Studies on the Transient, Continuous and Pulsed Regimes of High Power LEDs

Dan Tudor Vuza[1] and Marian Vlădescu[2(✉)]

[1] Institute of Mathematics of the Romanian Academy, Bucharest, Romania
danvuza@hotmail.com
[2] Optoelectronics Research Center, “Politehnica” University, Bucharest, Romania
marian.vladescu@upb.ro

Abstract. Monitoring the thermal regime of the high power LEDs used in lighting applications and in optical communications is nowadays a must. The paper presents our studies and experimental results concerning the transient, continuous and pulsed regimes of high power LEDs, based on a method for temperature measurement that makes use of the protection diode embedded in the LED package. The method proved to be consistent with the exponential law describing the transient regime and with the mathematical relation between continuous and pulsed regimes, qualifying thus as a potential monitoring tool for LED-based systems.

Keywords: High power LED · Temperature monitoring · Transient regime Continuous regime · Pulsed regime

1 Introduction

The increased interest of the industry for applications using IR and also visible light communications called for attention on monitoring the thermal regime of LEDs. Maintaining the LED temperature in the safety area is an essential condition for the reliability of LED-based communication systems. A method for measurement of LED temperature that makes use of the embedded protection diode has been proposed in [1]. In the present paper we apply the method to the study of the variation of the LED temperature under various working conditions. The principles of the method are briefly recalled in Sect. 2. The transient regime, that is the transitions from unpowered to continuously powered and from continuously powered to unpowered, is considered in Sect. 3, where it is shown that a one-exponential law is a reasonable approximation for the temperature variation. Finally in Sect. 4 we study the pulsed regime and we show how it can be used for predicting the steady-state temperature in the continuously powered regime.

2 The Method for Temperature Measurement

The power LEDs we have used in our experiments have embedded in their package a protection diode, reverse connected in relation to the LED anode-cathode, in order to suppress the reverse voltages that may occur accidentally and damage the LED. The

O. Fratu et al. (Eds.): FABULOUS 2017, LNICST 241, pp. 199–205, 2018.
https://doi.org/10.1007/978-3-319-92213-3_29

method relies on the assumption that we may find the junction temperature of the LED by measuring the junction temperature of the protection diode. For measuring the latter the procedure described in [2] was followed. Namely, the forward voltage V_F of a diode is related to the forward current I_C through the diode via the relation

$$I_C = I_S\left(\exp\left(\frac{V_F}{nV_T}\right) - 1\right) \tag{1}$$

where I_S is the reverse saturation current, n is the ideality factor and $V_T = kT/q$ is the thermal voltage. Provided that $V_F >> nV_T$, the product nV_T may be determined by measuring V_{F1} and V_{F2} at two values I_{C1} and I_{C2} of the forward current at the same temperature T and then using the relation

$$nV_T = \frac{V_{F1} - V_{F2}}{\ln\left(\frac{I_{C1}}{I_{C2}}\right)} \tag{2}$$

obtained from (1) by neglecting the term −1. The measurements are done by interrupting the direct current through the LED, sourcing reverse currents through the LED terminals that provide the direct currents I_{C1} and I_{C2} through the protection diode, taking voltage measurements and averaging in order to find V_{F1}, V_{F2}, I_{C1} and I_{C2} and using (2) for determining nV_T. For finding the temperature T a calibration procedure is needed, consisting of recording the value $(nV_T)_{REF}$ of the product nV_T at a known temperature T_{REF} (usually the ambient temperature). Then any other temperature T is determined from the formula

$$T = T_{REF}\frac{nV_T}{(nV_T)_{REF}} \tag{3}$$

in which nV_T has been computed with (2). The procedure is entirely automated and fast enough in order that the momentary interruption of the direct current through the LED has not an observable effect on its temperature. Details of the procedure and the schematic have been given in [1].

3 Transient and Continuous Regimes

In our experiments we have used four power LEDs of type SFH 4232 with embedded protection diodes, of which one mounted on a Bergquist thermal clad square footprint acting as a radiator and the rest unmounted.

The purpose of the experiments of this section was to establish whether a one-exponential law for the temperature evolution of the form

$$T(t) = T_0 + (T_\infty - T_0)(1 - \exp(-t/\tau)) \tag{4}$$

was adequate enough for describing the transient thermal regime of the LEDs. In (4) T_0 is the temperature at $t = 0$ and T_∞ is the limiting temperature as t approaches infinity.

To this purpose the LEDs, initially at ambient temperature, were powered with a current of 0.5 A and allowed to heat for a time Δt, after which the current was interrupted and the LEDs were allowed to cool for the same time Δt. We chose Δt = 10 min for the unmounted LEDs and Δt = 15 min for the LED with radiator. During the heating time the current was interrupted every one second and a measurement of the temperature was taken according to the method described in Sect. 2; each current interruption lasted for only 4 ms, meaning that the LED was almost continuously powered. During the cooling time, a measurement of the temperature was taken every 10 ms. The parameters T_0, T_∞ and τ from (4) were determined from the measurements via a best-fit procedure applied separately to the heating and to the cooling processes. Specifically, if T_n was the sequence of measured temperatures, then in a first step the time constant τ was estimated as the inverse of the slope a of the straight line $b - at$ that gave the best fit in the least square sense to the sequence of data $\ln|T_n - T_{n\text{-}k}|$ where k is a conveniently chosen constant (large enough in order that the argument of the logarithm is not too small). In a second step, the parameters T_0 and T_∞ were chosen in such way that the right side of (4) in which the already estimated τ has been used gave a best fit to the data T_n in the least square sense.

The estimates from the experimental data are presented below, together with the RMS error between data and estimated laws of the form (4).

Table 1. Heating transient regime

LED	τ (seconds)	T_0 (°C)	T_∞ (°C)	RMS error (°C)
Radiator	132.35	31.4	51.8	0.14
1	34.33	36.6	100.3	0.69
2	32.14	37.5	111.5	0.62
3	28.11	34.9	97.4	0.38

Table 2. Cooling transient regime

LED	τ (seconds)	T_0 (°C)	T_∞ (°C)	RMS error (°C)
Radiator	124.26	52.6	31.9	0.57
1	31.62	97.6	31.9	0.92
2	32.37	109.5	32.1	0.87
3	29.21	95.7	31.9	0.63

In all graphs below the horizontal units are seconds and the vertical units are °C. In Fig. 1 the experimental curves are in blue and the one-exponential curves with estimated parameters are in black; at the scale of the figure they are hardly distinguishable.

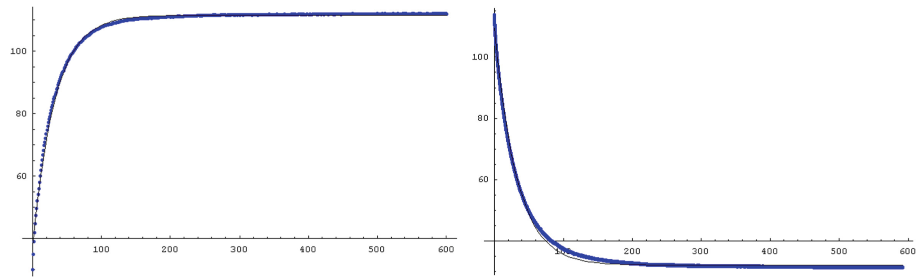

Fig. 1. Heating curve (left) and cooling curve (right) of LED 2 superimposed over one-exponential curves with parameters from Tables 1 and 2.

In Fig. 2 we take magnified views of parts of the heating curve of Fig. 1, which show that the one-exponential is a good approximation at the beginning of the time interval but not so good on the final part on the interval where curve and the data approach their asymptotic values.

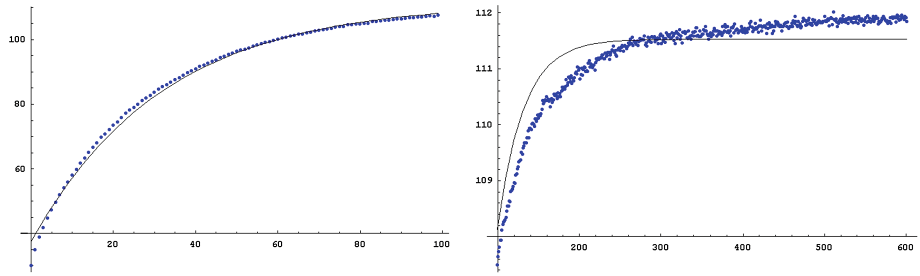

Fig. 2. Heating curve of Fig. 1 restricted to the first 100 s and to the last 500 s.

4 Pulsed Regime

Based on the results of Sect. 3, we shall assume that the one-exponential law (4) is a reasonable approximation of the transient thermal regime of the LED. Let us consider a time interval of length Δt and let T_1 and T_2 be the LED temperatures at the beginning and at the end of the interval. Assume that the LED is turned on at the beginning of the interval and is turned off after a time of $d\Delta t$, with $0 < d < 1$. If T_d is the LED temperature by the time the LED is turned off, then according to (4) T_1 and T_d are related by

$$T_d = T_1 + (T_C - T_1)\,(1 - \exp(-d\Delta t/\tau)). \tag{5}$$

where we have replaced T_∞ with T_C, the steady-state temperature of the LED when continuously powered. Also according to (4), T_d and T_2 are related by

$$T_2 = T_d + (T_A - T_d)\,(1 - \exp(-(1 - d)\Delta t/\tau)). \tag{6}$$

where we have replaced T_∞ with the ambient temperature T_A, the final temperature reached during cooling. Substituting (5) into (6) we find that T_2 is related to T_1 by

$$T_2 = aT_1 + b \tag{7}$$

where

$$\begin{aligned} a &= \exp(-\Delta t/\tau), \\ b &= \exp(-(1-d)\Delta t/\tau)\,(1-\exp(-d\Delta t/\tau))\,T_C + (1-\exp(-(1-d)\Delta t/\tau))\,T_A. \end{aligned} \tag{8}$$

Now assume that at time $t = 0$ we start with the LED at temperature T_0 and we submit it to a pulsed regime so that on every time interval $[(n-1)\Delta t, n\Delta t]$ the LED is turned on at the beginning of the interval and is turned off after a time of $d\Delta t$, d being the duty factor. By repeated application of (7), the temperature T_n at time point $n\Delta t$ equals

$$T_n = a^n T_0 + b\sum_{i=0}^{n-1} a^i = a^n T_0 + b\frac{1-a^n}{1-a}. \tag{9}$$

Since $0 < a < 1$ it follows from (9) that the steady-state temperature T_P reached during pulsed regime (that is, the limit of T_n as n grows to infinity) is given by

$$T_P = \frac{b}{1-a}. \tag{10}$$

Substituting (8) into (10) we arrive at the final expression

$$T_P = \frac{\exp(-(1-d)\Delta t/\tau)\,(1-\exp(-d\Delta t/\tau))\,T_C + (1-\exp(-(1-d)\Delta t/\tau))\,T_A}{1-\exp(-\Delta t/\tau)}. \tag{11}$$

In the case that the switching period Δt is much smaller than the time constant τ we may obtain a simpler form of (11) by approximating $\exp(x)$ with $1 + x$,

$$T_P = (1-(1-d)\Delta t/\tau)\,dT_C + (1-d)T_A. \tag{12}$$

Because we have already assumed $\Delta t/\tau << 1$ we may omit this number and obtain the final approximation

$$T_P = dT_C + (1-d)T_A. \tag{13}$$

In the experiments reported in Table 3 the LED was submitted to a pulsed regime with $\Delta t = 1$ ms and a current of 0.5 A. The temperature was measured every second with the method of Sect. 2. The measured steady-state temperature was compared with T_P computed with (13), where we took for T_C the continuous regime temperature of 87.92 °C and for T_A the ambient temperature of 30 °C.

Table 3. Pulsed regime

Duty factor	T_P measured	T_P computed
0.75	73.9	73.4
0.5	57.9	58.9
0.25	44.1	44.5

Table 3 shows a quite satisfactory agreement between the measured and computed temperatures. Based on this, one can propose the following application of formula (13). We have seen from Table 1 that a LED without any special means for heat dissipation may reach temperatures over 100 °C when continuously powered. Therefore it is not always safe to submit the LED to the continuous regime without knowing in advance what steady-state temperature would be reached. Instead, one may submit the LED to the pulsed regime during which lower, hence safer temperatures would be reached. Then, based on the measurements of T_P and of T_A, one can use (13) for predicting the steady-state temperature T_C of the continuous regime without actually submitting the LED to that regime.

5 Conclusions

We have shown that a one-exponential law is a reasonable approximation, although not the most precise, for both the heating curve (transition from unpowered to continuously powered) and the cooling curve (transition from powered to unpowered) of the LED obtained from experimental data. We may conclude that, at least for the purposes of monitoring the thermal regime of the LED, the one-exponential law is a reasonable approximation; according to Tables 1 and 2, it is also reasonable to assume that time constants of the heating and of the cooling curve are the same. The approximation is quite good at the beginning of the time interval and somewhat less precise on the rest of the interval. In Sect. 3 we saw how these conclusions may be used in the study of the pulsed regime. A more precise approximation might use two-exponential laws as proposed in [3].

Another significant conclusion concerns the influence of the radiator on the thermal regime. From Tables 1 and 2 we observe that the radiator reduced in half the maximal temperature reached by the continuously powered LED and at the same time increased the time constant four times.

Finally the method for temperature measurement proved to be consistent with the physical reality and therefore may be used for monitoring the thermal regime of LEDs with embedded protection diodes.

References

1. Vuza, D.T., Vlădescu, M.: Platform for monitoring the temperature of power LED junction by using the embedded protection diode. In: 2016 8th International Conference on Electronics, Computers and Artificial Intelligence (ECAI) Conference Proceedings, pp. 1–6. IEEE Conference Publications (2014)
2. Jones, M.: Accurate temperature sensing with an external P-N junction. Linear Technol. Appl. Note **137** (2012)
3. Han, K., Liu, M., Fan, S., Shen, H.: Improved electrical measurement method for junction temperature of light emitting diodes. Przegląd Elektrotechniczny (Electr. Rev.) **88**(3b), 180–184 (2012)