Temperature dependent thermal resistance in power LED assemblies and a way to cope with it

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Andras Poppe
Budapest University of Technology and Economics

Temperature dependent thermal resistance in power LED assemblies and a way to cope with it

András Poppe[1,2], Gábor Molnár[1], Tamás Temesvölgyi[1,2]
[1]Mentor Graphics MicReD Division
Budapest XI, Infopark D, Gábor Dénes utca 2, H-1117 Hungary
andras_poppe@mentor.com
[2]Budapest University of Technology and Economics, Department of Electron Devices
Budapest XI, Goldmann György tér 3, H-1111 Hungary
poppe@eet.bme.hu

Abstract

Different high-end white power LEDs from different LED vendors were studied. The aim of the study was to find the optimal choice of LEDs and thermal management solutions for a street-lighting application. The primary concern was the (real) junction-to-heatsink thermal resistance of the LED or LED assembly and the real junction temperature and the actual light output of the individual LEDs under test. Since in many cases the junction-to-heatsink thermal resistance showed temperature dependence, like-with-like comparison in terms of light output characteristics was done as function of the real junction temperature instead of the reference temperature.

Keywords

LED thermal management, junction temperature of LEDs

1. Introduction

As it is widely know, the light output characteristics of light emitting diodes (LEDs) strongly depend on the operating conditions. The forward current applied to the LEDs is the primary variable – the higher the supplied current, the more light is generated by the LED. Unfortunately when a LED is driven by a constant current source the light output drops when the temperature of the LED increases. This general feature of all LEDs is best illustrated by the dependence of their light output spectra – as shown in Figure 1. In addition to efficiency drop, the color of the LEDs' light also changes as it is shown by the shift of the peak wavelength.

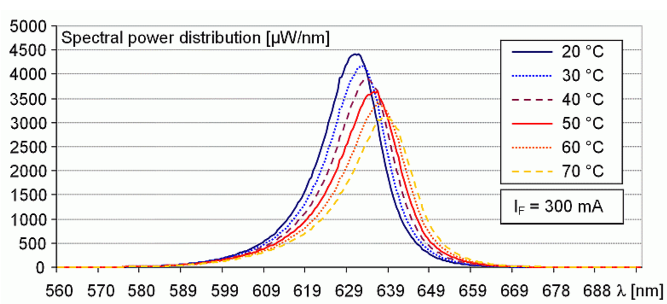


Figure 1: Current and temperature dependence of the spectral distribution of the light output of a red LED

Since light output characteristics change with temperature, proper thermal management is a key issue in power LED-based lighting applications. By keeping LEDs cool, high efficiency can be maintained. A thermal management solution that delivers better cooling also delivers more useful lumens in a given application.

This means that the real junction-to-ambient thermal resistance of the LEDs in their application environment is key factor in lighting design. Unfortunately different LED vendors report their products' thermal resistance and other temperature-related characteristics in diverse ways. Therefore standardization activities related to thermal issues of power LEDs were started in various thermal standardization bodies. A new standard for the proper measurement of LEDs' thermal resistance is currently being drafted by the JEDEC JC15 committee. This work relies on a whitepaper first published in 2008 [1] and updated several times in 2009 [2][3]. In addition to this, the International Lighting Committee (CIE) set up new technical committees (TC-2-63 and TC-2-64) to deal with the thermal aspects of LEDs. Among these committees an agreement is emerging that vendors need to consider the actual P_{opt} emitted optical power (that is, the radiant flux denoted as Φe) of the LEDs when calculating thermal resistance per the following formula:

$$R_{th\_real} = \Delta T_j / (I_F \times V_F - P_{opt}). \qquad (1)$$

Here the product of the LED's forward current and forward voltage ($I_F \times V_F$) represents the electrical power supplied to the LED and ΔT_j denotes the change of the LED chip's junction temperature as a response to the change of heating power. Precise discussion of LEDs' thermal resistance can be found e.g. in [2] or in [3].

Neglecting the optical power when determining an LED's thermal resistance yields values which are much lower than reality. If lighting designers use these numbers to calculate the expected light output of their LED-based lighting applications, the design will very likely fail to meet its light output specs. The real thermal resistance is higher, and therefore the junction temperatures will also be higher. As a result the actual luminous flux obtained from the luminaire will be below the required level. Clearly the real thermal data of the LEDs is essential to a successful LED design project.

The aim of the present study was to find the optimal choice of LEDs and thermal management solutions for a streetlighting application. The primary concern was the (real) junction-to-heatsink thermal resistance of the LED or LED assembly. Also, the temperature dependence of the light output characteristics was of major concern, since the useful lumens prescribed by the relevant national and European lighting standards had to be assured at all possible operating temperatures of the luminaire.

2. Devices under test

2.1. Aim of the study

The aim of the study was twofold. On one hand we tried to find a thermal management solution for the chosen power LEDs which had the best price/performance ratio considering also the manufacturability of the final product (street-lighting luminiare). On the other hand, the junction temperature dependence of the light output characteristics of the chosen LEDs was of major concern since even under the worst case operating conditions (highest possible luminaire temperature) the road surface illuminance level prescribed by the relevant lighting standards had to be assured.

From the point of view of the comparison of the different thermal management solutions, a precise like-with-like comparison was needed. Therefore the measurements had to provide the real junction-to-heatsink thermal resistance values (as per Eq 1). Structure function analysis of the measured thermal impedances was performed in order to allow the comparison of the different material and assembly combinations.

The measured light output characteristics were all re-scaled from the reference temperature to the junction temperature. Junction temperature was obtained as follows:

$$T_j = T_{ref} + R_{th\_real} \cdot (I_F \times V_F - P_{opt}). \qquad (2)$$

Plotting the light output characteristics (such luminous flux or efficacy) as function of the real junction temperature, again, allows like-with-like comparisons by absorbing the effect of the chosen thermal management solution. On one hand it allows to compare the LED samples of the same manufacture (providing information about the scatter of a parameter of a given product). On the other hand, LEDs from different vendors can also be compared in terms of their performance (e.g useful lumens at operating temperatures).

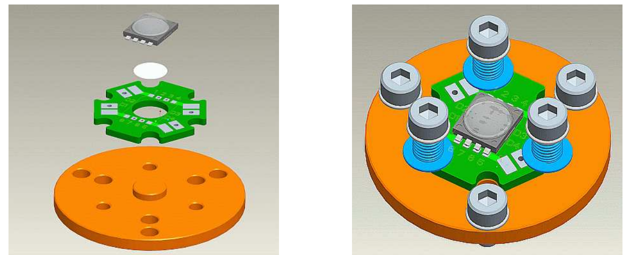
2.2. Different heat-flow path assemblies

Different high-end white power LEDs from different LED manufacturers have been studied. Here we present the measurement results for one particular vendor's multi-chip LED which is among the candidates for the final LED choice for the targeted street-lighting application. Based on these measurements the best thermal management solution was chosen and the temperature dependence of the light output characteristics was provided for the subsequent design steps such as optics design and system level thermal design.

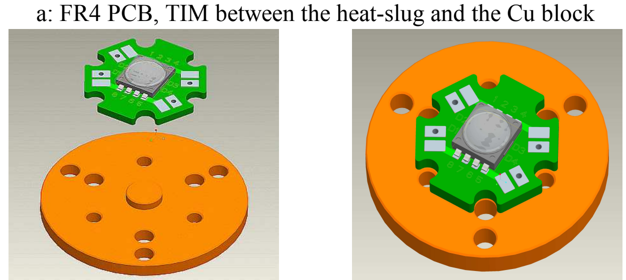
Different types of assemblies provided by the LED system integrator which were studied are as follows:

1. LED attached to an FR4 based PCB with a thermal contact hole in the middle, attached to a Cu heat-spreader block, high thermal conductivity TIM (Laird Technologies T-grease 2500 [4]) applied between the Cu block and the heat-slug of the LED package (as per Figure 2a);
2. The same setup as above (as per Figure 2a), but using a phase-change TIM (Laird Technologies T-pcm FSF-52 [5]);
3. LED attached to an FR4 based PCB with a thermal contact hole in the middle, the LED's heat-slug soldered to the Cu heat-spreader block underneath (as per Figure 2b);
4. Packaged power LED attached to an Cu-based MCPCB (as per Figure 2c) and a TIM layer applied between the MCPCB and the heat-slug;
5. same as #4, but using an Al-based MCPCB.

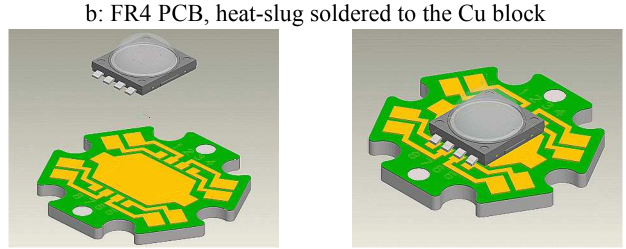
Photographs of the assembled test samples are shown in Figure 3.



a: FR4 PCB, TIM between the heat-slug and the Cu block



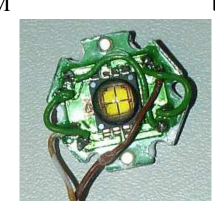
b: FR4 PCB, heat-slug soldered to the Cu block



c: MCPCB-s made of Al and Cu, heat-slug soldered

Figure 2: Mechanical setups of the different thermal management solutions which have been studied

a: FR4 + TIM b: FR4 + solder



c: Al / Cu MCPCB + TIM

Figure 3: Mechanical setups of Figure 2 assembled with Cree Xlamp MCE1 series white LEDs

3. Test setups

In all of the cases the LED assembly was attached to a temperature controlled stage (cold-plate) which was aimed to model the effect of the luminaire (large thermal capacitance). The temperature of the cold-plate was varied between 15°C and 85°C. With this we aimed to mimic the possibly large variation of the temperature of the street-lighting luminaire when exposed to real outdoor environment. (From the LEDs' operation point of view temperatures below 15°C are not critical, since LEDs' performance radically improve at lower operating temperatures.)

Combined thermal and radiometric/photometric measurements were performed, complying with the recommendations of the electrical test method as per JEDEC JESD51-1 [6] and the total flux measurement method for LEDs according to the CIE 127-2007 document [7]. The schematic diagram of the setup is shown in Figure 4. In such a setup electrical power of the LED under test is provided by the thermal test equipment. The light output of the LED is measured when it is driven by its prescribed operating current and is in thermal equilibrium (steady-state) as required by [7]. The reference temperature of the LED under test is the temperature of the cold-plate which is attached to the integrating sphere of the photometric test system.

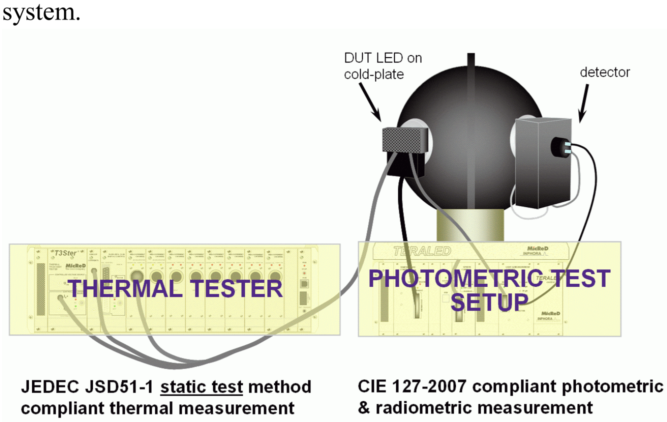


Figure 4: Schematic of the test setup suggested for combined thermal and radiometric/photometric measurement of power LEDs.

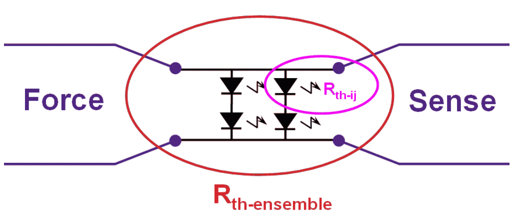


Figure 5: If a multi-chip LED package is not prepared for thermal testability, individual thermal resistances of the single chips can not be identified, only an "ensemble" thermal resistance can be measured.

With a test setup shown in Figure 4 one can make sure that the measured thermal and radiometric/photometric properties of the LED under test are consistent. Quantities ΔT_j, I_F and V_F of Eq. (1) are determined by the thermal test equipment. Quantity P_{opt} (emitted optical power) used in Eq. (1) is measured by the optical test system as the Φ_e *total radiant flux* of the LED under test. Depending on the capabilities of the optical test system, the Φ_V *total luminous flux* or the color coordinates of the LEDs light can also be measured. Thermal resistance and light output measurements can be performed for a given set of temperature and forward current values by setting electrical power level in the thermal test equipment and setting the T_{ref} temperature of the cold-plate.

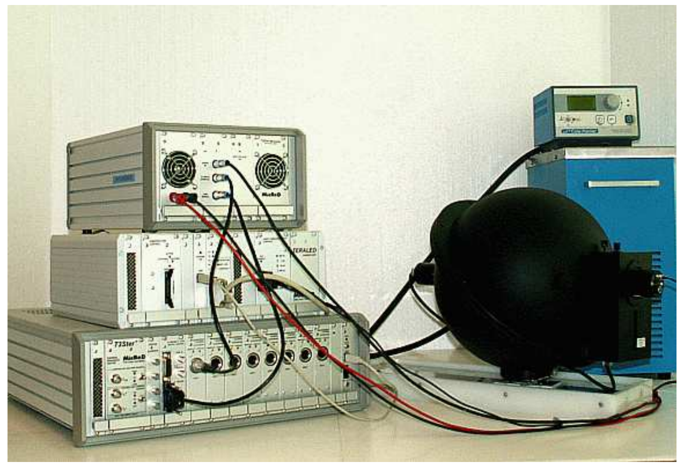


Figure 6: The actual physical test setup used to measure high power LED samples.

Figure 7: Test sample attached to water cooled cold-plate with a mechanical adaptor of the integrating sphere.

We had to measure LED packages with multiple chips connected in series (Xlamp MCE1 series of white LEDs from Cree – see Figure 3). In such cases one can measure the overall or "ensemble" thermal resistance of all the chips only, since the individual chips are not accessible for thermal testing. In case of the above mentioned Cree LEDs both the powering and the heat-sinking capabilities of our standard test equipment were exceeded. Therefore the Peltier-based temperature controlled DUT LED holder of the integrating sphere was replaced by a water cooled cold-plate and the thermal test equipment was extended with an appropriate power booster unit. The actual physical test setup is shown in Figure 6 and Figure 7.

4. Measurement results

10 samples of Cree Xlamp MCE1 series of white LEDs have been prepared and measured. From each assembly type (detailed in section 2) two samples were available for testing. All of the type 3 samples burnt out during the tests – probably due to the fact that during the soldering the samples suffered a fatal thermal shock. A further sample was also removed from the tests by one of our project partners dealing with optical design. Altogether results for 7 different samples are available and are reported here.

Both the thermal tests and the light output measurements were performed at 15°C, 25 °C, 40 °C, 55 °C, 70 °C and 85 °C cold-plate temperatures, using 350 mA and 700 mA forward current during heating and optical tests. For thermal tests 10 mA sensor current was applied. Optical properties were also measured at the sensor current.

4.1. Thermal measurements

In the following we present measurement results for three typical samples, being assembled in different ways: type 1 (blue line, label TG2500), type 2 (red line, label FSF52) and type 5 (green line, label AL) assemblies – as described in section 2.2.

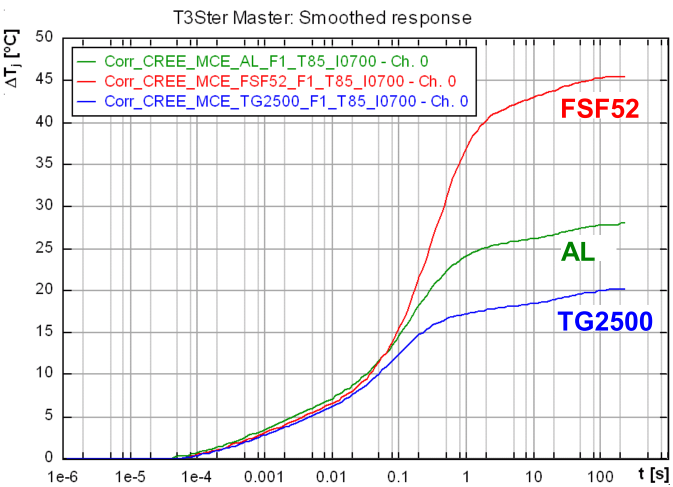


Figure 8: Junction temperature transients for three different assemblies of Cree Xlamp MCE1 series white LEDs (T_{ref}=85 °C, I_F=700 mA).

The junction temperature transients for I_F=700 mA at T_{ref}=85 °C are shown in Figure 8. These plots already suggest, that the type 1 assembly solution posses with the best heat removal property, since this resulted in the smallest junction temperature rise. The junction temperature transients divided by the real heating power (power corrected by emitted optical power) result in the real thermal impedance curves which are shown in Figure 9. From these plots we can already quantify the junction-to-heatsink thermal resistance values for each assembly. The best performing assembly solution is of type 1 (denoted by TG2500 in the result plots) with a thermal resistance value of ~3 K/W. (This value is very close to the data sheet value reported by the LED vendor.)

The thermal impedances can also be represented by means of structure functions as shown in Figure 10. The initial sections of the three structure functions coincide which corresponds to the fact, that the initial section of the three different heat-flow path structures are identical: heat-flow through the LED chip, die attach and the top of the heat-slug of the package. From the structure function plots one can see that there is a huge difference between the two types of TIMs applied by the LED system integrator.

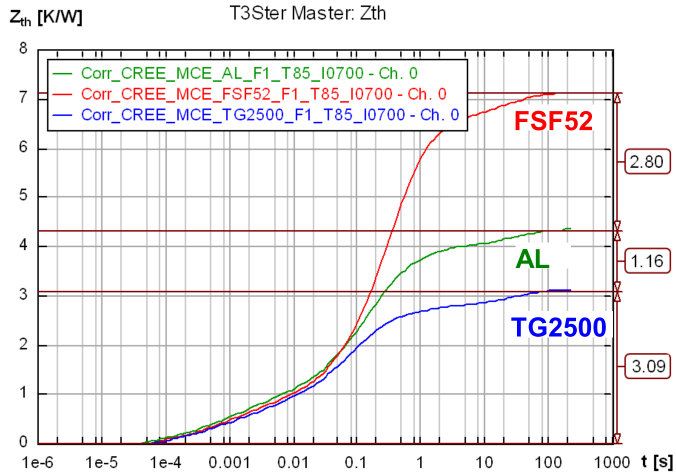


Figure 9: Thermal impedance curves for three different assemblies of Cree Xlamp MCE1 series white LEDs (T_{ref}=85 °C, I_F=700 mA).

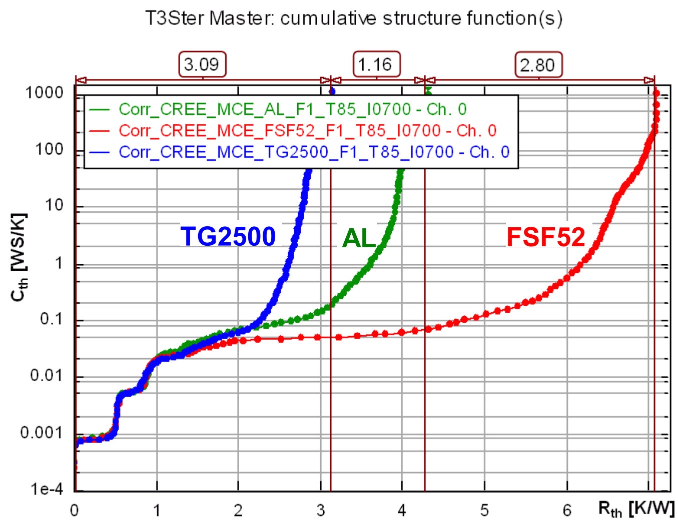


Figure 10: Structure function representation of the thermal impedances of three different assemblies of Cree Xlamp MCE1 series white LEDs (T_{ref}=85 °C, I_F=700mA).

In Figure 11 we present the structure function plots of the 2nd LED sample assembled on an Al-based MCPCB. Its thermal resistance at T_{ref} =85 °C is 3.9 K/W which is by 0.35 K/W smaller then the thermal resistance of the 1st sample of this kind (shown in Figure 10). What is interesting to note in Figure 11 is the temperature dependent variation of the thermal resistance of the LED assembly.

Such a temperature variation could be observed in case of all samples we measured. In every case the variation took place in the TIM layers. The tendency is that at higher reference temperatures the total junction-to-heatsink thermal resistance is reduced. This behavior is likely due to viscosity changes of the applied TIMs: at higher temperatures the TIMs fill the microscopic air-gaps of the adjecent interfaces better, resulting in smaller interfacial thermal resistances.

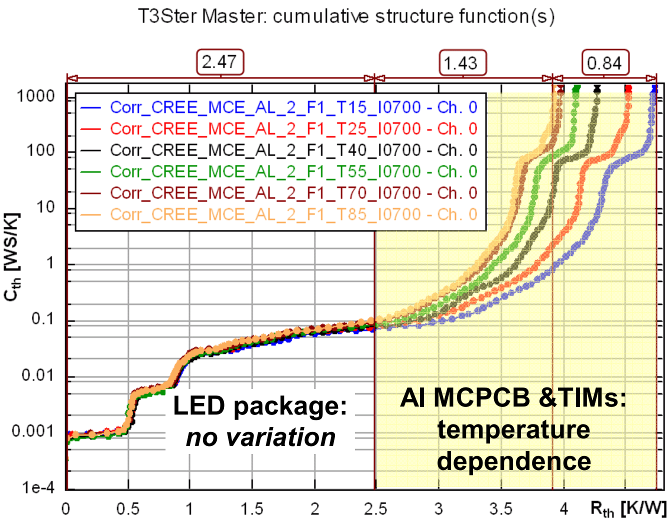


Figure 11: Structure function plots of the thermal impedance of sample marked AL_2 for I_F=700mA and of while T_{ref} vas varied between 15 °C and 85 °C.

The fact, that the total thermal resistance of the LED assembly may vary with the reference temperature highlights the importance that all metrics of power LEDs need to be reported as function of the *real junction temperature*.

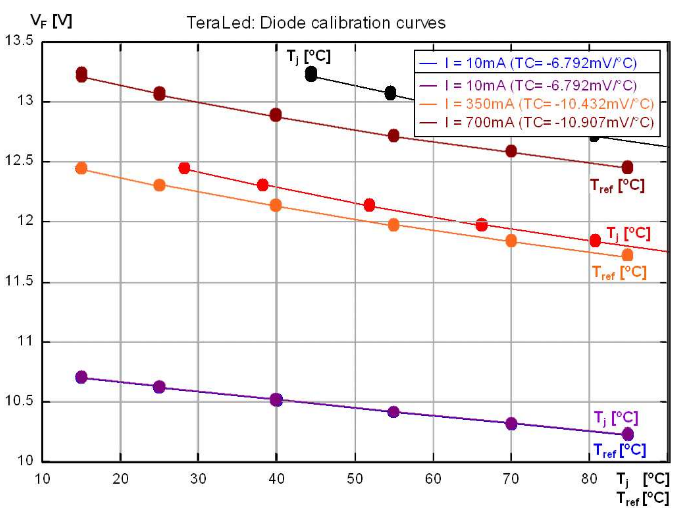


Figure 12: Temperature dependence of a LED's forward voltage at I_F=10mA (plots in the bottom), 350mA (middle plots) and 700 mA (plots on the top) shown as function of reference temperature and as function of junction temperature.

If we assume that the heating power is independent of the temperature (i.e. remains constant) while the reference temperature is increased, then in case of temperature independent thermal resistance any kind of device characteristics plotted as function of the reference temperature and plotted as function of the junction temperature must run parallel. The temperature dependent thermal resistance however, results in different slopes of e.g. the forward voltage plots as shown in Figure 12. At high forward current levels the plots have different slopes depending whether the measured data points are shown as function of the junction temperature (higher slope) or if they are shown as function of reference temperature. In case of the 10 mA sensor current however, since no significant self-heating took place at the junction, the two curves and the two slopes are identical. Again, this fact suggests that reporting of any LED device characteristic makes sense as function of the junction temperature. By doing so the effect of the temperature dependent thermal resistance can be eliminated.

4.2. Optical measurements

The usual photometric/radiometric parameters of the LEDs have been measured in our combined test setup: total radiant flux (also known as radiometric flux or emitted optical power), the total luminous flux and the color coordinates of the emitted light. From the measured color coordinates the correlated color temperature of the white LEDs was also calculated. We also calculated the energy conversion effecency and the efficacy from the measured radiant and luminous flux values, respectively.

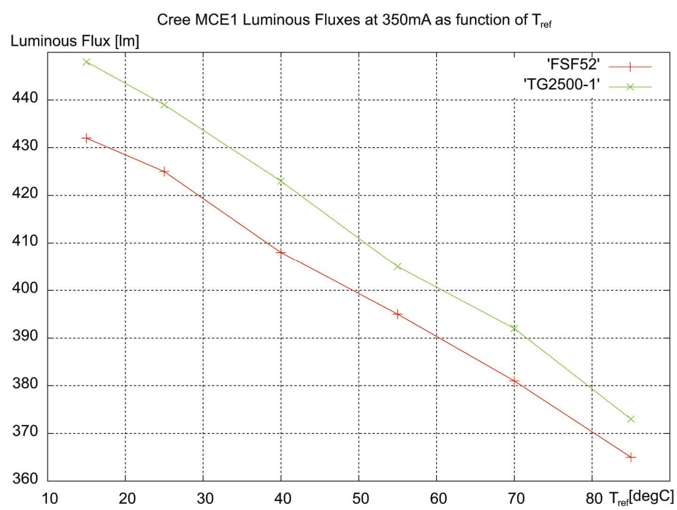


Figure 13: Luminous flux plots of Cree Xlamp MCE1 series white LEDs with two different assembly types as function of T_{ref} reference temperature (I_F=350 mA).

In Figure 13 luminous flux plots of two samples with different assemblies (thus, with different temperature dependent junction-to-heatsink thermal resistances) are shown as function of the reference temperature. As discussed in the last paragraph of section 4.1 these plots have an offset and have different slopes – as clearly seen in Figure 13. After re-scaling to junction temperature, the luminous flux diagrams of the two LED samples of the same manufacture coincide, as seen in Figure 14. Again, by re-scaling the plots of measured data points to the real junction temperatures of the devices we get rid off of the effect of the different temperature dependent thermal resistances..

In Figure 15 luminous flux plots of all measured samples with 4 kinds of different assemblies are shown as function of the junction temperature. Figure 16 presents the calculated efficacy values of the measured LEDs. Since by re-scaling the measured data to junction temperature the effect of the variations in thermal resistances is eliminated, the scatter among the plots corresponds to the scatter among the measured LED samples. We have to note, that the measured performance is better for all measured samples then the data sheet values published by the particular LED vendor.

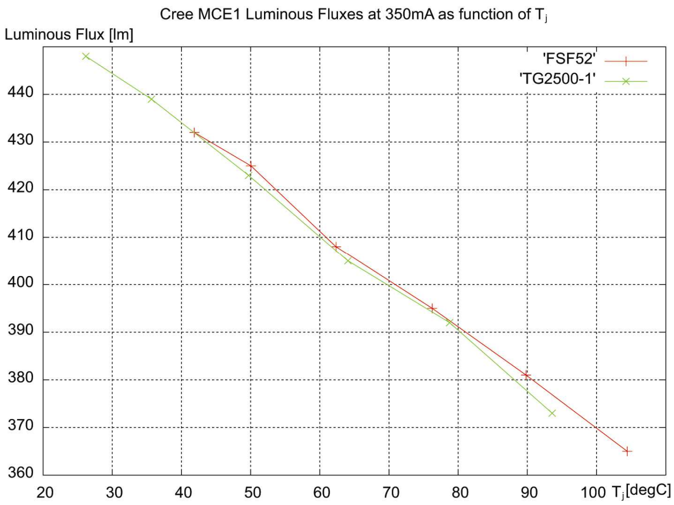


Figure 14: Luminous flux plots of Cree Xlamp MCE1 series white LEDs with two different assembly types as function of T_j junction temperature (I_F=350 mA).

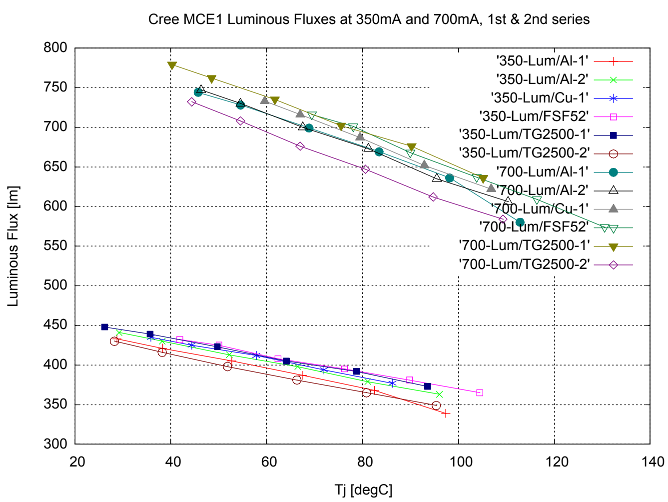


Figure 15: Luminous flux plots of 7 different samples of Cree Xlamp MCE1 series of white LEDs as function of junction temperature at 350mA (plots in the bottom) and 700mA (plots in the top) forward current

5. Conclusions

Different assembly solutions for a high power multi-chip white LED device were studied. Combined thermal and optical measurements were performed, this way the real thermal resistance of the different assembly solutions was identified and the real junction temperatures were calculated. This allowed a like-with-like comparison of the different assembly solutions. Temperature dependence of the measured thermal resistances was also observed. Its effect, however, could be eliminated by re-scaling all measured data to junction temperature. Again, this allows a fair like-with-like comparison among LED samples of the same manufacture or among LEDs of different vendors.

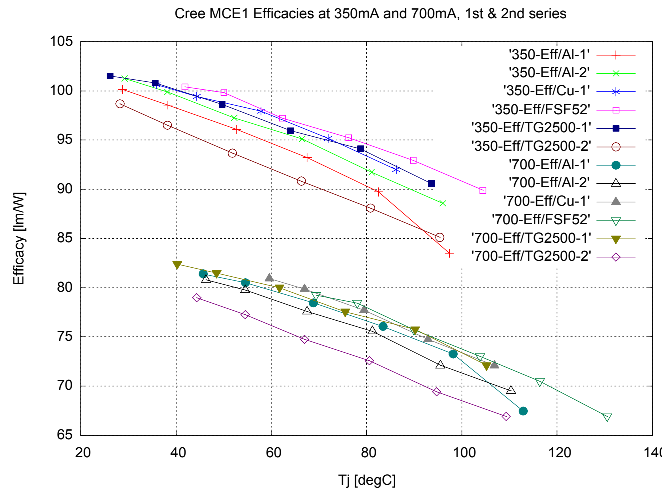


Figure 16: Luminous efficiency (efficacy) plots of 7 different samples of Cree Xlamp MCE1 series of white LEDs as function of junction temperature at 350mA (plots in the bottom) and 700mA (plots in the top) forward current

Acknowledgments

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