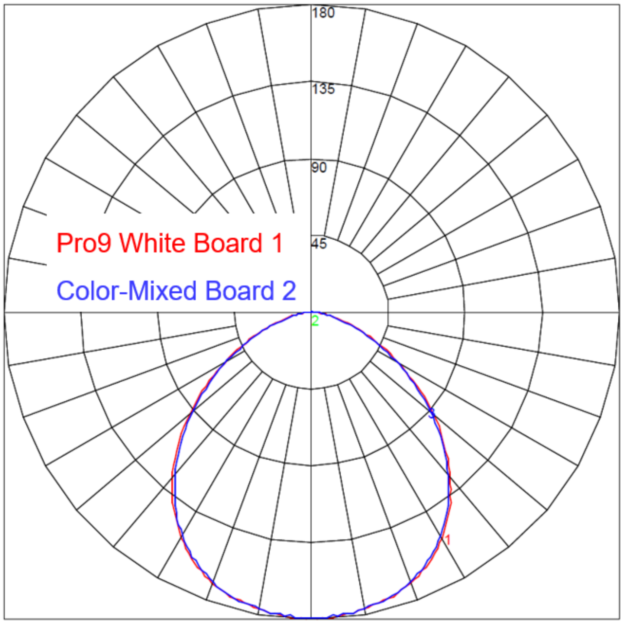

Figure 7: Light intensity distribution of the two luminaires as measured in a Type-C goniometer tuned to 3000 K.

Color Uniformity

The color uniformity of both fixtures is demonstrated in Figure 8 below. Both show excellent uniform white light when mounted to a reflective white wall. Board 2 had slightly worse color uniformity over vertical angle and more variation between horizontal planes when quantified by du’v’ in goniometer testing with both diffusers in place, shown in Figure 8. However, this difference is not visible to the naked eye.

Color over vertical angle of each luminaire

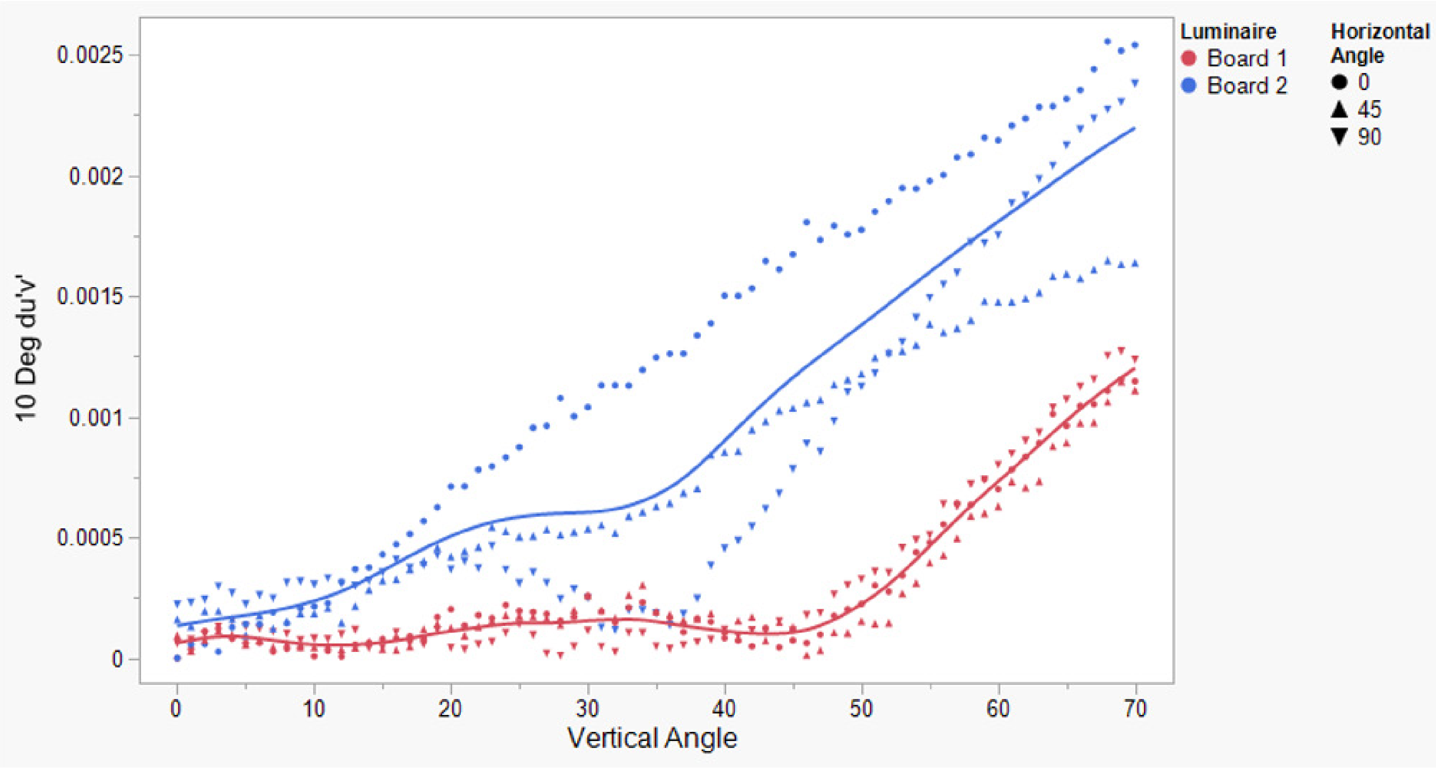

Figure 8: Color uniformity comparison of both luminaires over vertical angle, tuned to 3000 K. The shape of the markers represents the horizontal angle sampled. The fit line is a spline with Lambda = 100 averaging all three horizontal angles.

When the diffusers were removed (not shown), Board 2 had worse color uniformity compared to Board 1 due to the higher complexity of color mixing involved to generate white light. In most builds, only one diffuser may be necessary if only using Pro9 White LEDs.

Figure 9: True-color dark room comparison of the two modules tuned to 3000 K 90+ CRI in the wall-mounted downlight against a painted white background.

Spectral Comparison at 3000 K

A spectral comparison at 3000K 90+ CRI is shown in Figure 10 with basic color rendering metrics inset. Although the Pro9 Board 1 tends to have higher color rendering (CRI) and TM-30 Fidelity score (Rf), the Color board excels in gamut (Rg) and CRI R9 because the monochromatic LEDs help boost the saturation in specific wavelength bands like Red and Green. In this case, the Pro9 Board 1 also has more Cyan content (480 nm-510 nm), but the Color-mixed Board 2 could have J Series Color Cyan LEDs added to compensate, albeit with an efficacy tradeoff.

Spectral Comparison of Board 1 and Board 2 at 3000 K

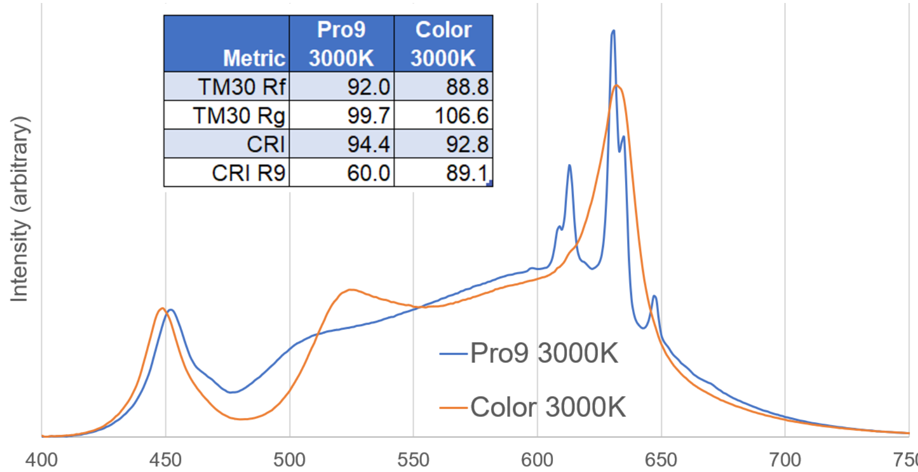

Figure 10: Spectral comparison of the Pro9 Board 1 and Color mixed Board 2, tuned to 3000 K at 90 CRI minimum. Important color rendering metrics are inset in the table.

ENERGY STAR® DOWNLIGHT CONSIDERATIONS

These luminaires would also qualify for the new ENERGY STAR® certification for downlights being released in 2024. The program requires, among other things:

1. A minimum of 82 LPW at all available operating conditions
2. A minimum of 80 CRI and 0 CRI R9
3. A maximum color shift of 0.006 du’v’ at the FWHM (50°).
4. At least 75% of zonal lumens must fall within the 0-60 degree zone from nadir.
   a. These luminaires have 85% of zonal lumens in this zone.

Figure 5 and Figure 6 above show that requirements 1 and 2 are met across the full CCT range at 1000 lm total output, and Figure 8 above shows that requirement 3 is met and data (not graphed) confirm that 85% of zonal lumens are in the 0-60° zone (requirement 4) in the 3000 K (highest input power) setting. At the maximum output that does not violate the maximum current ratings of the LEDs, with all necessary optics and diffusers, the lowest efficacy condition measured was 90 LPW at 2000 K.

LAYOUT AND SPACING OF LEDS ON BOARD

When arranging the LEDs on the board, the designer must balance the optimal color mixing with the complexity of traces and passive components needed to make it work. Follow the below guidelines for the best color mixing in an array, whenever possible:

- Colors of one region, e.g. Red, should be numerically balanced in the array quadrants and in the distance from the center to the array’s edge. For example, if most Reds are in one quadrant, a red splotch may be visible in the projected beam. Or, if all Blues are balanced by quadrant but mostly on the array perimeter, a blue ring may be visible.
- In Cree LED’s experience, Reds should specifically be embedded away from the center and edges of the array. This may depend on the optic chosen.

- When mixing to create white light, colors on opposite sides of the black body line (BBL) should be neighbors to avoid hue splotches. For example, Reds and Cyans or Blues and Greens should be paired.

Follow these guidelines for physical spacing, regardless of color:

- Asymmetric LEDs like the J Series 2835 can be rotated in any orientation for the best fit, like in the left side of Figure 1 where the inner circle is packed with long edges facing each other for the highest lumen density. Optically, these LEDs do not have emission asymmetry.
- LEDs should typically be staggered like bricks instead of arranged in a square grid to reduce interactions with neighbors, including absorption and phosphor excitation. This is less of a problem in mid-power packages with white polymer frames but can become significant in ceramic packages that may have light-absorbing aluminum nitride and clear silicone domes.
- The minimum trace width used in these designs was 10 mil (254 µm). This width is typically accepted by PCB manufacturers and can carry up to 2 amps of current on a metal-core board like the one used here. If a design pushed more than 2-amps through a single trace, or if FR4 material is used, the trace width should be increased.
- The minimum spacing used between traces (gap) was 8 mil (203 µm). This spacing is necessary to prevent shorting or arcing between traces due to small manufacturing defects and to account for manufacturing tolerances. This spacing can be used in most similar designs and is within the capabilities of most PCB manufacturers.

Board 1 used 38 LEDs and Board 2 used 36. The additional complexity of trace management in the color--mixing Board 2 limited it to only 36 LEDs in the pre-defined 35 mm diameter LES constraint. The closest corner-to-corner spacing used in these arrays was 0.85 mm. Tighter spacing is possible, but this distance often had to accommodate traces between the LEDs.

DIFFUSER SELECTION AND SPACING

The diffuser selection was limited by the LES dimensions compatible with the profile of the downlight. The initial set of diffuser, the C12598_LENINA-M reflector coupled with either the C12606_LENINA-DL diffused lens or the C15749_LENINA-CL clear lens or the F13671_ANGE-RZ-LENS color mixing dome was chosen.

The reflector chosen for this project gave a good starting point for diffuser selection because it had a ready-made family of diffusers that were mechanically compatible. Four options were evaluated:

1. LEDiL C12606_LENINA-DL diffuse lens
2. LEDiL C15749_LENINA-CL clear lens
3. LEDiL F13671_ANGE-RZ-LENS color mixing dome
4. Bright View C-HE55-PE07-S-M01

Through empirical testing, it was first determined that the diffuse lens had much better color mixing performance than the clear lens, but still resulted in color shadows when paired with the reflector. The color mixing dome was modified to fit this reflector system and showed small color mixing improvements but significantly reduced the luminous flux. Instead, a Bright View C-HE55-PE07-S-M01 was added as a secondary diffuser. This diffuser sheet had much better color performance (removing color shadows) compared to several other diffuser sheets tested. It created an additional 16% lumen loss, which was necessary and less loss than the color mixing dome.

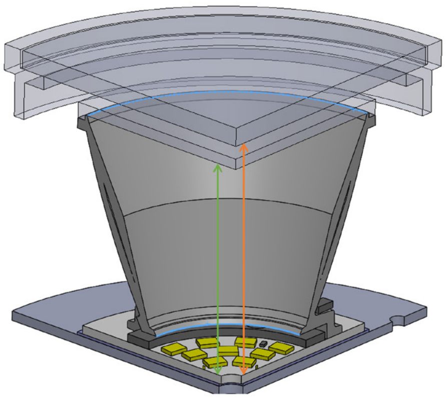

Figure 11: Cross-section rendering of full assembly. Arrows show the distance from the top of the PCB to the bottom of the first and second diffusers on top of the reflector.

The optical system used in this reference design had the following losses:

- 13% lumen loss from bare PCBA to installing into the fixture with the reflector
- Additional 6.7% lumen loss from adding the first diffuser on the entrance aperture
- Additional 16.0% lumen loss from adding the second diffuser on the exit aperture
- Total lumen losses were 32% compared to the bare LED board.

ACHIEVING A NARROW VIEW ANGLE LIGHT FOR CCT-TUNABLE WHITE

When a narrow beam, spotlight or track light with continuous color mixing is needed, consider using an array of high-power XD16 Premium White LEDs. These 1.6 mm ceramic packages can be closely packed into small arrays for the highest lumen density and thermal performance. See the XD16 Premium White Reference Design for more information.

ELECTRICAL CONSIDERATIONS

Multi-channel LED drivers are available, but they are often more expensive and harder to find than comparable single-channel drivers. They are often not configurable enough to accomplish color mixing with non-BBL parts as well. For these reasons, custom multi-channel drivers may be the best choice for color mixing applications.

For a custom driver, the first selection to make is usually the LED driver IC. In a mains-powered application, buck topology is typical. Buck LED driver ICs that produce a constant-current output to power LEDs are available in many current and voltage levels. If availability is low for a particular use case, standard constant-voltage buck converters can be made to work in a constant-current mode with the addition of current sensing circuitry.

In this application, all LED strings were below 24 V, so a relatively low-voltage LED driver was chosen. These LED drivers could in turn be powered by a bulk DC supply of 24 V from an off-the-shelf switch-mode power supply. The LED driver IC chosen was NCV30161. This IC was chosen primarily for the following attributes:

- Wide voltage input range up to 40 V
- External MOSFET for more flexibility on output current capability
- PWM dimming input

The circuit for the buck converter was taken directly from examples in the IC’s datasheet:

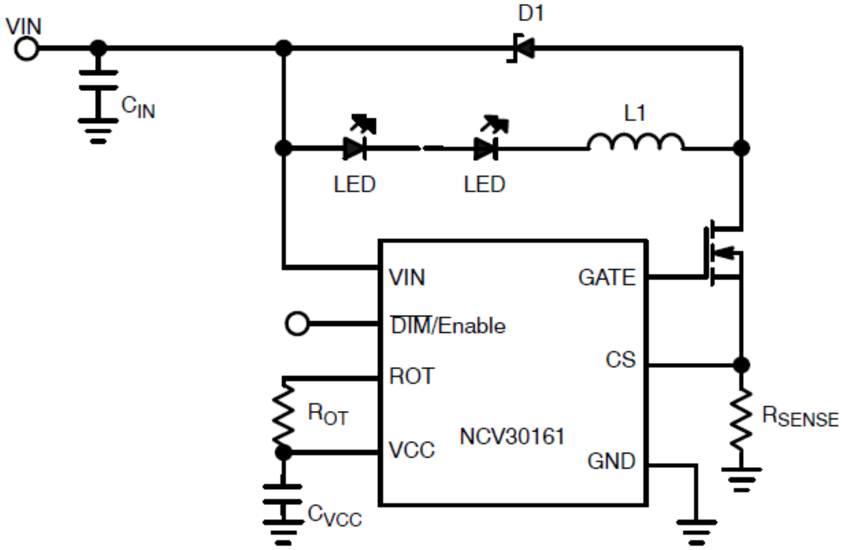

Figure 12: Circuit diagram provided by the manufacturer on the IC datasheet.

To control the output channels based on user input, a microcontroller was needed. This was chosen based on the following requirements:

- Hardware PWM generation
- Pin count for 3-4 PWM outputs and 2-3 user inputs
- Speed and memory size capable of running the interpolation algorithm

Based on these needs the PIC16F1575 microcontroller was chosen, primarily for its extremely high--resolution PWM peripheral. A PCB was designed which contained 4 copies of the buck LED driver circuit, the microcontroller to operate them, input and output connections and a few minor power management components.

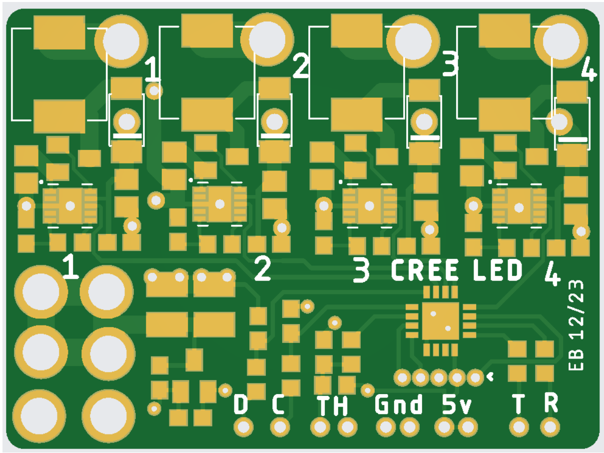

Figure 13: Custom 4-channel driver PCB used in this reference design.

During development, various color points were manually tuned to find the ratio of LED string currents that would produce desired BBL color points. The primary function of the firmware running on the driver is to interpolate among those tuned color points to produce any point between them, based on user input on the CCT. It also accepts a brightness input from the user and scales the PWM outputs accordingly. An example of the interpolation algorithm is below:

```
void linear_interpolate(unsigned int color, unsigned int bright)
{
    #define NUM_POINTS 8
    #define SEGMENT_SIZE 1024/(NUM_POINTS-1)
    static const unsigned int ch1_points[NUM_POINTS]=7535,  5642,   3458,   1875,   1638,   728,    364,    0;
    static const unsigned int ch2_points[NUM_POINTS]=0, 1274,   3276,   3822,   2457,   2639,   1365,   364;
    static const unsigned int ch3_points[NUM_POINTS]=0, 582,    910,    2057,   3640,   4550,   6370,   7917;

    unsigned char index;
    signed long outval;
    signed int low_value, delta_value;
    unsigned short long mult;

    for(char i=0; i<(NUM_POINTS-1); i++){
        if(color>=SEGMENT_SIZE*i && color<=SEGMENT_SIZE*(i+1)){
            index=i;
            break;
        }
    }

    low_value = ch1_points[index];
    delta_value = ch1_points[index+1] - low_value;
    outval = color - SEGMENT_SIZE*index;
    outval *= delta_value;
    outval /= SEGMENT_SIZE;
    outval += low_value;
    if(outval>RESOLUTION) outval=RESOLUTION;
    if(outval<0) outval=0;
    mult=outval;
    mult*=bright;
    mult/=2048;
    outval=mult;
    target[0]=outval;
```

Figure 14: Example of firmware used to interpolate between individual LED color points to estimate power levels for color mixing based on user input on a continuous color plot.

SYSTEM CONSIDERATIONS

Calibration Procedures for Production

When moving from prototypes to production of a color-tunable board, it is important to ensure that each board will create the intended color and to limit color and brightness variation between products. There are several methods for accomplishing this, depending on the quality standards and demands of the applications. In order starting from the highest quality:

1. Individually tune each luminaire's electronics before shipping.
    a. This ensures 100% accuracy at each CCT and consistency between luminaires that may be installed in the same space. It can be time-consuming, but automated programs can be used in conjunction with live feedback from an integrating sphere to iteratively find the correct power settings per channel for each luminaire. These costs can be offset in part by more flexibility in the LED order codes and bin size. This is the approach recommended by Cree LED.

2. Tune a sampling of a production batch, i.e. 5%, and apply the same settings to every luminaire.
    a. This method ensures a limited variability between luminaires but does not ensure every one meets the minimum CRI standards or is tuned to the black body line. Before implementing this method, a detailed analysis of worst-case LED bin mixing should be carried out to check the maximum color and brightness variability resulting from the extremes of each LED color bin.

3. Tune a prototype and use identical wavelength and color bins for production.
    a. This method allows a greater variability of color and brightness between fixtures but the worst case can be quantified and deemed acceptable based on the application. Like #2 above, a detailed analysis is needed before implementing this method.

One downside is that strict order codes for wavelength and brightness bins may be needed, and this could add cost, extend lead times or reduce flexibility in the supply chain.

CONTACT CREE LED

Please contact a Cree LED sales representative for further information and answers to questions about this reference design.