MULTI-DOMAIN MODELING OF POWER LEDS BASED ON MEASERD ISOTHERMAL I-V-L CHARACTERISTICS

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Abstract

The multi-domain operation of LEDs characterized by the tight coupling between their electrical, thermal and optical properties manifests not only on chip and package level, but has to be tracked in case of LED products of higher integration level such as LED modules or LED luminaires as well. An option for tracking this operation is to apply so called multi-domain Spice-like models of LEDs, suitable for implementation in circuit simulation programs. In this paper an LED model is presented, capable of calculating the self-heating and the emitted radiant flux of an LED chip along with its forward voltage – forward current characteristics and the temperature dependence thereof. The parameters of this model can be identified directly from combined thermal and radiometric measurements of LEDs, compliant to the most recent LED package level testing standards.

Keywords: LED modelling, LED simulation, radiometric measurement of LEDs

1 Introduction

Accurate design of LED based lighting applications needs precise characterization of HP (high power) LED packages, delivering the right input data for the designers. Operation of HP LEDs is complex, involving electrical thermal and optical domains tightly coupled: there is a mutual dependence among the major optical, electrical and thermal parameters.

Because of these strong interactions, performing precise simulation during the design of LED based lighting products such as LED luminaires may be essential already in the early design stage in order to avoid possible re-designs of the product. Simulation tasks include electrical stimulation of the complete LED + surrounding electronics (considering the thermal effect of the luminaire and its environment), optical simulation of the luminaire with "hot lumens" of the LEDs, and detailed thermal simulation of the luminaire, considering the heat transfer towards the environment. To achieve this, on one hand, a proper multi-domain model of the LED operation on chip level is required and on the other hand, a proper so called compact thermal model of the LED packages and their further thermal environment (i.e. the luminaire) is necessary. The two models combined are needed for a precise luminaire level numerical analysis of a given design.

Creating LED package thermal compact models has been discussed a lot and a couple of conference papers have been published about this in the last decade, see e.g. [POPPE2006], [POPPE2012]. The suggested models have been based on thermal transient measurement of LED packages. The measurements providing data for creating these models comply with JEDEC's latest standards regarding the measurement of the junction to case thermal resistance of power semiconductor device packages (the JESD 51-14 standard [JEDEC2010]) and the latest LED thermal testing standards (the JESD51-5x series of documents [JEDEC2012a], [JEDEC2012b], [JEDEC2012c]). The compliance to the JESD51-5x series of standards assures that the emitted total radiant flux of the LED under test is considered in the measurement, thus the so called "real thermal resistance" of the LED package is obtained [JEDEC2012b].

In terms of electrical modelling of LEDs nowadays "electrical-only" diode models are used in standard Spice or Spice-like circuit simulators. These lack the ability of considering the electrical operation and the device self-heating consistently. Furthermore, a standard diode electrical model does not calculate any property of the emitted light of an LED. Though, there are already Spice-like circuit simulators commercially available which support a tightly coupled electrical and thermal simulation [RAYNAUD2013], as of today no multi-domain Spice-like LED models are available in commercial simulation programs. The aim of this paper is to present an LED model that is capable of describing the multi-domain operation of LED chips and can be implemented in Spice-like circuit simulators (like the one described in [RAYNAUD2013]).

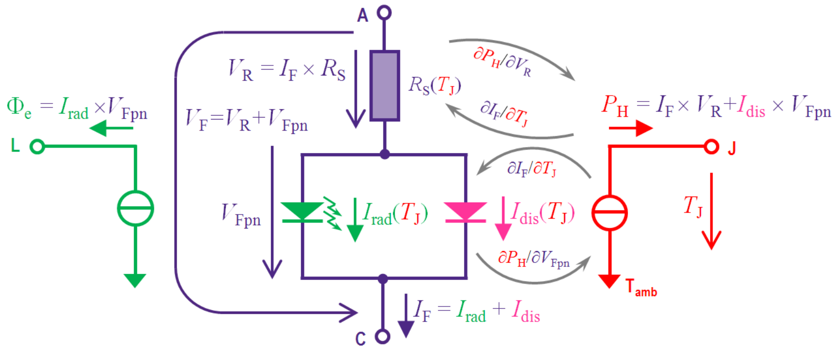

Figure 1 – The topology of our multi-domain LED model, suitable for implementation for Spice-like circuit simulation [POPPE2015a].

2 Combined electrical, thermal and light output model of LED chips

2.1 Basic modelling assumptions

In LED modelling our basic assumption was that the tight coupling between the thermal, electrical and light output properties should be considered on chip level only. Thus, a chip level multi-domain LED model is needed which can be completed with additional models describing the thermal environment or the electrical environment. With an LED chip model we aimed at describing the emitted total radiant flux only; further light output properties such as spectral power distribution or the total emitted luminous flux etc. could be obtained in a post processing step, based on the output quantities of the chip level multi-domain LED model. For modelling the LED chip we applied a "black box" approach, i.e. the model does not make any assumption about the LED itself; both phosphor converted white LEDs and colour LEDs are described in the same way. The model is based on Shockley's classical model of pn-junctions, relating the I_F forward current and the V_F forward voltage as follows:

$$I_F = I_0 \left[\exp \frac{V_F}{m \times V_T} - 1 \right] \tag{1}$$

where V_F denotes the forward voltage, I_F is the forward current; I_0 denotes the temperature dependent so called *saturation current*, V_T = k×T/q is the so called *thermal voltage* (k stays for Boltzmann's constant, q is the elementary charge, T is the absolute temperature of the pn-junction) and m is the *ideality factor* of the pn-junction.

Both I_0 and $m \times V_T$ are (junction temperature dependent) *model parameters*. The usual way of obtaining these model parameters is to fit Eq. (1) to a measured isothermal I-V curve of the diode. The identification of the temperature dependence of the model parameters in practice is based both on theoretical calculations and fitting Eq. (1) to isothermal characteristics measured at different (constant) junction temperatures.

The electrical power supplied to the LED is $P_{el} = I_F \times V_F$. The power dissipated in the pn-junction of an LED is

$$P_{dis} = P_{el} - \Phi_e = I_F \times V_F - \Phi_e \tag{2}$$

where Φ_e denotes the emitted total radiant flux.

Dividing Eq. (2) by the V_F forward voltage leads to the concept of a multi-domain LED model we suggest for implementation in a Spice-like circuit simulator:

$$(I_{dis} = P_{dis} / V_F) = I_F - (I_{rad} = \Phi_e / V_F) \tag{3}$$

In other words, we can split the total forward current into two components: into one which is responsible for the self-heating of the LED and into another one resulting in light output:

$$I_F = I_{rad}(V_F) + I_{dis}(V_F) \tag{4}$$

Current component I_{dis} is associated with non-radiative recombination processes and I_{rad} is associated with radiative recombination processes. Both current components can also be described by the Shockley-model.

Since high power / high brightness LEDs are operated at forward current levels where the voltage drop on the electrical series resistance of the LEDs is significant, the above model is completed by a resistor which is in series with the internal pn-junction* of the LED chip. Our ultimate model considers this, as shown in Figure 1. The V_F forward voltage used in equations (1)-(4) corresponds to the V_{Fpn} voltage drop on the internal pn-junction.

The current components for the internal junction also follow the Shockley-model, thus

$$I_{rad} = I_{0\_rad}\left[\exp\frac{V_{Fpn}}{m_{rad} \times V_T} - 1\right] \tag{5}$$

and

$$I_{dis} = I_{0\_dis}\left[\exp\frac{V_{Fpn}}{m_{dis} \times V_T} - 1\right] \tag{6}$$

resulting altogether in two current coefficients and in two ideality factors as parameters for a complete LED model.

As we aim at practical modelling of LEDs concentrating on the high current regime in the forward region, secondary effects such as deviation from the ideal Shockley model at low forward current levels and reverse characteristics are neglected.

For phosphor converted white LEDs we assume that the light converting phosphor layer is directly deposited on the blue LED chip and the phosphor and chip junction temperatures are identical. (In reality this is not the case but due to the lack of exact information regarding LED construction this is a viable assumption.) Any heating due to re-absorption of the generated photons as well as conversion losses in the phosphor are considered to contribute to the device self heating, thus, they are part of P_{dis} in Eq. (2). A further contribution to the P_H total heating power is the Joule heating taking place on the series resistance, as indicated in Figure 1:

$$P_H = (P_{dis} = I_{dis} \times V_{Fpn}) + I_F \times V_R \tag{7}$$

The thermal model of the LED package and its further environment is connected to the chip level multi-domain model through a current source, the current of which is set equal to the P_H total heating power. The heat-flow represented by this current is fed into the *junction node* of the model which is to be terminated by the thermal model of the LED package + environment. The potential of this node is the T_J junction temperature which is an input variable for the model equations (through their temperature dependent parameters).

The optical part of the multi-domain LED model is another controlled current source, the current of which is set equal to the emitted total radiant flux: $\Phi_e = I_{rad} \times V_{Fpn}$. The radiant flux is directly measured by the test equipment, thus, by knowing the value of the V_{Fpn} voltage drop on the internal pn-junction the value of I_{rad} can be easily identified – see Eq. (3).

* The term *junction* refers to the active layer of the LED chip, regardless of the actual LED chip construction.

2.2 Measurement of the temperature dependent LED characteristics

The set of LED characteristics needed to identify parameters of the above outlined LED models include isothermal $I_F(V_F)$ characteristics and isothermal $\Phi_e(V_F)$ characteristics measured at different junction temperatures.

There are two methods that can be used to control the junction temperature of an LED during measurement. Y. Zhong and Y. Ohno suggested a method setting LEDs' junction temperature for optical measurements [Zhong2008], [Zhong2009] and the JEDEC thermal testing standard [JEDEC2012b] also suggests a method in combination with the measurement of the real thermal resistance / impedance of LED packages. Both methods require that the LED to be tested should be mounted to a temperature controlled heat-sink (a cold-plate), as shown in Figure 2. E.g. according to [JEDEC2012b], the junction temperature can be indirectly identified if the LED's R_{th_real} real thermal resistance and T_{ref} (reference) temperature of the heat-sink are known:

$$T_J = T_{ref} + P_H \times R_{th\_real} \tag{8}$$

Eq. (8) means that the T_J junction temperature can be kept constant by adjusting the T_{ref} temperature of the temperature controlled heat-sink according to the actual P_H total heat dissipation and thermal resistance of the package. Using one of these procedures in combination with the measurement of the electrical properties and the light output properties would result in the set of isothermal LED characteristics which provide the necessary input data for finding the parameters of the chip. Such measured characteristics are shown in Figure 3 and Figure 4.

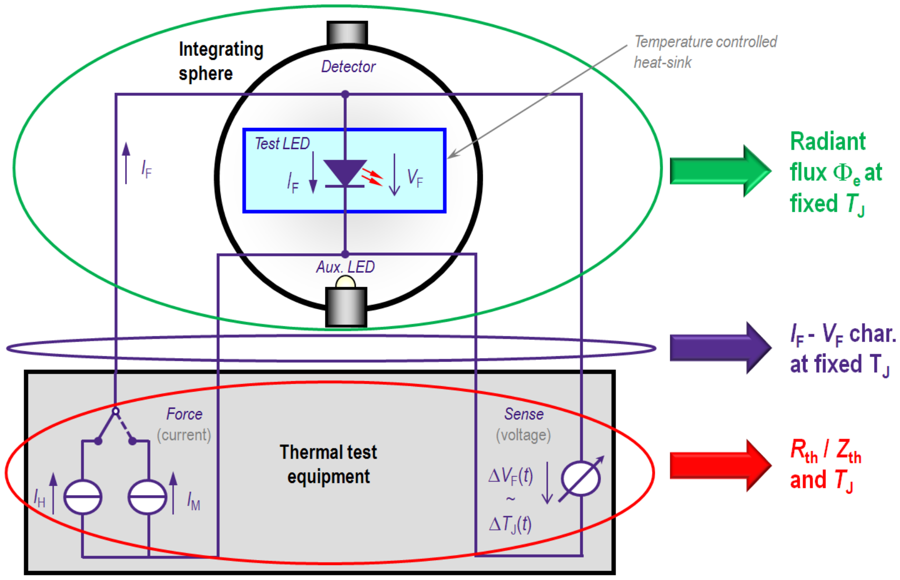

Figure 2 – Scheme of the JEDEC LED test standards [JEDEC2012b], [JEDEC2012c] compliant combined thermal and radiometric/photometric test setup used to measure isothermal LED characteristics.

Last but not least, it is important to note that most power LEDs today are operated in a forward current range of 100 mA .. 1000 mA range. Therefore our LED model should accurately capture this high current operation. This region of operation is dominated by the R_S electrical series resistance of the LEDs which manifests in the bending of the diode I-V characteristic in a lin-log plot (Figure 3). The initial straight sections in the 1 mA .. 100 mA forward current range indicate that the electrical operation follows the Shockley-model given by Eq. (1). Accurate modelling of power LED below the ~10 mA forward current is not critical. Some LED types follow the Shockley-model even below 10 mA, some other LED types have excess forward current in the mA range – this is a well-known deviation from the ideal diode characteristic. Our present model does not include this secondary effect therefore if measured I-V curves exhibit such behaviour then during the parameter identification process we exclude the corresponding data points.

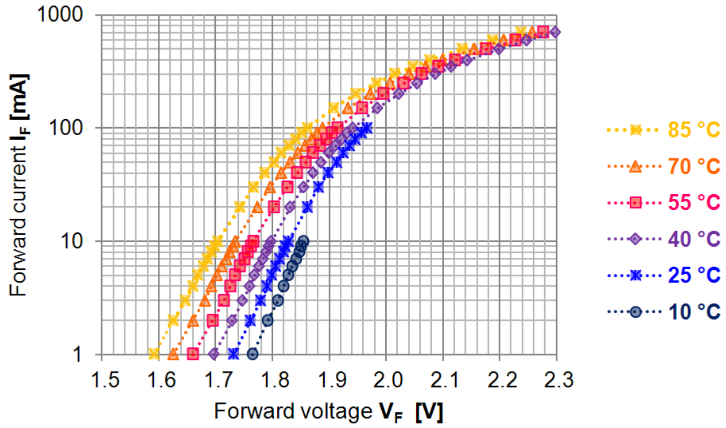

Figure 3 – Isothermal forward voltage – forward current characteristics of an amber LED measured at different junction temperatures by a test setup shown in Figure 2.

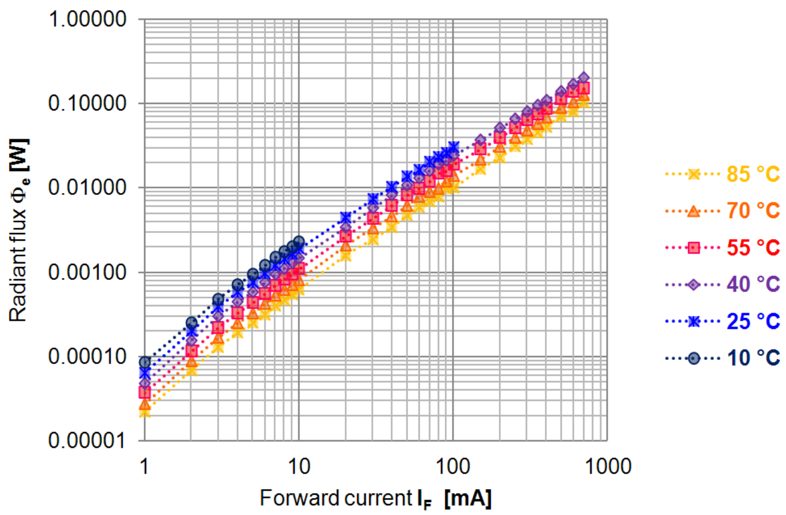

Figure 4 – Isothermal forward current – total radiant flux characteristics of an amber LED measured at different junction temperatures by a test setup shown in Figure 2.

2.3 Parameter identification

The parameter identification process starts with finding the value of the R_S series resistance, from the high forward current region of the LED I-V characteristics. At high currents the characteristics tend to exhibit a linear current-voltage relationship; the slope of the actual I-V curve provides a good approximation of the series resistance. Once the value of R_S is known the V_{Fpn} voltage drop on the “internal pn-junction” is calculated as

$$V_{\mathrm{Fpn}}(T_{\mathrm{Ji}}) = V_{\mathrm{F}}(T_{\mathrm{Ji}}) - R_{\mathrm{S}}(T_{\mathrm{Ji}}) \times I_F \qquad (9)$$

wehere T_{Ji} indicates the i-th junction temperature set, for further notations refer to Figure 1.

This way, for every forward current – junction temperature pair set by the test equipment (Figure 2) the $I_F(V_{Fpn})$ and $\Phi_e(V_{Fpn})$ data series can be produced (I_F is set, Φ_e is measured).

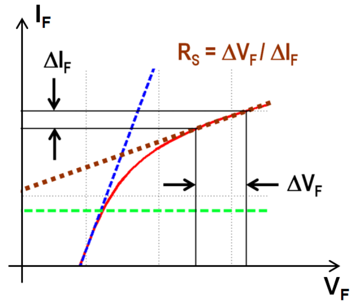

Figure 5 – A typical diode I-V characteristic at high forward currents.

As a next step, the I_F forward current is split into its I_{rad} and I_{dis} components using Eq. (3). For every T_{Ji} set, the resulting $I_{rad}(V_{Fpn})$ and $I_{dis}(V_{Fpn})$ data series are fitted to Eq. (5) and Eq. (6), respectively, yielding model parameter series $I_{0\_rad}(T_{Ji})$, $m_{rad}(T_{Ji})$ and $I_{0\_dis}(T_{Ji})$, $m_{dis}(T_{Ji})$. Figure 6 presents an example for m_{rad} and m_{dis} values identified this way. In Figure 7 an example is provided for the application of our model to I-V-L characteristics of a 1 W warm white LED measured at T_J = 85 °C. For details on temperature dependence of the model parameters refer to [POPPE2015].

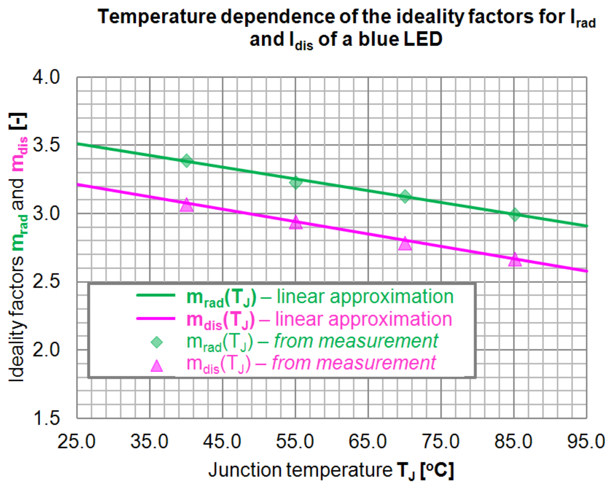

Figure 6 – Example for the temperature dependence of model parameters m_{rad} and m_{dis} [POPPE2015a].

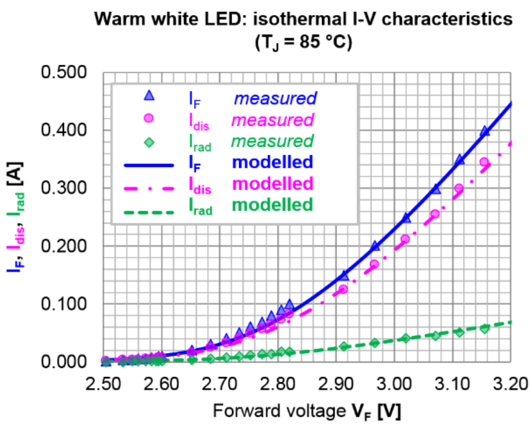

Figure 7 – Example for measured and modelled $I_F(V_F)$, $I_{rad}(V_F)$ and $I_{dis}(V_F)$ characteristics of 1 W warm white LED [POPPE2015a]. (Colour coding of curves corresponds to the colour coding applied to the forward current components shown in Figure 1.)

2.4 Implementation of the model

For the implementation of the proposed LED model a non-linear circuit simulation program capable of performing the so called fully coupled electro-thermal simulation is needed like the Spice compatible circuit simulator described in [RAYNAUD2013]. Most recently we implemented our model with the 2015 release of this program and successfully applied it e.g. for the system level multi-domain simulation of an LED based streetlighting luminaire. Further details about the model implementation are provided in [POPPE2016].

3 Application examples

3.1 Calculation of radiant flux transient

The tight coupling among the junction temperature, the electrical operating point and calculation of the radiant flux in our proposed multi-domain LED model allows simulating transient processes which are difficult to measure.

If the LED chip model is equipped with the thermal model of the environment (consisting of the LED packages dynamic compact thermal model and the dynamic compact thermal model of the cooling assembly such as a heat-sink) one has a complete model that can be used in the appropriate Spice-like circuit simulator. For our analysis we used the ELDO program from Mentor Graphics capable of performing fully-coupled electro-thermal simulation [RAYNAUD2013]. The schematic of the firs simulation example is shown in Figure 8.

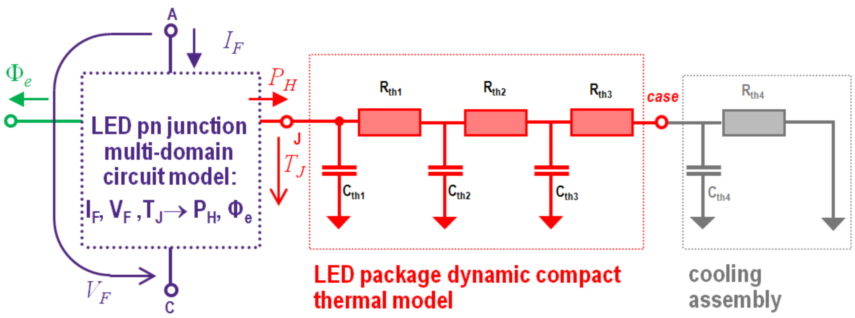

Figure 8 – Simulation model of a packaged LED chip equipped with a cooling assembly.

We modelled a 3 W white LED chip as described in Section 2. The parameters of the LED chip model were fitted to measured isothermal characteristics as described in subsection 2.3.

The same measurement setup was used to measure the dynamic thermal properties of the LED package with a procedure compliant to the LED thermal testing standards of JEDEC (see [JEDEC2012b] and [JEDEC2012c]) and the transient junction-to-case thermal measurement method of JEDEC (see [JEDEC2010]). From these results the LED package dynamic compact thermal model was created by the method described in [POPPE2006]. A similar thermal transient measurement and model identification technique was used to create the thermal RC network model of the heat-sink applied [POPPE2015b].

In a cathode grounded electrical setup the LED chip was driven by a 1 A forward current. With transient simulation we tracked the junction temperature increase and the resulting drop in the emitted total radiant flux of the LED. The recorded transients are shown in Figure 9. Such simulations (if the LED model + parameter set are properly validated) can support to better establish the correlation between the results of high-speed inline testing and laboratory measurements.

3.2 System level steady-state simulation of a streetlighting luminaire

Our second example is the system level steady-state analysis of a streetlighting luminaire containing an array of 48 LEDs. In this example we modelled a 1 W LED and its package based on measurement results obtained by the test setup shown in Figure 2.

In this case a CFD simulation based characterization method was used to obtain a thermal *N*-port model of the luminaire where the “ports” of the model were associated with the surfaces of the heat slugs used to mount the LEDs onto.

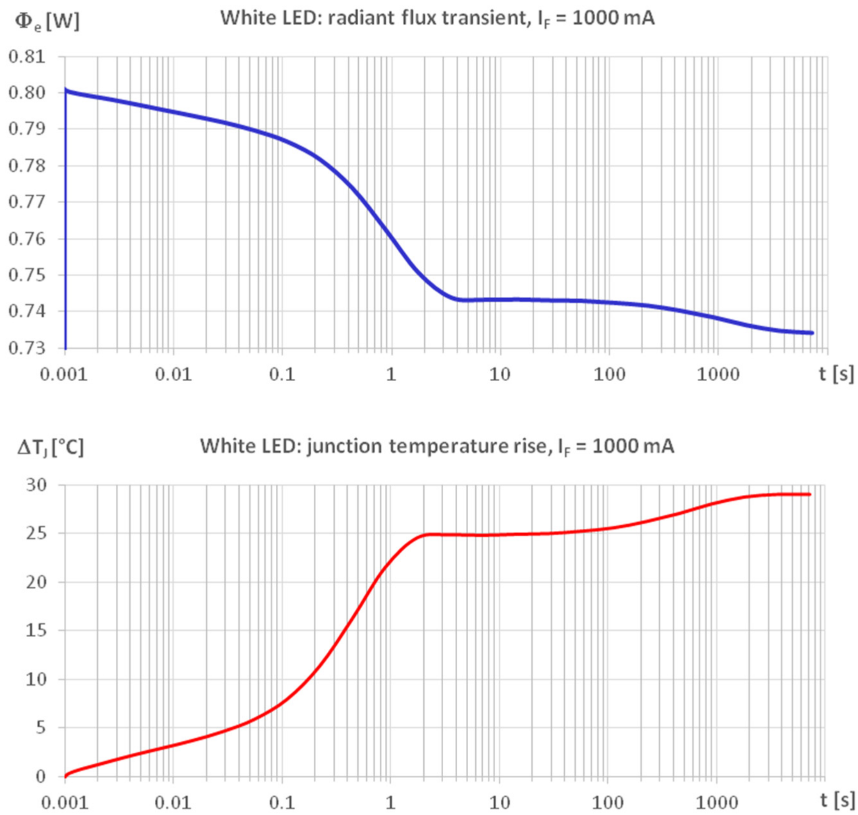

Figure 9 – Simulated transient of the radiant flux and the junction temperature rise of a 3 W white LED after 1 A forward current is switched on.

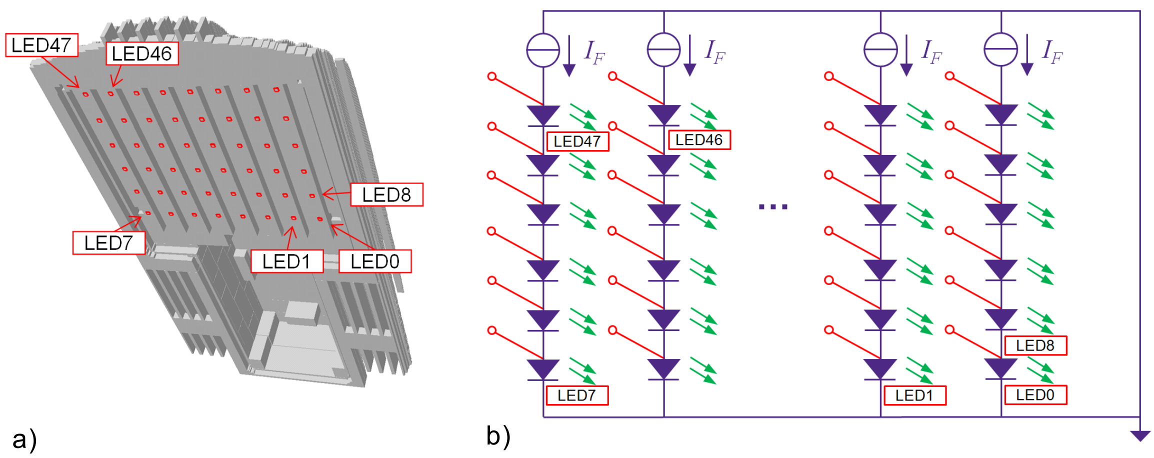

Figure 10 – a) The detailed 3D physical model of the luminaire, b) the schematic of the electrical setup of the LED array inside the luminaire (on the right) that was subject of system level multi-domain simulation.

The luminaire chosen was the largest member of a complete streetlighting luminaire family, containing 48 power LEDs in an 8×6 array (8 strings, containing 6 LEDs each). The detailed 3D physical model of this luminaire aimed at CFD simulation (indicating also the numbering of

LEDs in the array) is shown in Figure 10a. Figure 10b shows the electrical setup of the LED array inside the luminaire. The thermal ports (indicated by red in both images) of these models are connected by the thermal network model of the LED packages.

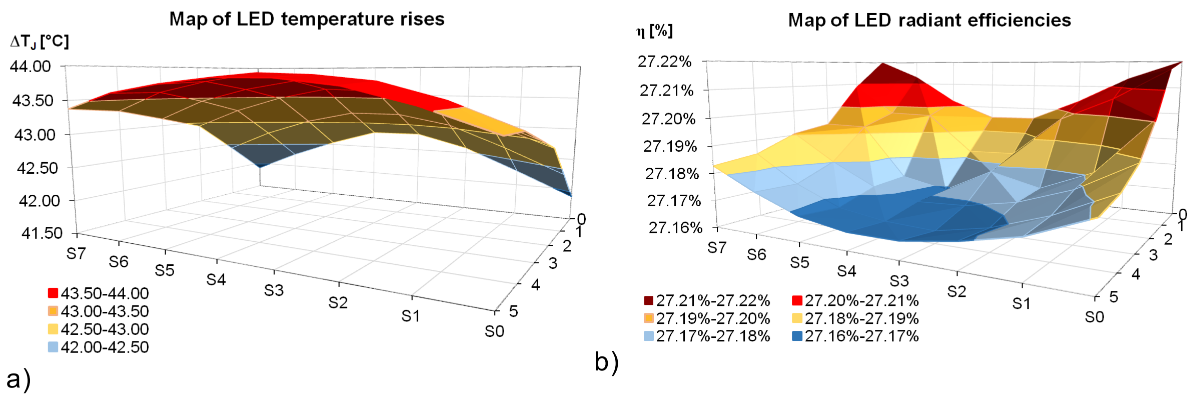

Figure 11 – a) Map of the junction temperature rise (w.r.t the ambient temperature) and b) the map of the radiant efficiency of the LED inside the luminaire shown in Figure 10.

The thermal characterization of the luminaire [POPPE2016] by 48 subsequent CFD simulation runs took approximately 4 hours on a usual PC (running at 3 GHz clock frequency). The steady-state multi-domain simulation took 3 s only for a DC operating point of the LED array. The simulation results were post processed. This way, among others, junction temperature and radiant efficiency maps of the array (shown in Figure 11) were obtained. The foreseen major applications of such simulations include “hot lumen” calculations (to provide more precise luminous flux data for optical simulation of the luminaire) and to allow studying different LED types in the same thermal environment quickly.

4 Conclusions

In this paper a chip level multi-domain LED model was presented which can be implemented in Spice-like circuit simulation programs. The branch equations of this model are formulated such that their parameters can be identified by fitting to measured isothermal current-voltage-radiant flux characteristics.

The advantage of this model is that through multi-domain circuit simulation it allows study LED properties that are difficult to measure. An example, the switch-on transient of the radiant flux was shown. In another example it was demonstrated how the actual configuration of an application environment (i.e. the 3D physical structure of a luminaire and the thermal boundary conditions) effects the LED operation.

With appropriate post processing and with a few additional models (such as a model of the spectral power distribution of colour LEDs [PAISNIK 2012] or a model of efficacy of radiation for white LEDs [POPPE2015a]) the effect of operating conditions on further light output properties can be also be studied.

Using circuit simulation programs for system level analysis of LED applications with this model assures quick execution times. For example results for single DC operating point of a complex system like a luminaire with a multiple dozens of LEDs are available in a few seconds only.

Wide spread application of this chip level LED model is expected only after LED manufacturers publish the right data for model parameter identification, ideally in a LED vendor neutral electronic test datasheet format. This needs action in the field of standardisation of LED test data reporting.

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