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Use of Junction Temperature in Control of CCT in LED Luminaire

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Abstract

By different coloured light emitting diodes (LEDs) it is possible to realize a luminaire with adjustable spectra and correlated colour temperature (CCT) in the white light region. Light output of each LED depends on its junction temperature and colour. To overcome this problem the LEDs system is equipped with a feedback feature. Junction temperature is indirectly measured from the forward voltage. Based on junction temperatures and known characters of LEDs, variations in light output are compensated.

Introduction

Light output of LEDs has increased more than tenfold within the last decade. Also the efficacy of the LEDs has been increased. The AlInGaP (Aluminum-Indium-Gallium-Phosphide) LED technology sector, which produce red and amber LEDs, has reported efficacies over 100 lumens per watt (Osram-OS 2004). The InGaN (Indium-Gallium-Nitride) LED technology sector, which produce green and blue LEDs, and also white LEDs with a phosphor, has reported efficacies almost 100 lm/W (LEDs Magazine 2004). However, these high efficacy products are not on the market yet and their power range is limited to lower end. In the high power LEDs highest efficacies on the market are around 50 lm per watt.

The price of a practical LED luminaire for general lighting is still rather high. However, LED luminaire have some value added features. The shape of the luminaire can be freely design. It is possible to produce vivid colours without any filters and colour temperature can be adjusted, which is difficult to implement with traditional light sources. These features do not justify the higher price in general, but in some cases they can be the reason to select LEDs.

Adjusting colour temperature is rarely used nowadays. Until now it has been difficult and expensive to realize. The simplest and limited way to do it has been the use of two different coloured fluorescent lamps in one luminaire.

With LEDs the proportions of the colours can be changed by adjusting the luminous flux of different coloured LEDs. Luminous flux of a single LED is easy to control using current pulse width modulation (PWM).

However, accurate adjusting colour temperature is not as straightforward as one might expect. One major problem to overcome is the dissimilar characteristics of AlInGaP and InGaN LEDs. For example, the different LEDs have diverse behaviour as the junction temperature changes. Red and amber LEDs are very sensitive to temperature changes. When junction temperature raises their lumen output drops fast. Blue and green LEDs are less sensitive to the temperature changes. In addition, the lumen maintenance is unlike with different coloured LEDs. (Muthu et al. 2002) Another problem is proper spatial mixing of the colours (Zhao et al 2002). In the centre of the illuminated area the mixture might look good, but in the edge of the area single colours may be distinguished, and shadows may be multicoloured.

In addition complex binning processes cause other problems. The forward voltage can vary from one LED to another as much as one volt, the flux can vary almost 300 % and the dominant wavelength can vary 30 nm. (Kubulins et al. 2004) These variations may lead to unwanted results if they are not taken into account. For the moment it is not possible to get LEDs all with the same bins, except paying a considerably higher price. Light sources for general lighting purposes have to fulfil some basic qualitative and quantitative requirements. Light production must have competitive efficacy and price. The colour of the light should be white and the colour rendering good. Further illuminances levels are rather high and the illumination should be uniform in the space. All main features, light intensity, colour temperature or colour rendering cannot change depending on ambient temperature or lifetime.

A LED luminaire with adjustable CCT needs a feedback system to compensate changes in luminous fluxes of different LEDs to fulfil quality requirements for the general lighting. One possible method is to measure the flux of LEDs using photodiodes to measure the output of each colour component (Muthu et al. 2002, Zukauskas et al. 2004). However, positioning these photodiodes might be cause problems for the luminaire design.

Another method for the feedback system is based on the measurement of the junction temperature. Measuring it directly is not practical but instead the temperature of the heatsink can be measured. (Muthu et al. 2002) If the heatsink is large, as it usually is in this kind of applications, the time constant is long and there is a delay in compensating the light output. This method does not take into account the aging of LEDs. Also the combination of these two methods is possible (Muthu et al. 2002).

In white LEDs the junction temperature can also be estimated from the W/B ratio. It is the ratio of the total radiant energy of the white LED spectrum (W) and the radiant energy of the blue emission peak (B). (Gu & Narendran 2004, Narendran et al. 2004) However, in practical luminaire it is difficult to implement required measurement.

Based on the junction temperature there is also another approach. As described earlier, when the junction temperature rises, the flux will decrease and vice versa. The wavelength will also change according to the junction temperature because of changes in optical characters of an LED. There are also small changes in electrical characters due the junction temperature. Forward voltage will decrease when junction temperature rises. In Luxeon emitter the change is -2 mV per 1 ºC at the operating temperature (Lumileds datasheet 2004). Measuring the forward voltage it is possible to measure junction temperature indirectly and in real time.

LED Luminaire with Adjustable CCT and feedback

The prototype luminaire consists of 61 high-power LEDs. Lumileds 1 watt Luxeon emitters with batwing optics were selected for the luminaire. Four colours were used: royal blue, green, amber and red. Numbers and dominant wavelength are presented in table 1.

Table 1. *Dominant wavelength and the number of the LEDs.*

Colour	Wavelength	Number
Royal Blue	455 nm	12
Green	530 nm	25
Amber	590 nm	17
Red	652 nm	7

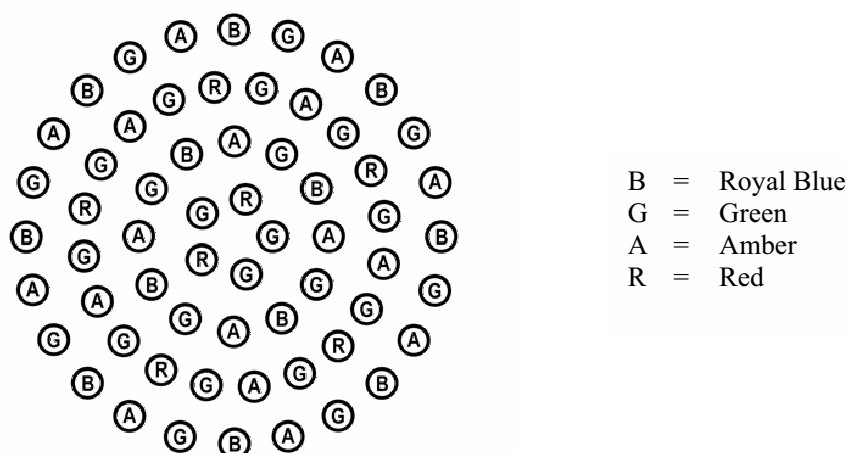|		
B	=	Royal Blue
G	=	Green
A	=	Amber
R	=	Red

Figure 1. *Arrangement of the LEDs.*

According to simulations only three reds would be sufficient but seven was chosen to make it more uniform. Also 15 Ambers should have been sufficient and green should have been two more. The changes were made to get better colour uniformity. LEDs are placed in four concentric circles according the figure 1. Diameter is 104 mm. LEDs are positioned as tight as it was possible. Connecting wires set the limitations for the minimum distance between LEDs.

LEDs are planted to metal-core printed circuit board (MCPCB) for the better heat extraction. Behind the MCPCB there is a heatsink with two fans. The speed of the fans can be controlled. Other side of the heatsink is eight-layer circuit board where the control systems are located. Behind it there is a four-layer circuit board which has PLC-modem (Power Line Communications). The system is connected to the computer via a power line network.

At the MCPCB there is the LM92 digital temperature sensor measuring its temperature. For the feedback system the forward voltages of eight LEDs is measured, two LEDs of each colour. One measured LED in each colour is located on the centre of the luminaire and another is located on the border.

The system is controlled with the computer software which controls each LED as a single unit or grouped according to the colour. The most important control is the whiteness control. In the system there are two control slides, one for colour temperature and another for dimming use.

Coordinates of the resulting white light is located on the Planckian locus. At each colour temperature there are a pre-calculated intensity values for all colours. Control is not continues but has steps of 50 Kelvin. It would be easy to make steps in every Kelvin but 50 K is sufficient for the most applications.

All LEDs are in parallel and they are driven by constant current source. Dimming is done using pulse width modulation (PWM) with modulation frequency 1 kHz. Dimming of the light does not change its colorimetric properties. The block diagram of the system is presented in figure 2.

The time constant for the junction temperature is about 0.001 seconds and the time constant for the slug of the LED is about one second. The time constant for MCPCB is approximately ten minutes.

When the luminaire is turned on it will initialize itself. In the first five milliseconds it will measure the temperature of the combination of the circuit board and the heatsink with the temperature sensor installed on the circuit board. At the same time the system will
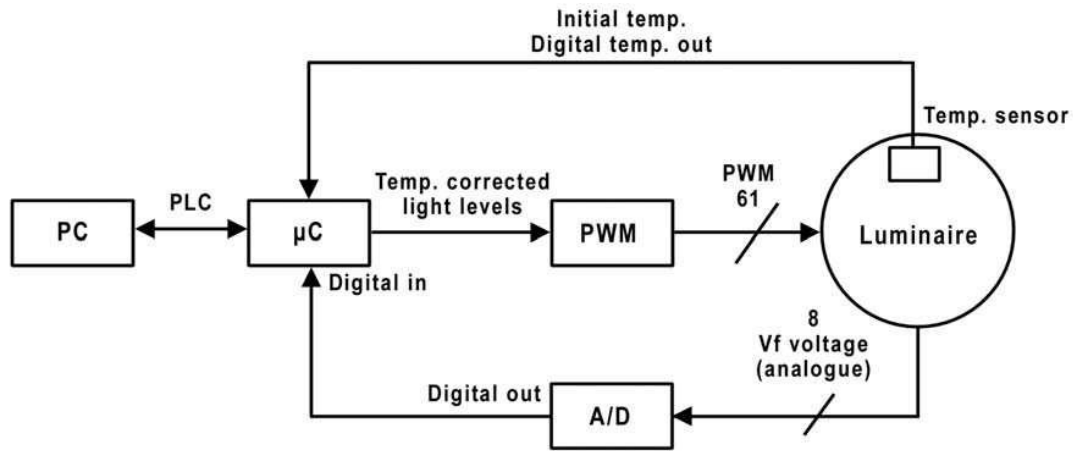
Figure 2. *Block diagram of the system.*

measure the forward voltages of the eight LEDs. From these values the junction temperature T_j can be calculated according to the equation:

$$T_j \approx (R_{j\text{-}b} \cdot V_f \cdot I_f) + T_b \tag{1}$$

Where Rj-b is the thermal resistance from the junction to the board, Vf is the forward voltage, If is the forward current and Tb is the board temperature. For the thermal resistance the value 20 K/W is used.

From the measurements we have the reference value to each LED; the junction temperature and corresponding forward voltage. Instead of using pre-determined forward voltage value that corresponds to some junction temperature, we can use these reference values. The problem from different forward voltages in various LEDs can be overcome with these measurements.

After the initialisation the forward voltage is measured in every 100 ms and based on that and initial measurements, the junction temperatures are calculated. Each colour has it own function of the junction temperature and the luminous flux. These functions are derived from the manufacturer's data and are scaled so that the flux Φ is corresponding one at 70 ºC:

BLUE $\quad \Phi = -0.0019286 \cdot T + 1.136$ (2)

GREEN $\quad \Phi = -0.004 \cdot T + 1.282$ (3)

AMBER $\quad \begin{cases} \Phi = -0.0165 \cdot T + 1.9545 & (T < 40°C \\ \Phi = \text{-}0.009 \cdot T + 1.6345 & (40°C \leq T \leq 80°C \\ \Phi = -0.0052 \cdot T + 0.3295 & (T > 80°C \end{cases}$ (4)

RED $\quad \begin{cases} \Phi = -0.00883 \cdot T + 1.566 & (T < 60°C \\ \Phi = -0.006 \cdot T + 1.423 & (T \geq 60°C \end{cases}$ (5)

Flowchart in figure 3 describes how to system works. The user can select the desired colour temperature and the dimming level. For each colour temperature there are pre-calculated intensities to each coloured LEDs. The computer selects the right values and multiplies those with the dimming level. Then the data is sent to the control system. The control system calculates the junction temperatures based on the measured forward voltages. After that it calculates temperature coefficients for all colours using equations 2–5. The target junction temperature is set to 70 ºC. The control system multiplies values send by the computer with the temperature coefficients. After that it checks if any value is over 100 %. If some value is over 100 %, all the values are scaled so that maximum value would be 100 %. The results of the calculation are intensities for each colour and resulting light is the white light with the desired colour temperature.
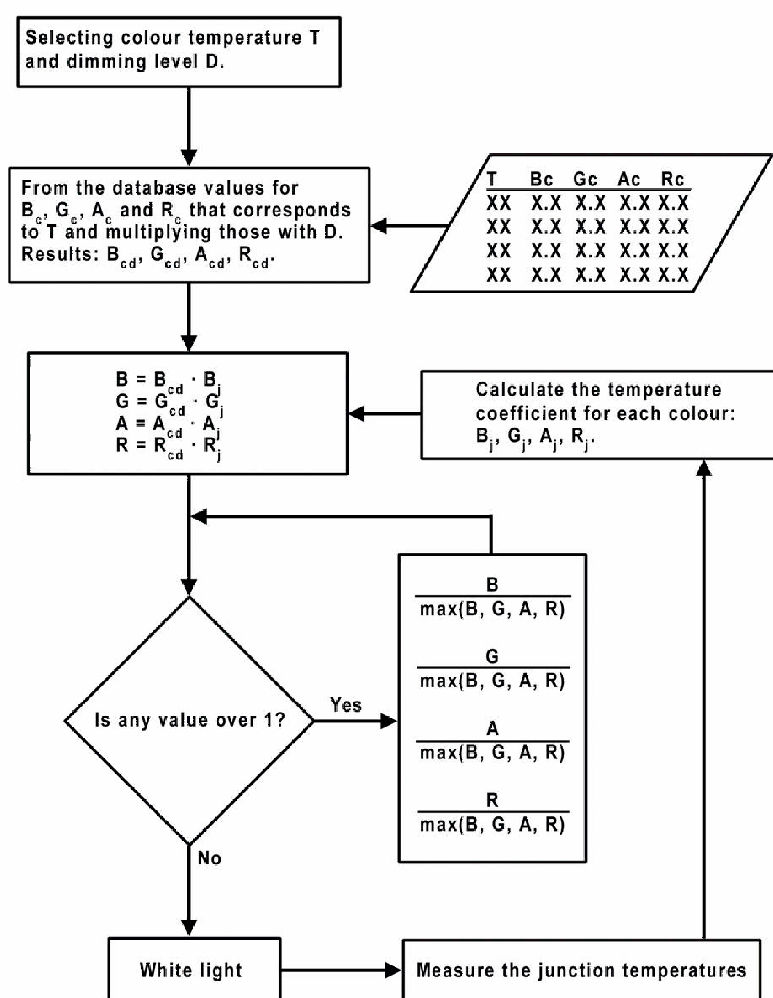

Figure 3. *Flowchart of the control.*

Discussion

By measuring the forward voltage it is possible to estimate the junction temperature of the LED. With the junction temperature based feedback it is possible to overcome some problems in LED luminaire. Changes in lumen output of the LEDs due to the high junction temperature can be compensated but it does not solve the light output depreciation problem caused by the burning hours.

Increasing the power of the LED to compensate its lowered light output caused by higher junction temperature will result to increased junction temperature. Higher junction temperature decreases the lumen output and more power is needed to compensate the lumen loss. The continuous loop has been created. However, it is not infinitive because there is a limitation for the power. When this limit has been reached, the only way to compensate the increased power need is actually to decrease the power of other LEDs. As a result the colour coordinates will remain constant but the total lumen output will drop.

The junction temperature of 70 ºC has been selected as a target temperature. In that temperature the light output is 10–50 % lower compared to 25 ºC. The smallest decrease will occur in blue LEDs and the biggest is in amber LEDs. Manufacturers give lumen values in their datasheets at the junction temperature of 25 ºC. To achieve this junction temperature in continuous operation the ambient temperature has to be around 0 ºC or below. Alternately there has to be a liquid cooling that is rather complicated and unreliable solution. However, the ambient temperature in normal room is usually over 20 ºC and with an optimal cooling system the junction temperature of about 45 ºC can be achieved. In the prototype luminaire the cooling system is not optimal, there are some compromises and the junction temperature of 55–60 ºC can be achieved. There can be some variation in temperatures according to the location of LED.

At the junction temperatures of 70 ºC the temperature coefficient gives value one. In higher junction temperatures the coefficient value would be over one and if the dimming level is set to maximum, over 100 % power would be required. Because this is not possible there would be a need to decrease intensities of other colours but as said earlier this would lead to the lowered total lumen output. However, by using the cooling system in its full power at the normal operating temperatures, the junction temperatures should remain below the target temperature and there should be no situations were over 100 % power would be required.

Selecting the junction temperature of 70 ºC as the target temperature, the lumen output does not drop at the expense of the CCT. However, in some cases the total lumen output could be higher than it is because if the junction temperature is under 70 ºC none of the LEDs are driven in full power even if the light level is set to the maximum. In the current research the optimization for the target junction temperature, for the cooling and for the control parameters of the prototype are underway. Higher allowed junction temperatures of LEDs may also give more possibilities for these kinds of luminaires.

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