Brilliant Mix System Design

Abstract

'Brilliant Mix' refers to a light system containing a mix of high efficacious EQ white LEDs with amber red LEDs. 'Brilliant Mix' allows high efficacious white light sources with high CRI at low color temperatures. As red LED's lumen output degrades faster with temperature than white LED's, a Brilliant Mix system might require an active feed back system for color control. Such a system also provides brightness control. This article describes the design approach for a Brilliant Mix system including LED system parameters, heat sink, LED driver, light sensor and feed back loop to control the color temperature and brightness of the light source.

Introduction

Brilliant Mix uses a combination of LEDs with different Cx, Cy in order to achieve a high CRI, high efficacious lighting system (see fig. 1). A basic system consists of EQ white LEDs which produce white light with a stronger portion of green on a high lumen per watt level. By adding amber or red LEDs in the range of 600 plus nm, the Cx, Cy of the system can be pulled back onto the Planck curve of the CIE color diagram. As amber / red LEDs are also more efficient than phosphor conversion from blue to red, the system achieves higher overall efficacies at lower color temperatures (like < 4000 K) than a system with only white LEDs. This article describes the steps for designing a Brilliant Mix system.

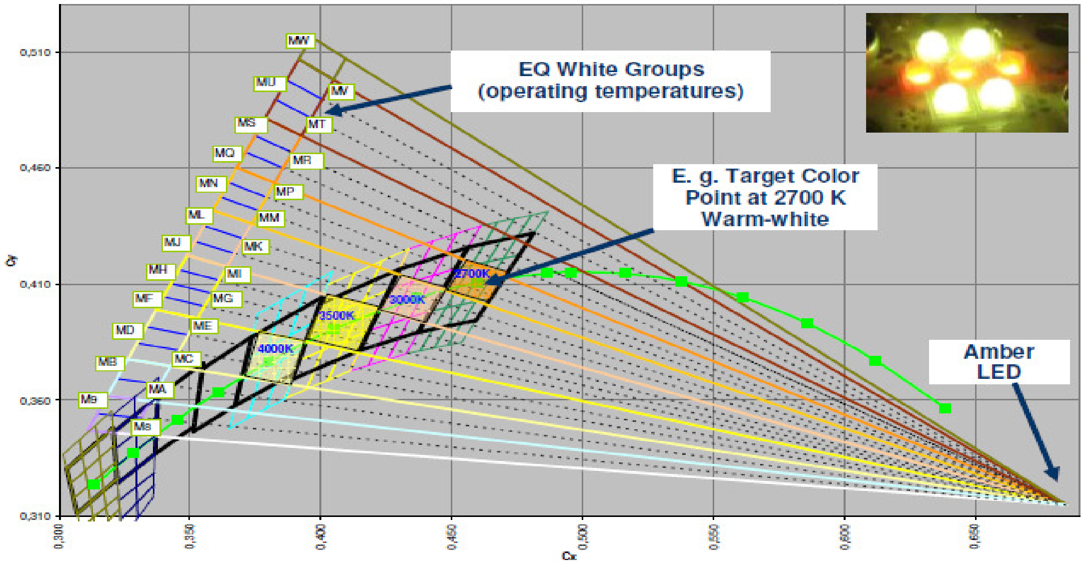

Fig. 1: Mixing EQ white with amber red to enable high CRI and efficacious warm white color sources.

Brilliant Mix system design summary

The system design process discussed in this paper can be summarized as follows:

- Estimate the efficiency of the optical system. 85 % is a good place to start.
- Find the amber and EQW lumens on LED level to satisfy the lamp specification.
- Assume a system limit for the LED junction temperature like 85ºC.
- Determine out of the lowest lumen bin the required number of LEDs to meet the lumen spec at the junction temperature limit at the end of the light engine life with nominal LED current.
- As an option, increase efficacy, by adding LEDs and reducing the drive current.
- Evaluate the performance of the heat sink. Raise or lower the system limit for LED junction temperature accordingly.
- Verify the heat sink performance and fine tune the LED placement and optics.
- Repeat the entire process if required.

After a few words about color mixing, the essential design steps will be addressed in more detail.

Color Mixing

For the design of a Brilliant Mix light engine the color point in the Cx, Cy color diagram needs to be set and maintained during the light engines life, and from light engine to light engine.

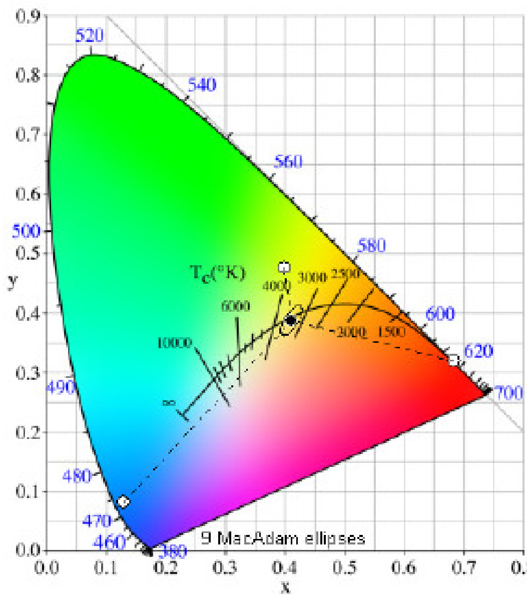

Fig. 2: The mixing of EQW, amber and blue light to 3500 K white is shown in the CIE 1931 color map.

The color point is determined by the Cx, Cy and lumen values of the individual LED groups. These values can be obtained from the LED data sheet, directly from the LED supplier or measured with most spectrometers. The generic approach to calculate the Cx, Cy and lumen level of a system of different LED colors is as follows.

Assume there are a number m different LED colors with 1931 CIE coordinates Cx_n, Cy_n, and lumen flux Φ_n where n goes from 1 to m. First transform into the new variables X_n and Z_n for each LED group n.

- $X_n = Cx_n \, \Phi_n / Cy_n$
- $Z_n = (1 - Cx_n - Cy_n) \, \Phi_n / Cy_n$

Now calculate the sum of the X_n, Φ_n and Z_n values over all LED groups 1 to m to obtain X_{mix}, Φ_{mix} and Z_{mix}.

- $X_{mix} = X_1 + X_2 + \dots X_m$
- $\Phi_{mix} = \Phi_1 + \Phi_2 + \dots \Phi_m$
- $Z_{mix} = Z_1 + Z_2 + \dots Z_m$

The light characteristics of the mixed light then equate to:

- $Cx_{mix} = X_{mix} / (X_{mix} + \Phi_{mix} + Z_{mix})$
- $Cy_{mix} = \Phi_{mix} / (X_{mix} + \Phi_{mix} + Z_{mix})$
- Φ_{mix} (see above) $= \Phi_1 + \Phi_2 + \dots \Phi_m$

This set of equations can easily be processed in a spread sheet, which is recommended for tolerance calculations.

As an example, assume two EQW LEDs and one amber LED are combined, both running at nominal current. The respective parameters might then look like:

OSRAM EQW LED:
LUW CQDP-MN-LR @ 0.35 A and RT

- $Cx_1 = 0.3764$
- $Cy_1 = 0.4554$
- $\Phi_1 = 131$ lm each

OSRAM Amber LED:
615 nm, LA CPDP @ 0.4 A and RT

- $Cx_2 = 0.6800$
- $Cy_2 = 0.3198$
- $\Phi_2 = 75$ lm

This results in:

- $X_1 = 0.3764 * 2 * 131 / 0.4554 = 216.55$ lm
- $Z_1 = (1 - 0.3764 - 0.4554)\ 2 * 131 / 0.4554 = 96.77$ lm
- $X_2 = 159.5$ lm
- $Z_2 = 0.04690$ lm
- $\Phi_{mix} = 2 * 131$ lm $+ 75$ lm $= 337$ lm

Therefore the mixed values are:

- $X_{mix} = 216.55 + 159.5 = 376.05$ lm
- $Z_{mix} = 96.77 + 0.0469 = 96.82$ lm
- Φ_{mix} (see above) $= 337$ lm

- $Cx_{mix} = 376.05 / (376.05 + 337 + 96.82) = 0.4643$

- $Cy_{mix} = 337 / (376.05 + 337 + 96.82) = 0.4161$

The parameters Cx_{mix} and Cy_{mix} are the values for the complete light engine and describe in this example a white point on the Planck curve close to 2700 K with a CRI and $R_9 > 0.9$. Using the OSRAM LEDs, the system runs on LED level at about 108 lm / W @ 25ºC junction temperature and 87 lm / W @ 85ºC junction temperature.

Variances in Color

Changes in the LEDs' Cx, Cy and lumen output need to be considered to keep the color point and the light output of the light engine constant. These parameters depend on the LED bin, the LED junction temperature, and, except for the Cx, Cy of non-phosphor LEDs, the LED current and the age of the LED. In general, a feedback system (fig. 3) is recommended to control the LED current or PWM duty cycle to compensate for temperature drift, and in some cases for the effects of LED aging. The feedback system measures the light output of the individual LED groups and the PCB temperature to provide fine tuning of the lumen target values. An additional blue LED might be implemented to allow proper color point adjustment when different EQW bins are used.

Fig. 4 and 5 show the drift in Cx, Cy over temperature with and without a feedback system. Without a feedback system a noticeable color drift is expected during the warm up of the light engine. To a lesser extent, aging of the LEDs will shift the Cx, Cy coordinates as well (fig. 6).

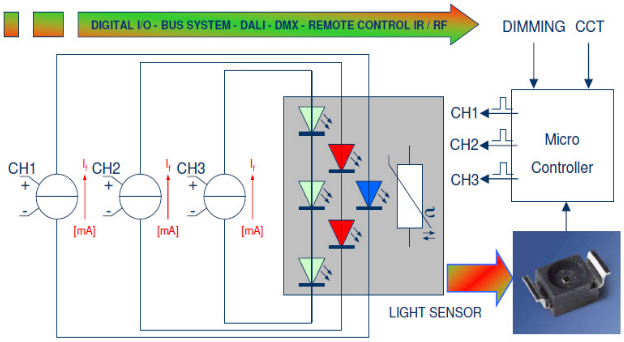

Fig. 3: Brilliant Mix system with light sensor and NTC feedback. The sensor inputs are used to fine tune the PWM duty cycles for EQW, amber and blue LEDs to stabilize the color point and the total lumen output against temperature drift and LED aging.

An initial calibration step after the light engine assembly should be used to correct for the variances from color and lumen binning. Fig. 7 shows the changes in the system Cx, Cy for one EQW bin (MK), no binning of the amber LEDs, and a system color point optimization with the LED lumens. For one EQW bin the variances are about 3 MacAdam ellipses and therefore acceptable.

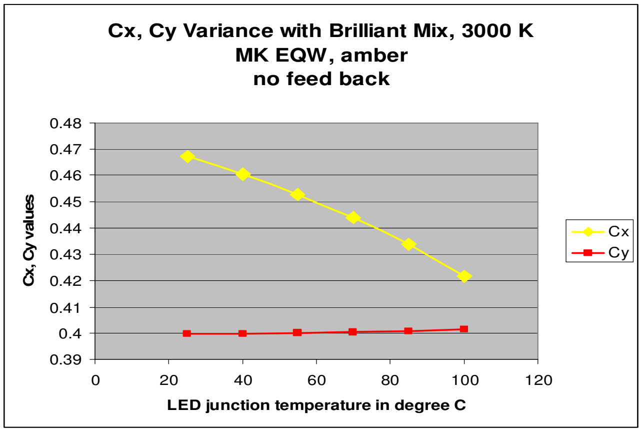

Fig. 4: Calculated Cx, Cy change in a Brilliant Mix system without feedback. The drift from 25 ºC to 85 ºC is > 10 MacAdam ellipses and clearly noticeable.

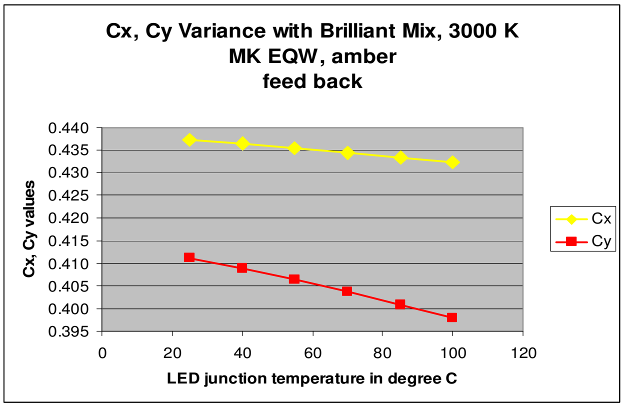

Fig. 5: Lower limit for Cx, Cy changes for a Brilliant Mix system with light and NTC feed back loop. The drift from 25 ºC to 85 ºC is about 3 MacAdam ellipses and is considered as not noticeable.

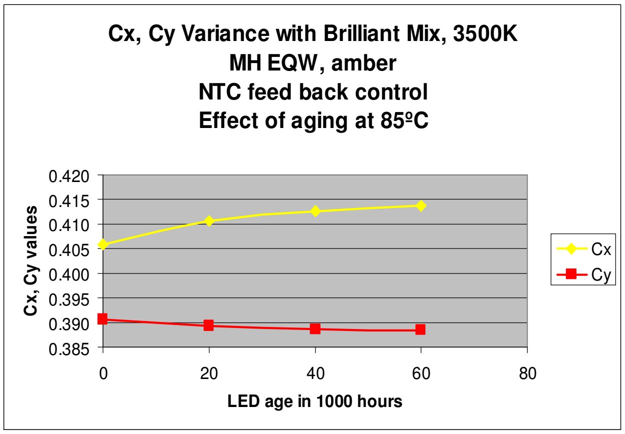

Fig. 6: Cx, Cy drift due to different aging characteristics of EQW and amber LEDs without optical feedback.

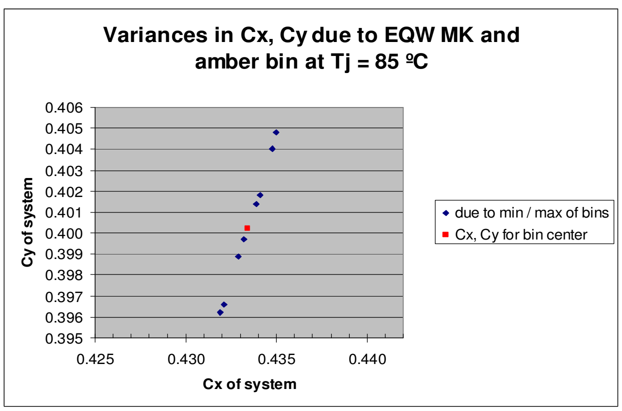

Fig. 7: Variances within 3 MacAdam ellipses of the system Cx and Cy for 3000 K white due to bin limit values of EQW MK and no binning of amber at T_J = 85ºC using a least square method to optimize Cx, Cy with amber lumen flux.

The use of wider bins might require the use of a low lumen blue emitter to keep the color point of the design fixed over production. Fig. 8 shows typical lumen values for a 1000 lm 3500 K Brilliant

Brilliant Mix Solution for 1000 lm of 3500 K white		EQW LR-MK bin	Amber 615 nm KX bin	Blue 470 nm GZ bin
3500 K white	Cx @ 85 ºC	0.3598	0.6901	0.1292
	Cy @ 85 ºC	0.4270	0.3100	0.0800
	Flux @ 85 ºC	858 lm	134 lm	7.6 lm
new LED @ RT, nominal current		131 lm	71 lm	25 lm
new LED @ 85ºC		111 lm	39 lm	23.5 lm
after 30 k hours and 85ºC		94.6 lm	36 lm	20.4 lm
# of LEDs		10	4	1
PWM duty cycle for new LED @ 85ºC		0.907	0.869	0.32

Fig. 8: Only 7.6 lm of blue (< 1 % of total lumens) are required to shift the CCT from 3000 K to 3500 K.

Mix light engine, blue shifted from 3000 K to 3500 K. Note how little blue is required.

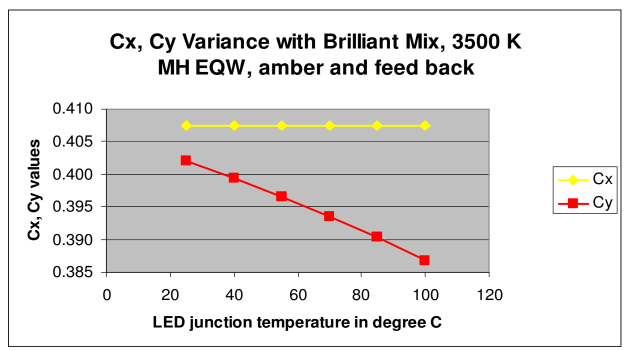

Fig. 9: Lower limit for Cx, Cy changes for a Brilliant Mix system with light and NTC feed back loop where for comparison purposed ΔCx was kept zero during the calculations. From 25 ºC to 85 ºC Cy drifts by - 0.0117.

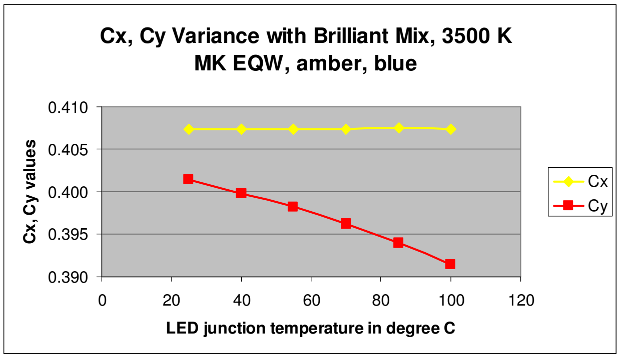

Fig. 10: Lower limit for Cx, Cy changes for a Brilliant Mix system (EQW, amber and blue) with light and NTC feedback loop where for comparison purpose ΔCx was kept zero. The Cy drift from 25 ºC to 85 ºC is - 0.0075.

Adding a little bit of blue also helps with the stabilization of the color point as shown in fig. 9 and 10. The Cy drift from 25 ºC to 85 ºC goes down from - 0.0117 to - 0.0075.

After explaining the mathematics of light mixing and some limitations of Brilliant Mix, the design a light engine with a light and a temperature sensor can now be discussed.

Brilliant Mix system design

For the design of a Brilliant Mix LED lighting system the following steps need to be addressed:

- Defining a target spec which includes:
    - Required fixture lumen output
    - Need for secondary optics
    - Light engine life
    - Fixture size
    - Choice of LEDs
- Setting a target for the LED junction temperature limit
- Determining the number of EQW, amber and blue LEDs
- Defining driver and sensor feedback system

Defining the target spec

First a target spec needs to be developed. For the operation of the light fixture, a certain amount of light in an application specific pattern has to be generated. As LED light output goes down with the LED temperature and LED age, the fixture needs to be able to produce enough light to compensate for these drops. As the system discussed here has an active feedback loop, the light output will stay fixed over all operating conditions. The essential parameters for the target spec are:

- Required lumen output of the light fixture
- Lowest lumen output of the light engine which occurs at the end of the LED life and at the highest defined LED junction tempera-ture.
- Optical efficiency of the LED lighting system defined by lenses, reflectors etc. Please note that the optics might require a diffuser to avoid shadows with reddish or green-white transition zones due to incomplete color mixing between EQW and amber LEDs.

The fixture lumen output divided by the optical efficiency gives the required lumens on LED level which need to be slightly surpassed by the lowest lumen output of the light engine.

For illustration purposes we assume the following lighting system:

- Required fixture light output of 1,500 lm
- Optical light fixture efficiency of 90%
- Light engine life of 30,000 hours
- Maximum ambient temperature of 40ºC
- A CCT of 3000 K
- Utilizing Brilliant Mix, 1,500 lm of 3000 K white split into
  - 1240 lm from the EQ white LEDs
  - 260 lm from 615 nm amber LEDs
- Use of high power OSRAM OSLON® SSL EQW and amber LEDs operated close to nominal current with individual PWM control.
- LED junction temperature target limit of 85 ºC causing a
  - 15% lumen reduction for the EQ white LEDs (85% of RT value)
  - 45% lumen reduction for the amber LEDs (55% of RT value)
- A light output reduction at the end of the light engine life of
  - 15 % for the EQ white LEDs (85% @ 30,000 hours)
  - 8 % for the amber LEDs (92% @ 30,000 hours)

To find the required lumens at the LED level and 85 ºC of a new system (0 hours run time) we divide the lumen requirement by the optical efficiency, and the lumen degradation at the end of 30 k hours:

- 1,240 lm / (0.90 0.85) = 1620 lm EQ white at T_j = 85ºC (1906 lm @ RT)
- 260 lm / (0.90 0.92) = 314 lm amber at T_j = 85ºC (570 lm @ RT)

In conclusion

- A significantly higher lumen output at the LED level is required than the fixture output of 1,500 lm.
- Each of the reduction factors plays an equally important role and should be addressed in the system design.
- A comparison of different LED solutions only makes sense under the same system conditions.

Target for the LED junction temperature limit

For specifying the lumen output capability of an LED, a target for the maximum LED junction temperature needs to be set. As a low LED junction temperature under operation is crucial to improve LED life and performance, the system hardware design should start with an estimate of the expected maximum LED junction temperature and the performance of the thermal system. For today's high power LEDs a target for T_J of 85 ºC is a good start. Parameters describing the thermal system are:

- Max. required ambient temperature
- Temperature adder due to heat sink

- Temperature adder due to PCB and interface material
- Thermal behavior of the LED
- Target of the LED junction temperature limit

Going back to the previous example, we assume the following:

- 40ºC as max. ambient temperature
- LEDs which produce 0.8 W of heat each
- 5 LEDs per square inch of PCB, thus producing 4 W of heat per square inch
- An interface material with a thermal resistance of 0.5 K / W per square inch
- A metal clad board with a thermal resistance of 3.5 K / W per square inch
- An LED with an thermal resistance of 7 K / W
- An LED junction temperature target limit of 85ºC

Conclusions:

- 4 W of heat cause a ΔT = 16ºC across the metal clad board and interface material.
- 0.8 W of heat within the LED package causes a ΔT = 6ºC between LED junction and metal clad board.
- That leaves for the heat sink a ΔT of 85ºC - 6ºC - 16ºC - 40ºC = 23ºC = 23 K.

Hence a heat sink with a thermal resistance of 23 K / 4 W = 5.8 K / W per square inch PCB area is required, which is achievable. If a respective heat sink performance is not reachable (due to space constrains for example), the calculations need to be repeated with a higher maximum LED junction temperature. Note, the optics might require a minimum distance between LEDs or a clustering of a few LEDs.

Defining the number of LEDs

LEDs are delivered in flux bins. In order to generate the required amount of light, the LEDs with the lowest flux from the lowest flux bin should be able to generate enough lumens, which has been for new LEDs in the examples provided:

- 1,620 lm of EQ white light @ T_j = 85ºC (1906 lm at RT)
- 314 lm of amber light @ T_j = 85ºC (570 lm at RT)

Looking at the white OSLON® SSL EQW LED 'LUW CQDP MK LR', the brightness bin 'LR' goes from 130 lm to 140 lm @ 350 mA and RT.

For the amber OSLON® SSL 'LA CPDP KX' the brightness bin 'KX' includes 71 lm to 82 lm @ 400 mA and RT. The light requirements are therefore satisfied with:

- 15 EQW (130 lm @ RT each) driven with 350 mA (= 1950 lm @ RT)
- 8 amber LEDs (71 lm @ RT each) driven with 410 mA (= 570 lm @ RT)

PWM settings

The 100 % duty cycle for PWM is defined by the lowest efficacy LED to be able to produce the required lumen level. For any other conditions the duty cycle is then < 100%. The lowest efficacy occurs with the least bright LED at 85 ºC at the end of the fixture life (30,000 hours).

From the example in the previous paragraph the lumen values for 100 % duty cycle are:

- 1,620 lm out of the least bright EQ white at T_j = 85 ºC (= 100 % duty cycle)
- 314 lm out of the least bright amber at T_j = 85 ºC (= 100 % duty cycle)

The 1,620 lm for the EQ white leave enough head room for LED aging while still satisfying the lumen output requirement.

As the amber LEDs change most over temperature, the smallest PWM duty cycle is required for new amber LEDs with the highest lumen output running at RT. When 314 lm of amber at 85 ºC are accomplished with 71 lm (lowest lumen level of bin) @ RT and 410 mA (= 100 % PWM value), the highest light output of the bin (82 lm) produces 363 lm at 85ºC or 660 lm at RT. The respective lowest duty cycle occurs at RT and is 314 lm / 660 lm = 47.6%.

Verification of the LED junction temperature

As the LED junction temperature plays such a crucial role for the LED light output and life, the performance of the heat sinking system should be verified. Measuring the temperature of the LED solder joints above ambient temperature quantifies the heat sink, the PCB and the thermal interface material between the two. Please note that:

- In most cases the performance of the heat sink significantly depends on its orientation.
- Non design related ambient air flows must be avoided during measurement.
- For thermal loads positioned at the center of a heat sink, the thermal resistance per square inch drops slower with increasing heat sink size. This refers to the fact that the outer portion of the heat sink does not dissipate much heat as their temperature over ambient is small. Heat sink suppliers have published correction factors to address this issue [1].
  This is not the case for LEDs evenly distributed over the whole heat sink. A thermal simulation can help to optimize the LED placement and heat sink characteristics. Otherwise a 3 x 3 LED matrix placed on a heat sink with the intended square inch fin surface per LED should be built and the solder joint temperature of the center LED measured.
- As the LED light output drops with the junction temperature, attempt to homogenize the heat sink temperature for all LEDs. This can be accomplished by limiting the heat sink beyond the LED placement area, providing higher fins in the center of the heat sink or openings in the heat sink base to increase vertical air flow.
- Convection between the heat sink and the ambient air is tempera-

ture dependent Respective temperature correction factors are available from heat sink suppliers[2].

- Dust or other contaminates can reduce the heat sink performance.
- Refer to the respective LED application note[3] for ways to measure the LED solder joint temperature.

Optics

Up to this point the number of required LEDs has been defined and the thermal management of the design was verified. The light engine has enough light capability at the application specific T_J max of the LEDs until the end of the required life. Though the efficiency of the optics was reviewed earlier, further details need to be addressed.

The function of the optics in a Brilliant Mix light engine is two-fold: To generate the required light pattern and secondly, to mix amber with EQW light so shadows don't show colored transition zones. Fig. 11 illustrates this effect. One of the effective ways to accomplish both goals is to:

- Mix the amber and EQW LEDs on the PCB instead of clustering amber and EQW individually
- Add a diffuser right on top of the LEDs
- Use a lens and / or reflector on top of the diffuser to reshape the beam.

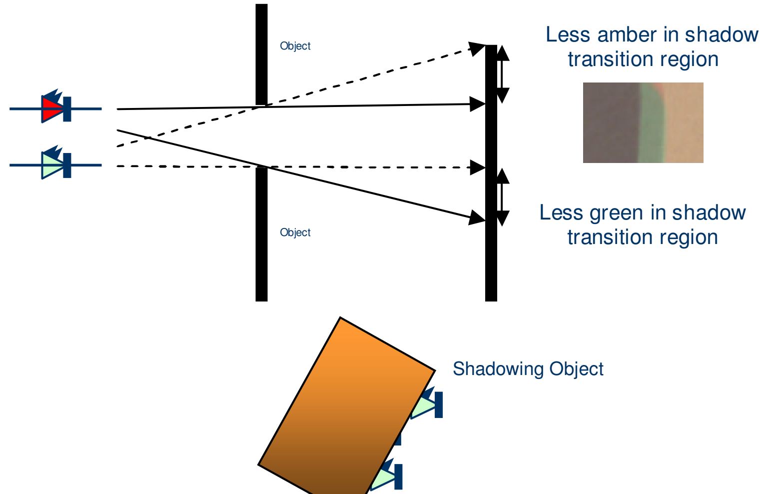

Fig. 11: Colored transition zones can appear around an object's shadow due to partial light blocking of a multi-color LED source.

Diffusers are an easy mean to mix light and / or to widen the beam. They are specified by two angles φ_x and φ_y in x and y (where the x, y plane is vertical to the beam propagation) indicating how much they diffuse the light. If α_x and α_y describe the beam width before it hits the diffuser, the resulting diffused beam is then:

- $\beta_x = \mathrm{sqrt}\,(\alpha_x^2 + \varphi_x^2)$
- $\beta_y = \mathrm{sqrt}\,(\alpha_y^2 + \varphi_y^2)$

For example a 30 ° diffuser widens the beam of a Lambertian radiator like an LED without lens (± 60 ° beam) to a 67 ° x 67 ° beam.

Sensors

The design proposal contains a light and a temperature sensor, such as an NTC resistor, measuring the temperature of the PCB close to an LED.

The temperature of interest is the junction temperature of the LEDs which can rarely be measured directly. However, with the solder joint temperature, the LED's thermal resistance, and the heat power generated by the LED, the junction temperature can be estimated. The short comings of this method are:

- There may be a tolerance in the delta between NTC reading and the solder joint temperature due to mounting tolerances of the NTC. Proper placement of the NTC and routing copper traces in heat contact with the LED around the NTC can help to reduce this effect.
- Tolerances of the NTC itself, therefore, low tolerance parts are preferred.
- Tolerances in the LED forward voltage from part to part change the ratio of light flux vs. heat power.
- Tolerances in the LED's thermal resistance.

The light sensor can be an ambient light sensor with good eye sensitivity match or a color sensor. The short comings of a light sensor configuration are:

- It detects the light of only a few LEDs
- It might show thermal drift of a few percent in its sensitivity. A temperature correction is recommended.
- Sensitivity varies from part to part. Therefore the sensor should be calibrated in the system.
- Amplification of the sensor photo current has to be adjusted once to the specific light engine design.
- Deviations from the eye sensitivity curve cause inaccuracies in the lumen measurements.
- The data might require an ambient light correction.

For our approach a light sensor, calibrated in the system, measures the light output. Due to a higher error margin an NTC is only used for corrections of second order.

Driver

The most common way to drive LEDs is with constant current sources. The LED brightness can be adjusted by changing the LED current or by switching a fixed LED current on and off with a PWM signal, defining the light output of the LED in a linear way by the duty cycle. In order to avoid noticeable flicker a PWM frequency of > 200 Hz is recommended.

Changing the LED current does not result in an exact linear light output change, which is not necessarily a concern for the control mechanism presented here. However, larger current variations will slightly shift Cx and Cy of EQW LEDs (like < + 0.002 from 350 mA to 175 mA, which is < one MacAdam ellipse at 3000 K). The feedback system can partly compensate for that as well.

In this example the use of the more common PWM control for the LED brightness is assumed. The system would then consist out of two or three

PWM controlled constant current sources, one for EQW LEDs, one for the amber LEDs and an optional one for the blue LEDs. As only very little blue is required, the blue LEDs can be driven via a low cost npn transistor in emitter configuration. The LED is placed in the collector branch and a resistor (limiting the collector current) in the emitter branch as shown in fig. 12.

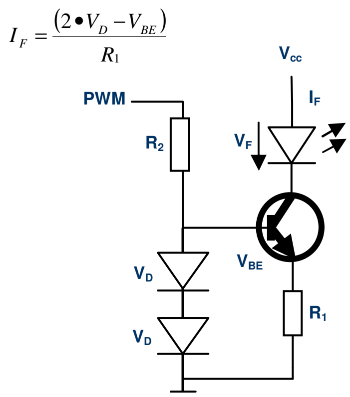

Fig. 12: Low cost constant current driver for the low power blue LED.

A micro controller reads the light and NTC sensor and defines the PWM duty cycles. State of the art 10 bit PWM modules provide sufficient resolution for Brilliant Mix systems (see fig. 13).

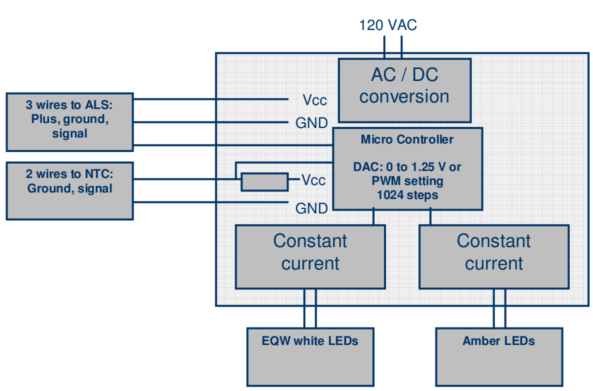

Fig. 13: Block diagram of a Brilliant Mix feedback system.

Especially for dimmable light engines, the LED driver needs to show a full response down to small bit values. Running for example the PWM with 500 Hz, which equals a period length of 2 ms, one bit of the 10 bit PWM lasts about 2 µs. Thus the current driver has to be able to light up the LEDs within that time. As an alternative, the dimming can be done with a combination of the LED current and PWM duty cycle reduction, limiting the PWM duty cycle for example to ≥ 40 %. This is also essential for the light measurements as discussed below.

Feedback control

The primary information about the state of the Brilliant Mix light engine is in this example provided by a light sensor. As lumens needs to be measured and not mW, the most simple light sensor system is an ambient light sensor with an excellent match to the human eye sensitivity curve (see fig. 14).

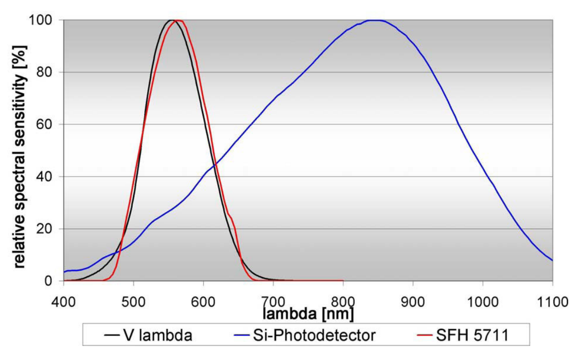

Fig. 14: Excellent match of the sensitivity curve of the OSRAM OS SFH 5711 ambient light sensor with the human eye sensitivity curve V_λ.

In order to measure the individual light contributions (EQW, amber), groups of

LEDs can be switched off between longer times with all LEDs active. To measure for example the generated amber light, EQW and blue can be switched off. As a result the system measures the LED produced amber light plus potential ambient light. The same procedure is then repeated for EQW. As calculations have shown, the blue duty cycle can be kept the same after calibration and does not need to be actively controlled. Finally all LEDs are off for measuring the ambient light level. The ambient light corrected EQW and amber values then define the changes of the respective PWM duty cycles in order to keep the color point and the overall light output of the light engine stable.

Ambient light might be continuous (like the sun) or pulsed light (like incandescent bulbs or fluorescent tubes). Pulsed ambient light can be measured by integration over a few pulse periods or by repeating the measurement many times and averaging the results. As LEDs are switched off during the measurement, a long integration time would result in a noticeable flicker. Therefore, the measurements are repeated many times (100 to 200 times). With regular operation in between a measurement update might require 10 to 20 seconds. As the thermal changes of the light engine are slow, the updates are still fast enough.

To avoid flicker, the light measurement should be in phase with the LED PWM duty cycles. After a few milli seconds of undisturbed light, the measurement cycle should only start after the completion of a PWM cycle. This can be done by setting for example the EQW PWM duty cycles to zero and waiting for the PWM cycle interrupt to make sure that the new zero duty cycle is in effect. The amber duty cycle remains constant. The amber light is measured during the amber on time. However, the on time has to be long enough for the sensor output to stabilize.

Adjusting the LED current to the maximum lighting requirements, allows a minimum duty cycle of around 47 % as shown above. If more light is produced, the minimum duty cycle needs to be lower. With a sensor / micro controller system able to measure within 100 µs, a PWM period of ≥ 250 µs (< 4 kHz) is feasible (100 µs are 40% of 250 µs, shorter than the minimum duty cycle of 47 %).

The NTC signal is used to correct sensitivity drifts of the light sensor with temperature and fine tune the amber lumen target values over temperature. These corrections can be calculated off line and stored in the micro controller as a look up table as a function of the junction or PCB temperature.

The PWM duty cycle can be adjusted easily. If the measured value is below the target value, the duty cycle is increased by 1 and vice versa. Though this mechanism is slow to initially stabilize the light, the factory calibration process can store the correct start value, so that the system is in close range when the lamp is switched on. On the other side, the algorithm doesn't produce noticeable oscillation in the light output as other faster algorithms could do.

For more details, please see the respective OSRAM Opto Semiconductors' application note about 'Brilliant Mix sensor feed back.'

References

1. Size correction factors for heat sinks: http://www.aavidthermalloy.com/technical/correct.shtml

2. Temperature correction factors for heat sinks: http://www.aavidthermalloy.com/technical/correct.shtml

3. OSRAM OS App. Note: Temperature Measurement with Thermocouples

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