Thermal Design Considerations for High Power LED Systems

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Executive Summary

Lighting efficiency is generally measured in Lumens per Watt (lm/W), the lower the value, the more heat is generated for lumen emitted. Currently high-power LEDs have are rated anywhere from 26-50lm/W rating while traditional incandescent tungsten bulbs are rated at 17.5lm/W. A problem in LED designs is that the heat generated by the light is conducted not radiated as it is in incandescent lights. Conducted heat has to be moved from the LED case to protect the LED and preserve the performance of the LED.

This article will discuss the removal of heat from the LED junction and the use of electronics (i.e. microcontrollers) for temperature protection and compensation of the LED.

This article will cover:

- Types of heat energy generated by lighting solutions: radiated and conducted
- The thermal runaway problem
    - Optical closed loop systems
    - Lower LED lifetime reduction at high heat
- Thermal runaway solutions:
    - Thermal management
    - Junction temperature measurement
- System implementation options
    - Brute Force - Board with copper plane and temp sensor
    - Elegant - Board with characterized thermal materials
- Conclusion

Introduction

Unlike incandescent tungsten light bulbs, high-power LEDs do not radiate heat. Instead, LEDs conduct heat from their PN junction to the thermal slug on the LED package. Because the heat generated by LEDs is conducted, the heat has a longer, more expensive, path to the atmosphere. In an LED, the heat path includes the thermal impedances from the junction to the slug, the slug to the board, the board to the heatsink, and the heatsink to the atmosphere. The heat path for a tungsten bulb is almost straight into the atmosphere, starting with the thermal resistance from the filament to the glass and ending with the thermal resistance from the glass to the atmosphere.

Longer lifetime, higher efficiency, and more flexible color output make LEDs the preeminent solution in architectural and entertainment lighting applications. The color output of LEDs is programmable; that is, a system of multiple LEDs combines, or mixes, to create different colors. One application of color mixing with LEDs is LCD backlighting. In this application multicolor LEDs are used to create a white light with a color temperature of 6500K.

High-end backlight LCDs require precise color matching throughout the display. To achieve precise color matching the thermal and optical design must be optimized for each system. Optimal optical designs use a color sensor to sustain high accuracy color as the LEDs heat, cool and age. A color sensor is used because the characteristics of LEDs will change as the junction temperature of the LEDs change.

Temperature effects on LEDs

The dominant wavelength, luminosity and forward voltage of the LED are all dependent on the junction temperature of the LED. Because the color and brightness properties are sensitive to temperature, it is essential to have control over the thermal performance of the LED lighting system. The plot in figure 1 shows light intensity, or brightness, versus junction temperature

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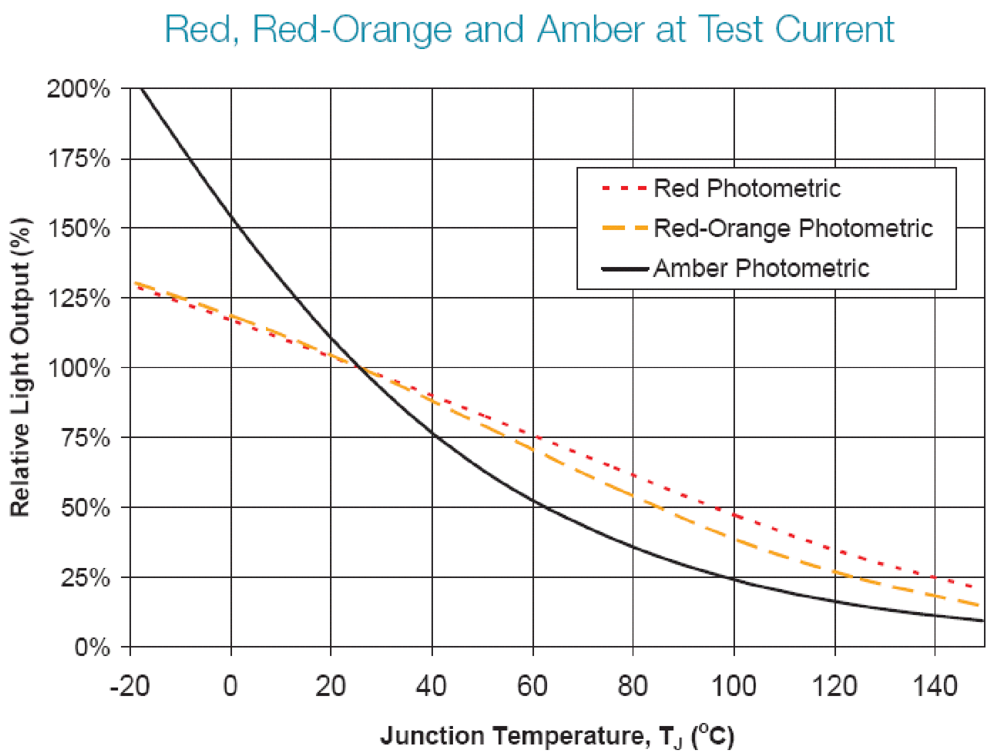
of Lumileds Luxeon K2 LEDs. You can see that the light intensity of the LEDs degrade significantly over temperature. In addition to changes in light intensity, the dominant wavelength (λ_D) or radiated color of the LED will drift slightly with temperature. Even though the λ_D drift is slight, if the junction temperature change is great there will be a noticeable change in the color temperature of the backlight.

Figure 1: Lumileds Luxeon K2 Light Output vs. Junction Temperature Plot



There are a few methods of compensating for changes in color output and brightness over temperature. Taking into consideration all aspects of the design, including electronic, optical and mechanical design, the simplest method of color compensation is to use junction temperature feedback and the most complex method is to use color sensor feedback.

The temperature control method first determines the LED junction temperature by measuring the board temperature and the LED forward voltage and current, as seen in equation 1. Using straight-line approximations of the vendor's temperature characteristic plots, the color and brightness properties of the LEDs are approximated and refreshed to be consistent with the new temperature. To achieve high color accuracy, the mixed color point of the LED is recalculated using the new LED properties from the straight line approximations.

Equation 1: LED Junction Temperature

$$T_J = T_B + \theta_{JB} I_{LED} V_f$$

A mixed-signal microcontroller allows designers to measure the LED parameters, calculate a mixed color point, and generate drive signals. It can drive multiple strings of different colored LEDs, measure board temperature, measure LED current and forward voltage and run calculations to drive the LEDs to the correct mixed color point. Devices that have the functionality to meet these requirements are the Analog Devices ADuC family and the Cypress PSoC family.

Color sensing feedback achieves greater color accuracy by using a color sensor to measure the light radiated by the LEDs. The light is measured using photodetectors tuned to wavelengths that correspond to red, green, blue and wideband (ambient) visible color spectra. The color sensor communicates the color spectra data back to the mixed signal device which processes the information with its on-chip microcontroller (MCU). If the color or the intensity level measured by the color sensor is incorrect, the processor corrects for the error by changing the intensity level of each LED in the system. Notably, the color sensor must be located in a position such that the light reaching the sensor is mixed to the same color as the light reaching the end-user. Not only is the placement of the color sensor important to color uniformity, but the temperature rise for each LED in the backlight should be the same.

Thermal Runaway

The main issue that comes out of the color sensor method is that as the temperature of an LED increases the luminous intensity of the LED degrades. Naturally, as the color sensor reports back a lower intensity level, the processor will try to increase the intensity of each LED, which is accomplished by driving the LEDs harder. By driving the LEDs harder, the power dissipated increases, and therefore more heat is generated by the LED. As the heat generated by the LED increases, the junction temperature the intensity will degrade and the processor will drive the LEDs harder, until the LEDs reach their thermal limit and prematurely fail. This thermal runaway problem happens in color sensor feedback systems that don't monitor or manage heat.

A simple LED protection method is to place a temperature sensor near the LEDs and approximate the junction temperature using equation 1. Similar to the temperature feedback method, when the junction temperature gets too hot, the LEDs are shut off until the system is determined to be safe again. Realistically, nobody wants their TV shutoff every couple of hours because the backlight needs to cool down so the brute force method isn't attractive as a stand-alone thermal management option for LCD TV manufacturers.

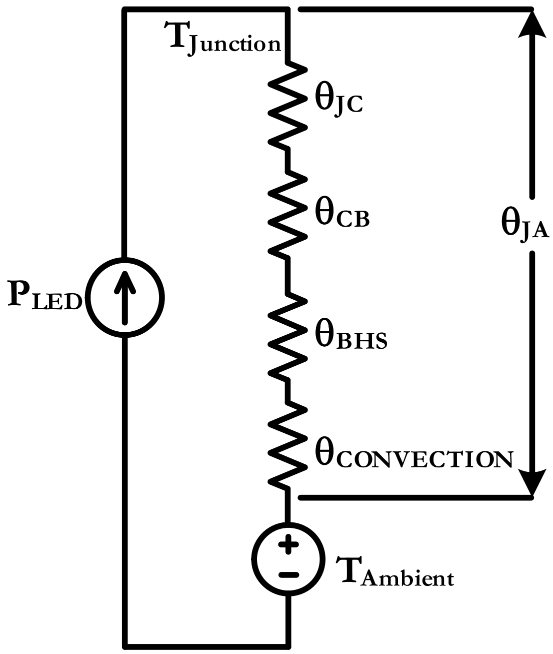
A more reliable technique is to design an electromechanical system with a controlled temperature rise for a given power dissipation. One way of controlling temperature rise is to use high thermal conductivity heat spreader materials. Metal core PCB (MCPCB) and natural graphite heat spreaders[1] are proven thermal management materials that will, when used properly, control temperature rise and maintain the temperature uniformity of a solid state lighting system.

Thermal Management

Recent experiments in LED driving demonstrated the pitfalls of designing with the brute force method of thermal management (described above). Using the brute force method on a small three-LED module led to a noticeable change in color output and singed fingers due to the fact that the temperature rise of the heat spreader was never calculated. The lesson learned is that it is essential to the success of every LED product to design with thermal management as the first or second most important design requirements (second only to color mixing firmware). The first step in creating a thermal management plan is to model your system with a thermal resistance network and to ensure that the temperature rise of the system is within the specifications of the LEDs.

To generate a thermal resistance network for your design, first consider the source of the heat, in this case the LED. The next consideration is the materials between the heat source, the ambient (which is analogous to earth ground in electrical systems) and finally, the ambient temperature itself. In thermal models, the power dissipation of the LED is modeled as a current source, the thermal resistance is modeled as a resistor and the ambient temperature is modeled as a voltage source as shown in figure 2. Intuitively, you can see that the LED junction temperature will be lower if the thermal impedance is smaller and likewise with a lower ambient temperature. To maximize the useful ambient temperature range for a given power dissipation, the total thermal resistance from junction-to-ambient (θ_{JA}) must be minimized.

Figure 2: Thermal Resistance Model



Figures 3 and 4 (shown below) show the physical LED subsystem and corroborate the thermal resistance model in figure 2. The cross-section of the LED and thermal mount provides insight into the possible sources of thermal impedance. Table 1 describes each of the thermal impedances in figure 2.

Figure 3: Cross section of LED with Natural Graphite Heat Spreader

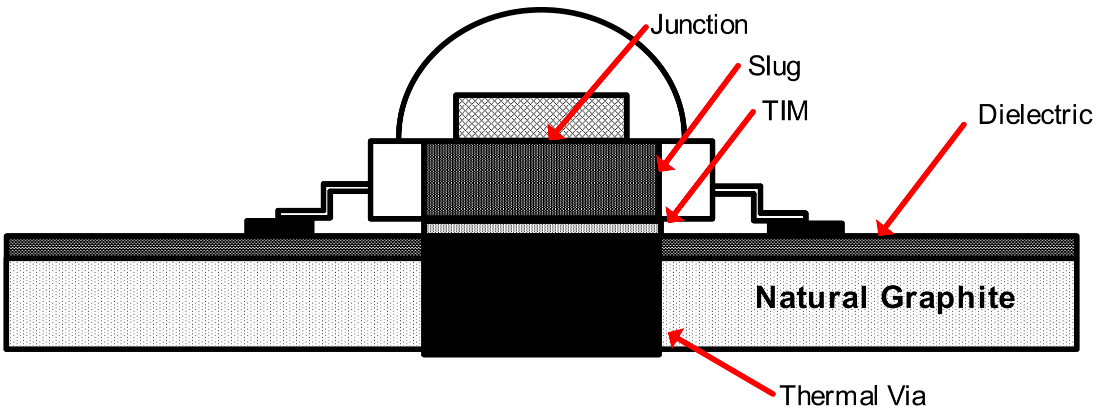


Figure 4: Cross Section of LED with MCPCB Heat Spreader

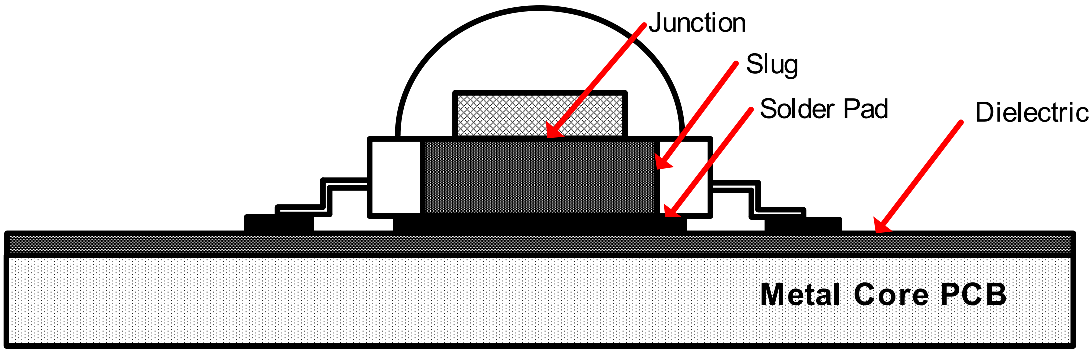


Table 1: Explanation of Thermal Resistances

Symbol	Description
θ_{JA}	Total thermal resistance from Junction-to-Ambient
θ_{JC}	Junction to Case also known as junction to solder-point, thermal resistance from the LED junction to the case
θ_{CB}	Case to Board: the thermal resistance of the thermal interface material (TIM) that bonds the LED slug to the thermal via(s)
θ_{BHS}	Board to Heat Spreader: the thermal resistance between the thermal via or dielectric and the heat spreader
$\theta_{Convection}$	Convection surface thermal resistance, this is the thermal impedance of convection from a heat spreader or heat sink

The values for the thermal impedances, with the exception of $\theta_{Convection}$, vary widely depending on the material or component supplier. For example, θ_{JC} (also known as $\theta_{J\text{-}SP}$, junction-to-solder point) will range from 2.6-18°C/W depending on the LED manufacturer. The thermal resistance of the TIM also will vary depending on the type of material that is selected. Common TIMs are epoxy, thermal grease, pressure sensitive adhesive (PSA) and solder. The value of θ_{BHS} for the MCPCB is mostly dependent on the dielectric, which can be any electrically insulative TIM. Natural graphite heat spreaders have no thermal resistance from the slug to the heat spreader.

The value of $\theta_{Convection}$ depends on the orientation and surface area of the material. If the heat spreader is vertically oriented it has less than half of the thermal resistance of a horizontally oriented heat spreader. $\theta_{Convection}$ is solved for by determining h_c, the heat transfer coefficient (HTC)[2] for the material, for instance, the heat spreader in an LCD backlight. Equation 2 shows the general form of the HTC equation.

Equation 2: Heat Transfer Coefficient Equation

$$h_c = D * E\frac{\Delta T^{0.25}}{L^{0.25}}$$

D = 0.56	Constant for air properties of a vertically oriented heat spreader; 0.26 for horizontally oriented heat spreaders
$E = 1.9 * 10^{-4}$	Constant for surface configuration of a heat spreader
L = 62cm	Length in cm of the dissipater surface (24.4in x 18.6in)
$\Delta T = 35°C$	Temperature difference between heat spreader (60°C) and ambient (25°C)
$h_c = 9.222*10^{-5}$	HTC for vertically oriented natural convection heat spreader

Using the HTC and the surface area of the heat spreader (units: cm^2) the value for $\theta_{Convection}$ can be determined. As an example, for a 20 inch TV, $\theta_{Convection}$ is given by equation 3:

Equation 3: Thermal Resistance of Natural Convection

$$\theta_{Convention} = \frac{1}{h_c A_s} = \frac{1}{9.222 \times 10^{-5}(1153)} = 9.4°C/W$$

Three-LED Module Thermal Design Example

As a design example, lets use three Luxeon K2 multicolored LEDs in a lighting module which dissipates 3.85W of power. Each lighting module contains a red, green and blue LED. The LEDs are mounted on a two inch by two inch horizontally oriented natural graphite heat spreader with solder as the TIM. Table 2 shows the thermal impedances for the lighting module.

Table 2: Three LED Module Thermal Resistances

$\mathbf{P_{LED}}$	**3.85**
θ_{JC}	9°C/W
θ_{CB} (Solder)	0.08°C/W
$\theta_{Convection}$	1.9°C/W[2]
$\boldsymbol{\theta_{JA}}$	**10.98°C/W**
$\mathbf{T_{A,MAX}}$	**50°C**

Solve for the maximum junction temperature ($T_{J,MAX}$) by substituting the values in bold above into equation 2:

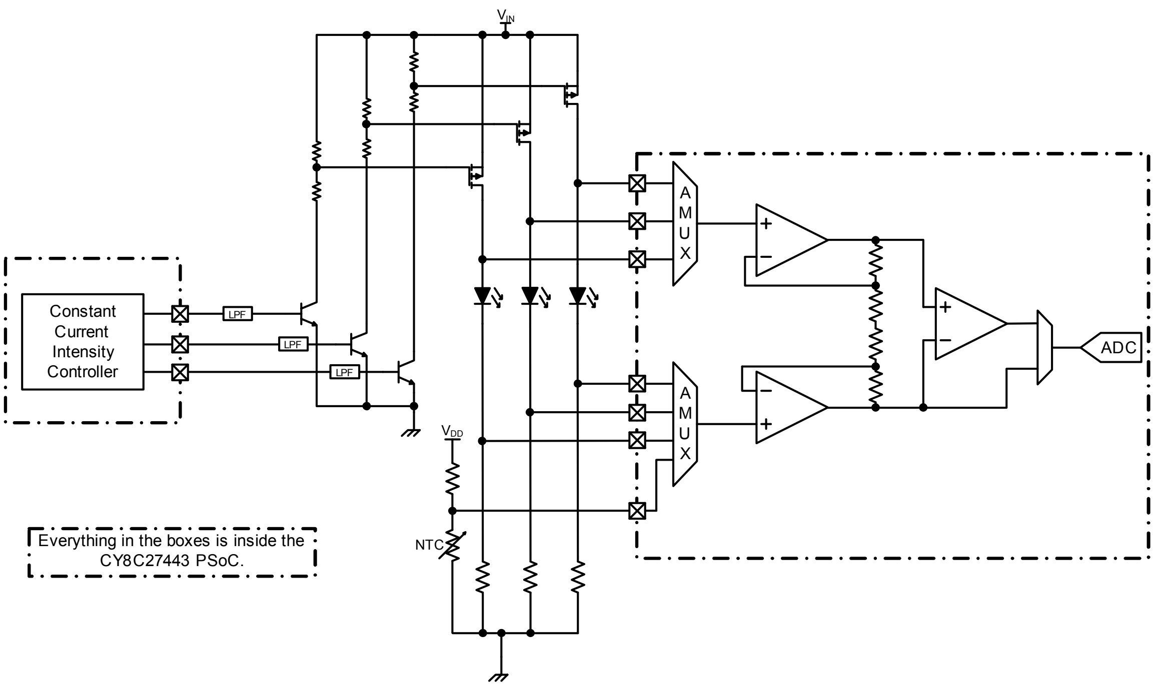
Equation 5: Maximum Junction Temperature

$$T_{J,MAX} = 50°C + 3.85W \times 10.98°C/W = 92.3°C$$

This junction temperature is within the safe operating range of the LED, but recall from figure 1 that the light output degrades significantly at this temperature. The red LED intensity will drop to about 55% of the rated value while the green LED will drop to 90% (not shown) and the blue will remain unchanged (not shown). This luminosity degradation phenomenon drastically affects the mixed-color output of the LED module. Therefore, a luminous intensity control system is necessary.

By sensing the junction temperature of the LEDs an MCU can correct for errors in the color output by changing the drive of each set of LED colors. A MCU based control loop is used rather than an analog control loop because the luminous intensity of each LED changes at a different rate versus temperature. The reconfigurable circuitry shown in figure 5 provides an apparatus for approximating the LED junction temperature

Figure 5: Mixed Signal Circuit for Measuring and Controlling LEDs



The analog input circuit in figure 5 works as both an instrumentation amplifier, for measuring the LED forward voltage, and a single-ended amplifier for amplifying the voltage on the current sense resistors and NTC thermistor. The amplifier changes from an instrumentation amplifier (INSAMP) (shown) to a non-inverting amplifier (PGA) (not shown) by changing the connection point of the internal resistor string. In the INSAMP configuration, the bottom of each amplifiers resistor string are tied to each other. In the PGA configuration the bottom of the resistor strings are tied to V_{SS}. Additionally, the analog multiplexers allow the measurement of up to 8 signals using the same amplifiers. In this case the forward voltage and current of three different LEDs and a thermistor are measured.

Conclusion

Designers attempting to create High Power LED systems are well served by understanding the thermal problems associated with LEDs. Smart thermal management will increase the operating temperature range and thermal monitoring will maintain the accuracy of LED products. Thermal monitoring of these systems with programmable mixed signal controllers offers superior advantages over conventional circuits. From temperature monitoring to color correction, these mixed signal controllers make thermal designs simpler and integrate the functions that normally consume board space and BOM budget.

References

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