Inter Laboratory Comparison of LED Measurements Aimed as Input for Multi-Domain Compact Model Development within the Delphi4LED H2020 Project

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***Abstract*— The goal of the Delphi4LED H2020 ECSEL project is to develop measurement, modelling and simulation methodologies that allow using multi-domain compact models of LED packages to be used at different integration levels (from simple LED assemblies up to complete luminaires) to be supported and used by all major stakeholders along the SSL supply chain. The target is to establish the right model topologies along with the right set of model equations and model parameters that connect measured LED characteristics to system level behaviour of a luminaire. To set the right expectations on the desired accuracy of the different models of LED packages the Delphi4LED consortium decided to launch a round-robin measurement of carefully selected LED packages with the participation of the testing laboratories of the consortium members. These testing laboratories include academic and industrial labs as well as accredited testing labs with different levels of expertise in different areas of LED measurements, having more or less similar testing apparatus. Besides the above mentioned goals another goal of this work was to test how the different laboratories can implement LED measurement procedures described in JEDEC and CIE LED testing guidelines.**

***Index Terms*— round-robin testing, LED junction temperature control, LED package electrical properties, LED package light output properties, LED package thermal properties.**

I. Introduction

There are a few bottlenecks hampering efficient design of LED based products on different integration levels of the SSL supply chain. One major issue is that data sheet information provided about packaged LEDs is usually insufficient and inconsistent among different LED vendors.

An international consortium of European SSL manufacturers including big and small companies, industrial and academic research labs and companies involved in LED test equipment manufacturing and suppliers of simulation tools has recently set an R&D project [1] – [4] with the ultimate goal of developing standardized methods to create accurate multi-domain LED compact models from testing data. Despite high accuracy expectations of end-users, model accuracy should not be defined higher than the uncertainty of LED measurement data achievable by typical test laboratories performing daily characterization of LEDs.

To assess the capabilities of their laboratories the consortium members with LED measurement facilities decided to carry out round robin testing of selected LED packages which have been defined as the most important ones from the point of view of system level design by Delphi4LED partner companies active in luminaire and lighting design.

In planning this round robin test, the outcome of earlier inter laboratory comparisons [5], [6] were carefully considered. The test protocol of the present round robin test is based on new measurement standards and recommendations published by JEDEC [7] – [9] and recently developed by CIE [10]. Our measurements form the first international round robin test based on these recommendations.

II. Participating Laboratories

Different kinds of laboratories participate in this inter laboratory comparison: industrial thermal and optical LED testing labs, research labs from the academia and accredited, independent testing labs providing testing services for the lighting industry and a laboratory of a test equipment manufacturer. There were all together 7 laboratories participating in this experiment, out of which 6 laboratories belong to members of the Delphi4LED consortium [1]. The 7th laboratory is an independent, accredited optical testing laboratory. The participants of this round-robin test were

- Budapest University of Technology and Economics (BME), Department of Electron Devices, Budapest, Hungary (organizing lab);
- Mentor – a Siemens business, Mechanical Analysis Division MicReD thermal testing lab, Budapest, Hungary (participating lab);
- LightingLab Calibration Laboratory, Veszprém, Hungary (participating lab);
- Philips Lighting France, Lyon, France (participating lab);
- PISEO, Lyon, France (participating lab);
- Philips Lighting Research, Eindhoven, The Netherlands (participating lab);
- VTT Research, Oulu, Finland (participating lab).

After careful considerations (taking into account among others their available infrastructure and expertise of their personnel) BME's thermal testing laboratory was chosen as the leading laboratory in this round-robin test.

In terms of their capabilities all laboratories are characterized by different profiles, e.g. some are in the frontend in R&D for combined thermal and optical testing of LEDs. Each laboratory is capable of setting the T_J junction temperature of LEDs for optical measurements and each laboratory is capable of measuring the spectral power distribution (SPD) and the total radiant and luminous fluxes of the test LEDs. Five laboratories out of the 7 participants have transient thermal testing capabilities with the equipment of the same manufacturer which allows the measurement of LEDs' $Z_{th}(t)$ thermal impedance curves and R_{th} thermal resistance. Again, four out of the seven labs have spectroradiometers from the same European manufacturer. Measurement of isothermal current-voltage-total flux (I-V-L) characteristics of test LEDs is daily practice at two laboratories, though, further two laboratories also have the equipment to implement such measurements. Table I lists the major LED testing capabilities of all laboratories.

TABLE I. MAJOR TESTING CAPABILITIES OF THE PARTICIPATING LABORATORIES

Laboratory code	Capabilities
1	T_J control capability, Z_{th} meas. capability, isothermal I-V-L meas. capability, SPD, total fluxes
2	T_J control capability, Z_{th} meas. capability, isothermal I-V-L meas. capability, SPD, total fluxes
3	T_J control capability, Z_{th} meas. capability, SPD, total fluxes
4	T_J control capability, Z_{th} meas. capability, isothermal I-V-L meas. capability, SPD, total fluxes
5	T_J control capability, SPD, total fluxes
6	T_J control capability, Z_{th} meas. capability, isothermal I-V-L capability, SPD, total fluxes
7	T_J control capability, SPD, total fluxes

Each participating testing laboratory was responsible for the calibration of their test equipment; there was no common reference source used in this experiment. This was in line with the goals of the Delphi4LED project, namely, to be aware how testing data of different manufacturers and end-users match and how well modelled and simulated LED characteristics may match these data.

Besides the testing laboratories listed above, further members of the Delphi4LED consortium have also contributed to this round-robin test. TU Eindhoven is responsible for the statistical analysis of the test results (not yet completed at the time of submission of this paper) and based on their expertise, Magillem develops data management schemes for the huge amount of data gathered during this experiment. The worked out scheme provides also the basis of test data management for the entire duration of Delphi4LED project. PI Lighting also contributed to LED selection and determination of sample sizes for the test.

III. LED Sample Selection

Selection of LEDs to be tested in this inter laboratory comparison was driven by the needs of the Delphi4LED project. A major aspect was to include today's mainstream LED package types used in luminaire design. Therefore, mainly high power (HP) LED packages were chosen, but an LED package type also represents the mid-power packages and a CoB LED was also chosen which represents the LEDs used in high flux applications. It was important to see how the different labs can identify the light output properties of LEDs aimed for general lighting applications, different representative phosphor converted white LEDs (cool and warm white, high CRI and low CRI versions) were chosen. Also, to learn about the testing capabilities in different ranges of the visible spectrum and also represent different LED chip and package designs, a red, a green and a blue LED type was also included into the set of test samples. Table II provides a summary of the major characteristics of the selected test LEDs.

The selected blue LED packages connects the colour LED samples to the white ones as it is produced by the same manufacturer as one of the white LED packages and the same blue LED chip is applied in this package as in the corresponding white LED package. This choice allows to study how the applied phosphor affects the different (thermal) properties of the entire assembly. (A preliminary study about the effect of the phosphor on the measured thermal properties of LED packages was published recently [11].) Besides this round robin test, these two LED types have also been selected for further, detailed regular measurements aimed to deliver input data for chip, package and assembly level compact modelling of LEDs in the Delphi4LED project. Further details of LED selection criteria can be found in another conference paper [12].

TABLE II. MAJOR CHARACTERISTICS OF THE TEST LEDS

LED type code	Package style	Colour	Manufacturer	Comment
A	high power	royal blue	1	same package style as B and C
B	high power	cool white	1	same blue chip as at type A
C	high power	red	1	same package style as A and B
D	CoB	warm white	2	"chip on board" devices with a sample holder
E	mid-power	green	2	package with no thermal pad

IV. SAMPLE SIZES, SAMPLE PREPARATION, SAMPLE HANDLING

For the sake of easy handling and reducing measurement uncertainties related to sample mounting, all bare packages of type A, B, C and E LEDs were assembled onto standard star shaped MCPCB substrates. All samples have been provided with individual identifiers laser engraved into their substrates. Also, to comply with the requirements of the considered LED testing guidelines [7]-[10] all LEDs have been equipped with four wire (Kelvin-type) electrical connections (reducing the forward voltage reading errors).

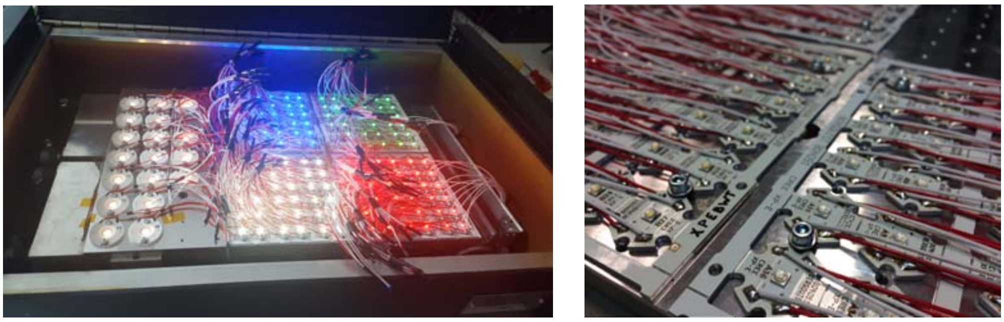

Figure 1. LED test samples in the aging chamber

The sample size chosen was determined also as a trade-off between the available resources and the need for gathering detailed information about the test LEDs. Ultimately, 36 samples of types A, B, C and E and 30 samples of CoB LEDs (type D) have been ordered, prepared for testing.

In their early life, LEDs are subjects to performance (flux, forward voltage, colour point) changes, which can be improvements or degradations. Therefore, 500 hours of ageing was thought to limit the impact of those early variations on the samples leading to more robust conclusions on the round robin test. All type A, B, C and E LEDs on standard MCPCB star board frames were assembled in BME's LM-80 standard compliant aging chamber as shown in Fig. 1. These star board frames occupied 2/3 of the available space in the chamber therefore only 18 pieces of type D LEDs (CoB LEDs) out of the available 30 CoB samples were assembled into the chamber. Thus, 3x36 MCPCB assembled LEDs and 18 CoB LEDs were subject of aging simultaneously. This was a trade-off that had to be made in order to keep the total power dissipated in the aging chamber within the heat-removal capacity limits of the thermostat used with the aging chamber. The remaining 12 CoB LED samples were subject of a second aging process before these samples were dispatched. For the aging the LED test samples were electrically connected in series, this way the same LED types were driven with the same steady forward current. The aging took place at a temperature of 85 ^{o}C. During the aging process 3 samples of type E LEDs went completely wrong.

In case of testing power components on cold plates a common practice is to apply thermal interface materials (TIMs) such as thermal grease or paste between the component's cooling surface and the cold plate in order to lower the junction-to-ambient thermal resistance of the component. Since in this round robin test we decided to measure LED properties at prescribed junction temperatures we decided NOT to use any TIM material in order to avoid possible optical degradation of the LED samples due to contamination of the lenses. Therefore, when measuring the R_{thJC} junction-to-case with the so called transient dual interface method, we had to deviate from the recommendations of the JEDEC JESD51-14 standard [9]. Thus, instead of applying "dry condition" (no TIM applied) and "wet condition" (TIM applied), we prescribed two "dry" conditions between the bottom of the MCPCB substrate (considered as the cooling surface or 'case' surface of the LED assembly): once the LEDs had to be mounted onto the temperature controlled cold plate without any TIM and for the second thermal transient measurement, a thin sheet of thermally insulating material had to be inserted between the cold plate and the MCPCB substrate. Such TIM foils with the right instructions for every LED type were also distributed to the participating laboratories.

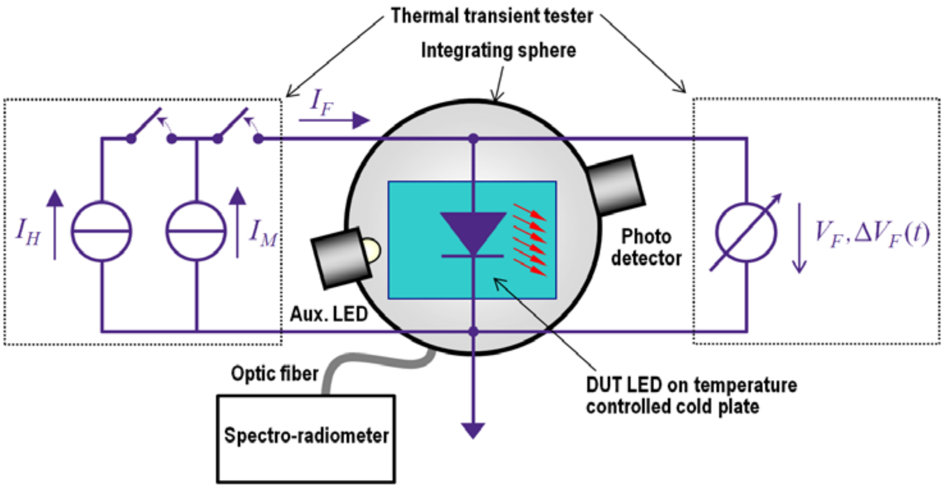

Figure 2. The generic test setup used in the measurements of this experiment. Some of the participating laboratories provided the current sources and the voltmeter integrated in a thermal test equipment, some laboratories provided these as individual units. At all laboratories the test LEDs were mounted onto a temperature controlled cold plate and the light output properties were measured in an integrating sphere with 2π geometry.

V. OVERALL TEST SETUP AND THE MEASURANDS

Both the latest JEDEC and CIE guidelines for testing high power LEDs [7], [8], [10] recommend the control/determination of the T_J junction temperature of the LED being measured. Therefore, all thermal and optical measurements of the test LEDs had to be performed such that the LEDs under test were mounted onto a temperature controlled cold plate. The optical measurements were always performed with an integrating sphere with 2π geometry, as recommended by [8] and [10]. The sketch of the test setup used by all participating laboratories is shown in Fig. 2.

The participating laboratories were free to choose the method of setting/controlling the T_J junction temperature, following either CIE's coming new recommendations [10] (which are based on a method originally proposed by Zong & Ohno [13]) or using the guidelines of JEDEC's LED thermal testing [7], [8]. Every participating lab has been provided with these recommendations and detailed instructions on sample handling. The test conditions for single operating point measurements are summarized in Table III. For types A, B and C the test conditions are characteristic to the foreseen real-life operating in an application. For types D and E LEDs the properties of the test samples and the available test equipment of the participating laboratories were the major factors to define the test conditions.

TABLE III. TEST CONDITIONS FOR SINGLE OPERATING POINT MEASUREMENTS

LED type code	I_F [mA]	T_J [ºC]
A	700	85
B	700	85
C	700	85
D	200	85
E	100	40

For all LED types tested the following parameters had to be measured/calculated and reported for the set forward current and targeted junction temperature: the forward voltage, the achieved junction temperature, the spectral power distribution, the measured or calculated radiant flux, luminous flux, chromaticity coordinates (CIE 1931, 2º), correlated colour temperature (if applicable), radiant efficiency, luminous efficacy, efficacy of source of radiation (CIE ILV term 17-730). The laboratories were also requested to report the steady-state junction-to-ambient thermal resistance of the measured LED samples. Laboratories with thermal transient testing capabilities were required to determine the transient R_{thJC} junction-to-case thermal resistance of the test samples, following the detailed measurement protocol derived from the JEDEC JESD51-14 standard. For all thermal measurements (based on the electrical test method [7]) for all LED samples the measurement current had to be set to 10 mA. For type A LEDs four participating labs volunteered to measure the isothermal I_F-V_F-Φ_e characteristics together with SPD for the combination of the following forward current and junction temperature settings: I_F = 20, 30, 60, 100, 350, 500, 700, 1000 mA, T_J = 30, 50, 70, 85, 110 °C, resulting in a total of 40 different operating points. These points were determined after a careful consideration of the features of the electrical and efficiency characteristics of these LEDs [14]. This is a minimum set of operating points thought to be sufficient to extract parameters for a multi-domain chip level model [15] of such LEDs aimed for simulation by a Spice-like electrical circuit simulation program.

VI. Results and conclusions

At the time of submission of this paper, the pre-characterization of LED samples was completed, establishing the reference values of the measurands for all LED samples distributed. According to the distribution scheme of the test samples, 5 samples of each LED type (altogether 25 samples) are circulated among the participating laboratories and each laboratory received further 3 aged and pre-characterised samples from each LED type. From types A, B and C reserve samples were kept at the organizing laboratory. Control measurements of the circulating samples took place at the organising laboratory after two participating laboratory performed their tests. (This sample circulation and control measurement scheme is a trade-off between the standard practice of round robin measurements, the high samples size of the present experiment and the available time frame and resources.) In order to allow early completion and reaching the final statistical analysis of the single operating point test results, the measurement of the isothermal I_F-V_F-Φ_e characteristics of the type A LEDs takes place in a second round by the volunteering laboratories.

At this stage we can state that except type D LEDs the control measurements did not show significant drift of the measurands. Based on the unprocessed, raw test results of the participating labs having already completed the single operating point measurements, the test results are in the expected ranges. Statistical analysis of the test results of the five samples of each LED type and the statistical analysis of the differences among the participating labs' test results will be published in detail in an open access journal paper.

It is worth noting, that this experiment is the first round robin test of the latest JEDEC and CIE package level LED measurement guidelines. Also, this experiment is aimed at providing actual experimental input for the work of the CIE TC2-84 technical committee which aims to work out recommendations on reporting LED test data aimed as input for automated LED model generation.

Acknowledgement

The contribution of the European Union for supporting this work in the context of the H2020 ECSEL Joint Undertaking programme (2016-2019) within the frames of the Delphi4LED project (grant agreement 692465) is acknowledged. Co-financing of the Delphi4LED project by the R&D funding organizations of the governments of the countries participating in this experiment through their national grant agreements is also acknowledged. We also thank J. Hegedüs from BME for his significant contributions to prepare and execute this round robin test.

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