Color detection for Multi Color LED Systems like Brilliant Mix

Abstract

Multi color LED systems refer to light engines utilizing different color / white LEDs. As an example 'Brilliant Mix' contains a mix of high efficacious EQ white with amber red LEDs. It allows high efficacious white light sources with high CRI at small color temperatures. As red LEDs degrade faster with temperature than white LEDs, an active feedback system for color control might be required. The feedback system can also serve to stabilize the light engine's brightness. This article describes the operation of light sensors including the achievable color control and the software routine to make the sensor work in conjunction with LED driver PWM control for EQW, amber and optional blue LEDs.

Introduction

Brilliant Mix systems combine EQW with amber red LEDs and optional blue LEDs to create a lighting system with a CRI > 90 and high efficacy at lower color temperatures (< 4000 K). Due to individual temperature drifts of the different LED colors a feedback control system might be required to keep the color point and the brightness constant over time and temperature. This paper discusses a control mechanism with an ambient light sensor and a temperature sensor for this type of feedback control

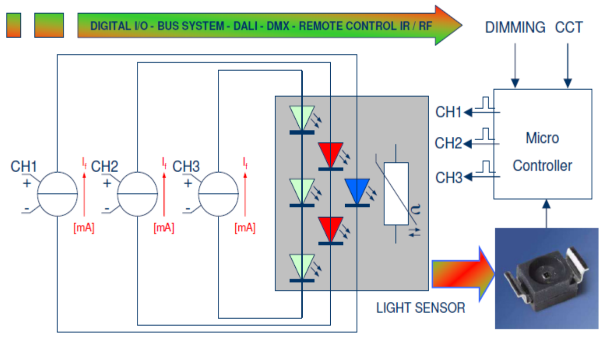

Figure 1: Brilliant Mix system with EQW, amber and blue LEDs, light and temperature feedback control

loop. Fig. 1 shows a respective system with individually PWM controlled constant current drivers for EQW, amber and blue LEDs.

The color point and lumens of the mixed system can be calculated with a set of equations as described in [1].

The article will begin with a discussion about the ambient light and temperature sensors and presents the PWM control mechanism in the second section.

OSRAM
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Part 1: Sensors

Light sensor placement

Using an ambient light sensor with excellent eye sensitivity match directly allows the measurement of lumens from the different color sources. Otherwise, the lumens need to be concluded from mW light measurements, LED spectral information and LED junction temperature to address wavelength drift. Due to the complexity of such a system a direct lumen measurement is preferred.
There are various means which can be used to improve a light sensor's match with the human eye sensitivity curve: Choice of semiconductor material, depth of the pn junction(s), use of dopants and dielectric or absorbent layers. The performance of most of these measures are susceptive to the angle of the incoming light as the light path length through the materials changes, for example shifting the sensitivity curve more into the red. An easy way to limit this effect is to put the sensor at the bottom of a cavity, ten times deeper than wide limiting the deviation of the light from the vertical to about ± 6 degrees. A sensitive area of 0.5 x 0.5 mm would require a depth of 5 mm, which is easy to integrate into a light fixture. The use of high refractive index layers additionally limits the deviation from the vertical. A diffuser on top of the opening can assure sufficient light mixing from different directions. The optical sensors used for this paper are the SFH 5711 and SFH 2270 from OSRAM Opto Semiconductors with excellent eye sensitivity match (see fig. 2) [2, 3] and fast measurement capability.

Light measuring error

Light measuring errors can occur due to various reasons:

- The sensor only detects a portion of the light of an LED group.
- The sensitivity curve drifts and / or changes with temperature.
- The sensor's deviation from linearity changes with temperature.
- A deviation between the sensor and the eye sensitivity curve.
- Limitation of the analog to digital conversion (ADC) resolution.

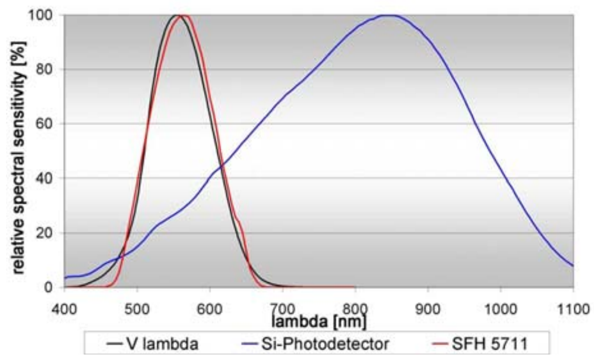

Figure 2: Excellent match of the sensitivity curve of the OSRAM Opto Semiconductors SFH 5711 ambient light sensor with the human eye sensitivity curve V_λ.

The effect of lumen measurement errors is shown in fig. 3 where the lumen values of EQW, amber and blue are

changed individually by ± 1%. For example the lumen value for blue is in-

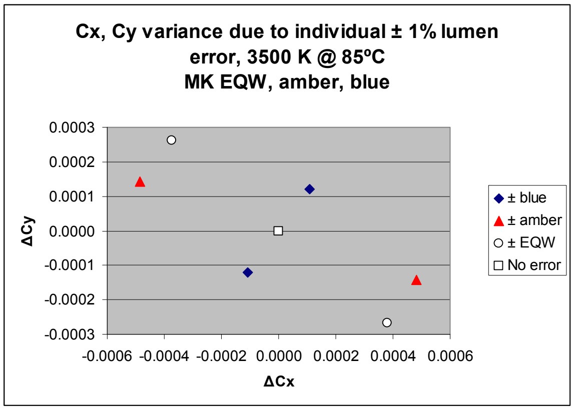

Figure 3: Variances in Cx and Cy due to ± 1% changes in flux of blue, amber or EQW LEDs.

creased by 1 %, while the EQW and amber lumens were kept the same. The changes are still small compared to one MacAdam ellipse and therefore a benchmark for a deviation limit in sensitivity.

Light sensor spectrum shift

A light sensor's sensitivity spectrum shift affects the lumen measurements. A spectrum shift can occur due to temperature drift or for incoming light angles deviating from 90 degrees. The following fig. 4 shows the variance of Cx and Cy of a 3500 K light engine using EQW, amber and blue LEDs, assuming a sensitivity spectrum shift towards the red. That means for the same amount of amber light lumens more mWs are detected. Due to an active

control loop this then results in a reduction of amber lumens. On the opposite side of the spectrum the control loop increases the amount of blue light.

The graph shows the Cx, Cy changes for a simplified -1 % amber light and + 1 % blue light, and then for ± 2% and ± 3% while in all cases EQW lumens were kept the same. The changes in Cx suggest a limit to the effect of a shift to less than 3 %.

Though a spectrum different from the eye sensitivity curve can accomplish proper Cx, Cy at a calibration temperature it measures a drift in amber lumens different from the human eye. In general the more the sensor sensitivity drifts the more the system relies on temperature measurements and correction tables.

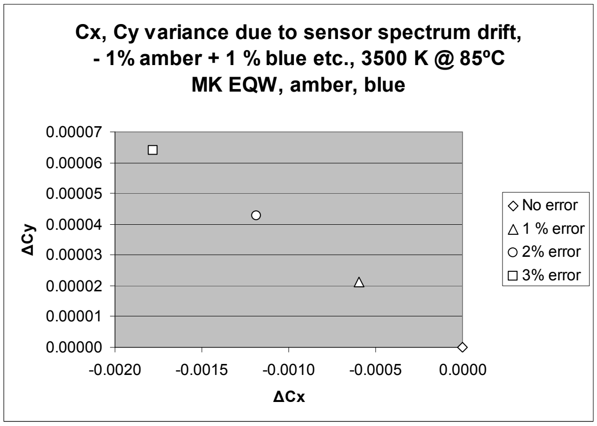

Figure 4: Variances in Cx and Cy due to sensor sensitivity spectrum shift from 25 ºC to 85 ºC.

Light control strategy

EQW and amber system: In a Brilliant Mix system with EQW and amber LEDs, a drift in the color point due to temperature can be compensated for

along the line between the Cx, Cy of EQW and amber, but not vertical to it. Fig. 5 shows the theoretical drift for a perfect feed back system. The control strategy used kept the lumen level of the EQW constant and varied the lumen level of the amber LED slightly with the LED junction temperature. These lumen changes depend on the color temperature of the system and can be stored as a look up table in the micro controller.

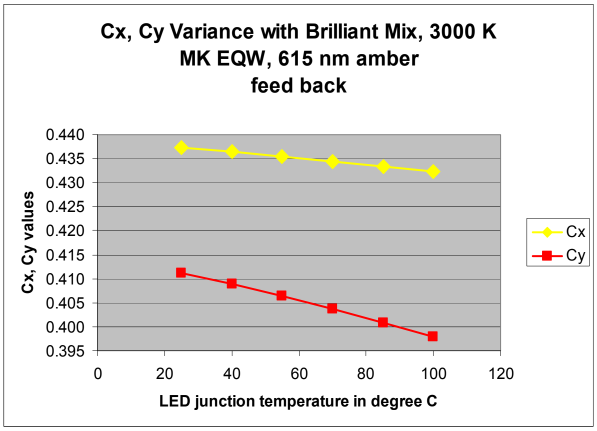

Figure 5: Cx, Cy variance due to thermal drift of the LED colors. Amber lumens were optimized with a least square change in Cx and Cy.

Fig. 6 shows the required amber lumen changes from fig. 5 to limit the ΔCx and ΔCy over temperature (least square method). They are listed relative to the lumen level at T_J = 25 ºC and are small.

For example at T_J = 85 ºC an amber lumen drop of only 1.2 % is required.

T_J of amber LED	Relative lumens
25 ºC	1.000
40 ºC	0.992
55 ºC	0.981
70 ºC	0.981
85 ºC	0.988
100 ºC	0.997

Figure 6 : Relative lumens of amber over temperature to reduce ΔCx and ΔCy variances of the system due to temperature drift of EQW and amber LEDs.

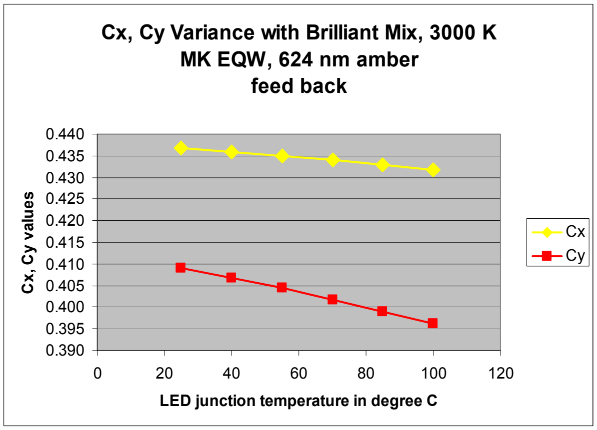

Figure 7: Cx, Cy variance due to thermal drift of the LED colors, but with 624 nm amber LEDs. Amber lumens were optimized with least square method for Cx and Cy.

Fig. 7 shows the Cx, Cy variance with temperature for a 624 nm amber LED. Though Cx, Cy start at a slightly different color point than a EQW, 615 nm amber system (fig. 5) the variances with temperature are comparable.

EQW, amber and blue system: With three colors, the color point can be maintained over temperature. Fig. 8 shows the required lumen levels for

3500 K	Lumens		
T_J of LEDs	EQW MK	Amber	Blue
25 °C	846.4	142.4	11.2
40 °C	849.5	139.9	10.6
55 °C	852.5	137.6	9.9
70 °C	855.1	135.9	9.0
85 °C	857.1	135.0	7.9
100 °C	859.7	133.7	6.6

Figure 8: Lumen target values for 1000 lm 3500 K white, Cx = 0.4074, Cy = 0.3935 and different LED junction temperatures.

1000 lm of 3500 K white for EQW, amber and blue LEDs. To take advantage of this method, the LED junction temperature has to be known. In reality it is estimated from a temperature measurement at the PCB level which causes some tolerances.

For example taking the Cx, Cy values for T_J = 100 ºC but assuming due to errors from ALS and temperature measurements the lumen levels of 85 ºC the errors in ΔC = - 0.001 and ΔCy = - 0.002 are still small.
While the lumen levels in fig. 8 keep Cx and Cy fixed, fig. 9 shows what happens when the temperature drift is ignored and the lumens of EQW, amber and blue are simply kept the same.

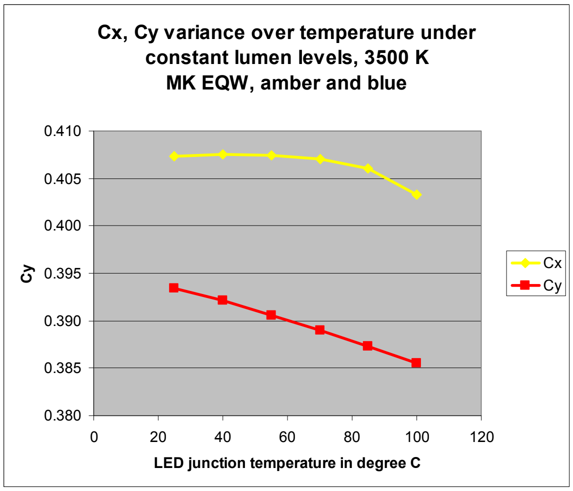

Figure 9: Cx, Cy drift of 3500 K mixed white with temperature when lumen level for EQW, amber and blue individually kept constant.

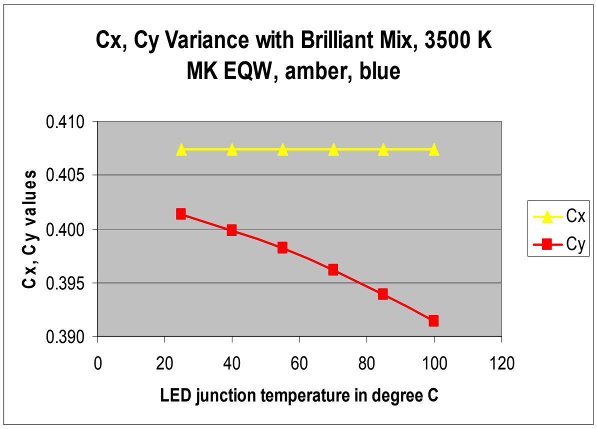

Figure 10: Cy changes with temperature where EQW lumens were kept constant, amber lumens were fine tuned over temperature and changes in blue ignored. Amber lumens were set to keep Cx constant.

Fig. 10 shows the Cx, Cy drift when the EQW lumens were kept constant, the amber lumens were fine tuned over temperature (for $\Delta Cx = 0$) and changes in blue were ignored.

Light measurement

As groups of LEDs are switched off during light measurement, the measurement time has to be short to avoid noticeable light flicker. In terms of flicker avoidance it is also helpful to keep the current PWM duty cycle for the LED group to be measured. Thus, the on time during the PWM period defines how fast a light measurement has to be.

Assuming a PWM period of 250 µs and a minimum expected duty cycle of 40 % in a Brilliant Mix system (amber LED), the light measuring time is limited to 40 % of 250 µs which requires a measurement time of ≤ 100 µs.

Assuming that one controller clock cycle is the time of one PWM bit, a 10 bit PWM with 250 µs period requires a 250 µs / 1024 ≈ 0.25 µs clock cycle or a ≥ 4 MHz micro controller.

The PWM duty cycle of the optional blue LEDs might be too short for the sensor response time. Utilizing a look up table with the temperature measurement can be sufficient for maintaining blue.

For a light sensor which puts a photo current out, a typical circuit is shown in fig. 11. The ambient light photo diode is in reverse operation. The photo current I_P creates a voltage across resistor R1. The voltage gets amplified before read out typically done by an ADC of a micro controller. In order to keep the response

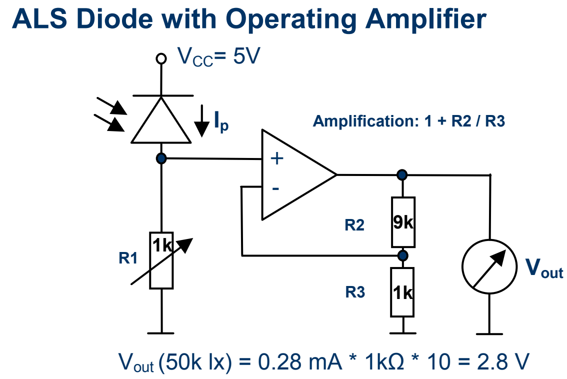

Figure 11: Light sensor circuit for fast measurement.

time of the system short a small R1 should be chosen to allow fast charge / discharge of the photo diode capacitance(s). The operating amplifier then raises the signal to levels where most of the ADC range can be utilized.

Short rise and fall times are both important depending on the duty cycle of the PWM before the light measurement. For significant off times during the duty cycle, the rise time of the sensor from lower to higher lumen levels counts. When the LEDs run at a almost 100 % duty cycle, the fall time from higher to lower lumen levels defines the response time.

ADC settings for light measurement

Referring to the lumen values in fig. 8. the EQW and amber light need to be measured with an accuracy of 2 lumens and 1 lumen, respectively. The SFH 5711 ambient light sensor has a logarithmic output defining an output current I_{out} by:

I_{out} = 10 µA log (light level in lx / 1 lx)

Taking the lumen delta for EQW of 0.3 % from fig. 8 (85 ºC to 100 ºC), the respective ΔI_{out} at around 1000 lx would result in about 0.04%. That's too small for a 10 bit ADC resolution (≈ 0.1 %). However, if the ADC runs on a tighter reference voltage range ($V_{ref\ low}$ > ground), this resolution can be accomplished.

This measure is not necessary to detect the changes in amber as the relative changes are larger.

The SFH 2270 is a photo diode with linear lux to photo current relationship. Here a 10 bit resolution of 1 in 1023 is sufficient.

Requirements for the light sensor

In summary the following is required from a light sensor system:

- Excellent match of eye sensitivity curve.
- Measurement time < 100 µs.
- ADC accuracy to resolve signal changes around 0.3 %.
- Temperature compensation for spectrum drift.
- EQW and amber: Generation of comparable lx levels at the sensor to reduce errors from deviations in the sensor linearity.
- Blue: Control by temperature and look up table.

Temperature sensor

As discussed above, knowing the LED junction temperature helps to fine tune the LED lumens for better color point stabilization. The most popular temperature sensors today are resistors with **N**egative **T**emperature **C**oefficient (NTC) which are available in small SMD sizes like regular resistors. An NTC changes its resistance with temperature in a defined way as shown in fig. 12.

Fig. 13 shows how the NTC temperature can be calculated out of its resistance at temperature T (in Kelvin), where 'ln' stands for the natural logarithm to the base e (2.718 …). The NTC resistance change is usually transformed into a voltage change by using a regular resistor in series.

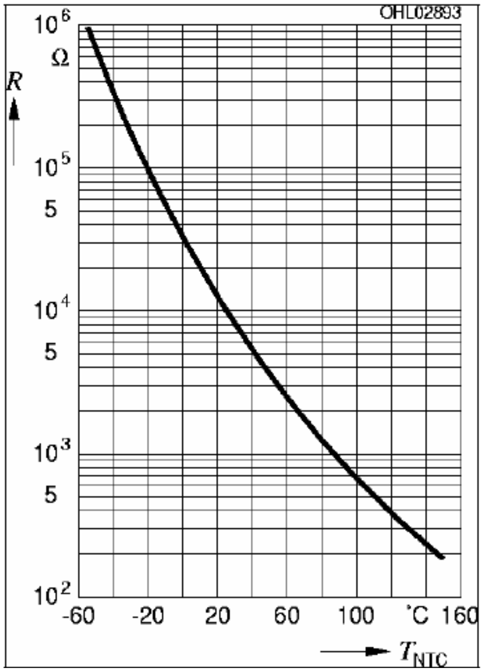

Figure 12: Resistance change with temperature for a 10 k Ω NTC with B = 3940.

1/T = 1/To + 1/B ln (R / Ro)

Figure 13: NTC temperature T in Kelvin as a function of the NTC resistance R at T, the resistance Ro at temperature To and the NTC parameter B.

The NTC needs to be placed on the PCB which carries the LEDs, preferably close to one LED representing the average LED solder joint temperature. The goal is to keep the ΔT between the NTC and the LED solder joint small and secondly as independent of the precise NTC soldering and PCB heat sink mounting as possible.

From the solder joint temperature and the thermal resistance of the LED the LED junction temperature can be calculated. At the end this is the parameter used for fine tuning the lumen targets. The thermal resistance of the LED package might vary from part to part adding to the measurement error (OSRAM OSLON SSL at nominal current Δ T ≈ ± 2 ºC).

Additionally it is recommended to consider the following, where respective ΔT error values are calculated for a temperature change from RT to 80 ºC:

- a 10 bit ADC, adding to the ΔT ± 0.4 ºC from bit resolution
- an NTC with sufficient dynamic at the operating temperature
- an NTC with a ≤ 1% tolerances
- a serial resistor with a ≤ 1 % tolerance
- a serial resistor matching the NTC resistance at the typical operating temperature.

The ± 1% accuracy for both resistors limits the Δ T to about ± 0.7 ºC for a B = 3940 NTC.

From the discussion above about the fine tuning of light (see fig. 8 for example) an overall accuracy of up to ± 5 ºC for the estimated LED junction temperature should be sufficient. To accomplish this value some design tweaking might be required.

Part 2: PWM Control

PWM phase match

Micro controllers are not only useful to determine the required LED PWM duty cycle they also can provide the respective PWM signal. Thus the PWM signal phase can be timed with the light measurement. For the measurement all LED groups except one are switched off. In order to avoid noticeable light flicker, the measurement should not interrupt a PWM cycle but wait until the PWM cycle is complete. The following program section (fig. 14) explains this process where we use the following Microchip® defined variables:

- **TMR2** as the timer running from 0 to 255 to define the PWM period
- **CCPR2L** as the upper 8 bits of the PWM duty cycle
- **CCP2CONbits.DC2B** as the lower 2 bits of the PWM duty cycle
- A pre-scale value of the timer **TMR2** (0 to 255) to time the duty cycle (0 to 1024)
- A new duty cycle setting which is buffered first. It only becomes active when new cycle starts.

PWM adjustment

After a light measurement is performed the question is how to close the potential gap between the light target and the

Changing of duty cycles for measurement after full PWM period

```
while (TMR2 < 0xFF);      // waits till PWM cycle is complete
Delay;                    // wait to get TMR2 to << 255
                          // avoids duty cycle change during reload
CCPR2L = 0x00;            // duty cycle buffer of EQW is set to zero
CCP2CONbits.DC2B = 0;
                          // duty cycle buffer value not loaded yet
                          // => duty cycle not changed yet

INTCONbits.GIE = 0;       // disable global interrupts to avoid delays
while (TMR2 < 0xFF);      // wait till PWM period is over

Measurement;              // New PWM cycle with EQW off

INTCONbits.GIE = 1;       // enable global interrupts
```

Figure 14: C routine for Microchip controller to start amber light measurement in phase with PWM cycles.

measured value which translates into a change of the PWM duty cycle. There are many control mechanisms available ideally to close the gap as quickly as possible without causing strong oscillations around the target later. For this paper a rather simple mechanism was selected. Fig. 15 shows the C code, where:

- **White_target** is the target EQW light value in lux
- **result** is the measured EQW light level without ambient light
- **PWM_W** is the PWM duty cycle for the EQW LEDs

PWM control algorithm:

```
if ((White_target < (result - 1))  && (PWM_W >  0))
        PWM_W = PWM_W - 1;

if ((White_target > (result + 1))  && (PWM_W < 1023))
        PWM_W = PWM_W + 1;
```

Figure 15: Control algorithm for PWM duty cycle to bring the light output to the target level.

The PWM_W > 0 and PWM_W < 1023 statements ensure that the 10 bit number does not flip from 1023 + 1 to zero or from 0 – 1 to 1023.

For the range 'result ± 1' the duty cycle stays the same. Though this mechanism is slow in bridging a larger gap, it avoids excessive oscillations around the target value. When the system is powered up after calibration it can start close to the right PWM duty cycle and only needs to compensate for slow thermal changes.

Of course bigger steps can be used when a larger gap is detected.

Ambient light

Ambient light might enter the light fixture and bias the light measurement of the individual LED groups. Ambient light can be continuous (sun) or pulsed (incandescent or fluorescent lights). As the ambient light measurement occurs at a different time than the LED measurements, the light level of an pulsed external source can be different. In general there are two ways to compensate for that: To average over a few cycles of the pulsed ambient light or to repeat a short measurement many times.

As all the LEDs are off during the ambient light measurement, a measurement over several milli seconds would cause a noticeable flicker. The period of an incandescent light bulb for example is defined by twice the AC frequency (50 or 60 Hz). A period of 120 Hz is about 8.3 ms. That would be the minimum off time for the LEDs, too long not to cause a flicker. Thus, repeating a short measurement many times appears here as the better option.

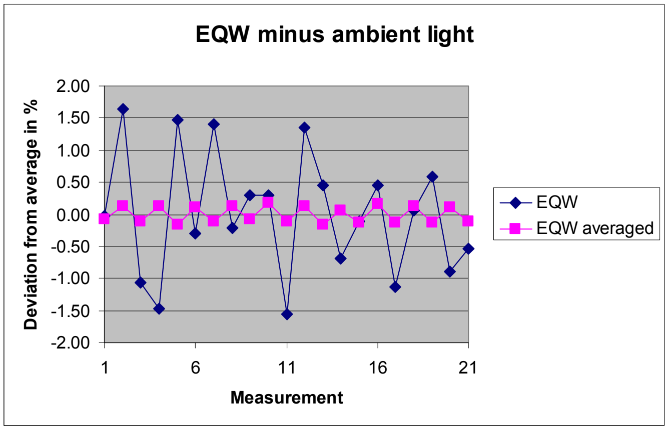

Figure 16: Reducing the variations in EQW lumen measurements due to pulsed ambient light (incandescent light bulb) by averaging light measurements of ambient plus EQW light and ambient light alone.

Fig. 16 shows ambient light corrected EQW light values. Each measurement, EQW plus ambient, and ambient alone was performed 100 times. The individual

and averaged results are shown for an incandescent light used as ambient light source. The deviation goes down from ± 1.5 % (no averaging) to ± 0.16 % (when averaged over 100 measurements each). The remaining oscillation in the averaged data would further shrink for means out of more than 100 measurements (like out of 500 data points).

Averaging slows down the reaction time of the system. One possibility (for a system averaging 100 measurements) is to store the data of the last 80 measurements and update the PWM when 20 new measurements will be taken.

In order to get the mechanism to work, it is important that the measurements are not in phase with the pulsed ambient light source. It is therefore recommended to scramble the time between the light measurements a little.

Summary

The requirements for operating a light sensor to measure the lumen levels of the LED color groups in a mixed color light engine were discussed. Control strategies were presented to maintain the color point of the light system over temperature and life. The benefits and limitations of using an NTC for fine tuning the LED lumen targets over temperature were introduced.

It was shown how LED and ambient light measurements can be intertwined with the regular PWM operation and how the influence of pulsed or continuous ambient light can be removed from the data.

References:

1. OSRAM Opto Semiconductors: Brilliant Mix Tech Note.

2. OSRAM Opto Semiconductors ambient light sensor SFH 5711 with excellent eye sensitivity match.

3. OSRAM Opto Semicondcutors ambient light sensor SFH 2270 R with excellent eye sensitivity match.

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