FINAL PUBLISHABLE JRP REPORT

JRP-Contract number	ENG62
JRP short name	MESaIL
JRP full title	Metrology for efficient and safe innovative lighting
Version numbers of latest contracted Annex Ia and Annex Ib against which the assessment will be made	Annex Ia: V1.2 Annex Ib: V1.01
Period covered (dates)	From 01 June 2014 To 31 May 2017
JRP-Coordinator	
Name, title, organisation	Dongsheng Zhao, Dr., VSL, The Netherlands
Tel:	+31 15 269 1500 (ext. 1741)
Email:	dzhao@vsl.nl
JRP website address	http://www.eng62-mesail.eu/
Other JRP-Partners	
Short name, country	CMI, Czech Republic CSIC, Spain INRIM, Italy LNE, France METAS, Switzerland VTT, Finland PTB, Germany RISE, Sweden TUBITAK, Turkey Inmetro, Brazil OSRAM, Germany

Report Status: PU Public

EMRP
European Metrology Research Programme
Programme of EURAMET

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

REG1-Researcher (associated Home Organisation)		
Researcher name, title (Home organisation Short name, country)	Guoqi Zhang, Prof.dr. TU Delft, The Netherlands	Start date:1 Jun 2015 Duration: 29 months
REG2-Researcher (associated Home Organisation)		
Researcher name, title (Home organisation Short name, country)	Sönke Fündling, Dr.-Ing. TUBS, Germany	Start date: 1 Jan 2015 Duration: 29 months
REG3-Researcher (associated Home Organisation)		
Researcher name, title (Home organisation Short name, country)	Claude Gronifer, Dr. INSERM, France	Start date:1 Sep. 2015 Duration: 21 months

TABLE OF CONTENTS

1 Executive Summary

Introduction

The ‘Europe 2020 Strategy’ is pursuing an overall objective of saving 20% of the EU’s primary energy consumption by 2020. This is possible through innovations such as the enhanced energy efficiency, quality and useful life of innovative lighting. Initial Solid State Lighting (SSL) products, based on light-emitting diode (LED) technology, had clear advantages in energy efficiency over conventional lighting technologies though suffered from reduced light quality and variable performance. The development of basic metrology for SSL (ENG05 “Metrology for Solid State Lighting”) led to considerable improvements towards the reliable measurement of SSL performance.

However, with the gradual maturing of novel SSL technologies,, there is a need for research in metrology to keep pace to measure the performance of novel SSL products. Through this project dedicated traceable measurement solutions and an advanced metrological framework were developed which will serve to sustain the innovation and user uptake of novel SSL products..

The Problem

SSL technology is developing continuously and new types of SSL products, many of which are unproven, frequently appear on the market. Notable new technologies include organic light emitting diodes (OLED) and flexible LEDs, phosphor-free LEDs and pulsed LED systems. These products have distinct characteristics, which have to be taken into account in the performance measurement procedure to avoid measurement errors.

Optical measurement solutions have to be developed to deal with large area and curved light emitting surfaces (e.g. OLED and flexible SSL). Electrical parameters measurement has to keep pace with the developments of new electronic circuits used to drive novel SSLs. Metrics and validated measurement procedures have to be developed to cover safety and health aspects.

The need for reliable methods for lifetime determination is a key concern for producers. End-users are not ready to pay for unproven/unlabelled highly priced products. Lifetime is an important factor to be determined accurately (previously this was not possible), because it does not only govern the long-term quality experience of users but it also underpins economic models for lamp replacement. User confidence may be damaged by faulty lifetime estimates and uptake will correspondingly suffer.

The Solution

In response to this problem, the project set out to deliver an advanced metrological framework for novel SSL by providing transfer standards applicable at NMI and test laboratory level, to develop measurement solutions for large area and pulsed SSL by improving measurement methods and decreasing uncertainty, to provide metrics and equipment accounting for safety and comfort aspects of novel SSL by developing full measurement solution and by performing physiological studies, and to assure longer lifetime and provide its traceability by investigating various ageing mechanisms involved in material degradation.

Impact

The project outputs have been shared widely with the metrology, instrumentation and industrial communities. In total 23 papers were published, and 3 stakeholder workshops and 2 training courses were organized in the lifetime of this project.

The project made major contributions to the CIE Division 2, 4 and 6 through CIE Tutorial and Practical Workshop. In addition, this project provided input during the preparation of the draft documentary standard EN 13032-4:2015 Light and lighting – Measurement and presentation of photometric data - Part 4: LED lamps, modules and luminaries.

The new LED-based calibration source Multiple Transfer Standard (MTS) allows testing laboratories to calibrate measurement setups, and also get additional information about the sensitivity necessary to estimate uncertainties. A leader in the global lighting market has shown a great interest in taking over further development of the device.

The MTS, the Impedance Stabilisation Network (ISN), the validation approach of the high speed testing method and the uncertainty evaluation tool for the electrical parameters measurements developed in this project were demonstrated and used in conferences, stakeholder workshops and training courses. Several stakeholders showed great interesting to buy these developed devices or to use these approaches and software.

This results of this project will deliver an advanced metrological framework for novel SSL, and impact across the entire SSL value chain is expected.

2 Project context, rationale and objectives

2.1 Context

There is a pressing need for a reduction of global energy consumption, to supplement efforts for sustainable energy production. The Europe 2020 Strategy's objective is to save 20 % of the EU's primary energy consumption by 2020 and of making further improvements after 2020. The ideal scenario is to achieve the reduction in energy consumption while maintaining or even improving the quality of life. This is possible, but only if the energy efficiency of products is improved, so that they deliver the same value for less energy.

Lighting is a primary example of an area where substantial achievements in energy efficiency are possible, while not only maintaining, but actually improving product quality. It is also an area where a lot of energy is consumed, so that improvements in efficiency will have a direct and non-trivial effect on the total energy consumption. The EU Green Paper "Lighting the Future - Accelerating the deployment of innovative lighting technologies" states that "As 19 % of electricity consumption worldwide is used for lighting, more efficient lighting can give huge energy savings. This is one of the reasons why the EU has decided to progressively phase out existing inefficient incandescent light bulbs from the European market."

The energy efficiency improvements in lighting are made possible by the application of novel technologies, in particular SSL, which comprises both non-organic semiconductor-based LEDs and OLEDs. The technology behind SSL has made rapid advances over the past years and will continue to do so for the near future. As a result of this ongoing development, SSL products have appeared on the market in various forms and have gradually taken over conventional lighting in areas ranging from general interior lighting to decorative lighting and safety-related areas such as road lighting.

Initial commercial SSL products, based on LED technology, suffered from reduced light quality and variable performance, often well below stated performance claims, which seriously hampered initial user uptake of SSL. The gradual maturing of SSL technology has led to a steady increase in product quality. In tandem with this, the development of new metrology dedicated to SSL has made considerable improvements towards the reliable measurement of SSL performance. A pioneering role was played by the EMRP JRP ENG05 "Metrology for Solid State Lighting" and there is now awareness amongst parties involved in the measurement of SSL that traditional photometric techniques based on broad-spectrum, fairly uniformly radiating incandescent sources are no longer applicable to SSL. In addition, that traceability and measurement methods exist for the measurement of the most important performance parameters of SSL, notably luminous flux and luminous efficacy.

However, this does not mean that there is no need for further action. In fact the opposite is true: new metrology research is needed to sustain the development and uptake of SSL. SSL technology is developing continuously and new types of SSL products appear on the market, notably OLEDs and OLED arrays, nano-structured and phosphor-free LEDs, and high-power LED structures. These products have distinct characteristics, which have to be taken into account in the procedure of performance measurement to avoid measurement errors. Measurement solutions also have to be developed to deal with large area and possibly curved light emitting surfaces. Metrics and validated measurement procedures have to be developed to cover safety aspects related to high power LEDs and new electronic circuits are being developed to drive SSLs, and the electrical characterisation has to keep pace with these developments.

If there is no reliable metrology on which to base the claims of improved performance for novel SSL products, this will seriously interfere with the future development of energy-efficient lighting technology. End-users will be reluctant to embrace the new and unproven technologies and manufacturers will suffer. The Federation of National Manufacturers Association for Luminaires and Electrotechnical Components for Luminaires in the EU has published a paper, "Apples & Pears, a CELMA guiding paper: Why standardisation of performance criteria for LED luminaires is important", stating that "the lighting market has been flooded by a vast number of new and unproven entrants." Europe at present has a large total market share in lighting and is at the forefront of quality lighting products. To demonstrate this quality in a field of increasing competition from other countries, reliable metrology is needed.

A second need to be addressed is the reliability of lifetime claims. One of the advantages of SSL over conventional lighting is its much longer lifetime, which often extends to tens of thousands of hours. However, here as well as in other areas of SSL performance, the claims do not always live up to user expectation: "… Low-quality LED products: While there are already some good-quality LED products on the EU market, many LED products on offer are rather poorly designed and manufactured, emitting low-quality cold white light and are mainly serving as replacement lamps. Consumers also experience much shorter actual lifetimes than those claimed on the package." The need for reliable methods for lifetime determination is broadly felt. It features prominently on the agenda of European Commission, which lists as key topics: LED luminaire lifetime, definition for acceptable colour shift or power consumption over the lifetime of an LED luminaire, LED lifetime prediction, and OLED lifetime requirements.

Lifetime is an important parameter to determine accurately, because it not only governs long-term quality experience of users, but also underpins economic models for lamp replacement. New SSL technologies such as OLED involve large investment costs for developers and producers, which translate into high initial prices. These prices can be justified economically from the user perspective by the reduced energy consumption, but only if the long expected lifetime bears out. If user confidence is damaged by faulty lifetime estimates, uptake will suffer. Direct measurement of the very long lifetimes of SSL is currently not possible. Indirect measurement and model based extrapolation can be carried out but so far no uncertainty statement can be attached to the outcomes. Metrology institutes have experience in quantifying the reliability of measurement results; therefore their involvement in lifetime prediction is urgently needed.

Documents which are treated like international standards for testing, such as CIE 127:2007 and IES LM-79-08, provide the basic methods for measuring LEDs and SSLs, but do not give detailed instructions on how to obtain or apply some of the corrections needed, or how to determine the measurement uncertainties for SSLs of different types. Another big issue is that these documents mainly focus on optical measurements, giving almost no information on how to reliably measure the electrical power consumption of SSLs. Therefore, it is highly important to address this issue as it can be one of the largest uncertainty components in determining the energy efficiency of SSL products. CIE TC2-71, CEN TC169 WG7 and IEC TC34 are currently developing written standards for testing the electrical and optical properties of SSLs, but the work is still under way. However, it is stated in the CIE and CEN standard that "This standard… (for LED lamps, modules and luminaires)… does not cover LED packages and products based on OLEDs (organic LEDs)", where LED packages means "single discrete component encapsulating one or more LED dies, possibly with optical elements and thermal, mechanical, and electrical interfaces". Recommendations for measuring new generation SSLs, such as OLEDs are also under development. CIE TC2-68 and CIE TC2-75 will address these issues, but the work has just started.

2.2 Objectives

The aim of this JRP was to provide essential and currently missing metrology for SSL, with an emphasis on dedicated metrology for novel SSL concepts such as OLEDs and nano-structured, phosphor-free LEDs.

The following specific objectives were addressed in this project:

1. To develop sets of optical and electrical reference standards to calibrate as well as to characterise the setups used in test laboratories and to verify their capability to perform particular measurements of novel SSL;
2. To study the feasibility of using standard measurement equipment for 3D complex goniometric measurements of large area and/or complex "next generation" SSL;
3. To develop methods for reliable electrical power measurements of AC-operated mature SSLs with the focus on developing an impedance stabilisation network. In addition, to develop methods for electrical and optical measurements of pulsed SSL;
4. To improve measurement methods and decrease uncertainty in photometrical parameters of OLED measurements;
5. To deliver a set of metrics, currently lacking in metrology, for safety and comfort aspects through the development of instrumentation and measurement methods and through performing studies on (a) flicker/stroboscopic effect; (b) blue hazard; (c) well-being/comfort experience; (d) lighting quality perception;

6. To develop measurement methods and establish traceability for lifetime and reliability testing of SSL products and disseminate these to international standardisation bodies. As well as investigating various ageing mechanisms involved in material degradation of novel SSL devices.

3 Research results

Since metrology for SSL covers a wide set of parameters, some related to optical output, some to electrical aspects, some to reliability and some to perception and safety, a broad range of expertise is needed. This is why a consortium of JRP-Partners with complementary knowledge and facilities worked in a collaborative approach in this project. The research results of the project are presented in detail below on an objective by objective basis.

3.1 Developing optical and electrical reference standards

A sphere measurement setup is an ideal measurement system to compare lamps, if the lamps to be compared a) are of exact same size and form, b) have the same spectral power distribution, c) have the same light distribution and d) show the same time dependency. If one of these boundary condition is not fulfilled - as it is typically the case when a test laboratory calibrates its sphere setup with a standard lamp and uses this calibrated sphere to measure customer lamps - corrections must be applied and/or the expected uncertainty of the comparison may be drastically increased. The reasons for the need of corrections is the different weighting of the emitted radiant flux by the sphere setup due to manifold of reasons, which comprise the non-uniformity of the sphere coating with respect to its absolute spectral and geometrical reflectivity, the influence of the size and geometry of baffles, the type of auxiliary lamp used, the capability of the detecting system, the capability of the power supply, connectors and the electronic measurement system, and finally the repeatability of the sphere lock.

To apply corrections or to determine the estimated increase in uncertainty depending on the device under test (DUT), at least some information about the influence of the sphere setup on the measurement result with respect to the influencing parameters a) to d) is needed. A straightforward approach to solve this problem is, to build a couple of different transfer standards with different spectral, geometrical, distributional and temporal behaviour, where every single standard will be traceably calibrated to National Standards. If these transfer standards are used in an ideal sphere, the sphere calibration factor calculated from every single of these different transfer standards will be the same. However, using an imperfect sphere, the sphere calibration factor will differ between the standards used, depending on the sensitivity of the sphere with respect to spectral, geometrical and temporal variations of the radiant flux.

Taking into account the needs of test laboratories, a novel multiple transfer standard (MTS) device is introduced by PTB as an optical reference standard which was designed not only capable of calibrating a sphere setup under one defined radiant condition but also to characterise the measurement setup with respect to various conditions.

The MTS is basically a temperature stabilised cube, where 5 of its 6 surfaces are covered with printed circuit boards (PCBs), each assembled with 5 stable LEDs of different colours. Every PCB has its own microcontroller which can be wirelessly programed by commands so that every single LED can be addressed separately set to its current and temporal modulation. In addition, the MTS can also be equipped with additional geometrical accessories to mimic a spherical globe, a linear tube or a panel type of source. It is capable to emit different spectra with different shapes and different spatial distributions and the ability to run under different modulation conditions. A MTS without additional accessories and with diffusing globe accessory is shown in
Figure 1.

The operating voltage of an MTS is 24 Volt DC. The typical current at maximum current setting of the LEDs is about 6 Ampere. During operation, the MTS is computer controlled via wireless connection using an eRIC4 module (433MHz). An internal multi-master bus using RS-485 (8N1,19800 baud) can be used for services and change of default settings. The stabilisation temperature of the PCBs is set by default to 35 °C to allow the system to stabilize even if all LEDs of the cube are operating at about maximum power. Temperature control can be linked to only one PCB-board or to the averaged reading of all PCB-board on the cube to avoid unbalanced thermal operation.

Figure 1. MTS without additional accessories (left) and with diffusing globe accessory (right).

Depending on the set values, the LED-driver can operate the LEDs in continuous mode as well as in modulation mode. The highest frequency of the step function used to modulate the LED current, i.e. the light output, of the LED is restricted to 20 kHz. A screenshot of the MTS control software is shown in Figure 2.

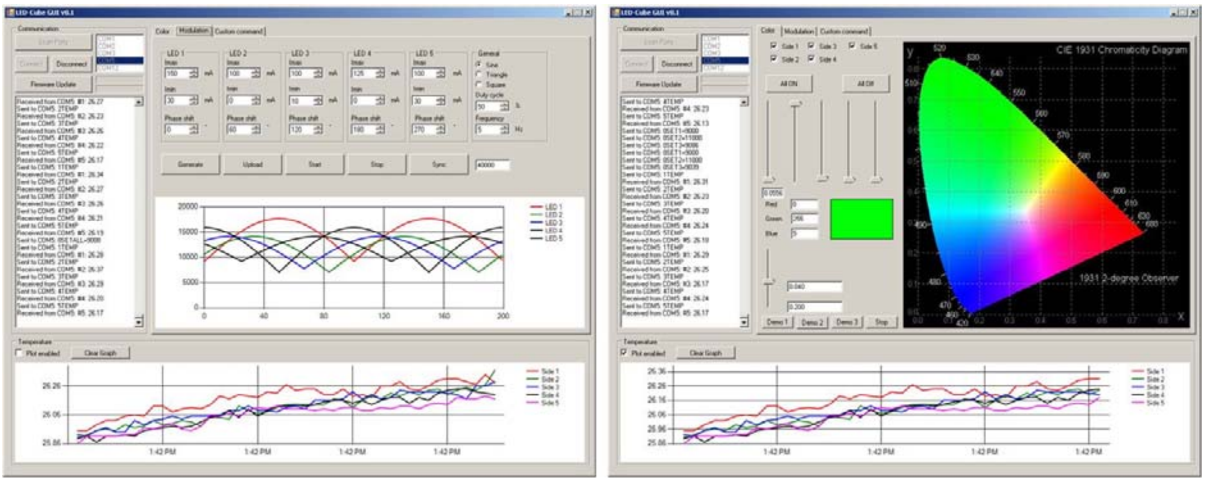

Figure 2. The screenshot of MTS control software

The MTS was fully calibrated at PTB using PTB's robot-goniophotometer and used afterwards to characterise the two different integrating spheres of PTB with different coatings and one integrating sphere of OSRAM. The partners VTT, METAS, LNE and VSL have completed full characterisation of the optimised MTSs equipped with the specific diffuse fixtures (globe, tube) designed and constructed by LNE using their facilities. The results clearly show that the MTS is a very useful tool to characterise integrating sphere setups. If calibrated with a goniophotometer, it can be used to verify spatial as well as spectral properties of sphere setups. It can also be determined whether or not the sphere coating produces fluorescence. There are even more potential applications of the MTS, which can be exploited with the taking over and further development of the device by OSRAM, a leader in the global lighting market.

Five MTS devices were built and characterised by partners involved in the project consortium. SSL devices used for the comparison have been fully characterised after final selection. A series of bilateral characterisation and measurement campaigns between the NMIs and test laboratories of the respective countries based on the MTS have been completed or planned. Most test laboratories are stakeholders of this project. For each intercomparison, a report includes the characterising measurements carried out with the MTS at the test laboratory and the interomparison result between the test laboratory and the NMI laboratory on the set of SSL lamps selected by CMI. The unique MTS allows testing laboratories to calibrate measurement setups, and also get additional information about the sensitivity necessary to estimate uncertainties. The measurement setups of these stakeholders can be improved through this comparison campaign.

In this project, an e-MTS was designed and built by VSL to be used as an electrical reference standards. The standard is a reference phantom power standard which can simulate up to 8 different SSL lamps and 1 incandescent lamp. The operation is through the front panel as shown in Figure 3. The e-MTS simulating the voltage and current of SSL products is able to validate electrical power measurement setups of test laboratories. The typical wiring configuration is shown in Figure 4. The bandwidth of the voltage amplifier is 200 kHz and the bandwidth of the trans-conductance amplifier is 100 kHz. Both voltage amplifier and trans-conductance amplifier have enough bandwidth to reproduce the voltage and current waveforms without distortion. Measurement results show that the power variations of all simulated LED lamps are all limited below 0.01 W. Another significant advantage of e-MTS is that there is no waiting time before the device reaches stablization. Normally, the commercial LED lamp takes over 45 minutes to reach stabilization. With this power standard, stabilization can be instantly achieved. The bilateral comparison of the eMTS developed has been carried out between VSL and PTB.

Figure 3. The front panel of the e-MTS

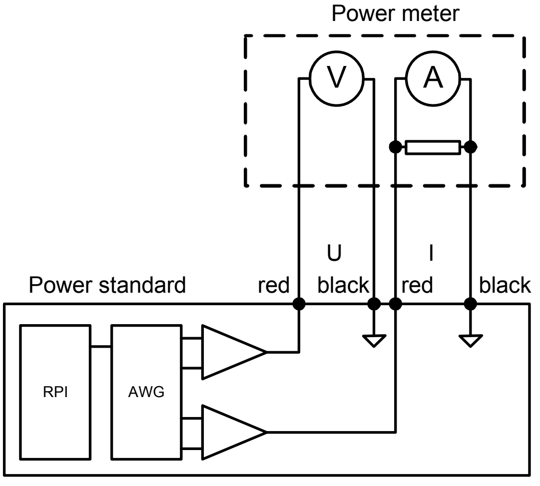

Figure 4. Wiring configuration of the e-MTS to validate an electrical power measurement setup

The feasibility of using OLEDs as transfer standards for luminance measurement devices was examined by ISIC. The steps to convert a given OLED in a transfer standard for luminance measurement devices were proposed. In order to use OLEDs as transfer standards for luminance measurement devices, the relevant variables of their radiant flux for this task were investigated, including stability, uniformity and spectral distribution. The impact of these variables in the uncertainty budget was explored, and the assessment results are summarized below:

1. The short-term stability of less than 0.3 % is achievable with OLED technology.
2. The impact of inhomogeneity must be carefully considered in scenarios for which OLEDs is used with a different aperture radius to the one used in the calibration. The impact of the inhomogeneity in the uncertainty budget may be up to 2 % if a mistake is made. From Figure 5, for most of the cases, the radius variation from 0.5 cm to 1.7 cm implies a variation of less than 2 % is achievable.

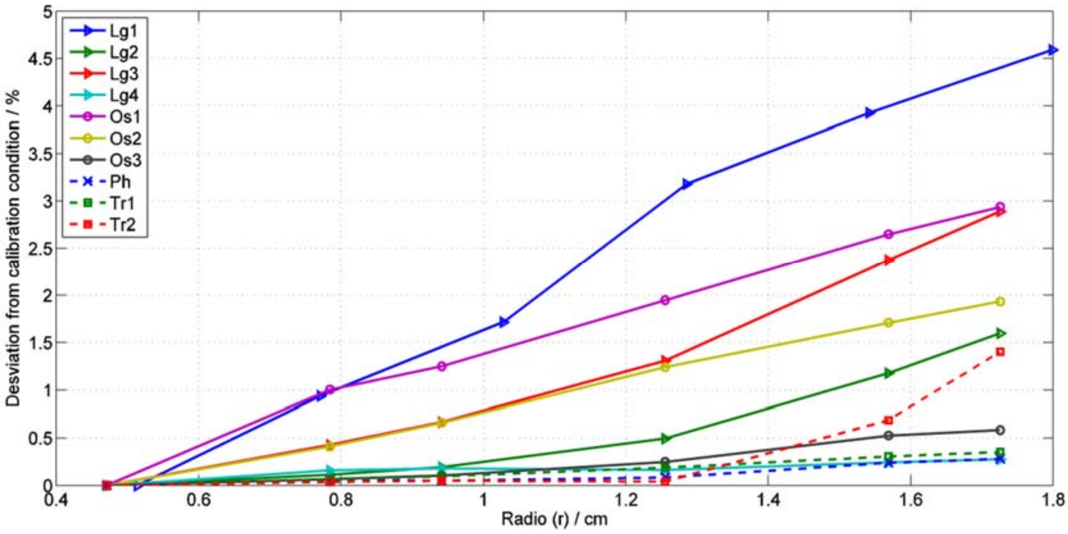

Figure 5. Variation with radius of circular measurement area of the measured average luminance of the selected OLEDs.

3. Uncertainty caused by spectral mismatch of OLEDs relative spectral distributions with respect to Standard Illuminant A reaches a typical value between 0.15 and 0.3.

The LED-based mosaic test standard device for Imaging Luminance Measuring Devices (ILMD) as shown in Figure 6. Picture of the LED mosaic to be used as test standard for ILMDs.Figure 6 was developed and the quality indices of the ILMD, such as general V(λ) mismatch index, stray light influence for negative contrast, edge function, size-of-source effect, effect of the surrounding field, linearity for a luminance range, non-uniformity and smear have been extensively analysed in this project. Characterization of the effect of the surrounding field is shown in Figure 7.

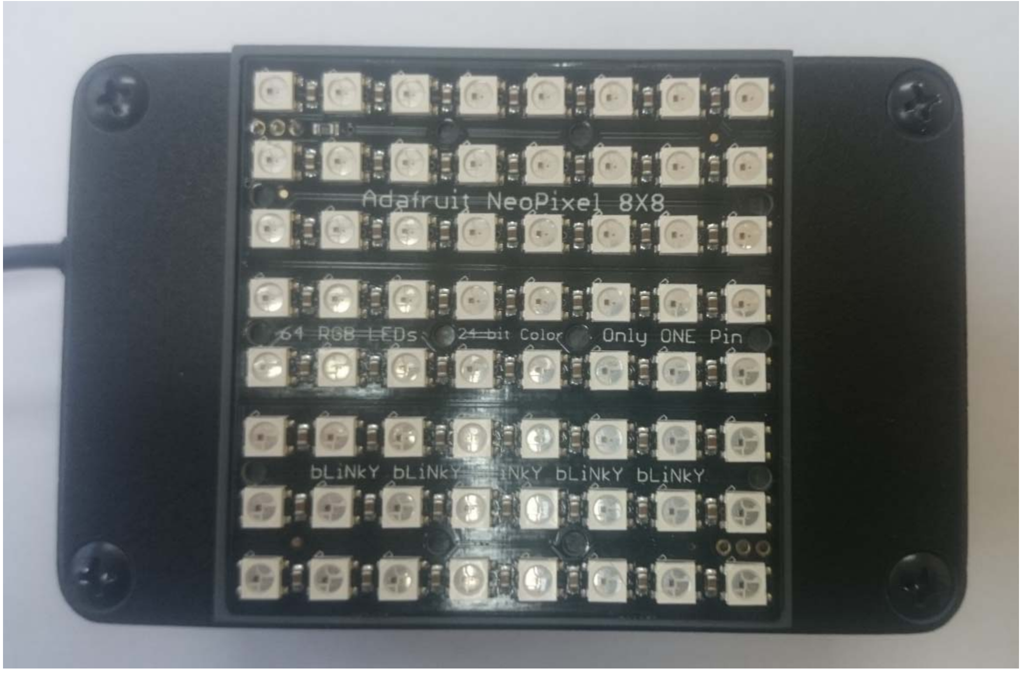

Figure 6. Picture of the LED mosaic to be used as test standard for ILMDs.

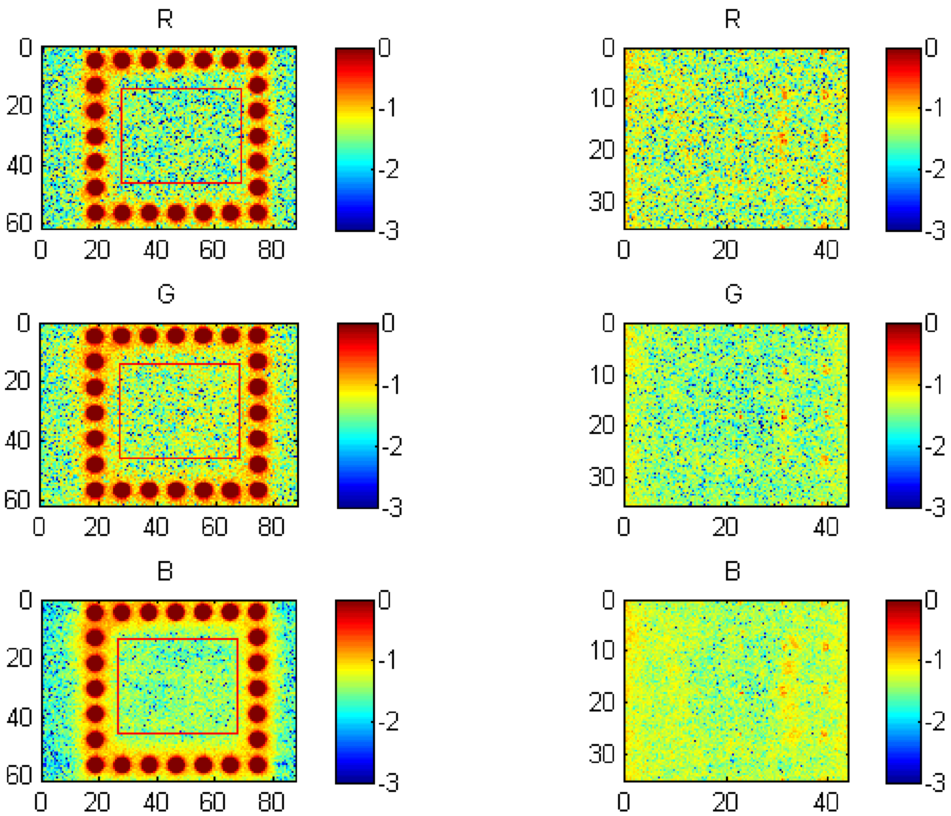

Figure 7. Characterisation of the effect of the surrounding field. On the left, HDR images acquired at a far distance, showing the rectangle of LEDs. On the right, HDR images acquired at a short distance. In this case, the field of view of the camera does not include the rectangle of LEDs. Each line of images corresponds with a different type of LED (R, G and B). Notice that the colorbars represent in color code the decimal logarithm of the values of the pixels.

Summary: Developing optical and electrical reference standards

Proper characterisation of test-setups used in industry for the testing and traceable measurement of lighting devices by substitution methods is an important task. In many cases the properties of the device under test (DUT) differ from the transfer standard used which may cause significant errors, e.g. if an LED-based lamp is calibrated in an integrating sphere which was calibrated with a halogen lamp.

In this project, a novel MTS is introduced which was designed not only to transfer a single calibration value but also to enable the characterisation of test setups by means of additional calibrated output features. The MTS is basically a temperature stabilised cube, where 5 of its 6 surfaces are covered with printed circuit boards (PCBs), each assembled with 5 stable LEDs of different colours. Every single LED can be addressed separately by wireless connection to set its current and temporal modulation. In addition, the MTS can also be equipped with additional geometrical accessories to mimic a spherical globe, a linear tube or a panel type of source. Five MTS devices were built and characterised by partners involved in the project consortium. SSL devices used for the comparison have been fully characterised after final selection. A series of bilateral characterisation and measurement campaigns between the NMIs and test laboratories of the respective countries based on the MTS have been completed or planned. The unique MTS allows testing laboratories to calibrate the luminous flux responsivity of measurement setups, and also get additional information about the sensitivity of the system to spectral, spatial and time dependent properties that are necessary in estimation of uncertainties in testing of luminous flux and efficacy of new lighting products entering the market.

In this project, a novel e-MTS was designed and built. The standard is a reference phantom power standard which can simulate up to 8 different SSL lamps and 1 incandescent lamp. The e-MTS simulating the voltage and current of SSL products is able to validate electrical measurement setups of test laboratories. Both voltage amplifier and trans-conductance amplifier have enough bandwidth to reproduce the voltage and current waveforms without distortion. Measurement results show that the power variations of all simulated LED lamps are all limited below 0.01 W.

In this project, the feasibility of using OLEDs as transfer standards for luminance measurement devices was examined. The LED-based mosaic test standard device for Imaging Luminance Measuring Devices (ILMD) was developed and the quality indices of the ILMD have been extensively analysed in this project.

3.2 Using standard measurement equipment for 3D complex goniometric measurements of novel SSL

In this project, PTB and TUBS investigated packaged devices with an ensemble of 3D core-shell LED columns as well as 3D structured axial LEDs using a ILMD and a near-field goniophotometer giving valuable insight to the pattern, directionality, and overall efficiency of the emission. Emphasis was put on the behaviour of luminous flux versus driving current of the device, in addition to the work plan this was also discussed with respect to its heat sink temperature. The setup at PTB was extended by two manipulators enabling on-wafer measurements of not completely processed (or not packaged) LED wafers and dies, as shown Figure 8, which speeds up the feedback loop for verification of device processing schemes. In summary, a hexagonal luminous intensity distribution was found for all investigated devices with ensembles of 3D core-shell LED columns which is assigned to the ensemble geometry. Along with the integral electroluminescence emission (EL) also the absolute luminous and radiative efficiency characteristic could be derived, resulting in an external quantum efficiency (EQE) maximum in the range of 10 %.

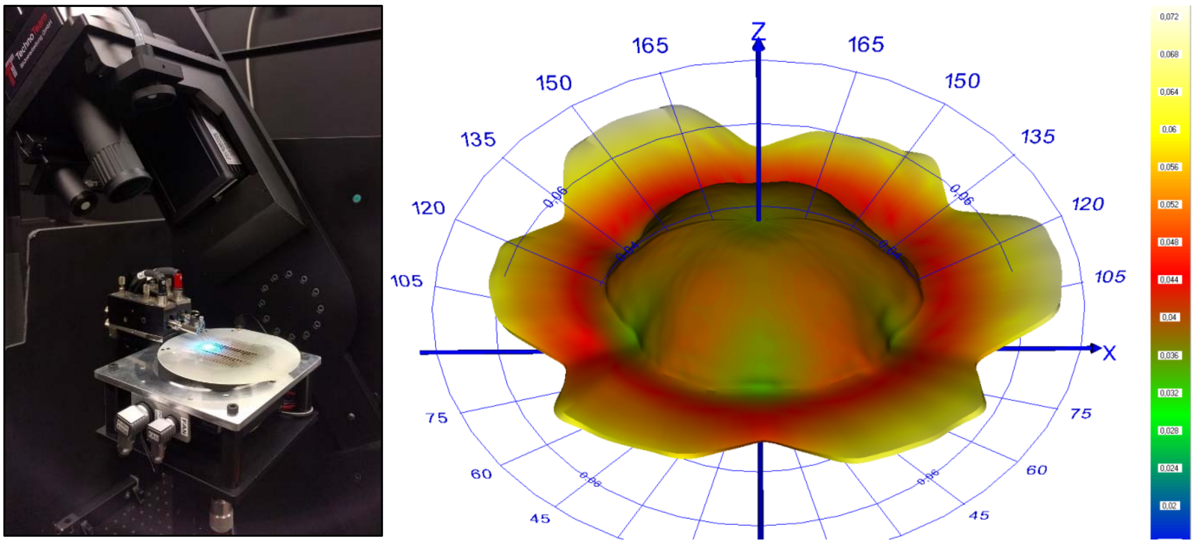

Figure 8: Photo of the setup for on-wafer measurements at the near-field goniophotometer at PTB showing EL from a 4” wafer with an axial LED and structured metal contacts (left) and luminous intensity of a 3D core-shell LED package with lens operated at 30mA (3D-polar plot in birds-eye view, right).

Summary: Using standard measurement equipment for 3D complex goniometric measurements of novel SSL

The feasibility of using standard measurement equipment for 3D complex goniometric measurements of large area and complex SSL (3D nano-structured) was studied. The measurement setup was extended by manipulators with probe tips, enabling on-wafer measurements by ILMDs and a near field goniophotometer. The near-field goniometer measurements of the prototypes are completed and were evaluated during the research period.

3.3 Improving measurement methods for ac-operated SSL and pulsed SSL

The ISN developed by VTT, VSL and METAS in the project is a unique device which can provide equalised impedance in laboratories to improve electrical measurements of SSL products with different AC sources. One of the four constructed ISN prototypes is shown in Figure 9. The circuit diagram is illustrated in Figure 10. The values of the components in the diagram are optimised carefully to reduce the total power consumption while still limit the maximum relative deviation in the root mean square (RMS) current value within an acceptable level. When connected to an AC voltage source with 230 VAC (RMS) output, the ISN will consume about 5 W of active power and 110 var of reactive power, when no DUT is connected. The results of impedance and phase response of the four ISNs was measured in the frequency range of between 20 Hz and 5 MHz using an automated LCR-bridge and presented in Figure 11. Two rounds of inter-laboratory comparisons on electrical measurement parameters were carried out. In these measurements, the behaviour of the ISN and a selected group of SSL artefacts were measured with different source-lamp configurations. Encouraging results show the potential of the ISN to improve electrical measurements of SSL products with different AC sources.

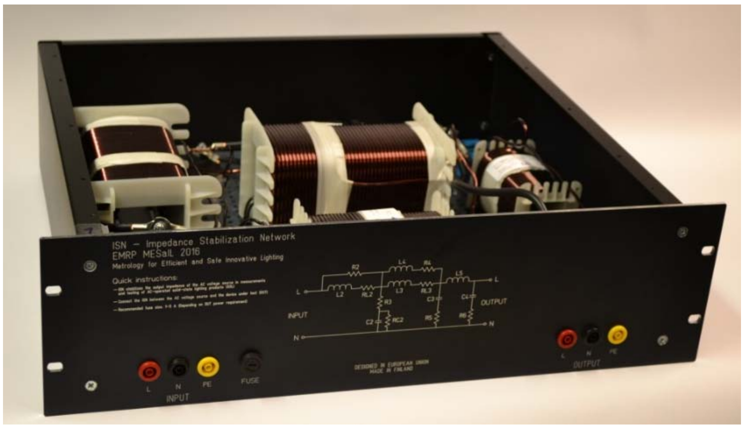

Figure 9. One of the constructed ISN prototypes built at MIKES. The rack enclosure was left open for illustration purposes.

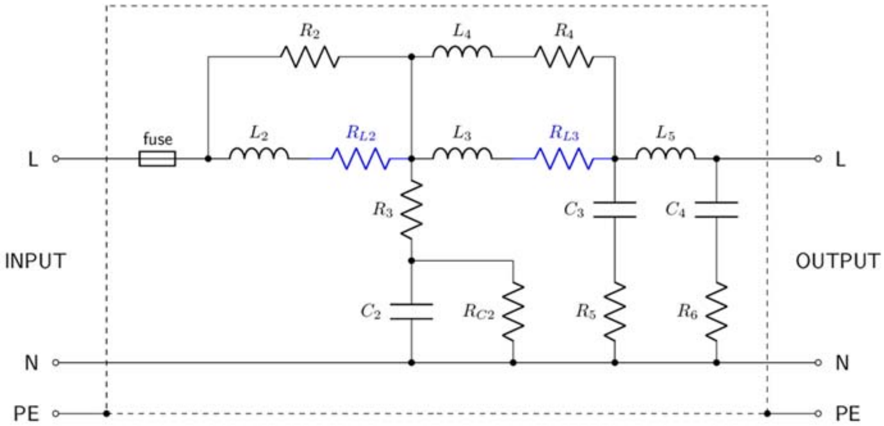

Figure 10. Circuit diagram of the impedance stabilization network. Components $\mathbf{R_{L2}}$ and $\mathbf{R_{L3}}$ are not discretely present in the device.

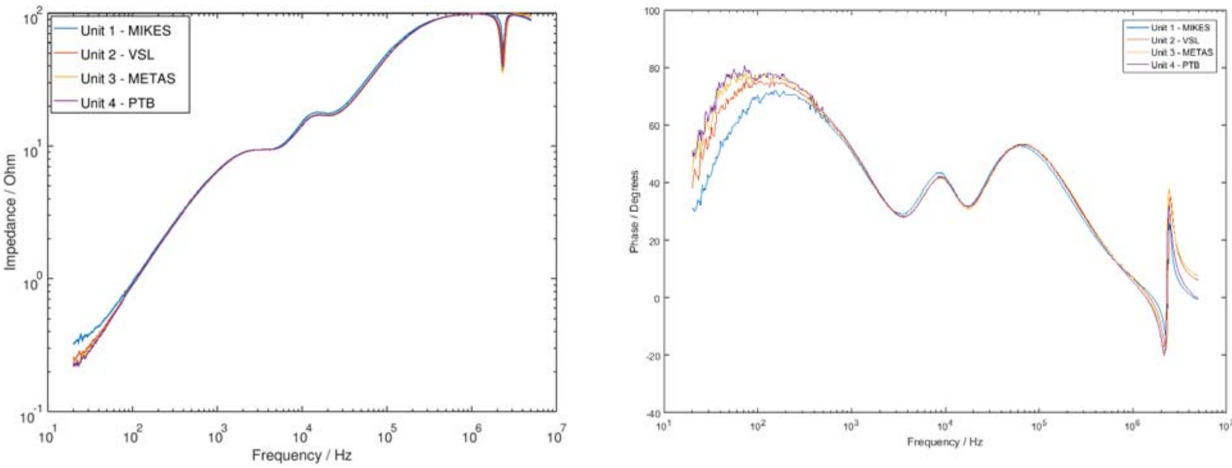

Figure 11. The measured impedance responses (left) and phase response (right) of the four ISNs constructed.

At least 6 luxmeters, 1 luminancemeter, a filter colorimeter and 3 array spectrometers were independently studied by LNE and RISE in this project with respect to integration time and response time using different optical waveform shapes, frequencies and modulation parameters (PWM, sinewave, triangular wave, offset, duty cycle). It is found that most of handheld instruments, having or not a flicker mode, are sensitive to all modulation parameters and provide underestimated measurements, mainly due to clipping. One typical measurement result is shown in

Figure 12. Therefore, the integration time or response time needs to be set correctly with respect to the modulation period to provide stable and consistent measurement results in continuous waveforms or modulated waveforms.

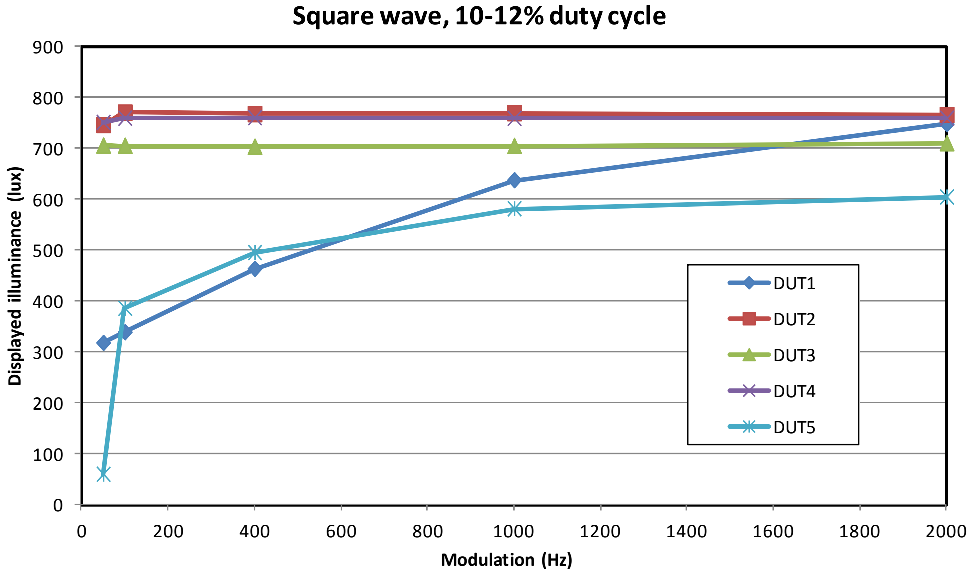

Figure 12. Measured displayed illuminance with respect to variant modulation frequency.

In addition, the short-pulse testing method used in industry to evaluate light output performance of the LEDs during production has been validated by VSL in this project. The short-pulse method is very efficient in case a well-defined electrical current pulse is applied and the stabilisation time of the device is “a priori” accurately determined. For the tested DUTs, the stabilisation time of an optical output was found to be at around of 40 ms. No spectral (colour) shift but only an amplitude increase of around 8 % for the whole spectrum is observed when DC measurements are substituted by the short pulse. The largest contributors to the measurement uncertainty are identified. The total expanded uncertainty of the measured total radiant power at a particular wavelength is around 7 %. By increasing the amount of spectral filters in the Optical Detector System and adding measurements of time-resolved surface temperatures, the total expanded uncertainty (k=2) may be reduced to 3 %.

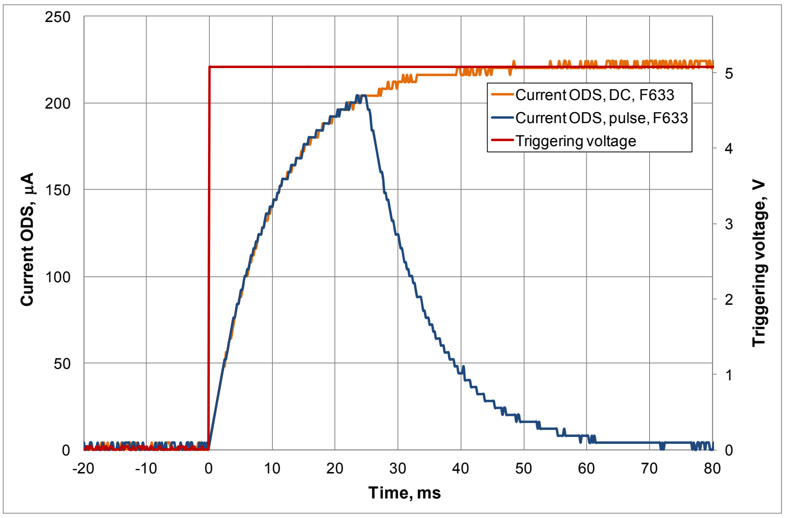

Figure 13. Comparison of short-pulse and DC-driven resulting optical signal of DUT as measured by the filtered Optical Detector System. Triggering voltage is given for reference (right vertical axis).

Summary: Improving measurement methods for ac-operated SSL and pulsed SSL

The ISN developed in the project is a unique device which can provide equalised impedance in laboratories to reduce the uncertainty of performing electrical measurements of SSL products with different AC sources. Two inter-laboratory comparisons on electrical measurement parameters were carried out. In these measurements, the behaviour of the ISN and a selected group of SSL artefacts were measured with different source-lamp configurations. Encouraging results show the potential of the ISN to improve electrical measurements of SSL products with different AC sources.

Various photo-detector/amplifier/digitiser systems and spectroradiometers are independently studied in this project with respect to integration time and response time using modulated light. It is found that most of handheld instruments, having or not a flicker mode, are sensitive to all modulation parameters and provide underestimated measurements, mainly due to clipping. Therefore, the integration time or response time needs to be set correctly with respect to the modulation period to provide stable and consistent measurement results in continuous waves or modulated waves.

In addition, the short-pulse testing method used in industry to evaluate light output performance of the LEDs during production has been validated in this project. The short-pulse method is very efficient in case a well-defined electrical current pulse is applied and the stabilisation time of the device is “a priori” accurately determined. No colour shift is observed. The largest contributors to the measurement uncertainty are identified to be poorly-defined current pulse and inaccurate calibration factor.

3.4 Improving measurement methods for OLED

In the project, optical and electrical measurements were performed to evaluate the influence of bending of an OLED. It is interesting that in the center part of an OLED, after bending, the measurement data of luminance get lower, but in the side parts of OLED, the changes go the opposite direction. The variation is in the range between -9 % and 10 %. The harmonic distribution (dc-5000th Harmonic) data is also analysed. The bend has no influence on the harmonic distribution on the ac input side.

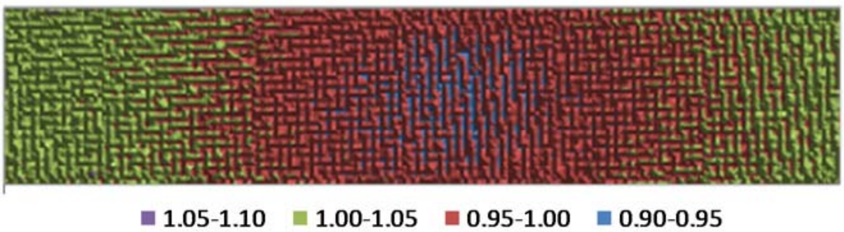

Figure 14. Ratio of the measured displayed illuminances when the OLED was in flat and in bending positions.

Moreover, improved methods for measuring luminous flux and spectral radiant flux of OLEDs using an integrating sphere were developed. The spatial corrections methods of OLEDs in 4π sphere geometries with various geometrical alignments to suppress edge-emission were proposed for the first time in this project. The effects caused by spectral self-absorption effects of the SSL devices are evaluated. In Figure 15, an OLED being measured in the sphere is illustrated. The uncertainty analysis of the luminous flux measurement of a typical and a problematic OLED is presented in Table 1.

Figure 15. OLED attached to the OLED holder and pointing towards the bottom of the sphere in the integrating sphere measurements.

Table 1 Simplified uncertainty budget of luminous flux measurement of OLED.

	100 × relative uncertainty	
Source of uncertainty	Typical OLED	Problematic OLED
Luminous flux responsivity	0.3	0.3
Drift of the sphere photometer	0.1	0.1
Stability of the luminous flux	0.05	0.2
Photocurrent measurement	< 0.01	< 0.01
Spectral mismatch correction, $c_\mathrm{i}/c_\mathrm{e}$	0.2	0.2
Self-absorption correction, α	0.2	0.2
Spatial non-uniformity correction		
for internal source, k_int	0.06	0.06
for external source, k_ext	0.06	0.06
Combined standard uncertainty	0.44	0.48
Expanded uncertainty ($k = 2$)	0.88	0.96

In this project, a complete procedure was developed by CSIC to reduce the near–field experimental data by characterising the spectral and angular distribution of small areas of the source, or subsources. Once these subsources are photometrically characterised, any photometric quantity of the complete source can be calculated by integration in a very modest lapse of time, which is a clear advantage with respect to ray-tracing methods for real time visualisation applications. This luminance equation is also an important starting point to identify the relevant uncertainty sources in a near-field measurement. This procedure has been tested using the near–field goniospectroradiometer developed at IO-CSIC, which allows also spectral, angular and spatial photometric measurement to be carried out. A set of OLEDs from different sizes, shapes and manufactures have been used as test sources. The results obtained by the procedure have been compared with those experimentally obtained by conventional far–field goniophotometry. The relative deviations between calculated and experimental data are given in Figure 16, as a function the distance normalised by the half size of the largest side or by radius of the OLED.

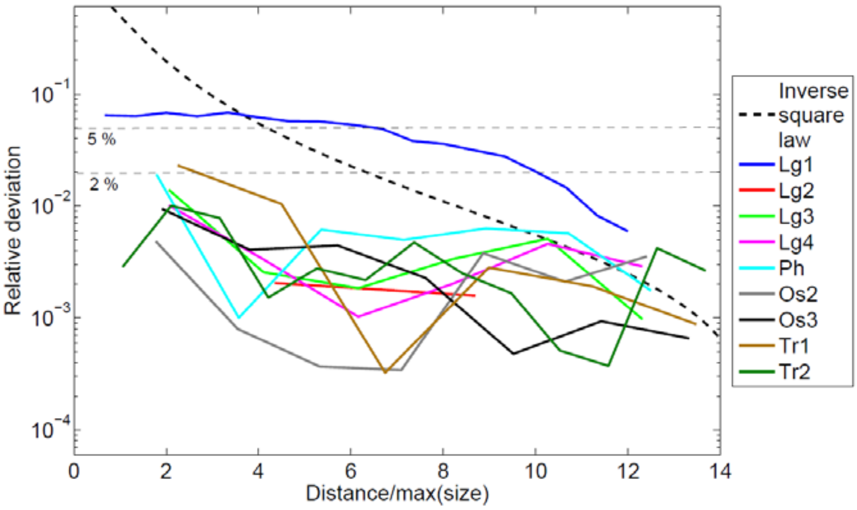

Figure 16. Relative deviations between calculated and experimental luminous fluxes of several OLEDs at different distances. The distance is normalised by the half size of the largest side or radius of the OLED.

Summary: Improving measurement methods for OLED

In the project, optical and electrical measurements were performed to evaluate the influence of bending of an OLED. The spectral and spatial corrections and methods to suppress edge-emission were studied for the first time in this project of OLEDs in 4π sphere geometries with various geometrical alignments.

Several OLEDs and SSL devices were measured in different spheres and goniophotometers. The effects caused by edge-emission, spectral self-absorption and fluorescence effects are rather small for most of the SSL devices tested. With most of the OLEDs tested, the luminous flux values measured in vertical and horizontal panel orientations showed less than 1.3 % difference in the luminous performance of the panel. To verify the results, a group of three different types of OLEDs were measured using a 4π integrating sphere of VTT, a 2π integrating sphere of LNE and a mirror goniophotometer of CMI. Despite the fact that some of the OLED panels were not stable enough for comparison purposes, the standard deviations calculated for the measured luminous flux values for the three panels were 0.75 %, 1.16 % and 2.4 %. The highest standard deviation of 2.4 % is partly explained by the fact that it had the least operating hours of the three panels measured. The results show that it is possible to measure the luminous flux of OLEDs in integrating spheres with expanded uncertainties at around 1.0-1.5 % (k = 2), when the results are corrected for the spectral and spatial properties of the system. In the case of stable, fully seasoned OLEDs, the corresponding uncertainties smaller than 1 % can be obtained. With the panels tested, the effect of the edge-emission to the value of total luminous flux was less than 0.05 %, and thus is negligible in most testing of luminous efficacy of OLEDs. However, it is more important to take the edge-emission into account in design of luminaires, because despite the low luminous level, it can be visually perceived and often has very different spectral contribution (such as blue or green tint) compared to the white main emitting surface. Depending on the design of the luminaire, the edge-emission may be perceived as a fault of the light source, or as a decorative design element.

3.5 Metrics for safety and comfort aspects

In this project, guidelines for the evaluation of a SSL lit environment considering the blue light hazard has been prepared. The Spectral Power Distribution (SPD) of different white LEDs (Blue and Violet LED) have been measured and shown in Figure 17. A report on potential hazards of the blue light hazard for population without crystalline lenses is prepared.

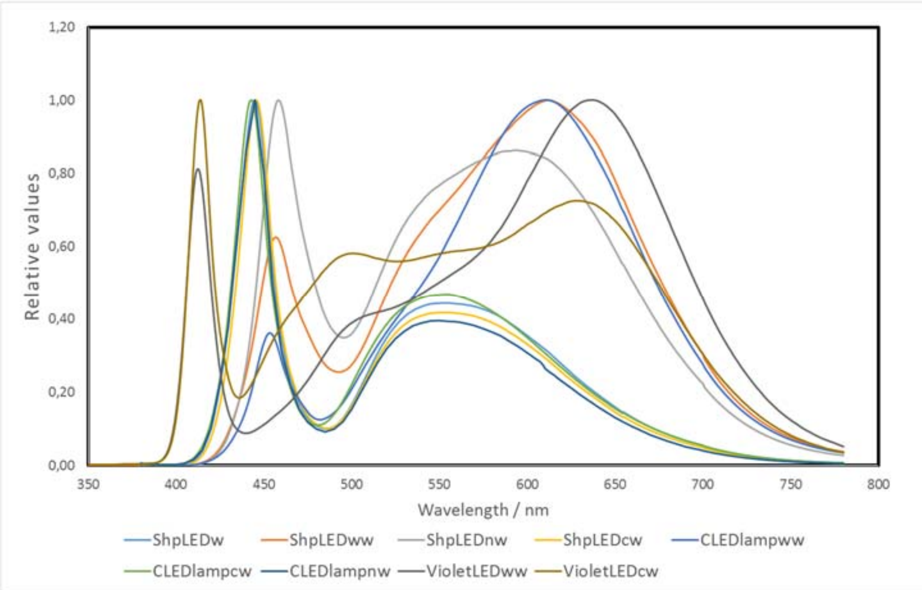

Figure 17. Relative spectral power distribution of different white LED sources

A subjective experiment of short-term effects of time-modulated lighting has been carried out at LNE with 30 subjects. Five test signals were used (PWM 100, 250,417 HZ, sinewave 250 Hz, saw tooth 100 Hz) for 3 visual tasks (reading, searching words, connecting dots) and the observation of a pendulum with fast oscillations for stroboscopic effect visibility. Results shows that waveform shape and frequency impact the perceived comfort but the most surprising is that the preference of lighting for comfort increases as the modulation frequency decreases. A multichannel driver is programmed to generate different waveforms and flicker frequencies to evaluate effects of non-visual optical flicker in an office with different light sources. In Figure 18, the LNE test living room with time-modulated diffuse lighting is shown.

Figure 18. LNE test living room with time–modulated diffuse lighting.

RISE did an investigation on how people experience lighting in an office where the light from the ceiling and the light from the desk lamp are modulated separately with different frequencies. Most test persons found the double 100 Hz modulated scenario the most disturbing, and many also experienced some discomfort with the other modulated scenarios. Only a few did not notice any stroboscopic effects or other discomfort in any of the scenarios. The study confirms what other studies have shown, that the experience of optical flicker is very individual, however more perceived at lower frequencies but noticeable up to at least 400 Hz.

Based on the results obtained in this project, it is concluded that comfort and task performance are missed in the existing flicker index. Recommendation of reconsidering the flicker index is proposed.

An experiment was performed in the laboratory conditions in INRIM to evaluate flicker effects in tunnel lighting. The effects of flicker in tunnel lighting due to passage of drivers through different luminaires inside a tunnel lit by LED luminaires is investigated with a subjective experiment on a laboratory using an eye tracker system to evaluate physiological eye parameters like pupil diameter and fixation times of several selected subjects. One example of the driver eye movement and variation of the pupil diameter when the car pass under strong glaring light is shown in Figure 19 below. In laboratory, the Landolt ring table was lit using LED sources driven under

DC voltage (steady on) and at different frequency to simulate AC flickering (50 Hz) and different frequencies of 20 Hz, 5 Hz, 3 Hz, 2 Hz and 1 Hz the lowest values to simulate motion flickering due to the passage under different luminaires during driving in a tunnel. Considering the common distance of 10 m between consecutive luminaires in the internal zone of a tunnel the last three tested frequencies correspond to an average speed of 108 km/h, 72 km/h and 36 km/h. Subjects had also to answer to a questionnaire regarding the discomfort they experienced at the different flickering frequencies. The results and influences are published in [17] as well as discussed in future implementations in the UNI tunnel lighting standard and suggestion for future work in CEN and CIE working group.

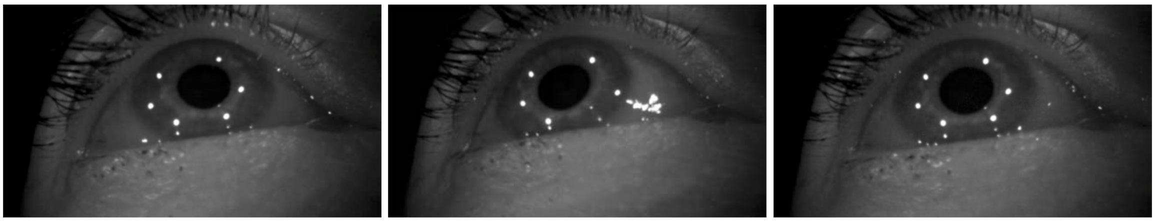

Figure 19. Example of the driver eye movement and variation of the pupil diameter when the car pass under a strong glaring light (from left to right: before, during, after).

To study the effect of light-mediated by the eye on circadian rhythm and non-visual functions, an accurate radiometric wearable instrument capable of measuring the level and spectral content of light reaching the cornea during day and night time was needed but not available in market. A novel autonomous system was developed by LNE and INSERM in this project featured with a photodiode, with photonic filter, and a mini-spectrometer to accurately measure resolved spectra and a large range of illumination, which is shown in Figure 20.

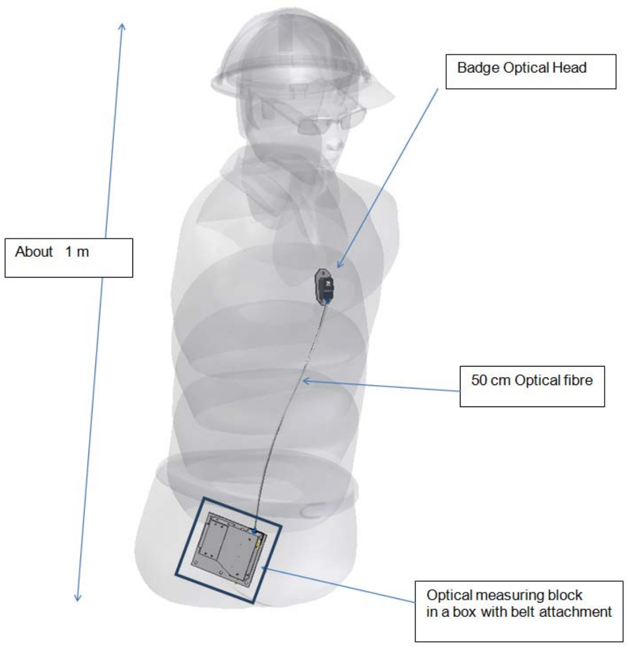

Figure 20. Wearable radiometric instruments mounting on a subject.

The system consists of two blocks linked by an optical fibre. This optical design has been achieved with the integration of a STS Ocean’s optics spectro-radiometer and a photopic detector based on a photodiode. The STS spectro-radiometer is provided with a developer kit including a RaspberryPi computer with software for spectra acquisition and storage, WIFI configuration and communication .The GPOI ports of the RaspberryPi helps for driving custom electronics such as a photodiode amplifier with programmable gain. The configuration of complete radiometric instrument is shown in Figure 21.

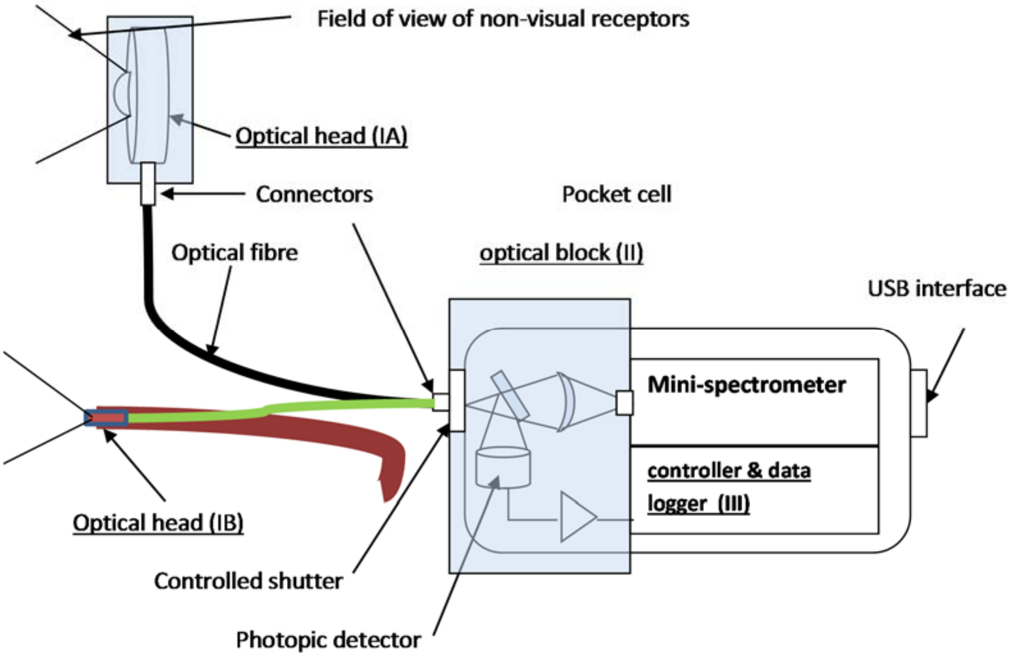

Figure 21. Configuration of the radiometric instruments

In addition, a pilot study was carried out to investigate a method to evaluate non-visual effects of variable lighting in workplaces using both self-assessed and physical data.

One of the living labs at RISE used for the test and a close up of the luminaires are shown in Figure 22. In each lab, which is a single person office, two tuneable 60×60 cm LED-panels are installed. The luminaires have a prismatic diffuser and the CCT of the emitted light can be tuned by mixing three different LED-sources in the panel (blue, white and red LEDs). The area of each office is 4 m^2.

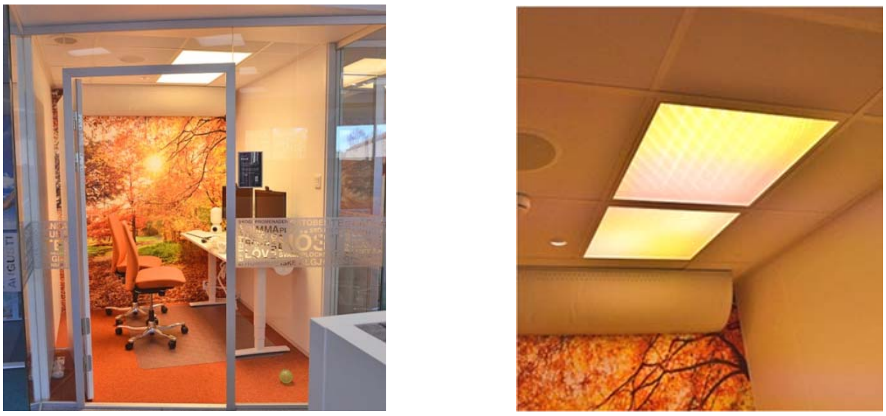

Figure 22. One of the offices in the living lab (left) and close up of the luminaires (right).

Two test subjects perform their daily work in an office with controlled lighting for five weeks. Their alertness, well-being and mood are documented through weekly questionnaires and activity bracelets. The bracelets monitor pulse, movement and sleep quality. The control system was programmed to vary the lighting according to three different schedules. The scenarios used are constant, daylight adapted, and activity promoting as described in the DIN standard on biological effective lighting.

The method was successful and provided interesting results on the measured physical data. The resting pulse was lowered and the sleep quality improved for the test subjects during the weeks of dynamic office lighting. The method used in this pilot study has given valuable knowledge to be used in future studies in this field. The compliance with the experiment, wearing the activity bracelet and filling out the questionnaires was excellent and it was clearly beneficial to enhance questionnaires with physical measurements.

Summary: Metrics for safety and comfort aspects

In this project, guidelines for the evaluation of a SSL lit environment considering the blue light hazard has been prepared. The Spectral Power Distribution (SPD) of different white LEDs (Blue and Violet LED) have been measured. A report on potential hazards of the blue light hazard for population without crystalline lenses is prepared.

A subjective experiment of short-term effects of time-modulated lighting has been carried out at LNE with 30 subjects. Various test signals were used for 3 visual tasks (reading, searching words, connecting dots) and the observation of a pendulum with fast oscillations for stroboscopic effect visibility. Results shows that waveform shape and frequency impact the perceived comfort but the most surprising is that the preference for comfort increases as the modulation frequency decreases. A multichannel driver is programmed to generate different waveforms and flicker frequencies to evaluate effects of non-visual optical flicker in an office with different light sources.

Based on the results obtained in this project, it is concluded that comfort and task performance are missed in the existing flicker index. A recommendation for reconsidering the flicker index is proposed. An experiment was performed in laboratory conditions to evaluate flicker effects in tunnel lighting. The target (a Landolt ring table) was lighted at typical conditions found in tunnel entrance zones and in the middle of the transition zones. Flicker at different frequencies of 20 Hz, 5 Hz, 3 Hz, 2 Hz and 1 Hz, the lowest values to simulate also motion flickering due to the passage under different luminaires during driving in the tunnel, does not influence the visual acuity and have insignificant influence on the pupil's diameters.

To study the effect of light-mediated by the eye on circadian rhythm and non-visual functions, an accurate radiometric wearable instrument capable of measuring the level and spectral content of light reaching the cornea during day and night time was needed but not available in market. A novel autonomous system was developed in this project featured with a photodiode, with photonic filter, and a mini-spectrometer to accurately measure resolved spectra and a large range of illumination.

In addition, a pilot study is carried out to investigate a method to evaluate non-visual effects of variable lighting in workplaces using both self-assessed and physical data. The method was successful and provided interesting results on the measured physical data. The resting pulse was lowered and the sleep quality improved for the test subjects during the weeks of dynamic office lighting.

3.6 Lifetime and reliability testing for LED-based SSL products

Firstly, the reliability and lifetime standards for LED-based SSL products are assessed. Research work covers the major failure mechanisms and reliability issues that are commonly found in SSL system, including lumen depreciation, colour shift, solder fatigue, phosphor degradation, driver failure, accelerated testing and system reliability modelling.

In this project, a test approach based on high precision electrical measurement that has the potential to identify solder fatigue crack initiation in-situ is proposed by TU Delft. A series of individual solder joints were tested in a double lap shear (DLS) test with in-situ high precision electrical resistance monitoring for each solder joint. The measurement setup is shown in Figure 23. It is found that with the specially aligned electrodes, signal patterns with an early decay phase in a resistance-test cycle curve are observed. It suggests that viscoplastic deformation and crack related matters are the causes of the decay and increasing phase respectively. Therefore, it indicates that the crack initiation point is in the transition zone of the resistance-test cycle curve. This finding is agreed with results from FEA simulation, which offers great potential to reduce testing time and facilitate online prognostic for solder interconnect.

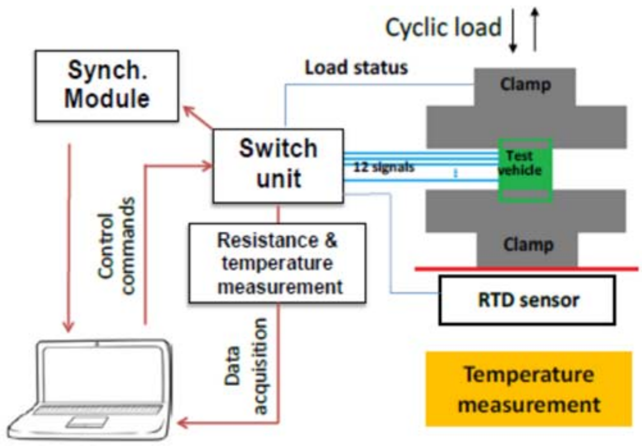

Figure 23. Schematic diagram of the resistance online monitor set-up

Furthermore, a modified Brownian motion process is used to describe lumen degradation for mid-power white-light LED packages, which were aged under a step stress accelerated degradation test (SSADT). First, a SSADT model has been established based on the theory of equivalent accumulative damage. Then, a method was proposed by TU Delft to improve the accuracy of the parameter estimation by carefully modifying the estimator, which was proposed in the previous research. Experimental data show that parameters estimated by using the SSADT model are very close to those estimated by using a constant stress accelerated degradation test (CSADT) model, indicating the feasibility of the SSADT model. The experiment also indicates that SSADT can be used as an alternative to CSADT, as it enables comparable estimation accuracy, while using less testing time, a smaller sample size and less test capacity.

In this project, a new methodology to de-couple different degradation models are developed by TU Delft. Two types of phosphor-converted white LED Chip Scale Packagings (CSP) with different target correlated colour temperatures (CCT) by using two mixed phosphor materials were used in the study. To assess the reliability of prepared two Pc-white LED CSPs, a thermal analysis through both IR thermometry and electrical measurements and thermal simulation were conducted first to evaluate chip-on-board heat dissipation performance. Next, the luminescence mechanism of multicolour phosphor mixtures was studied with the spectral power distribution (SPD) simulation and near-field optical measurement. Finally, the extracted features of SPDs and electrical current-output power (I-P) curves measured before and after a long-term high temperature accelerated aging test were applied to analyse the degradation mechanisms. These series of tests and simulations were conducted to characterise both short- and long-term performance of prepared samples. Through this approach, the dominate degradation mechanism (LED chip degrades or Phosphor degrades or Encapsulation degrades) under this test condition attributed to the degradation of blue LED chip can be identified. Figure 24 illustrates the influences on the SPD of the Pc-white LED CSP caused by three different degradation mechanisms.

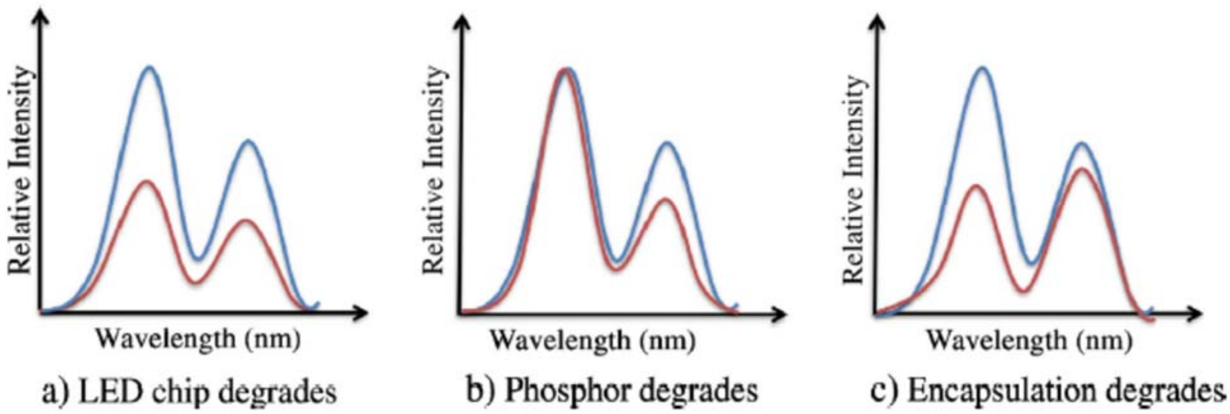

Figure 24. Degradation mechanisms in a Pc-white LED CSP (the blue and red curves represent the initial and aged SPDs, respectively)

In VTT, modules were aged for around 8000 hours. Data of two measurement rounds was acquired containing results from 5 OLEDs, 10 COBs, 10 CoFs and 10 MPCB LEDs. LNE has completed the natural ageing of a set of 5 OLEDs and the ageing data have been gathered in an Excel file showing a uniform strong average radiance drop (> 50%) over 7100 h. The results of RISE were presented in the final stakeholder workshop. Measurement Protocol and the datasets for accelerated ageing tests are available. LNE has seasoned all the products (including OLED) in accordance with the protocol for 100 hours at room temperature since Nov 2016. Between Nov 2016 and Dec 2016, LNE has completed the accelerated ageing of 33 SSL devices of type OLED (3), CoF (10), CoB (10) and GaN-Si (10) under damp-heat stress at 85°C/85% for two periods of 500 hours. The relative flux and CCT evolution with accelerated ageing are shown in Figure 25. All the OLEDs broke down before the end of the second period. VTT ran the accelerated ageing since July 2016 using temperature controlled mounting plates provided by PTB. VTT completed the UV stressing and panel measurements in Dec 2016. TUBITAK has performed measurements of 10 Tridonic OLEDs in accordance with the protocol. OLEDs were applied totally 455 hours UV exposure in the UV preconditioning chamber after 13 individual cycles. After each cycle, measurement results of photometric quantities of OLEDs in integrating sphere and on optical bench were evaluated to study the effects caused by UV stress. Both the natural ageing data and the accelerated ageing data are available for the curve and CoB products to establish the correlation between the natural ageing and the accelerated ageing test.

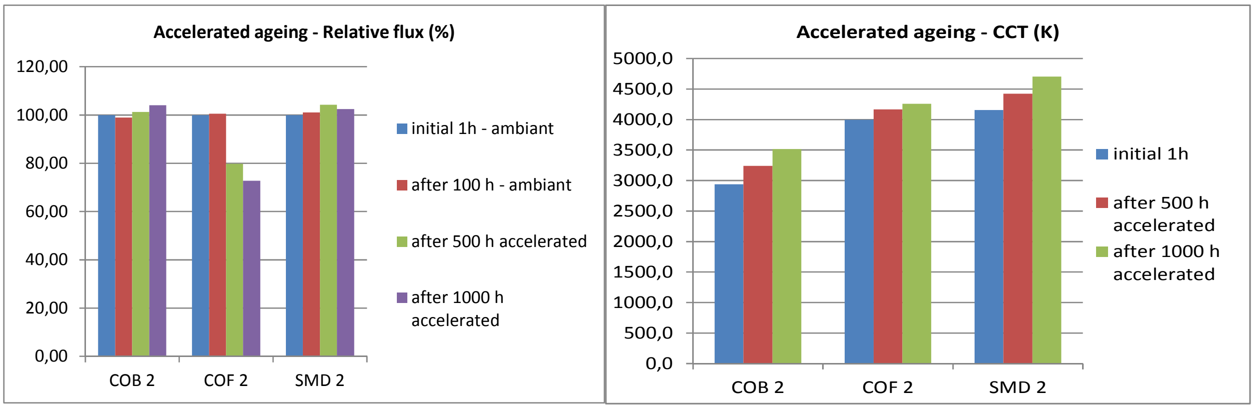

Figure 25: Bar plot of flux and CCT evolution with accelerated ageing at LNE

Finally, two prototypes of packaged core-shell LEDs (with and without high-refractive index encapsulation) with improved processing were measured. Electro-optical test measurements were carried out using a commercial remote phosphor- converter. The qualitative electro-optical properties, emission directionality and the dependence on temperature cycles of single devices are intensively investigated.

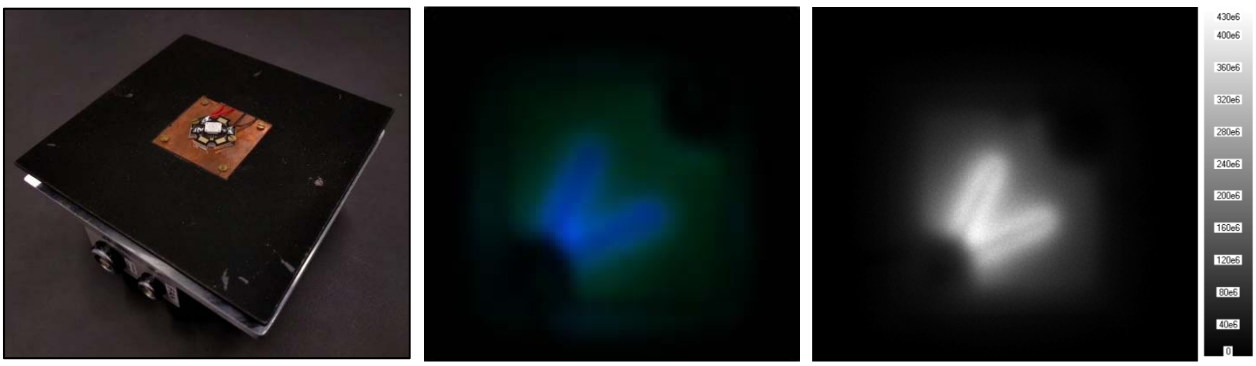

Figure 26: Photo of a 3D core-shell device with lens soldered on an MCB and mounted in the 2π-holder of the near-field goniophotometer at PBT surrounded by a black cover (left), color HDR-Photo of a chip without lens at a driving current of 40 mA (center) and corresponding luminous emittance calculated from ray data for a plane of 1 mm² (right).

Summary: Lifetime and reliability testing for LED-based SSL products

The reliability and lifetime standards for LED-based SSL products were assessed. Research work covers the major failure mechanisms and reliability issues that are commonly found in SSL system, including lumen depreciation, colour shift, solder fatigue, phosphor degradation, driver failure, accelerated testing and system reliability modelling. In this project, a new reliability evaluating approach with an innovative accelerated testing method, a newly developed reliability and lifetime prediction model, and finally a new methodology to decouple different failure models are developed.

Two prototypes of packaged core-shell LEDs (with and without high-refractive index encapsulation) with improved processing were measured. Electro-optical test measurements were carried out using a commercial remote phosphor converter. The qualitative electro-optical properties, emission directionality and the dependence on temperature cycles of single devices are intensively investigated.

In this project, natural ageing measurements and accelerated ageing measurements were performed by 4 partners. The ageing data have been acquired containing results from various SSL products. Accelerated ageing was performed using damp-heat stress, temperature stress and UV exposure methods.

Natural ageing of the inorganic LED artefacts resulted in small changes after 8000 h, for average luminous flux : +0.8 % and -2,4% respectively for GaN-Si and Chip-on-flex (COF) type 1 artefacts and -4,1% for Chip-on-board (COB) type 2 artefacts. For all variations between artefacts of same type are greater than the effects ageing (7% for COB). The colorimetric quantities are stable with CCT changes less than 31 K.

Accelerated ageing with damp/heat at 85°C/85%HR resulted also in stable luminous flux for GaN-Si type 2 (+2.5%) and COB type 2 (+4%) artefacts but with large changes in colorimetric quantities +548 K and +575 K respectively for the CCT. The luminous flux of CoF type 2 shows a strong flux drop of -27.2% with an increase of CCT of 263 K. It seems that accelerated ageing with damp/heat affected severely the yellow phosphors, changing spectral shape or decreasing efficiency of emission and a bit the blue LED emission.

The only artefacts to be compared, with natural and accelerated ageing, are the CoB type 2 artefacts, but behaviours during ageing are opposite, flux increasing or decreasing, and changes in spectrum are quite different, with no change for natural ageing, see Figure 25 bellow. So the damp/heat stress at 85°C/85%HR does not reflect natural ageing with an acceleration factor.

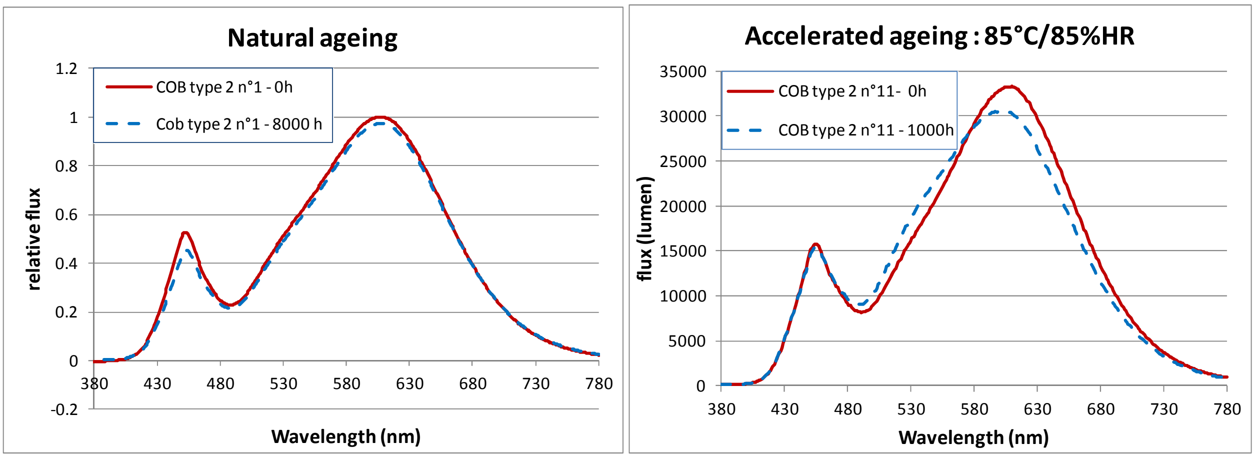

Figure 27: The variation of the luminous flux with natural ageing and accelerated ageing

Regarding OLEDs, they are not as robust as LEDs and should not be tested in the 85°C/85%HR atmosphere. Furthermore, the panels showed significant degradation upon UV-exposure. The analysis is still ongoing and will be presented in a scientific paper within a short time.

3.7 Key results and conclusions

- In this project, a novel multiple transfer standard (MTS) device is introduced. The unique optical reference standard allows testing laboratories to calibrate the luminous flux responsivity of measurement setups, and also get additional information about the sensitivity of the system to spectral, spatial and time dependent properties that are necessary in estimation of uncertainties in testing of luminous flux and efficacy of new lighting products entering the market. In addition, an electrical reference standard (e-MTS) device was developed to verify electrical measurement setups used in test laboratories. The LED-based mosaic test standard device for Imaging Luminance Measuring Devices (ILMD) was developed and the quality indices of the ILMD have been first-time extensively analysed.
- The feasibility of using standard measurement equipment for 3D complex goniometric measurements of large area and complex SSL (3D nano-structured) was studied. The measurement setup was extended by manipulators with probe tips, enabling on-wafer measurements by ILMDs and near field goniophotometer.
- The ISN developed in the project is a unique device which can provide equalised impedance in laboratories to reduce the uncertainty of performing electrical measurements of SSL products with different AC sources. In the project, it is found that the integration time or response time of most of handheld instruments needs to be set correctly with respect to the modulation period to avoid underestimated measurement results in modulated waves. In addition, the short-pulse testing method used in industry to evaluate light output performance of the LEDs during production has been validated in this project. The measurement uncertainty resources are identified.
- In the project, optical and electrical measurements were performed to evaluate the influence of bending of an OLED. The spectral and spatial corrections and methods to suppress edge-emission were studied extensively for the first time in this project. The approaches can decrease uncertainty in photometrical parameters of OLED measurements;
- In this project, a subjective experiment of short-term effects of time-modulated lighting has been carried out. Results shows that waveform shape and frequency impact the perceived comfort but the most surprising is that the preference for comfort increases as the modulation frequency decreases. It is concluded that comfort and task performance are missed in the existing flicker index. The effects of non-visual optical flicker in an office with different light sources are evaluated. In addition, an experiment was performed in laboratory conditions to evaluate flicker effects in tunnel lighting. A novel accurate radiometric wearable instrument was developed in this project which is capable of measuring the level and spectral content of light reaching the cornea during day and night time. In addition, a pilot study is carried out to investigate a method to evaluate non-visual effects of variable lighting in workplaces using both self-assessed and physical data.
- In this project, a new reliability evaluating approach with an innovative accelerated testing method, a newly developed reliability and lifetime prediction model, and finally a new methodology to decouple different failure models are developed. Two prototypes of packaged core-shell LEDs (with and without high-refractive index encapsulation) with improved processing were measured. Electro-optical test measurements were carried out using a commercial remote phosphor converter. The qualitative electro-optical properties, emission directionality and the dependence on temperature cycles of single devices are intensively investigated. Furthermore, in this project, natural ageing measurements and accelerated ageing measurements were performed by 4 partners. The correlation between the natural ageing and the accelerated ageing test was established based on the ageing data acquired.

4 Actual and potential impact

4.1 *Dissemination Activities*

4.1.1 Scientific publications

The project outputs have been shared widely with the metrology, instrumentation and industrial communities. The JRP output and impact report lists **23** publications, **24** presentations and **no** patent for the life of this project.

4.1.2 Stakeholder Engagement

The list of stakeholders counts 24 members.

OSRAM, a leader in the global lighting market, has shown a great interest in taking over further development of the MTS as it offers key features for the end user including ease of use and affordability.

Three stakeholder workshops were organized by VSL, PTB and METAS in Sep 2014, Nov 2015 and May 2017. These three stakeholder workshops are connected with the “CIE Tutorial and Expert Symposium on Measurement Uncertainties in Photometry and Radiometry for Industry”, the ”CIE Tutorial and Expert Symposium on the CIE S025 LED Lamps, LED Luminaires and LED Modules Test Standard” and the “CIE Tutorial and Practical Workshop on LED Lamp and Luminaire Testing to CIE S 025” respectively. The aim of the workshops was to disseminate the results of the project to the user community. The consortium members were invited to present the JRP results in the CIE tutorial and symposium. There was very positive feedback from the industry at the final discussion.

Two joint JRP-CIE Tutorial and Practical Workshops were successfully organized for stakeholders in Nov 2015 and May 2017 with supported by the European National Committees of CIE and all project partners. The first training course took place on 24 - 26 November 2017 in PTB, Germany. The second training course took place on 9 - 10 May 2017 in METAS, Switzerland. Each training course consists of several sessions, including goniophotometry, integrating sphere, spectroradiometry, electrical parameters measurements and introduction to uncertainties.

METAS has presented the outcome of the project at the last meeting of the technical committee on photometry of the Swiss Society of Lighting (SLG Fachgruppe Lichtmesstechnik). In this committee all testing laboratories of the major LED lamp and luminaire manufacturers are represented.

In addition, several stakeholders and Inmetro joined the bilateral comparisons between NMIs and stakeholders with the aim to prove the applicability of MTS. Some comparisons have already been completed and some of them are already planned.

4.1.3 Standards

In the field of light and lighting on an International level, CIE is the most relevant partner for standardisation and pre-normative work. CIE is organised through different technical committees. The output of this JRP is relevant mainly to Division 2, 4 and 6.

The project made major contributions to the CIE through CIE Tutorials and Practical Workshops. The consortium members were invited to present the JRP results in the CIE tutorial and symposium. Relevant CIE TC members followed the presentations and communicated with the partners sufficiently on the project output. Particularly, the outputs of the project were sent to the following TCs:

TC 2-68: Optical Measurement Methods for OLEDs used for Lighting;

TC 2-75: Photometry of Curved and Flexible OLED and LED Sources;

TC 2-76: Characterisation of AC-driven LED Products for SSL Applications;

TC 2-79: Integrating Sphere Photometry and Spectroradiometry;

TC 2-83: CIE Standard on test methods for OLED light sources;

TC 4-51: Optimization of Road Lighting;

TC 4-53: Tunnel Lighting Evolution;

TC 6-45: Optical Radiation Hazard Measurements in the Work Space;

TC 6-63: Photobiological Strategies for Adjusting Circadian Phase to Minimize the Impact of Shift Work and Jet Lag.

In addition, this project provided input during the preparation of the draft documentary standard EN 13032-4:2015 Light and lighting – Measurement and presentation of photometric data - Part 4: LED lamps, modules and luminaries.

The possibility to include the developed ISN into the future measurement standard was discussed between the project partner and CIE member. The research work showed some encouraging results however the ISN has been shown that in some cases the ISN didn't reduced the discrepancies as expect and further investigations which are beyond this project are necessary.

4.2 Examples of early impact

4.2.1 User Uptake

OSRAM, a leader in the global lighting market, will take over further development of the MTS as it offers key features for the end user including ease of use and affordability.

An optical head for measuring luminous flux reaching the eye has the potential to be the subject of a patent application. Further commercial exploitation of R&D is possible, as is the case with the e-MTS and ISN developed in this project.

The MTS, the ISN and the uncertainty evaluation tool for the electrical parameters measurements developed in this project showed their effectiveness and they will be adopted in the CIE Training courses in the future.

Finally, end users from testing labs and industry of USA have shown their interest in results of validation of high speed testing method during production of LEDs, which was presented at Annual IES Conference. The main accent was made on the traceability issues and uncertainty evaluation of the results.

4.3 Potential impact

The results of this project will deliver an advanced metrological framework for novel SSL. This will enable the reliable measurement of SSL performance in the broadest sense, including basic light output and efficacy, light distribution, light quality, light perception, safety aspects and life-time aspects. A particular emphasis made on novel SSL technologies, which with the proper metrological support, will become more important in the coming years.

The project has an expected impact across the entire SSL value chain; providing developers, designers, producers, distributors and end-users with the tools they need to improve, predict and specify SSL performance based on reliable measurements.

For end-users, the improved energy efficiency will help to reduce energy bills and the availability of reliable data on light output, energy consumption, safety/health aspects and lifetime will allow informed and objective decisions.

5 Website address and contact details

The web site will continue to be online till 2019 after the project.

Project Web Site: http://www.eng62-mesail.eu/

6 List of publications

[1] J.L. Velázquez, A. Ferrero, A. Pons, J. Campos and M.L. Hernanz, “Zernike polynomials for photometric characterization of LEDs,” Journal of Optica, Jan 2016, Number 18, Issue 2, pp.1-9

[2] U. Krüger, P. Blattner, R. Hornischer, W. Bechter, W. Steudtner and W. Jordan, “Measurement uncertainty of photometric measurements considering the requirements of the new international standard CIE S 025 / E:2015 "Test Method for LED Lamps, LED Luminaires and LED Modules,” in Proceedings of the 28th Session of the CIE Manchester, United Kingdom, 28 June – 4 July 2015

[3] J.L. Velázquez, A. Ferrero, A. Pons, J. Campos and M.L. Hernanz, “Photometric characterization of extended sources by subsource goniospectroradiometry,” in Proceedings of the CIE Tutorial and Expert Symposium on the CIE S 025 LED Lamps, LED Luminaires and LED Modules Test Standard, 26 November 2015, Braunshweig, Germany, pp.24-33, 2015

[4] A. Sperling, S. Penda, M. Taddeo, E Revtova, D. Renoux, P. Blattner, T. Poikonen, W. Jordan, “Multiple Transfer Standard for characterisation of sphere test setups,” in Proceedings of the CIE Tutorial and Expert Symposium on the CIE S 025 LED Lamps, LED Luminaires and LED Modules Test Standard, 26 November 2015, Braunshweig, Germany, pp.1-5, 2015
[5] J. Huang, D.S. Golubović, S. Koh, D. Yang, X. Li, X. Fan and G.Q. Zhang, “Lumen degradation modeling of white-light LEDs in step stress accelerated degradation test,” Reliability Engineering and System Safety 154, pp.152–159
[6] B. Sun, X. Fan, L. Li, H. Ye, W. van Driel and G.Q. Zhang, “A Reliability Evaluation for Electrolytic Capacitor Free LED Driver,” submitted to IEEE transaction on Components, Packaging and Manufacturing Technology, 2016
[7] J. Fan, C. Qian, M. Zhang, Y. Li, X. Fan and G.Q. Zhang, “Thermal/Luminescence Characterization and Degradation Mechanism Analysis on Phosphor-converted White LED Chip Scale Packages,” submitted to Microelectronic Reliability, 2016
[8] D. Zhao, G. Rietveld, J.-P. Braun, F. Overney, T. Lippert and A. Christensen, “Traceable measurements of the electrical parameters of solid-state lighting products,” Metrologia, 2016, 53(6): pp.1384-1394
[9] D. Zhao, “AC powered SSL lamps load impedance characterisation in the time domain,” in Proceedings of the CIE Tutorial and Expert Symposium on the CIE S 025 LED Lamps, LED Luminaires and LED Modules Test Standard, 26 November 2015, Braunshweig, Germany, pp.38-43, 2015
[10] J. Ledig, S. Fündling, M. Popp, F. Steib, J. Hartmann, H.-H. Wehmann, A. Sperling and A. Waag, “3D GAN LEDs - Technologies and analytics,” in Proceedings of the CIE Tutorial and Expert Symposium on the CIE S 025 LED Lamps, LED Luminaires and LED Modules Test Standard, 26 November 2015, Braunshweig, Germany, pp.77-85, 2015
[11] J. Zhang, H. van Zeijl and G.Q. Zhang, “Feasibility of solder crack initiation identification using insitu high precision electrical resistance monitoring,” in Proceedings of the CIE Tutorial and Expert Symposium on the CIE S 025 LED Lamps, LED Luminaires and LED Modules Test Standard, 26 November 2015, Braunshweig, Germany, pp.86-96, 2015
[12] J. Askola, “Characterization of an Integrating Sphere Setup for Measurements of Organic LEDs,” master thesis of Aalto University, 55p (2015).
[13] Y. Zhu, “Development of Transfer Standards for SSL Measurement,” master thesis of Delft University of Technology, 94p (2017).
[14] J.L.V. Molinero, “Estudio de las propiedades fotométricas de sistemas de iluminación de estado sólido en campo cercano y campo lejano,” PhD Tesis of Universidad de Granada. 2016
[15] P. Iacomussi, M. Radis and G. Rossi, “European EMRP Projects About LED Lighting”, Energy Procedia 78 (2015) 2675-2680
[16] G. Rossi, “The evaluation of measurement uncertainty of SSL luminaire for industrial applications, ” in Proceedings of Lux Europa 2017, Ljubljana, Slovenia, September 18-20, 2017
[17] P. Iacomussi, G. Rossi, M. Radis, “Flicker effects in tunnel lighting,” in Proceedings of CIE 2017 Midterm Meeting in Jeju, Republic of Korea, October 22–25, 2017
[18] E. Revtova, E. Vuelban, D. Zhao, J. Brenkman, H. Ulden, “Traceability validation of high speed short-pulse testing methods used in LED production,” submitted to International Journal of Metrology and Quality Engineering (IJMQE)
[19] M. Nilsson Tengelin and S. Källberg, “Effects of non-visual optical flicker in an office with two different light sources,” in Proceedings of CIE 2017 Midterm Meeting in Jeju, Republic of Korea, October 22–25, 2017
[20] M. Nilsson Tengelin and S. Källberg, “Measurement of the Effect of Dynamic Lighting on Alertness, Mood and Sleepiness, ” in Proceedings of Lux Europa 2017, Ljubljana, Slovenia, September 18-20, 2017
[21] J. Ledig, A. Avramescu, T. Schimpke, T. Varghese, G. Roßbach, B. Galler, H. Doblinger, T. Gerloff, F. Steib, S. Fündling, M. Strassburg, H.-J. Lugauer, A. Waag and A. Sperling, “Quantitative electroluminescence characteristics of packaged LED devices from ensembles of AlInGaN based core-shell microrods,” in Proceedings of 12th International Conference on Nitride Semiconductors (ICNS-12), Strassburg
[22] J. Hartmann; F. Steib; H. Zhou; J. Ledig; L. Nicolai; S. Fündling; T. Schimpke; J. Hartmann; A. Avramescu; T. Varghese; L. Nicolai; A. Trampert; M. Strassburg; H.-J. Lugauer; H.-H. Wehmann and A. Waag, “Study of 3D-growth conditions for selective area MOVPE of high aspect ratio GaN fins with non-polar vertical sidewalls,” J. Cryst. Growth, vol. 476, pp. 90–98, Oct. 2017.
[23] A. Sperling, M. Meyer, T. Gerloff, W. Jordan, E. Revtova, T. Poikonen, D. Renoux and P. Blattner, “Multiple Transfer Standard for Calibration and Characterisation of Test Setups in Industry,” in Proceedings of 13th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2017), Tokyo, Japan, June 13-16, 2017