Karlsruhe Institute of Technology

Lichttechnisches Institut

Lighting Technology Lab
Thermal and spectral behaviour of LEDs

Light Technology Institute

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Group L09

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1. Introduction

LEDs have nowadays a broad field of use: lamps, automotive industry, data transfer, displays, stadium display boards. While running the LED, a part of the electrical energy is transferred into thermal energy, the system heats up. Although there are different cooling methods from just simple fans up to complex water-cooling systems, a change in temperature has to be accepted.
Thus, in fields where high colour accuracy is required the thermal behaviour of the LEDs has to be taken into consideration. In this report the thermal behaviour of a RGB and a white LED in the range of 15°C to 80°C is characterised.

Theory

The typical bandgap of a semiconductor is in the range of 0.5eV to 5eV. By doping with donators[1] and acceptors[2], n- and p-semiconductors are created. By connecting the p- and n-doped semiconductors diffusion process of electrons will happen till a certain potential difference occur.
When applying external potential, the electrons are shifted into the p-doped region. Electrons and electron holes can recombine. The recombination leads to an energy release in form of a photon equal to the energy of the bandgap.

According to Einstein the peak wavelength of an LED λ_{peak} refers to the bandgap energy E_g, h is the Planck constant and c the velocity of light in vacuum.

$$\lambda_{peak} = \frac{h \cdot c}{E_g} = \frac{1240nm\ eV}{E_g} \tag{1}$$

Indeed, the LED does not emit light at a discrete wavelength but a certain spectral range. The spectrum $\Delta\lambda$ of a LED refers to its temperature. With k_B for the Boltzmann constant

$$\Delta\lambda \approx \frac{3k_B \cdot T}{h \cdot c} \lambda_{peak}^2 \tag{2}$$

Moreover, thermal energy leads to a reduction in the bandgap, thus a shift in the peak wavelength. This phenomenon is called *red shift*.
In addition to the red shift also the emitted radiant power *I* of a LED decreases with increasing temperature and the material dependent degradation constant *t*. The exponential dependence can be described by:

$$I(T + \Delta T) = I(T)e^{-\Delta T/t} \tag{3}$$

[1] Donators have free charge carriers available
[2] Acceptors can take up electrons (electron-holes)

2. Procedure

Equipment:

- Spectrometer: Instruments Systems MAS40
- Integrating sphere: Instruments Systems
- Peltier element
- TEC Controller NT 10 A
- Keithley Multimeter 2000
- Agilent Power Supply 6632 B
- PC with "Specwin light"
- White LED (warmwhite)
- RGB LED

RGB Measurements:
LEDs are controlled by current, to reassure equal current on each LED they are connected in series. For a more reliable and flexible measurement each LED was observed by an independent voltmeter which is connected parallel to the LED (see *figure 1*).

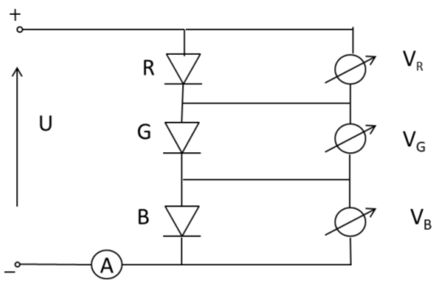

Figure 1 Electrical circuit for measuring voltage drop over each RGB-LED

Measurements are made in specific conditions. Characteristics in three temperatures are made: 15°C, 20°C and 80°C. For 20°C and 80°C three currents are set: 50mA, 100mA and 350mA. Lower temperature is set just to compare voltage and efficiency difference. With Peltier elements and TEC Controller, temperature is measured and controlled, current is set with Agilent Power supply.
The interesting part is how efficiency and colour spectrum is changing in different settings. To measure it, spectrometer from Instruments Systems MS40 is used with integration sphere (see *figure 2*). The Ulbricht sphere adapter is used to obtain a homogeneous mixture of the three different colour chips. To avoid overexposure OD2 filter is installed.

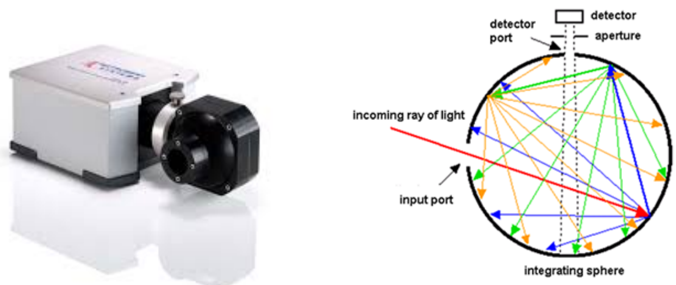

Figure 2 Spectrometer with integrating sphere (left) [2] and schematic principle of Ulbricht sphere (right) [3] .

3. Evaluation

In this section the evaluation of the measurements is performed, which includes analysis of UI-characteristics, spectra and CIE diagrams for the RGB LED and the white LED at different temperatures.

3.1 RGB LED

The results of the measurements are summarized in *table 1*

Table 1 Thermal dependency of electrical parameters for RGB LED

Temp [°C]	Voltage [V]			Current [mA]	Voltage [V]
	Red	Green	Blue		
20	2,175	3,236	3,122	350,43	8,533
20	1,941	2,976	2,861	100,39	7,778
20	1,871	2,862	2,766	49,82	7,499
80	2,046	3,012	2,912	350,41	7,97
80	1,83	2,75	2,712	100,37	7,292
80	1,767	2,637	2,642	49,81	7,046
15	2,188	3,25	3,142	350,38	8,58

The measured UI-characteristics of the RGB LED at two different temperatures (20°C and 80°C) are presented in the *figure 3*.

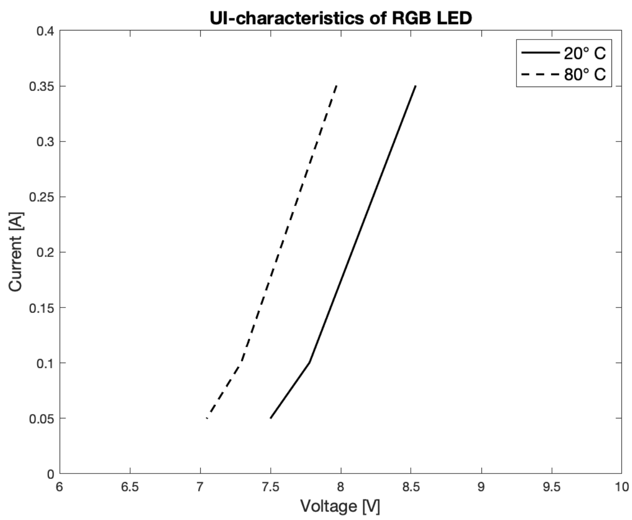

Figure 3 UI-characteristics for the RGB LED.

The distinct parallel shift in the UI-characteristics results from the fact that the bandgap energy of the LED's material decreases with increasing temperature. Since the electrical resistance depends on temperature as well, the voltage-drop over the LED is lower.

The same behaviour can be noticed for each single RGB chip (see *figure 4*). In general, the voltage-drop over the different chips should rise from higher wavelength to lower one. Unexpectedly, the green LED's voltage exceeds the voltage of the blue LED, which might be caused by different efficiency of the used materials.

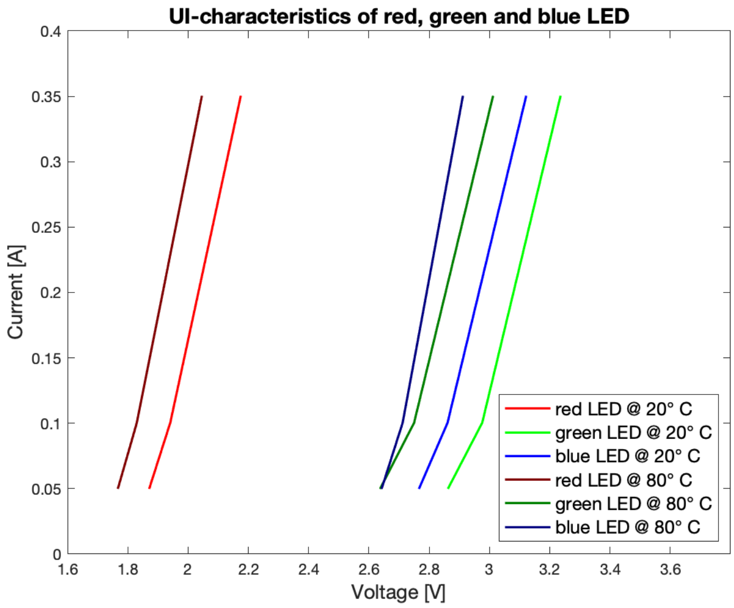

Figure 4 UI-characteristics for red, green and blue LED.

The measured spectra for the RGB LED at different temperatures (15° C, 20° C and 80° C) can be seen in the figure below.

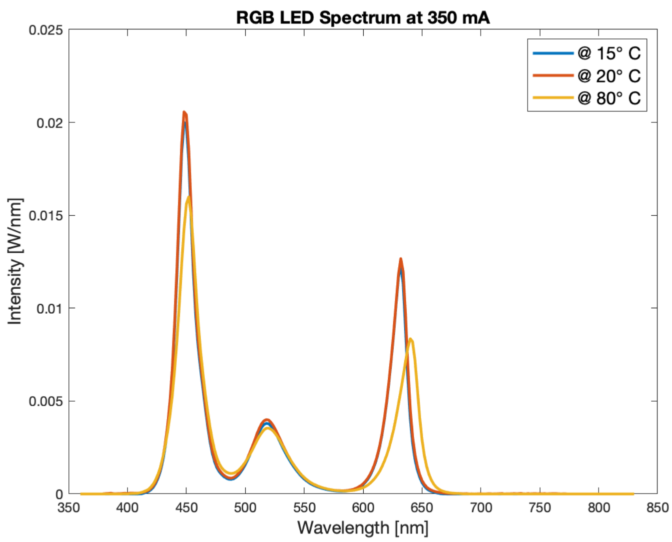

Figure 5 Spectrum of RGB LED at different temperatures.

The light intensity of the LED reaches its maximum at room temperature and drops for higher and lower temperatures. The red shift and spectral broadening are also visible in the figure. It can be also noticed that the biggest peak wavelength shift appears for red.
Furthermore, the intensity decrease is not proportional for each chip. This results from usage of different materials which have different thermal behaviour and degradation constants *t* (*equation 3).*

Figure 6 presents separately the spectrum for the red, green and blue LED at 20° C, which overlaps with the spectrum of the whole RGB LED.

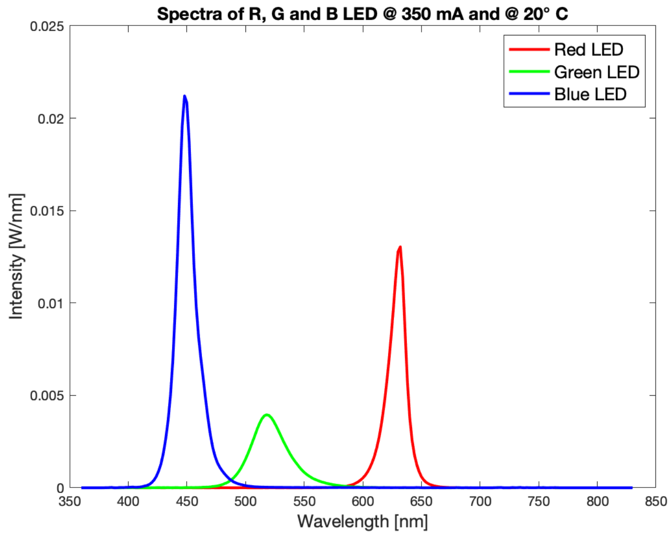

Figure 6 Spectra for red, green and blue LED.

Both spectra (see *figure 5* and *figure 6)* were measured at the same current which was equal 350 mA. The behaviour of the RGB LED at different currents at fixed temperature (20° C) can be seen in the spectrum below (figure 7).

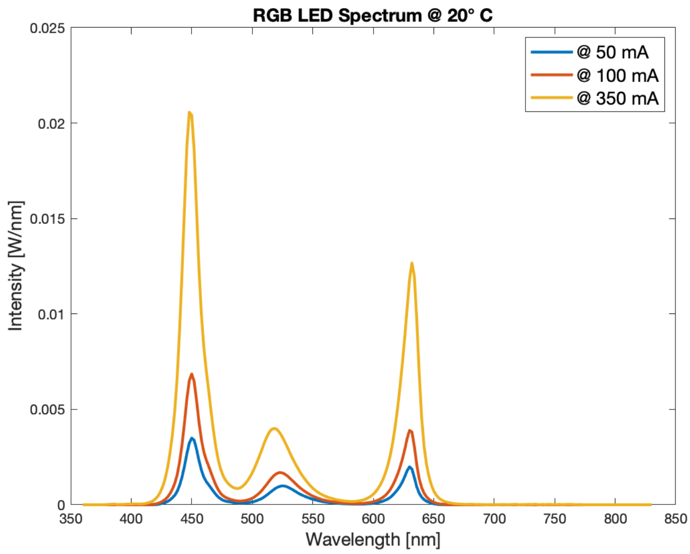

Figure 7 Spectra of RGB LED at different currents.

The spectrum (see *figure 7)* shows that the light intensity of the LED is directly proportional to the current. It means that the amount of current flowing through the LED determines how bright it is.
The colour output from the RGB LED and separately from the red, green and blue LEDs is marked on the CIE diagram (figure 8).

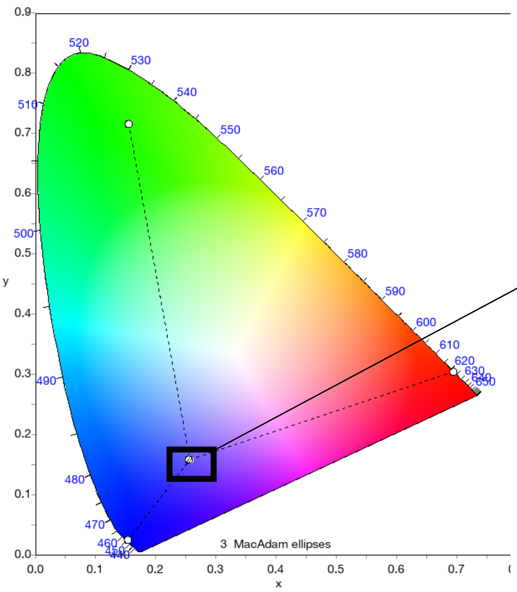

Figure 8 CIE diagram with marked colour output of RGB LED, measured at 20°C and 350 mA.

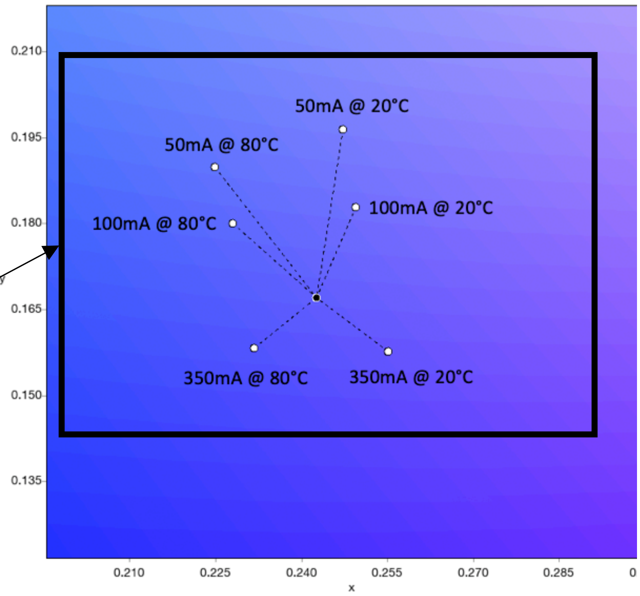

Figure 9 Zoomed-in part of the CIE, LED colour output at different currents and temperatures

The colour output of the RGB LED overlaps with the one obtained as a result of mixing three LED colours. *Figure 9* shows how temperature and different currents influence the colour output of the LED. Although there is a red shift of each colour LED for increased temperatures, the output of a multi-colour chip LED does not have consequently to be red shifted (see *figure 9, e.g.* 350mA @ 20°C → 350mA @ 80°C).

Since the output colour from RGB refers to the ratio of the three colours (see *figure 10*), the relative intensity changes of the chips (see *figure 5)* has to be considered as well. This explains the colour change over different currents too (see *figure 10*).

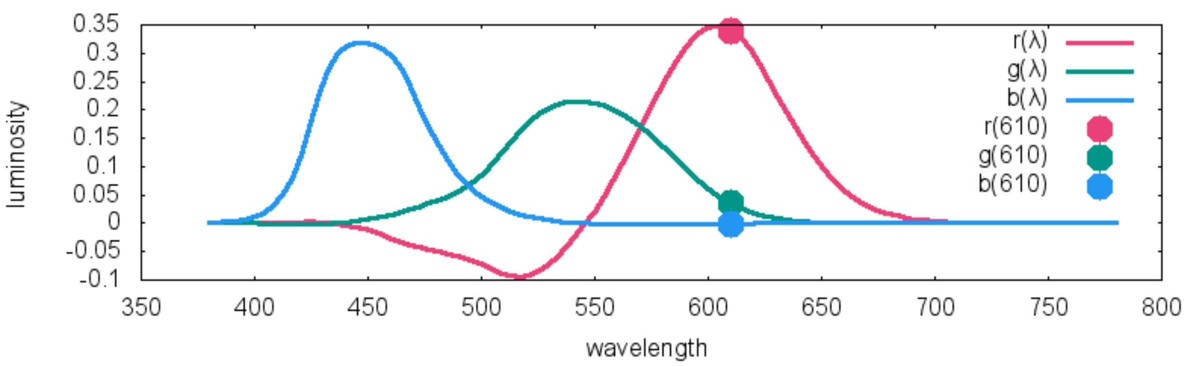

Figure 10 Wavelength to RGB conversion [4]

3.2 White LED

Unfortunately, the measurement of the white LED is not possible. The LED is not working properly. The connections of the Peltier element seem to be interchanged. Although the LED is cooled quite strong, the measured temperature rises. A reliable measurement is not possible. Nevertheless, an interpretation of the expected outcoming is provided

The change in the spectrum of a white LED can be explained by two phenomena. The blue LED itself has a slight red shift by increasing temperature. Moreover, the radiation power drops, this consequently leads to a drop of yellow emitted light, produced by fluorescence, from the Phosphor as well. The ratio of blue and yellow yet will not be correct to receive white light.

4. Conclusion

Thermal influences can be problematic while manufacturing LED lighting. The temperature affects LED's UI-characteristics, spectra and colour output. Based on the measurements that were conducted during the lab, it is visible that the voltage drops for the higher temperatures. The spectra show the red shift, intensity decrease, as well as peak wavelength shift, especially for red part of the spectrum. The intensity changes are not proportional for each chip. For this reason, the white colour output is not easily achievable in RGB LEDs. According to measurements, changes in current cause also disproportionate intensity differences. To conclude, receiving the white colour output from RGB is possible only with constant temperature and current. To overcome this problem, system manufacturers include appropriate heat sinking mechanisms and compensation circuit that adjusts the current through the LED. Such systems ensure stable light output and preserve LEDs from early degradation [5].

References

[1] “Thermal and spectral behaviour of LEDs”, LTI script

[2] http://xn--80aajzhcnfck0a.xn--p1ai/PublicDocuments/0911971.pdf (Instruments systems datasheet)

[3] https://www.ophiropt.com/laser--measurement/knowledge-center/article/10145

[4] https://medium.com/hipster-color-science/a-beginners-guide-to-colorimetry-401f1830b65a

[5] https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/led/heat.asp