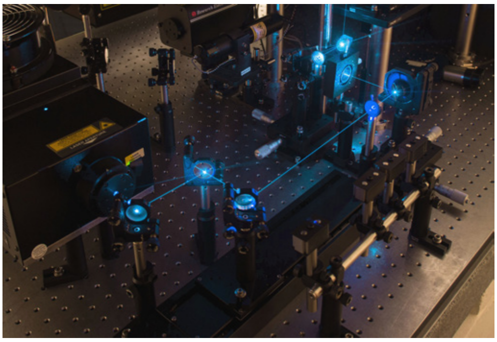
Metrology Research Institute BIENNIAL REPORT 2013-2014 Aalto University

Department of Signal Processing and Acoustics

BIENNIAL REPORT 2013-2014

Metrology Research Institute



Aalto University

SCIENCE + TECHNOLOGY

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BIENNIAL REPORT 2013-2014

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Aalto University
School of Electrical Engineering
Department of Signal Processing and Acoustics
Metrology Research Institute

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1 INTRODUCTION

One of the highlights of the period 2013–2014 was the twelfth NEWRAD Conference which the Metrology Research Institute of Aalto University and the Centre for Metrology and Accreditation (MIKES) jointly organized in the Otaniemi campus area during 24 – 27 June 2014. NEWRAD is the most important conference in optical radiometry where researchers from the national metrology institutes and the principal user communities of advanced radiometry convene every third year. Furthermore, journal Metrologia selected two publications, with authors from the Metrology Research Institute, as their Highlights of the year 2013. These articles (Sildoja *et al*, Metrologia **50**, 385, 2013 and Müller *et al*, Metrologia **50**, 395, 2013) were selected “for their presentation of outstanding new research” concerning the Predictable Quantum Efficient Detector.

There is traditionally very close collaboration within the Metrology Research Institute between MIKES and Aalto University. For example, doctoral students with fixed term contracts have moved between the two legal organizations and there are also joint senior researcher posts. Earlier MIKES was an independent small research organization under the Ministry of Employment and the Economy, but from the beginning of 2015 it was merged to the VTT Technical Research Centre of Finland Ltd, which is a 30-times larger organization under the same Ministry. The merge may require fine tuning in the relations between VTT and the Metrology Research Institute to fully utilize the advantages offered by the new host organization of MIKES.

The Metrology Research Institute provides teaching within the Aalto University and it operates under the Finnish name MIKES-Aalto Mittaustekniikka as the Finnish national standards laboratory for optical quantities. Two doctoral degrees and six M.Sc. degrees were achieved in 2013–2014. The number of degrees is slightly more than that for the period 2011–2012. The number of calibration certificates issued in 2013–2014 is 99, which is about the same number as for the period 2011–2012.

The Metrology Research Institute has active international collaboration with world leading research units. Altogether twenty completed and ongoing European projects, where the Institute participates, are listed on the following page and some related research contributions are described in more detail in Sec. 5 of this biennial report.

Completed EMRP (European Metrology Research Program) projects where the Metrology Research Institute participates

Candela: Towards Quantum-Based Photon Standards (2008–2011)

Metrology for Solid State Lighting (2010–2013)

Metrology for Earth Observation and Climate (2011–2014)

Traceability for Surface Spectral Solar Ultraviolet Radiation (2011–2014)

Metrology for Industrial Quantum Communication Technologies (2011–2014)

Metrology for the Manufacturing of Thin Films (2011–2014)

Ongoing EMRP and EMPIR (European Metrology Program for Innovation and Research) projects where the Metrology Research Institute participates

Metrology of Electro-Thermal Coupling for New Functional Materials Technology (2012–2015)

Multidimensional Reflectometry for Industry (2013–2016)

Single-Photon Sources for Quantum Technologies (2013–2016)

New Primary Standards and Traceability for Radiometry (2013–2016)

Traceability for Atmospheric Total Column Ozone (2014–2017)

Metrology for Earth Observation and Climate II (2014–2017)

Metrology for III-V Materials Based High Efficiency Multi-Junction Solar Cells (2014–2017)

Traceable Characterisation of Thin-Film Materials for Energy Applications (2014–2017)

Towards an Energy-Based Parameter for Photovoltaic Classification (2014–2017)

Metrology for Efficient and Safe Innovative Lighting (2014–2017)

Metrology for Airborne Molecular Contamination in Manufacturing Environments (2014–2016), Research Excellence Grant

Metrology for Electrical Power Industry (2015–2018)

Optical Metrology for Quantum-Enhanced Secure Telecommunication (2015–2018)

Metrology for the Photonics Industry – Optical Fibres, Waveguides and Applications (2015–2018)

2 PERSONNEL

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In 2013–2014, the total number of employees working at the Metrology Research Institute was 27.

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3 TEACHING

3.1 Degrees

3.1.1 Doctor of Science (Technology), D.Sc. (Tech.)

Meelis-Mait Sildoja (2013), *Predictable Quantum Efficient Detector*, Opponent: Dr. Marla Dowell, National Institute of Standards and Technology, USA.

Juha Kangasrääsiö (2014), *Improving the Metrological Traceability of Online Dry Grammage Measurement Used in the Paper Industry*, Opponent: Prof. Risto Ritala, Tampere University of Technology, Finland.

3.1.2 Licentiate of Science (Technology), L.Sc. (Tech.)

Juha-Matti Hirvonen (2013), *Spectrally Adjustable Radiance Source*, guided by Petri Kärhä.

Antti Kivioja (2013), *Spectroscopic Metrology and New Applications*, guided by Tapani Vuorinen and Patrick Gane.

3.1.3 Master of Science (Technology), M.Sc. (Tech.)

Teemu Jaakkola (2013), *High-Accuracy Step Gauge Interferometer* (in Finnish) guided by Petri Kärhä.

Anna Vaskuri (2014), *Multi-Wavelength Setup Based on Lasers for Characterizing Optical Detectors and Materials*, guided by Petri Kärhä and Timo Dönsberg.

Teemu Koskinen (2014), *Effect of Power Line Impedance on Luminous Efficacy Measurements of Energy Saving Lamps* (in Finnish), guided by Tuomas Poikonen.

Miikka Kivi (2014), *Sample Alignment for Diffuse Reflectance Measurements*, guided by Priit Jaanson.

Esko Lehtomäki (2014), *Measuring System for Properties of Detectors in Fou-*

rier Transform Infrared Spectrometer (in Finnish), guided by Folke Stenman.

Teemu Kääriäinen (2014), *Long Distance Hyperspectral Lidar for Target Recognition*, guided by Albert Manninen.

3.2 Bachelor of Science (B.Sc.) Theses

Henri Honkonen (2013), *LED-lamppujen sähkötehomittaukset 1 MHz:n teho-analysaattorilla*, guided by Tuomas Poikonen.

Aake Ilomäki (2013), *LED-vakiovirtalähteet*, guided by Hans Baumgartner.

Alexander Kokka (2013), *UV-indeksin mittaaminen*, guided by Tomi Pulli.

Juuso Mantere (2013), *Ajoneuvojen ja ihmisten havaitsemismenetelmiä osana energiatehokasta valaistusta*, guided by Petri Kärhä.

Jussi Nurminen (2013), *Ohjelmistokehitys sulautetuissa järjestelmissä*, guided by Hans Baumgartner.

Johannes Oksanen (2013), *Alykäs led-katuvalaistus*, guided by Hans Baumgartner.

Tuukka Pekkanen (2013), *Säteen kollimointijärjestelmän kehittäminen*, guided by Petri Kärhä.

Olli-Matti Saario (2013), *Atmel ARM-mikrokontrollerit*, guided by Hans Baumgartner.

Minna Santaholma (2013), *OLED-paneelien valotehokkuuden mittaaminen integroivalla pallolla*, guided by Tuomas Poikonen.

Veera Seppälä (2013), *III—V-moniliitosaurinkokennot*, guided by Timo Dönsberg.

Esko Honkala (2014), *Otsonikerroksen paksuuden määrittäminen*, guided by Tomi Pulli.

Aarni Javanainen (2014), *Pulssinleveysmoduloidun LED-tasavirtahakkurin adaptiivinen PID-säätö*, guided by Hans Baumgartner.

Mikko Jäntti (2014), *Laboratoriotilojen lämpötilan ja ilmankosteuden mittaaminen*, guided by Timo Dönsberg.

Tatu Peltola (2014), *Nopea kanttiaaltolähde Josephson-vaihtojännitenormaaliin*, guided by Petri Kärhä.

Teemu Sillanpää (2014), *Fotodiodin virta-jännitemuuntimen optimointi*, guided by Timo Dönsberg.

Teemu Tomberg (2014), *$^{88}Sr^{+}$-ionikellon magneettinen suojaus*, guided by Timo Dönsberg.

Sebastian Verho (2014), *Elektroniikan teholähteet ja maadoitus*, guided by Petri Kärhä.

3.3 Courses

The following courses were offered by the Metrology Research Institute in 2013–2014. Those marked by * are given biennially.

S-108.1010	Fundamentals of Measurements A, 4 p (Petri Kärhä, Maija Ojanen)
S-108.1020	Fundamentals of Measurements Y, 3 p (Petri Kärhä, Maija Ojanen)
S-108.2010	Electronic Measurements, 3 p (Tuomas Poikonen)
S-108.2110	Optics, 5 p (Meelis Sildoja, Tuomas Hieta, Toni Laurila)
S-108.3011	Sensors and Measurement Methods, 5 p (Maksim Shpak)
S-108.3020	Electromagnetic Compatibility, 2 p (Esa Häkkinen)

S-108.3030	Virtual Instrumentation, 5 p (Farshid Manoocheri, Tomi Pulli)
S-108.3120	Project work, 2–8 p (Erkki Ikonen, Timo Dönsberg)
S-108.3130	Project Work in Measurement Science and Technology, 2–10 p (Erkki Ikonen, Timo Dönsberg)
S-108.3140	Project Work in Optical Technology, 2–10 p (Erkki Ikonen, Timo Dönsberg)
S-108.4010	Postgraduate Course in Measurement Technology, 10 p* (Petri Kärhä)
S-108.4020	Research Seminar on Measurement Science, 2 p (Erkki Ikonen)
S-108.4110	Biological Effects and Measurements of Electromagnetic Fields and Optical Radiation, 4 p* (Kari Jokela)
ELEC-C5070	Elektroniikkapaja, 5 p (Petri Kärhä, Tuomas Poikonen)

4 NATIONAL STANDARDS LABORATORY

Metrology Research Institute (MRI) is the Finnish national standards laboratory for the measurements of optical quantities, as appointed by the Centre for Metrology and Accreditation (MIKES) in April 1996.

The institute gives official calibration certificates on various optical quantities in the fields of Photometry, Radiometry, Spectrophotometry and Fiber Optics. During 2013, 53 calibration certificates were issued. In 2014, the number of calibration certificates was 46. The calibration services are mainly used by the Finnish industry and various research organizations. There are three accredited calibration laboratories in the field of optical quantities.

The Institute offers also other measurement services and consultation in the field of measurement technology. Various memberships in international organizations ensure that the laboratory can also influence e.g. international standardization so that it takes into account the national needs.

The Metrology Research Institute performs its calibration measurements under a quality system approved by MIKES. The quality system is based on ISO/IEC 17025.

Further information on the offered calibration services can be obtained from the web-pages of the laboratory (http://metrology.tkk.fi/). Especially the following sub-pages might be useful:

Maintained quantities: http://metrology.tkk.fi/cgi-bin/index.cgi?calibration

Price list for regular services: http://metrology.tkk.fi/files/pricelist.pdf

Quality system: http://metrology.tkk.fi/quality/

Additional information may also be asked from Farshid Manoocheri (Head of Calibration Services) or Petri Kärhä (Quality Manager):

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Petri.Karha (at) aalto.fi, Tel. +358 50 596 8469

5 RESEARCH PROJECTS

5.1 Electrical Instrumentation

Aalto EEM "Mixed AC/DC networks for built environment"

The energy efficiency research program EEF of Aalto ELEC started in fall 2012. The EEM-project of EEF focused on developing electrical power systems with energy sources and complex loads, including LED products. The role of Metrology Research Institute (MRI) in the project was to develop traceable measurements for energy-saving lighting products, with main task to design and build an impedance stabilization network for electrical power measurements.

Aalto EEM: Adjustable power line impedance emulator (APLIE)

APLIE (Figure 1) was designed for luminous efficacy (lm/W) measurements of energy-saving lamps as a stabilization network to reduce the sensitivity of lamp electronics to the output impedances of various types of AC voltage sources found at NMIs and at test laboratories. The passive single-phase LCR network can emulate various impedance curves found in typical low-voltage power distribution networks. Three impedance preset settings can be selected using switches (minimum, average and maximum). In the measurements, APLIE is connected between the AC voltage source and the lamp under measurement.

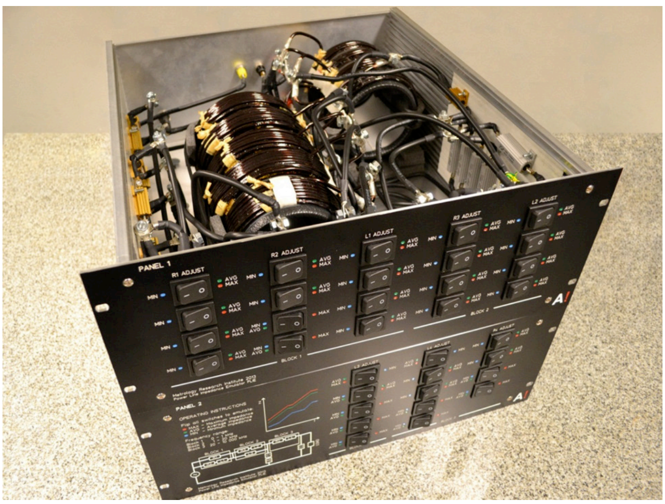

Figure 1. Adjustable power line impedance emulator (APLIE) developed for luminous efficacy measurements of energy-saving lighting products.

The impedance curves of APLIE were measured using a custom-built LCR-meter. A LabVIEW program controls a function generator and a 12-bit digital oscilloscope, and measures the amplitude and phase response of APLIE within frequency range of 50 Hz – 5 MHz using a predefined list of measurement frequencies. The repeatability of the method in the impedance characterization is better than 1 %. According to the characterization measurements, APLIE can emulate the simulated impedance curves with less than 5 % difference within frequency range of 50 Hz – 2 MHz. The APLIE will be utilized in the EMRP project MESaIL for traceable measurement methods.

High-gain transimpedance amplifier for photo detectors

A new transimpedance amplifier was developed to replace old Vinculum current-to-voltage converters (Figure 2). The device converts weak current signal, typically smaller than 1 uA, from a photo detector to a voltage signal between -10 V and 10 V. The gain of the device can be adjusted between 10^3 and 10^{11} V/A. The current resolution of the device was measured to be 10 fA. The device comprises of two separate printed circuit boards (PCBs).

Figure 2. Current-to-voltage converter for measurements with photo detectors developed at the Metrology Research Institute.

The built-in linear power supply with output voltages of +5 V, +12 V, and -12 V, and the bandwidth limiting low-pass filter are located on the main PCB. Special care was taken in the design of filtering the DC-voltages to minimize the voltage ripple of the DC-rails. The high-precision transimpedance amplifier is constructed on a separate PCB enclosed into an additional metallic enclosure inside the aluminium enclosure. The high-precision transimpedance amplifier is capable of amplifying the current signal with gain settings between 10^3 and 10^9 V/A. High precision thin film resistors are used to achieve the best possible temperature stability and gain accuracy.

5.2 Optical Radiation Measurements

EMRP SolarUV "Traceability for surface spectral solar ultraviolet radiation"

SolarUV was a three-year project funded by the European Metrology Research Programme (EMRP) that ended in July 2014. The aim of the project was to significantly enhance the reliability of the measurement of spectral solar UV radiation in the wavelength range from 300 nm to 400 nm. The target uncertainty of solar UV irradiance measurements was less than 2 %. MRI had two major tasks in the project: 1) To help develop new entrance optics for global solar UV spectroradiometers by studying novel diffuser materials and constructing a diffuser simulation software, and 2) To build a measurement setup for determining the linearity of UV array spectrometers. The tasks are described in more detail in the following sections. In addition to these tasks, MRI maintained the UVNet and published two issues of the UVNews newsletter.

EMRP SolarUV: Realization of improved solar UV diffusers

Global solar ultraviolet (UV) irradiance measurements require diffuser assemblies whose angular response is proportional to the cosine of the zenith angle of radiation. Non-ideal angular response of the instrument is one of the most significant sources of uncertainty in solar UV irradiance measurements. For this reason, the angular response of the entrance optics of the instrument measuring global solar UV irradiance needs to be carefully optimized to minimize the cosine error. To aid the diffuser optimization process, a diffuser simulation software was developed. The software accounts for the diffuser elements itself as well as the surrounding structures of the diffuser assembly, such as the protective weather dome and the light-blocking shadow ring of the diffuser. The software was used to optimize the various dimensions of the diffuser assembly. Two diffusers were built based on the results of the simulations, one for Brewer spectrophotometer and the other to be used with an optical fiber or a fiber bundle (Figure 3).

Figure 3: Diffuser of the Brewer spectrophotometer (left), and the fiber-coupled diffuser (right) during the measurement campaign in Davos, Switzerland in July 2014.

These two diffusers were built by project partners Kipp & Zonen and CMS Schreder, respectively. The dimensions of the diffuser assemblies were further fine-tuned during the assembly-phase, but the final dimensions are still similar to those obtained through the simulations. Figure 4 shows the cosine error of the fiber-coupled diffuser. The measured and simulated cosine errors agree well once the diameter of the area of the diffuser that is visible to the fiber is reduced by 1.3 mm in the simulations. This difference in one of the dimensions is most likely explained by the angular response of the fiber head of the detector. The integrated cosine errors of the Brewer diffuser and the fiber-coupled diffuser were f_2 = 1.3 % and f_2 = 1.4 %, respectively.

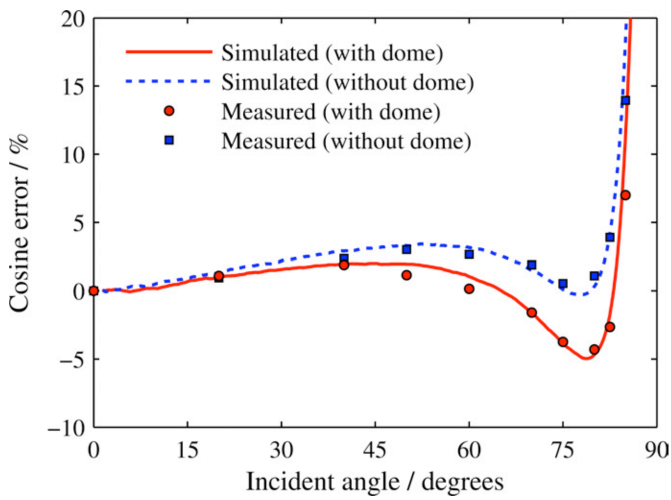

Figure 4: Measured and simulated cosine errors of the diffuser with the fiber connector. The effect of the weather dome of the diffuser assembly on the angular response is clearly visible in the results.

EMRP SolarUV: Linearity characterization of array spectrometers

Terrestrial solar UV irradiance varies over 5 to 6 orders of magnitude in the UVA+B range (280–400 nm) with maximum spectral irradiance of about 1 W/(m^2 nm). In order to measure the spectral irradiance of solar UV radiation with low uncertainty, the linearity of the spectroradiometer needs to be known accurately. To study the linearity of array spectrometers, a linearity characterization setup was built. The schematic view of the instrument is presented in Figure 5. The setup consists of two light sources (500 W Xenon and 1 kW Mercury lamps), a monochromator, and a set of neutral density (ND) filters to attenuate the beam. The beam exiting the monochromator is collimated and split into two branches. The signal of the spectrometer under test is compared to that of the photodiode which acts as the linearity reference detector.

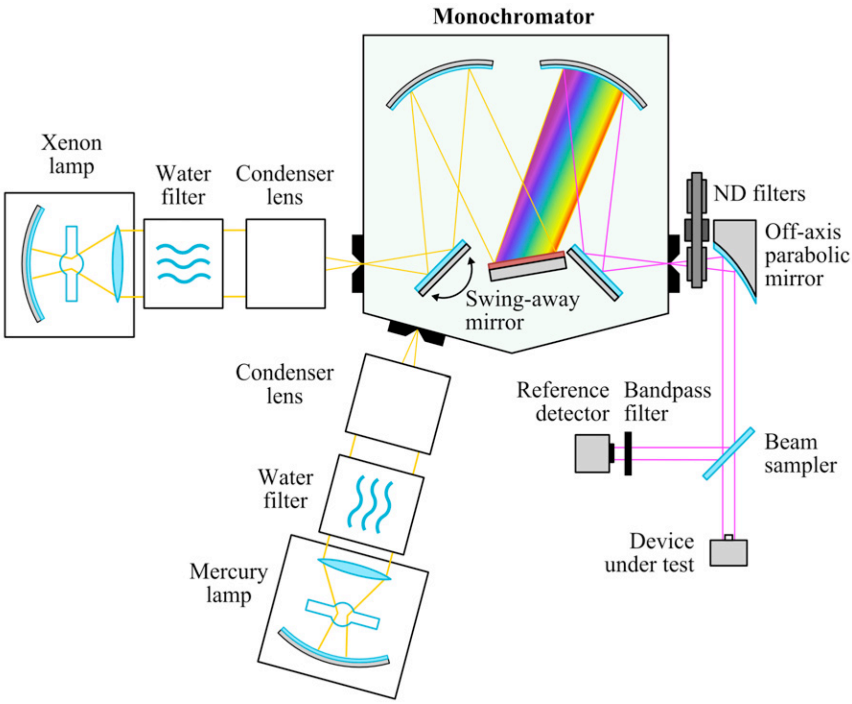

Figure 5: The schematic view of the linearity characterization setup.

The linearity setup was used for characterizing two array-based UV spectrometers at different irradiance levels, wavelengths, and integration times. The results were compared to the measurement results of the tuneable laser based linearity setup of PTB and laser and polarizer based linearity setup of VSL. The results were in good agreement.

The deviation from linearity of one of the measured spectrometers as a function of spectrometer counts is shown in Figure 6. The figure combines measurements carried out at different integration times, irradiance levels, and wavelengths. It was discovered that the nonlinearities of the two instruments under study were dominated by the nonlinearities related to spectrometer counts, which suggests that the signal processing electronics of the instruments are the cause of the non-linearity. This nonlinearity was corrected by fitting a polynomial to the linearity results as a function of instrument counts. Once this correction was applied, no additional nonlinearity for irradiances of up to 2 $W \cdot m^{-2} nm^{-1}$ could be detected.

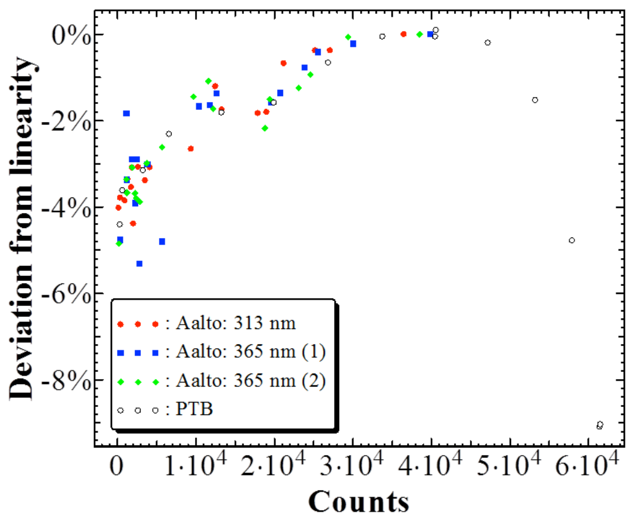

Figure 6: Linearity of AvaSpec spectrometer as a function of instrument counts.

EMRP Atmoz "Traceability for atmospheric total column ozone"

Atmoz is a three-year project funded by the EMRP that started in October 2014. The aim of the project is to achieve traceable measurements of total column ozone with relative uncertainties better than 1 % by a systematic investigation of radiometric (instrumental parameters), spectroscopic (ozone absorption cross sections) and respective methodologies. At present, the results of the instruments of the two ground-based ozone retrieval networks – Brewer and Dobson spectrophotometer networks – differ by up to 3 %. MRI has two major tasks in the project: 1) To characterize the out-of-range stray-light properties of single-monochromator Brewer photometer using lasers in the visible wavelength range, and 2) to develop a method to estimate the uncertainty of total column ozone retrieval by taking into account correlations between spectral irradiance values at different wavelengths. In addition to these tasks, MRI will maintain the UVNet and publish two issues of the UVNews newsletter.

EMRP MetEOC "Metrology for earth observation and climate"

MetEOC was a three year EMRP project that ended in September 2014. The aims of the project were to improve the measurement accuracies involved in Earth observation by improving the pre-launch, post-launch and on-board calibration capabilities, refining models and data processing methods, and developing new standards and detectors. The tasks of MRI were building and characterizing artificial targets (Figure 7) as first step in establishing the SI-traceability of Radiative Transfer (RT) codes which simulate the transfer of (optical) radiation through Earth's atmosphere by transmission, absorption and scattering. In addition BRDF (bidirectional reflectance distribution function) model suitability validation was carried out in MRI and a new BRDF model to be implemented in an RT code was suggested.

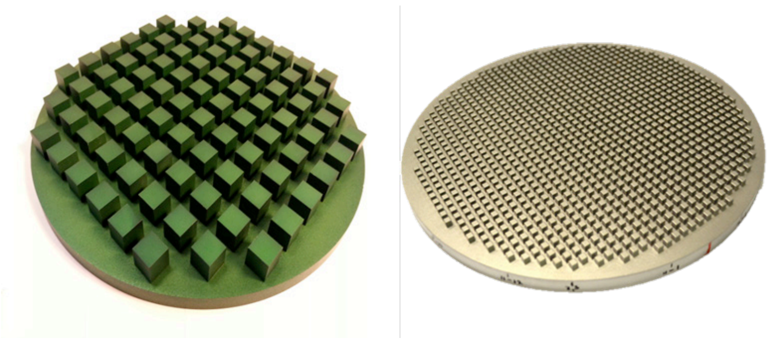

Figure 7. Green anodised aluminium cubes (GAC) target (left) and non-anodised aluminium cubes (NAC) target (right).

Three circular targets were manufactured, each 22 cm in diameter. The first was made from aluminium, with a sanded surface. The second was also made from aluminium, but its top surface was mechanically grooved so that a matrix of 1168 cubes, each of edge length approximately 3 mm, was formed. The third target consisted of a circular baseplate and 88 cubes with a 12 mm edge length.

All the components were made of standard 7075 aluminium, sanded and anodized with green pigments, measured individually, and assembled. The targets were characterized for BRDF on the micro-scale, surface roughness and geometry. In addition the macro-scale BRDF characterization was performed at NPL.

The micro-scale BRDF measurement results of the non-anodized coating (NAC) target (Figure 8) were used to retrieve material parameters by reverse fitting a BRDF model by using hybrid genetic algorithms of optimisation. The retrieved parameters in turn together with the results from surface roughness and geometry measurements were used in the RT code Raytran to simulate the macro-scale BRDF measurement results. The Raytran modelled results were compared with the macro-scale BRDF measurement results. The mismatch between the modelled and measured data for the anodized target was larger than expected. The work continues in the topics of finding improved algorithms for model parameter retrieval, and better estimation of measurement parameters and their effects on measurement results.

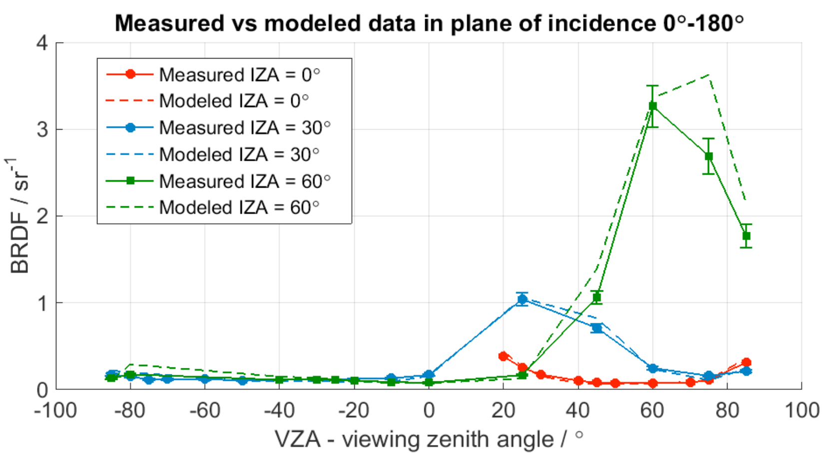

Figure 8. Comparison of results for the NAC target.

EMRP MetEOC 2 “Metrology for earth observation and climate”

MetEOC 2 is a three-year project funded by the EMRP that started in September 2014. The aim of the project is to improve the accuracy of the remote sensing measurements of various climate indicators that are needed to improve our understanding of the Earth system and particularly the climate change. In the project, MRI together with NPL will study alternative UV stable diffuser materials that could replace the space-grade Spectralon that is commonly used in Earth observation systems to monitor the in-flight drift of the sensors. In addition to fulfilling all the basic requirements of satellite diffusers, the new material should be more resistant to degradation under UV radiation than space-grade Spectralon and, ideally, be less susceptible to contamination. In the task, MRI will simulate the diffuse reflectance properties of various diffuser alternatives as well as perform ageing tests on several diffuser samples under UV exposure.

Hyperspectral Remote Sensing Using Supercontinuum Light Source

Hyperspectral sensors look at objects using a broad portion of the electromagnetic spectrum. Many objects have ‘spectral fingerprints' in the visible and infrared spectral region of the electromagnetic spectrum allowing the identification of materials that make up the measured object. Applications of remote hyperspectral sensing, that is, the measurement is done at a distance from the object, include mineral and oil exploration, identification of vegetation for diversity studies, and detection of objects and atmospheric constituents and conditions.

Active hyperspectral detection of diffusive targets with measuring ranges of a few hundred meters, employing rather expensive instrumentation for generating and detecting the IR radiation, have been reported. Modern supercontinuum (SC) light sources employing nonlinear optical fibers for the SC generation are attractive for remote hyperspectral sensing applications due to their unique combination of laser-like directionality and broad wavelength coverage. However, typical commercial SC sources are limited in optical power due to the small core size of the highly nonlinear optical fibers used for SC generation. The optical power is indeed one of the major factors determining the achievable measurement range in lidar (light detection and ranging) studies.

The objective of our study was to develop and test the feasibility of an affordable active hyperspectral instrument for the measurement of IR reflection spectra of diffusive targets over a measurement range of one kilometer. A broadband SC light source having 16 W total optical output power in the near infrared spectral range 1000–2300 nm was developed. In contrast to expensive highly non-linear optical fibres, a standard low-cost normal dispersion multi-mode fiber was used for the SC generation. The large core size of the multi-mode allowed us to high pump power (20 W) resulting in 16 W total optical output power in the SC. A commercial 256-channel infrared spectrometer was used for broadband detection of light reflected from various remote objects. The feasibility of the presented hyperspectral set-up was studied both indoors and in the field. Reflection spectra from several diffusive targets were measured and a measurement range of 1.5 km was demonstrated. The work was done in collaboration with the Technical Research Centre of the Finnish Defence Forces and Lasersec Systems Ltd.

EMRP xDReflect "Multi-dimensional reflectometry for industry"

XDReflect is a three year EMRP project which started in September 2013. The aim of the project is to validate reliable optical measurements with traceability to the SI-system to describe the overall macroscopic appearances of surfaces with modern coatings.

The main task for MRI in this project is leading the Work Package 3: Fluorescence, which aims to develop traceable facilities, methods, and reference materials that can be used to improve the uncertainties of appearance measurements of fluorescent surfaces. The main parts of WP3 are performing an inter-laboratory comparison for measurements of luminescent radiance factors of fluorescent standard materials (Figure 9), developing new potential standard materials, investigating the translucency of the fluorescent standard materials and investing potential gaps in the colour gamut of existing standard materials.

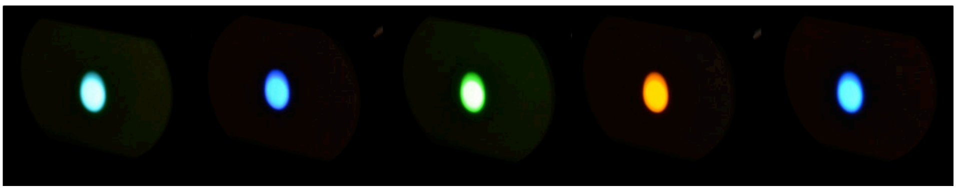

Figure 9. Samples used in the inter-laboratory comparison measurements.

The existing fluorescent standard materials are widely believed to exhibit Lambertian emission behaviour. However, the emission from such standards has been proven to be non-Lambertian (Figure 10). One of the important tasks in the project is to identify materials or methods for achieving more Lambertian emission behaviour, which may significantly reduce the errors introduced in absolute quantification of fluorescent emission and therefore save costs in adding fluorophores and whitening agents to end-user products in various industries.

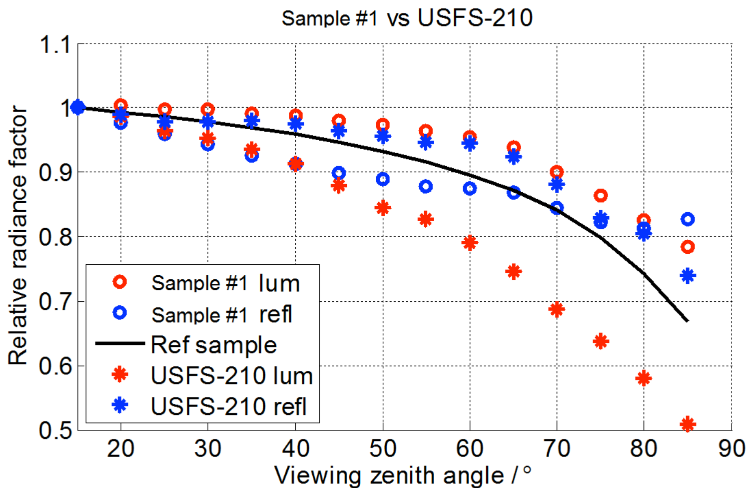

Figure 10. The angular emission of fluorescence from a widely used commercial standard material (USFS-210) and a novel standard material (Sample #1). It can be seen, that the fluorescence emission is more Lambertian for the novel standard material.

EMRP METCO "Metrology of electrothermal coupling for new functional materials technology"

Emergence of new piezoelectric materials capable of operating at high temperatures requires new metrological approaches for their traceable characterization. METCO is a three-year project funded by the EMPR that started in June 2012. The goal of the project is to develop the metrological infrastructure and facilities within Europe for the traceable metrology of piezoelectric, ferroelectric, thermal, and electro-caloric properties at high temperatures and electric fields.

MRI works in the project in collaboration with MIKES. The main task is leading the Work Package 4, where the aims are investigation of thermophysical properties of ferroelectric and electrocaloric materials, and the development of non-contact high temperature measurement techniques.

The emissivity behaviour of a high Curie temperature piezoelectric ceramic material $0.5(Bi_{0.95}La_{0.05})FeO_3$-$0.5PbTiO_3$ (BFPT) was investigated at temperatures between 500 °C and 800 °C, and in the wavelength range of 400–2000 nm. This was performed by heating the sample in the furnace and directly comparing its radiance to that of a blackbody at the same temperature using a spectroradiometer with focusing optics. The spectral radiance of the blackbody is calculated from the Planck's radiation law. Due to the difficulty of obtaining a reference temperature reading from the surface of the sample, its specular reflectance was measured with 633 nm and 1523 nm He-Ne lasers. A lock-in technique was developed for this measurement. For temperatures below 500 °C the emissivity was measured by other partners in the project using reflectometry.

EMRP SolCell "Metrology for III-V multi-junction solar cell"

Multi-junction solar cells based on III-V materials are part of the third generation of photovoltaic cells. They comprise of multiple p-n junctions absorbing a separate portion of the solar energy spectrum, allowing for solar energy conversion with efficiencies as high as 44 %. The SolCell project addresses the main metrological challenges faced by the present developments of the high-efficient III-V multi-junction solar cells. In the project, MRI will develop measurement technology to measure the reflectance and band-gap energies of the III-V solar cells (Figure 11).

Figure 11. Reflectance measurements of new type of solar cells are carried out by Metrology Research Institute.

The new type of solar cells can convert light with wavelengths above 2 000 nm to electrical energy. To measure the optical properties of the solar cells in a near-infrared region, new measurement methods need to be developed. MRI will develop and extend the existing reflectance and spectral response setups to fulfill the requirements of the III-V multi-junction solar cells.

EMRP PhotoClass "Towards an energy-based parameter for photovoltaic classification"

Photovoltaic devices are sold according to their output power as measured under standard test conditions. These conditions represent a cloudless sunny day in the middle of the USA, with an artificial and unrealistically low device temperature. The current peak-efficiency metric leads to inaccurate estimates of the energy generated under real operating conditions. The project aims to develop a new metric, based on energy output under European climate conditions. This will allow a risk assessment to be undertaken based on more reliable results, which will enable system planners and financial institutions to optimize their services.

In the project, MRI will develop a differential spectral responsivity measurement facility for solar cell measurements (Figure 12), and measure optical properties, such as reflectance, spectral responsivity and stability, of mono- and multi crystal solar panel mini modules developed by Naps Systems, Finland.

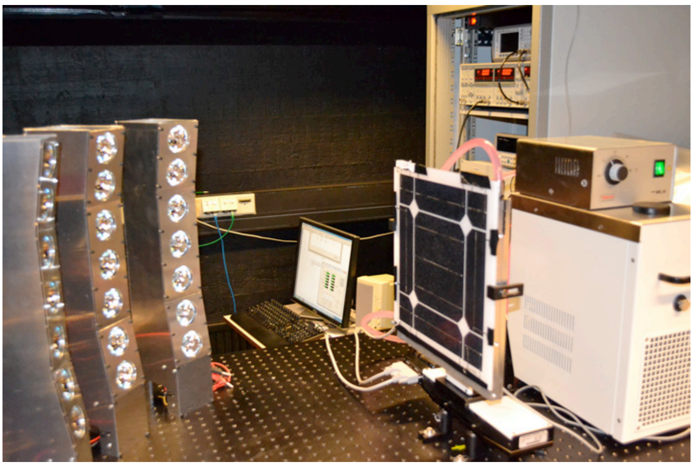

Figure 12. Differential spectral responsivity measurement facility.

UVIADEM: High-resolution setup for measuring photoyellowing of translucent materials

In this project funded by the Academy of Finland, a new high-resolution laser-based transmittance measurement setup, shown in Figures 13 and 14, has been developed for measuring color changes, such as the photoyellowing of translucent materials exposed to ultraviolet radiation with a spectrograph. The setup includes 14 power-stabilized laser lines between 325 nm and 933 nm, of which one at a time is directed on to the aged sample. The beam power varies <0.007 % over 8 h time period with a peak-to-peak deviation of <0.05 % for the wavelengths between 425 nm and 780 nm. Outside this range, the power varies <0.02 % with a peak-to-peak deviation of <0.2 %.

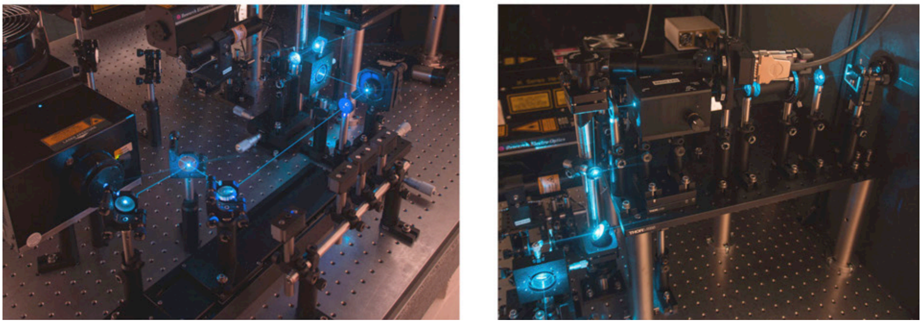

Figure 13. One laser beam is selected by moving the mirror (left), and optics for improving the quality of the selected beam (right).

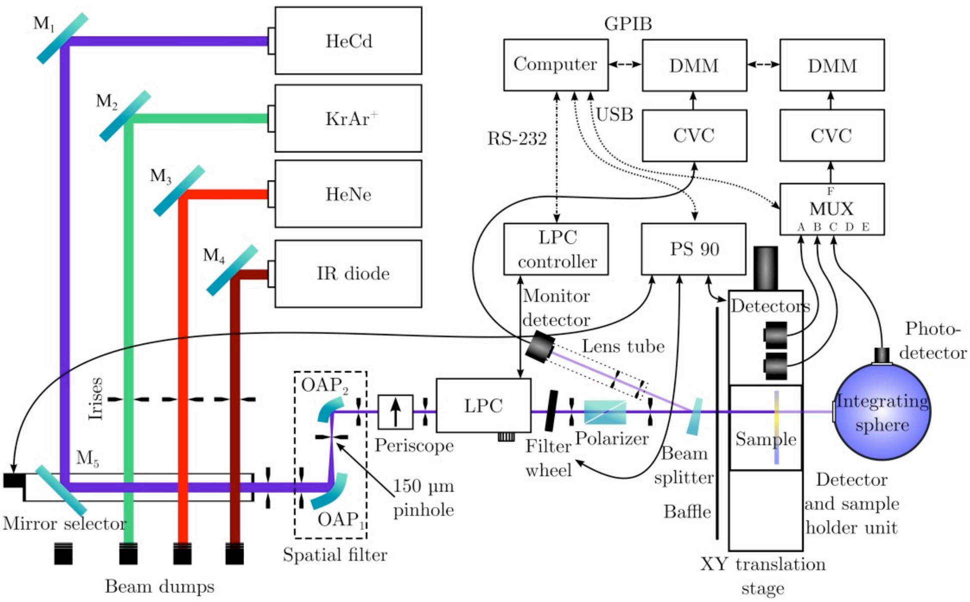

Figure 14. Structure of the laser-based transmittance measurement setup.

The power transmitted through the sample is measured with a silicon detector utilizing an integrating sphere. Measurement at various locations aged with different wavelengths of exposure radiation gives the transmittance data required for acquiring the action spectrum also known as the wavelength sensitivity of degradation. In addition to the material research, the setup can be used for characterizing optical detectors, e.g., for absolute power responsivities, or they can be scanned to obtain spatial uniformities.

EMRP SSL "Metrology for solid state lighting"

Metrology for Solid State Lighting was a three-year project funded by the EMRP. The project ended in April 2013. Since then, MRI continues the work within the Aalto-funded projects Effinano and Light Energy. The work is divided in three tasks: 1) Building a mesopic photometer, 2) Developing a method for predicting the average junction temperatures of the LEDs inside an LED lamp from spectral measurements, and 3) Studying the ageing of the photometric properties of the LED lamps.

EMRP SSL: A two-channel luminance meter for mesopic measurement range

The mesopic photometer work resulted in a dual-channel luminance meter for simultaneous measurement of luminance with photopic and scotopic weightings. The work was published in *Meas. Sci. Technol.* in 2014. Such measurements are useful in mesopic conditions, i.e., when the luminance is in the range of 0.005–5 cd m^{-2}.

The two instrument channels were characterized for spectral responsivities. Characterization measurements were carried out for the instrument's linearity (Figure 15), stray light sensitivity and polarization dependence. The results showed very good noise performance, allowing fast measurements over the whole mesopic range. The noise equivalent power was measured to be approximately 20 fW $Hz^{-1/2}$, equal to a noise equivalent luminance of 30 µcd m^{-2} $Hz^{-1/2}$. Estimated uncertainty of measurements for typical light sources is 2.2 % (k = 2) at the lowest luminance levels of the mesopic range.

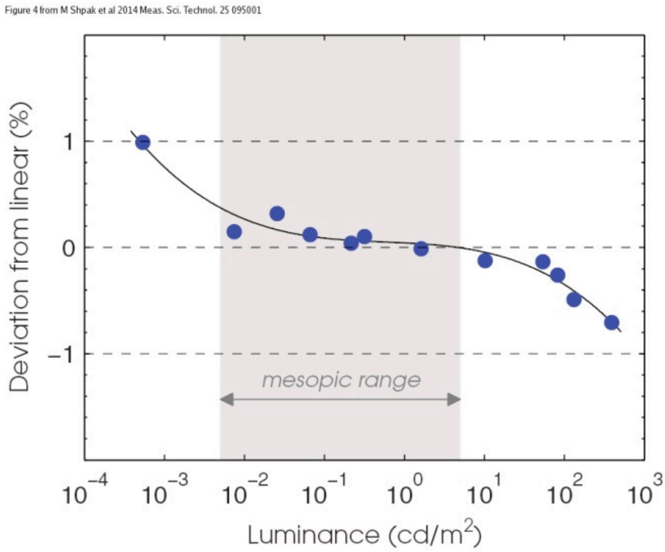

Figure 15. Deviation from the linear response of the developed photopic-scotopic luminance meter as a function of measured photopic luminance.

EMRP SSL: Radiometric determination of the junction temperature of light-emitting diodes

Five different types of LEDs were studied for the relationships between the junction temperatures and the output spectra over a wide temperature range from 303 K to 423 K with the goal of developing a method for predicting junction temperature from the spectrum. It appeared that finding a universal model to determine the junction temperature optically is challenging. The relationships between the junction temperature and the forward voltage varied considerably among LED types, and even between different specimens of the same LED type. The same appeared with the relationships between the optically determined inverse derivative temperatures and the junction temperatures.

With all of the LEDs studied, there was a linear relationship between the optically derived inverse derivative temperature and the junction temperature. A linear relationship was also found between the junction temperature and the forward voltage. This implies that four measurements can describe the relationship between the junction temperature and the output spectrum of an LED over the temperature region studied. In the linear relationship between the inverse derivative temperature and the junction temperature, the variation in the slope was less than 5 % among different LED specimens. Changing the current changed the slope by 2–5 %. The effects of lamp housing and phosphor coating on the spectra and temperatures were studied. Generally, the plastic lamp bulb absorbs in the blue region, thus lowering the radiometrically obtained temperatures by 0.5–2 %. The radiometric temperatures of individual LEDs in an LED lamp were surprisingly close to each other within 0.8–4.4 %. An apparent lamp temperature derived for a bunch of LEDs was very close to the average temperature of the individual LEDs.

The measurement results and derived models were tested on obtaining temperatures for five lamps undergoing natural ageing (Figure 16). The temperatures varied within 65–150 °C.

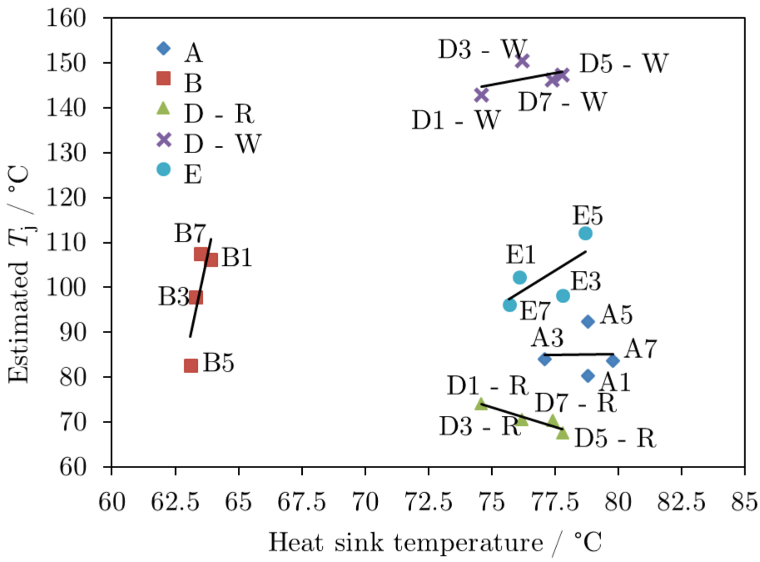

Figure 16. Estimated junction temperatures T_j of the lamps as a function of the heat sink temperatures.

EMRP SSL: Lifetime expectancy of SSLs

Five different types of LED lamps from two different manufacturers were aged for 35 months at room temperature and for 6 months at the elevated temperatures of 45 °C and 60 °C. Luminous flux, luminous efficacy, and spectral properties of the lamps were measured periodically. The lifetimes for the lamps aged were predicted from the luminous flux measurement results according to IES

TM-21-11. This was possible for three out of the five lamp types, as the luminous flux of two lamps did not decline.

Lifetimes under room temperature were calculated using four different time periods between 5 500 h and 24 500 h. It appeared that the first estimates are somewhat pessimistic with some lamp types. The lifetimes at the end of the test appeared many times longer than the first estimates using the first 5 500 h of data. The results at the elevated temperatures show that ageing can be accelerated by modest heating. On the average, heating to 45 °C reduced the lifetime by a factor of 1.35, and heating to 60 °C by a factor of 2.36.

An alternative method to analyse ageing was developed that also can be used for lamps whose luminous fluxes do not decline (Figure 17). Time series of accelerated data are stretched so that the data overlap with those of non-accelerated tests. Using this method and including four lamp types, it was concluded that on the average, the acceleration factors of time were 1.34 when heated to 45 °C and 2.93 when heated to 60 °C. The acceleration factors vary among lamp types so we conclude that when carrying out accelerated tests, natural ageing should be carried out as well to determine the acceleration factor.

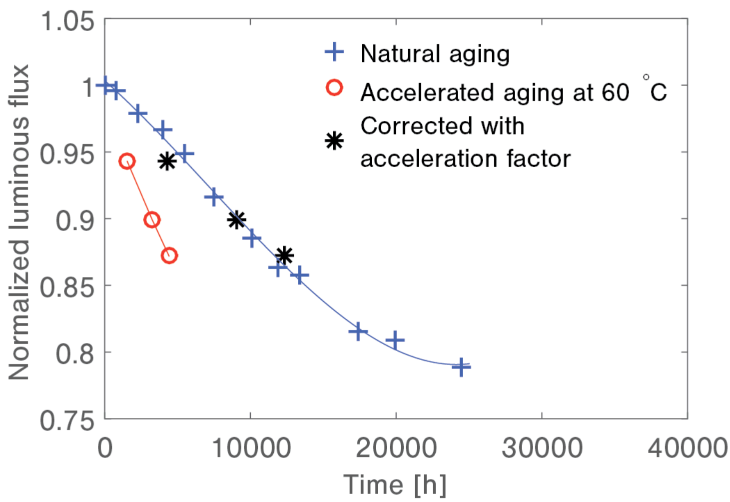

Figure 17. Normalized luminous flux data for Osram A60 lamp. Black asterisks (*) indicate the accelerated data set, where the time values have been multiplied with an acceleration factor.

During the ageing period of 24 500 h, the changes in correlated colour temperatures of four lamp types were smaller than the measurement uncertainty of 2 %. For one lamp type the correlated colour temperature increased by 4.3 % during the ageing.

Light Energy "Efficient and Safe Traffic Environments"

Light Energy is a multi-disciplinary research project funded through the Aalto University Energy Efficiency Research Programme (AEF). The project started in October 2012 and continues until the end of September 2016. The goal of the project is optimization of street lighting energy efficiency through the study of technical, safety, environmental and economic factors. Main roles of MRI in this project are divided between development of instrumentation for luminance measurements under mesopic lighting conditions and study of ageing characteristics of LED street lights.

MRI has continued the study and development of a photometer for the mesopic luminance range in this project. A detailed characterization of the existing photopic-scotopic dual-channel instrument was performed and the requirements for the next version defined. Second version of the photometer will include a capability of measuring adaptation level directly, thus enabling the measurement of a true mesopic luminance value. Additionally, a detailed study of the mesopic system published by CIE (CIE 191:2010) is being performed, its behavior in the whole mesopic region is being evaluated in terms of application in a practical measurement system. One of the potential problems with the published mesopic system is its reliance on the iterative calculation method for obtaining adaptation value. Our effort is to parametrize the mesopic region and produce a closed-form equation that could be used in an integrated mesopic instrument with a well defined measurement uncertainty.

Another task of MRI includes the study of ageing characteristic of LED street lamps under different operating regimes. With the advance of the LED based street lamps, a smart control of lighting levels becomes possible. The light output of LED source can be rapidly and accurately adjusted based on the need for light at each moment. The goal of this research is to find the effect of switched operation on the ageing behavior of the lamps. Hypothetically the lifetime of a lamp that is adjusted continuously could be extended due to the lower average power output, however the thermal and electrical stress of adjustment might have an opposite effect. In this study 20 lamps were selected of two different types: 10 lamps made by iGuzzini lams and 10 lamps made by Philips. Five lamps of each type serve as a control group, being operated continuously, while the other five of each group are being switched between 100 % and 20 % power output every 30 seconds. All the lamps are completely switched off for 3 hours after each 9 hour operating period. Luminous efficacy and colourimetric properties of the lamps are being measured approximately every 3 months. The ageing started in March 2014, and the first meaningful results could potentially be obtained in 2015.

EMRP MESaIL "Metrology for efficient and safe innovative lighting"

MESaIL is a three-year project funded by the EMRP that started in June 2014. The project is continuation to the earlier EMRP project "Metrology for solid-state lighting." In MESaIL, the target is to develop measurement methods and traceability for new solid-state lighting technologies, such as OLEDs and different types of LEDs, including chip on board (CoF), chip on flex (CoF), and 3d nano-structured LEDs. Special emphasis is given to development of measurement methods for test laboratories to allow lower measurement uncertainties in luminous flux and electrical power measurements. MRI leads the Work Package on traceable measurement methods. The WP includes development of an impedance stabilization network for electrical power measurements of SSL products and luminous efficacy measurement of OLEDs using an integrating sphere. In addition, MRI work is included in tasks investigating new standards for test laboratories, and ageing test methods for new types of LED modules and OLEDs.

Luminous efficacy measurement of OLEDs

A two-axis holder (Figure 18) was designed and constructed for characterization of organic light-emitting diodes (OLEDs) using a 1.65-m integrating sphere. The sphere was first modeled with a 3D-modeling program for optimizing holder dimensions so that the detector port baffle blocks the direct view of the system. The developed holder allows OLEDs of different sizes to be measured in arbitrary geometrical alignments and the construction was designed to minimize the absorption of the edge emission and backward emission. The holder is equipped with two built-in temperature sensors. During the measurement, the OLED is connected to a DC-source using a 4-wire connection.

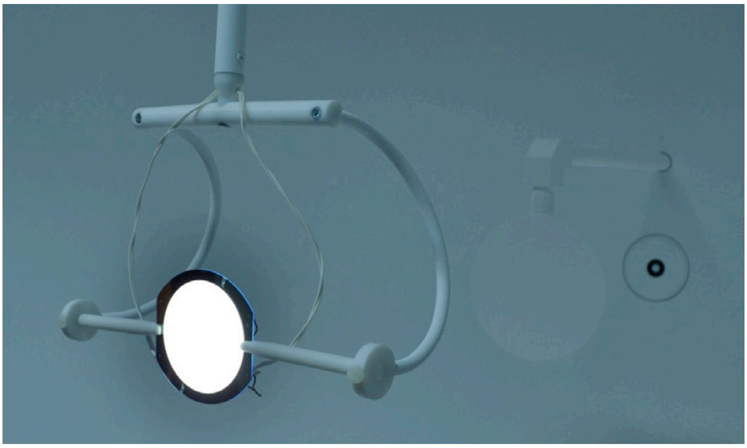

Figure 18. OLED-panel attached for measurement using the developed 2-axis holder.

Luminous efficacy test measurements were carried out for three forward-emitting OLEDs from different manufacturers in both vertical and horizontal positions. To calculate the spatial non-uniformity correction some changes were made to the analysis program to take into account the varying position of the OLED panel. The differences in the measured luminous efficacies between the vertical and horizontal operating positions were less than 0.22 %. The influence of the edge emission on the measured luminous efficacy was investigated by scanning the luminance and spectral radiance of the OLED panels, as well as their edges in the vertical position. The effect of the edge emission on the results of the luminous efficacy test measurements is only 0.01–0.05 %. The developed holder will be utilized in the measurements of the EMRP MESaiL-project.

EMRP NewStar "New primary standards and traceability for radiometry"

NewStar is a three-year project funded by the EMRP that started in October 2014. The project complements and builds on earlier iMERA+ project qu-Candela "Candela: Towards quantum based photon standards", where MRI developed a novel photodetector called the Predictable Quantum Efficient Detector (PQED). The PQED consists of two custom-made induced junction silicon photodiodes mounted in a wedged trap configuration. The internal quantum efficiency of the PQED is predictable within 1 ppm and 70 ppm in the visible range at cryogenic temperatures (~77 K) and at room temperature, respectively. Comparisons with cryogenic radiometers confirm the predicted responsivity within the measurement uncertainties. As the responsivity of the PQED was predicted on the basis of fundamental constants and material parameters, the PQED proposes a new and advanced means of realizing the unit of optical power and other derived SI units, and a simplified traceability through more practical and cost efficient techniques. The main objectives of the NewStar project are to develop primary standards for absolute radiometry at 1 ppm uncertainty in the visible wavelength range by PQED operating at cryogenic temperatures (~77 K), and to develop traceable spectral radiometry by implementing room-temperature PQED primary standards in applications such as filter radiometry and photometry at 100 ppm uncertainty.

In the NewStar project, MRI has designed the room-temperature PQED, shown in Figure 19. It consists of the Brewster window for high transmission of *p* polarized light, adjustment screws, flexible bellows and the photodiode chamber. The developed detector provides the benefits of compact size and ease of use similar to conventional trap detectors. It can also be operated without the Brewster window, in which case a dry nitrogen flow is directed into the detector chamber in order to prevent dust contamination of the photodiodes. This eliminates the need for window transmittance correction, which is a major contribution to the uncertainty.

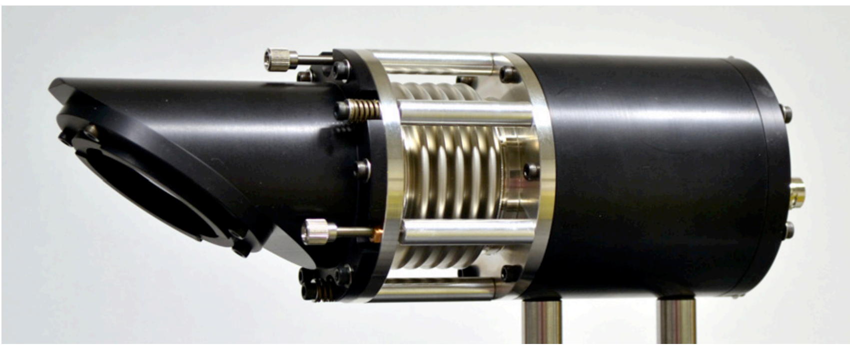

Figure 19. Photograph of the developed room-temperature PQED.

MRI tested if the room-temperature PQED meets the requirements for a primary standard detector. These include predictable and spatially uniform responsivity, and congruent responsivity and reflectance between individual detectors. Measurements of individual detectors indicate that the spatial responsivity and internal quantum efficiency are spatially uniform within at least 50 ppm in the central area of 4 mm in diameter. The reflectance and spectral responsivity of the PQED are congruent within 4 ppm and 31 ppm, respectively, and agree with the predicted values. These measurement results provide evidence that the room-temperature PQED may replace the cryogenic radiometer as a primary standard of optical power in the visible wavelength range.

Also the reflectance losses of the PQED were analysed when used with light sources of uncontrolled state of polarization. An efficient method to determine the reflectance losses without direct measurement of the reflectance for an unknown state of polarization of the incident light was developed. The method is demonstrated in Figure 20. By the photocurrent ratio of the two photodiodes it is possible to estimate the relative s- and p-polarization components in the incident light. The knowledge of these components enables the reflectance of the wedged trap structure of the PQED to be calculated.

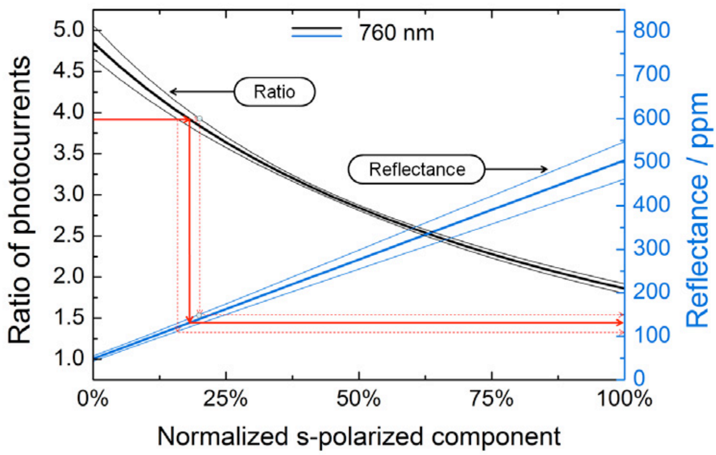

Figure 20. Ratio of photocurrents and corresponding reflectances of the PQED as a function of polarization. Thinner lines indicate the standard uncertainty corridors. Red arrows show the steps to be taken for estimating reflectance based on photocurrent ratio.

New source and detector technology for the realization of photometric units

The production of incandescent light bulbs is bound to end, as incandescent lighting is being phased out globally in favour of more energy-efficient and sustainable solutions. Therefore, new photometric source standards are also needed to replace the traditional incandescent lamps. Light emitting diodes (LEDs) are promising candidates as new reference standards, as they have the benefits of long lifetime, exceptional stability and reduced out-of-band leakage. Traditionally, photometric quantities are realized by using a filter, the transmittance of which closely follows the spectral luminous efficiency function $V(\lambda)$. The uncertainty of this method may increase when LEDs are measured instead of incandescent lamps due to the narrow and complicated spectra of LEDs. MRI has developed a novel method for the realization of photometric units based on the Predictable Quantum Efficient Detector (PQED). The new method completely eliminates the need to use $V(\lambda)$ filters. Instead, the photometric weighting is taken into account numerically by measuring the relative spectral irradiance. The method is applicable for LEDs, the spectra of which are limited to the visible wavelengths.

The illuminance values of a blue and a red LED were determined using the new method and a conventional reference photometer (Figure 21). The values obtained by the two methods deviated from each other by 0.06 % and 0.48 % for the blue and red LED, respectively. The PQED-based values have much lower standard uncertainty (0.17 % to 0.18 %) than the uncertainty of the values based on the conventional photometer (0.46 % to 0.51 %).

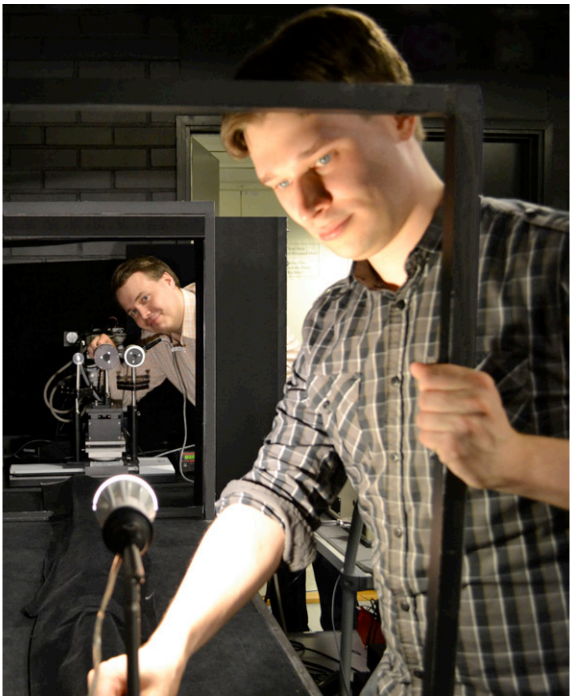

Figure 21. Comparison measurement of LED light sources using the new PQED method and a conventional reference photometer.

EMRP Thin Films "Metrology for manufacturing of thin films"

In this EMRP project, analysis methods and instrumentation for obtaining optical parameters and thickness profiles of thin-film samples were studied. MRI in collaboration with the Federal Institute for Materials Research and Testing (Germany) used spectrophotometric and ellipsometric methods to measure such samples as thermally grown SiO_2 on silicon, evaporated SiO_2 on silicon, a polymer photoresist layer on silicon, and a nominally 300 nm thick layer of thermally grown SiO_2 on an induced junction silicon photodiode used in the PQED.

A detailed study of the oxide layer in induced junction photodiodes is important, because the refractive index and layer thickness determine the spectral responsivity of the PQED. Experimental results at multiple sample positions give the thickness uniformity and optical constants of thin films. The thickness results obtained with spectrophotometry and ellipsometry agree within 1 nm for the 300 nm thick layer of SiO_2 on silicon.

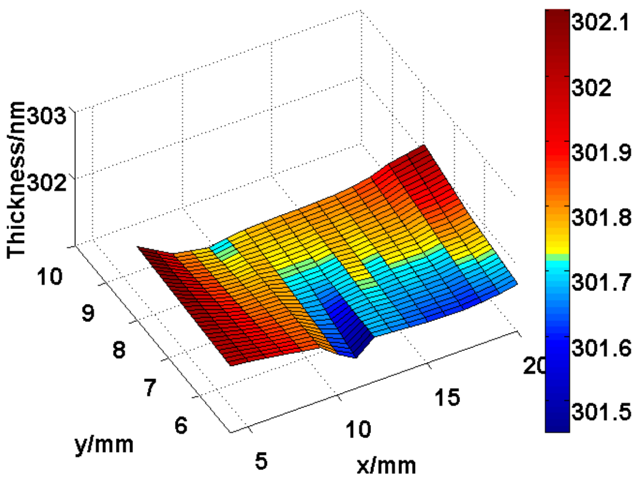

Figure 22. Spatial uniformity of photodiode oxide layer.

Figure 22 shows the spatial oxide layer thickness of an area of 18 mm × 4 mm sampled at regular intervals across the photodiode surface. The fitted thickness of the SiO_2/air interface surface roughness layer is 3 nm with the standard uncertainty of 1 nm. This value is in good agreement with peak-to-peak surface profile variations of 2 to 3 nm measured by atomic force microscopy over an area of 80 × 80 μm^2 in a similar photodiode. In Figure 23, the measured values for the SiO_2 refractive index are higher by 0.002 as compared with the reported ellipsometry results. Both the thickness non-uniformity and refractive index of the PQED photodiodes are well within the standard uncertainties of 2 nm and 0.003, respectively.

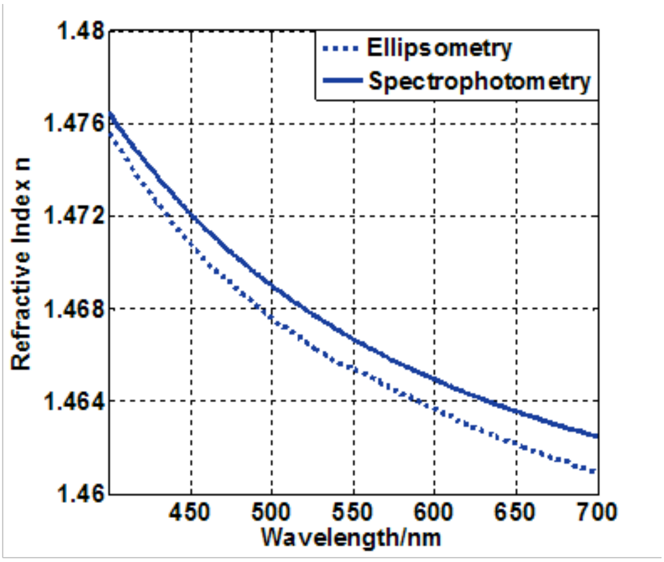

Figure 23. Refractive index of the photodiode's SiO_2 layer as determined by the fitted Cauchy dispersion relation (solid line) and comparison with reported ellipsometry data (dashed line).

EMRP ThinErgy "Traceable characterisation of thin-film materials for energy applications"

Started in July 2014, ThinErgy is a three-year project funded by the EMRP. The project is a continuation to the earlier EMRP project "Metrology for the manufacturing of thin films." The goal of the project is to develop complementary metrology tools for thin film characterization. MRI in collaboration with MIKES contributes in a work package to develop multi-spectral methodologies for characterising the properties of thin-layer materials used in energy conversion technology and energy efficient lighting. The main task of MRI is to investigate the optical properties of the black silicon samples used in the fabrication of solar cells.

EMRP MIQC “Metrology for industrial quantum communications”

The MIQC project has developed measurement techniques for the characterization of quantum key distribution (QKD) quantum optical components at telecom wavelengths (around 1.55 μm). The characteristics of quantum optical components are crucial for security analysis on the quantum optical level. Because an efficient way to attack the channel by an eavesdropper relies on exploiting inefficiencies of the components to hide himself in the system, security of practical QKD systems demands an accurate knowledge of optical and electronic properties of the QKD components. This will allow the sender and receiver to eliminate anomalies due to imperfections and to home in on the eavesdropper. In this project MRI in collaboration with MIKES and Metrosert have constructed and fully characterized an optical attenuator based on transmission trap design (Figure 24).

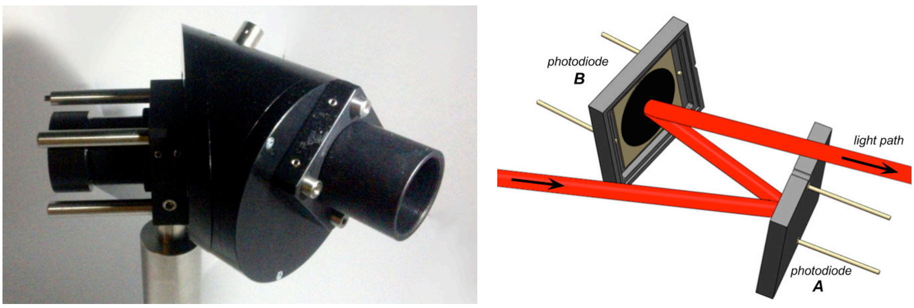

Figure 24. Body and light path of the transmission trap detector–attenuator.
Light enters to the leftmost and exits from the rightmost part of the detector.

The attenuator is used to generate optical pulses at single photon level with known mean photon number. The two 10 mm diameter photodiodes were mounted into the trap detector in such a way that reflection from photodiode surfaces takes place at the angle of incidence of 17°. The planes of incidence of the photodiodes are perpendicular to each other ensuring polarization insensitivity of the total reflection and attenuation. The reflected, non-absorbed fraction of incoming beam exits from the output aperture of the attenuator at the angle of 34° relative to the direction of the incoming beam. At first the attenuator attenuation is characterized at high input power levels (mW) using conventional calibrated power meters. Then the system is used to attenuate the low incident power (nW) down to power levels suitable for single photon counters.

The attenuator provides a free space attenuation of 3.6×10^{-5} with expanded uncertainty of 4.4 % (k = 2) at the wavelength of 1550 nm. The attenuation was directly measured to be independent of incident power over the range of 10 nW up to 1mW. While the transmission trap detector is used as a fibre coupled attenuator the uncertainty at k = 2 level for total attenuation is 3 %. The comparison of photocurrents from the two photodiodes (photodiode A and photodiode B) mounted inside the attenuator confirm that the loss mechanisms of the photodiodes are not dependent on the incident power (Figure 25).

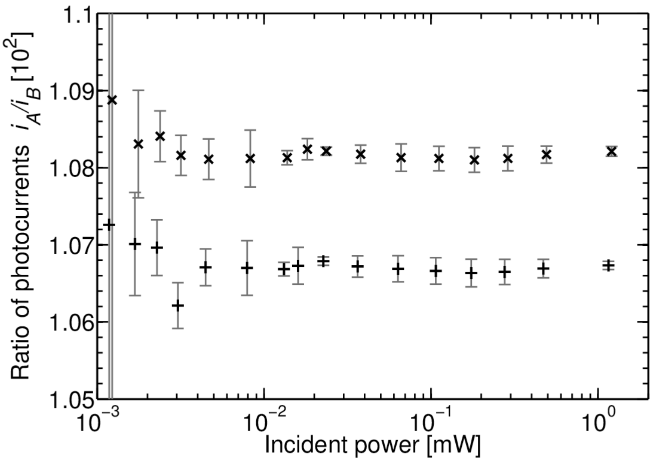

Figure 25. The ratio of photocurrents from the photodiodes mounted inside the attenuator. The signal from photodiode A divided by the signal from photodiode B.

EMRP SIQUTE "Single-photon sources for quantum technologies"

The aim of SIQUTE project is to develop deterministic, compact and efficient single-photon sources for needs of cutting edge quantum optical technologies such as quantum communication, quantum computation and quantum metrology. One way of developing a fully deterministic single photon source is to take advantage of an emission of an excited vacancy center in a nano-diamond. A state of art optical antenna surrounding the nano-diamond allows collection efficiency more than 95 % of emitted photons. The vacancy center will be a predictable single photon source only if it is excited with short optical pulse. The energy of the pulse needs to be enough to saturate the vacancy center and significantly shorter than the lifetime of exited state. To fulfill these needs a high-performing laser system is needed. In this project, MRI in collaboration with MIKES is developing an optical excitation system capable of producing sub nanosecond pulses with adjustable repetition rate ranging from 100 kHz up to 100 MHz at the wavelength of 685 nm. The peak power of the pulses is aimed to be at least 50 mW.

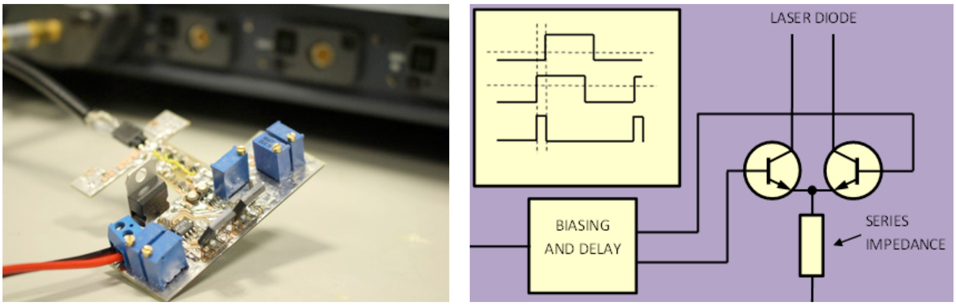

Figure 26. Differential pair driver electronics under testing (left). The basic idea of differential pair driver (right). The current is switched between the dummy load and the laser diode to achieve fast and stable output.

In the first stage of SIQUTE, a generic diode laser driving electronics was produced (Figure 26), compatible with different lasers and wavelengths. The voltage and the current of pulses are in the range of 2–3 V and 150–200 mA, respectively. Bias current, not exceeding the lasing threshold of the laser, is supplied between the pulses to facilitate stable performance. In addition, the laser is electronically protected from inversed polarity and exceeding maximum current. The pulsing electronics is based on differential pair design. This type of driver consists of RF-transistor pair and steering circuitry. The first control pulse from the signal generator switches the laser current on. The second control pulse, delayed by the desired width of the optical pulse, has higher offset voltage, thus switching the current to the dummy load instead. The benefit of the differential pair design is the stability, as the same current is provided by the current source and is switched between the laser diode and the dummy load.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

Since 2005, the Metrology Research Institute has participated in key comparisons under the name MIKES (Centre for Metrology and Accreditation).

Key comparison CCPR-K2.c, spectral responsivity 200–400 nm, pilot PTB

Draft A was received in April 2013. Aalto results were well within uncertainties. Final report was published in May 2014.

Key comparison EURAMET.PR-K3.a, luminous intensity, pilot PTB

Measurements were completed in 2009. Final report was published in July 2014.

Key comparison EURAMET.PR-K4, luminous flux, pilot PTB

Measurements were completed in 2009. Draft A appeared in February 2014. The final report has not been published yet.

Comparison of luminous efficacy of SSL products (EMRP ENG05-2.2.1)

The measurements were completed in 2012. Results of the intercomparison of EMRP SSL project were published in spring 2013 and the MRI results were in good agreement with the average of the results.

6.2 Conferences and Meetings

EMRP 'Metrology for Solid State Lighting' Workshop for the EURAMET TC-PR, February 26, 2013, Copenhagen, Denmark; *Petri Kärhä, Timo Dönsberg, Erkki Ikonen*

EMRP 'New primary standards and traceability for radiometry' Pre-start Meeting (February 26, 2013) EURAMET TCPR Meeting (February 27–28, 2013), Copenhagen, Denmark; *Timo Dönsberg, Erkki Ikonen*

Project proposal evaluation for the Research Council of Lithuania, March 6–7, 2013, Vilnius, Lithuania; *Erkki Ikonen*

CIE Centenary Conference: Towards a new century of light, April 15–16, 2013, Paris, France; *Petri Kärhä, Maksim Shpak, Tuomas Poikonen, Erkki Ikonen*

EMRP Sub-committee Meeting, April 16–19, 2013, Braunschweig, Germany; *Erkki Ikonen*

CIE Division 2 Technical Committee Meetings, April 17–19, 2014, Paris, France; *Maksim Shpak*

CCPR Working Group Meetings, April 21–24, 2013, Paris, France; *Erkki Ikonen*

EMRP 'Metrology for Solid State Lighting' Final Meeting, April 22–25, 2013, London, UK; *Hans Baumgartner, Petri Kärhä*

EURAMET General Assembly and EMRP Committee Meeting, May 28 – June 1, 2013, Reykjavik, Iceland; *Erkki Ikonen*

EMRP project 'Single-photon sources for quantum technologies' Kick-off Meeting, June 25–26, 2013, Braunschweig, Germany; *Erkki Ikonen, Albert Manninen*

EMRP Project Partnering Meetings, June 26–27, 2013, PTB, Berlin, Germany; *Farshid Manoocheri, Petri Kärhä*

EMRP Project Partnering Meetings, July 1–3, 2013, NPL, Teddington, UK; *Tuomas Poikonen, Hans Baumgartner, Tomi Pulli*

EMRP 'Traceability for surface solar UV measurements' Workshop and Project Meeting, August 26–30, 2013, Davos, Switzerland; *Petri Kärhä, Tomi Pulli, Erkki Ikonen*

Optics in Engineering Symposium, September 1–4, 2013, Utsunomiya, Japan; *Erkki Ikonen*

EMRP ‘Metrology for manufacturing of thin films’ Project Meeting, September 10–11, 2013, Berlin, Germany; *Farshid Manoocheri*

EMRP ‘Metrology for manufacturing of thin films’ Project Workshop, September 12, 2013, Berlin, Germany; *Farshid Manoocheri*

EMRP ‘Multi-dimensional reflectometry for industry’ Kick-off Meeting, September 17–18, 2013, Paris, France; *Farshid Manoocheri, Priit Jaanson*

Extra EMRP Sub-committee Meeting for EMPIR Preparation, September 23–24, 2013, Braunschweig, Germany; *Erkki Ikonen*

EMRP ‘New primary standards and traceability for radiometry’ Kick-off Meeting, October 1–2, 2013, PTB, Berlin, Germany; *Timo Dönsberg, Mikko Merimaa, Erkki Ikonen*

CIE Division 2 Technical Committee Meetings, October 6–7, 2013, Bled, Slovenia; *Erkki Ikonen*

International Congress of Metrology, October 7–10, 2013, Paris, France; *Timo Dönsberg*

CIE Division 2 Expert Workshop, October 8–9, 2013, Bled, Slovenia; *Erkki Ikonen*

EMRP ‘Metrology for Earth observation and climate’ Project Meeting, October 30–31, 2013, Ispra, Italy; *Farshid Manoocheri, Priit Jaanson, Erkki Ikonen*

Workshop on Key Comparison Data Evaluation and GUM Workshop, November 6–8, 2013, Teddington, UK; *Erkki Ikonen*

EMRP ‘Metrology of electrothermal coupling for new functional materials technology’ Project Meeting, November 12–13, 2013, CMI, Prague, Czech Republic; *Maksim Shpak*

EMRP ‘Single-photon sources for quantum technologies’ Project Meeting, November 13–14, 2013, CEA, Grenoble, France; *Albert Manninen, Erkki Ikonen*

EMRP Proposal Review Conference, November 17–20, 2013, Monaco; *Erkki Ikonen*

EMRP/EMPIR Committee Meeting, November 25–26, 2013, Berlin, Germany; *Erkki Ikonen*

EMRP 'Multi-dimensional reflectometry for industry' Project Meeting, January 14–15, 2014, PTB, Braunschweig, Germany; *Farshid Manoocheri, Priit Jaanson*

EMRP 'New primary standards and traceability for radiometry' Project Meeting of photodiode design, January 14–16, 2014, Oslo, Norway; *Erkki Ikonen, Mikko Juntunen*

EMRP 'Metrology for industrial quantum communications' Project Meeting, February 3–5, 2014, Braunschweig, Germany; *Erkki Ikonen, Aigar Vaigu*

EMRP 'Metrology for manufacturing of thin films' Project Meeting, February 11, 2014, NPL London, UK; *Farshid Manoocheri*

EMRP 'Metrology for Earth observation and climate' Project Meeting, March 19–20, 2014, Teddington, UK; *Erkki Ikonen, Priit Jaanson*

EMRP 'New primary standards and traceability for radiometry' Project Meeting, March 31 – April 1, 2014, LNE, Paris, France; *Meelis Sildoja, Timo Dönsberg, Erkki Ikonen*

EMRP 'New primary standards and traceability for radiometry' Stakeholder Meeting, April 1, 2014, LNE, Paris, France; *Meelis Sildoja, Timo Dönsberg, Erkki Ikonen*

EURAMET TC-PR meeting, April 2–3, 2014, LNE, Trappes, France; *Erkki Ikonen*

CIE Lighting Quality and Energy Efficiency Conference, April 23–26, 2014, Kuala Lumpur, Malaysia; *Tuomas Poikonen, Erkki Ikonen*

CIE Division 2 Technical Committee Meetings, April 28–30, 2014, Kuala Lumpur, Malaysia; *Tuomas Poikonen*

EMRP/EMPIR Research Sub-committee Meeting, April 28–30, 2014, Prague, Czech Republik; *Erkki Ikonen*

EMPIR Stage 2 Documents Workshop, May 15–16, 2014, MIKES, Espoo, Finland; *Erkki Ikonen*

EMRP 'Single-photon sources for quantum technologies' Project Meeting, May 22–23, 2014, INRIM, Turin, Italy; *Erkki Ikonen, Aigar Vaigu*

The 2014 Spring Conference of the European Materials Research Society (E-MRS), May 28–29, 2014, Lille, France; *Farshid Manoocheri*

EURAMET General Assembly and EMRP/EMPIR Committee Meeting, June 4–6, 2014, Dubrovnik, Croatia; *Erkki Ikonen*

EMRP 'Metrology of electrothermal coupling for new functional materials technology' Project Meeting, June 4–5, 2014, PTB, Braunschweig, Germany; *Maksim Shpak*

EMRP 'Multi-dimensional reflectometry for industry' Project Meeting, June 23, 2014, Espoo, Finland; *Priit Jaanson, Farshid Manoocheri, Ana Rabal, Erkki Ikonen*

The 12th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2014) Conference, June 23–27, 2014, Espoo, Finland; *All personnel of MRI, Petri Kärhä (Chaiman of the Local Organizing Committee), Erkki Ikonen (Chairman of the Scientific Committee)*

EMPIR SRT-i24, 'Optical metrology solutions for next generation lithography' Partnering Meeting, July 1–2, 2014, Berlin, Germany; *Farshid Manoocheri*

EMRP 'Metrology for Efficient and Safe Innovative Lighting' Kick-off Meeting, July 1–2, Delft, Netherlands; *Tuomas Poikonen*

EMPIR SRT-i27 'Improved measurement technology for optically complex materials' Partnering Meeting, July 3–4, 2014, Berlin, Germany; *Farshid Manoocheri*

EMRP ‘Traceability for surface spectral solar ultraviolet radiation’ Workshop and Project Meeting, July 14–18, 2014, Davos, Switzerland; *Petri Kärhä*, *Tomi Pulli*

EMPIR SRT-g24 ‘Electromobility’ Partnering Meeting, July 22, 2014, Berlin, Germany; *Hans Baumgartner*

EMRP ‘Metrology for manufacturing of thin films’ Project Meeting, July 23, 2014, NPL, Teddington, UK, *Farshid Manoocheri*

EMRP ‘Traceable characterisation of thin-film materials for energy applications’ Kick-off Meeting, July 24–25, 2014, NPL Teddington, UK; *Farshid Manoocheri*

EMRP ‘Metrology for industrial quantum communications’ Project Meeting, August 28–29, 2014, NPL, Teddington, UK; *Aigar Vaigu, Erkki Ikonen*

QCrypt 2014 Conference, September 1–5, Paris, France, 2014; *Aigar Vaigu*

EMRP ‘New primary standards and traceability for radiometry’ Project Meeting, September 9–10, 2014, CMI, Prague, Czech Republic; *Timo Dönsberg, Erkki Ikonen*

CIE Division 2 Technical Committee Meetings, September 9–10, 2014, Vienna Austria; *Tuomas Poikonen*

EMRP ‘Metrology for III-V multi-junction solar cells’ Kick-off Meeting, September 10–11, 2014, Paris, France; *Hans Baumgartner*

EMRP ‘Metrology for earth observation and climate’ Project Meeting, September 10–11, 2014, Teddington, UK; *Tomi Pulli*

CIE Tutorial and Expert Symposium on Measurement Uncertainties in Photometry and Radiometry for Industry, September 11–12, 2014, Vienna, Austria; *Tuomas Poikonen*

CIE Expert Symposium on Measurement Uncertainties in Photometry and Radiometry for Industry, September 12, 2014, Vienna, Austria; *Erkki Ikonen*

EMRP ‘Metrology for Efficient and Safe Innovative Lighting’ Stakeholder Meeting, September 13, 2014, Vienna, Austria; *Tuomas Poikonen*

EOSAM Conference, September 15–19, 2014, Berlin, Germany; *Meelis Sildoja*

CCPR WG-CMC, WG-KC and WG-SP Meetings, September 15–16, 2014, BIPM, Paris, France; *Erkki Ikonen*

CCPR Meeting, September 17–18, 2014, BIPM, Paris, France; *Erkki Ikonen*

EMRP ‘Towards an energy-based parameter for photovoltaic classification’ Kick-off Meeting, September 18–19, PTB, Braunschweig, Germany; *Tuomas Poikonen*

EMRP ‘Metrology for Earth observation and climate’ Project Meeting, September 22, 2014, NPL, Teddington, UK; *Erkki Ikonen*

EMRP ‘Traceability for atmospheric total column ozone’ Project Meeting, October 23–24, 2014, Davos, Switzerland; *Tomi Pulli, Petri Kärhä*

EMRP ‘Single-photon sources for quantum technologies’ Project Meeting, November 4–5, 2014, Prague, Czech Republic; *Albert Manninen, Erkki Ikonen*

EMPIR-Stair Kick-off Meeting, November 6, 2014, Brussels, Belgium; *Erkki Ikonen*

Aalto University Academic Summit, November 18–19, 2014, Espoo, Finland; *Erkki Ikonen*

EMRP ‘Metrology of electrothermal coupling for new functional materials technology’ Project Meeting, November 19–20, 2014, Aachen, Germany; *Maksim Shpak*

EMRP/ EMPIR Committee Meeting, November 24–25, 2014, Berlin, Germany; *Erkki Ikonen*

EMRP ‘Multi-dimensional reflectometry for industry’ Project Meeting, December 2–5, 2014, Alicante, Spain; *Priit Jaanson*

6.3 Visits by the Laboratory Personnel

Toni Laurila, Friedrich-Alexander Universität and Max Planck Institute, Erlangen, Germany, February 4-8, 2013

Erkki Ikonen, Friedrich-Alexander Universität and Max Planck Institute, Erlangen, Germany, February 6-8, 2013

Petri Kärhä, LNE, Paris, France, April 17, 2013

Farshid Manoocheri, Priit Jaanson, LNE, Paris, France, September 18, 2013

Timo Dönsberg¸ LNE, Trappes, France, October 8, 2013

Maksim Shpak, CMI, Brno, Czech Republic, 12 November, 2013

Meelis Sildoja, Tõravere Observatory, Estonia, December 27, 2013

Tomi Pulli, NPL, Teddington, UK, June 13, 2014

Tuomas Poikonen, VSL, Netherlands, July 2, 2014

Hans Baumgartner¸ LNE, Trappes, France, September 12, 2014

Tuomas Poikonen, PTB, Braunschweig, Germany, September 18, 2014

Meelis Sildoja, PTB, Adlershof, Germany, September 19, 2014

Erkki Ikonen, MKEH, Budapest, Hungary, November 11, 2014

6.4 Research Work Abroad

Aigar Vaigu, NPL, Teddington, UK, March 17–21, 2014

Timo Dönsberg, CMI, Prague, Czech Republic, September 2–10, 2014

Priit Jaanson, JRC, Ispra, Italy, June 1–13 and July 1 – September 30, 2014

6.5 Visits to the Laboratory

Luiz Carlos de Azevedo, Cepel, Brazil, March 12, 2013

Carlos Hall, DEE, Brazil, March 12, 2013

Olga Tarasova, BelGIM, Belarus, May 21–22, 2013

Dmitriy Scums, BelGIM, Belarus, May 21–22, 2013

Siarhey Nikanenka, IP NASB, Belarus, May 21–22, 2013

Anja Geburtig, BAM, Germany, June 14, 2013

Marla Dowell, NIST, USA, 11–14 December, 2013

Geiland Porrovecchio, CMI, Czech Republic, February 25–28, 2014

Emma Woolliams, NPL, UK, September 24, 2014

Johannes Heinsoo, ETHZ, Switzerland, September 26, 2014

Brian Eves, NRC, Canada, December 4–5, 2014

EMRP MetEOC Project Meeting attendees, April 9–10, 2013

Eija Honkavaara, FGI, Finland

Lauri Markelin, FGI, Finland

Jouni Peltoniemi, FGI, Finland

Marco Pisani, INRIM, Italy

Mauro Rajteri, INRIM, Italy

Christian Monte, PTB, Germany

Dieter Taubert, PTB, Germany

Romaine Etienne, LNE, France

Wolfgang Finsterle, SFI Davos

Jean-Luc Widlowski, JRC, Italy

EMRP METCO Project Meeting attendees, May 14, 2013

Paul Weaver, NPL, UK

Peter Woolliams, NPL, UK

Tatiana Correia, NPL, UK

Hameury Jacques, LNE, France

Christopher Shaw, Cranfield University, UK

Participants of the NEWRAD 2014 Conference, June 27, 2014 – Excursion to the laboratories of Metrology Research Institute and MIKES, total of 75 guests

Ian Littler, NMIA, Australia, June 23, 2014

Khaled Mahmoud, KRISS, June 30, 2014

Wen-Chun Liu, ITRI, Taiwan, June 30, 2014

Yi-Chen Chuang, ITRI, Taiwan, June 30, 2014

6.6 Thematic Network for Ultraviolet Radiation Measurements

The Thematic Network for Ultraviolet Measurements (UVNet) was very active during this period. The UVNet including its mailing list was used to disseminate progress and results of the EU-funded EMRP project Solar UV, Traceability for surface spectral solar ultraviolet radiation. This project was coordinated by Julian Gröbner and Luca Egli of the PMOD/WRC in Davos, Switzerland.

UVnet produced two newsletters, *UVNews* **9** in January 2013 and *UVNews* **10** in July 2014. These newsletters included altogether 28 articles on 92 pages presenting the project results and other UV related activities.

Two UV Workshops were arranged in Davos in August 2013 and in July 2014. These workshops gathered scientists all around the world. During the second workshop, an intercomparison campaign was arranged as well (Figure 27). In this occasion, participants had the opportunity to use the techniques developed in the project to characterize their own devices.

Figure 27. View from the roof of PMOD/WRC
during the intercomparison campaign in July 2014.

7 PUBLICATIONS

7.1 Articles in International Journals

T. Pulli, P. Kärhä, J. Mes, J. Schreder, P. Jaanson, and F. Manoocheri, "Improved Diffusers for Solar UV Spectroradiometers," Radiation Processes in the Atmosphere and Ocean (IRS2012), *AIP Conference Proceedings* **1531**, 813–816 (2013).

T. Pulli, P. Kärhä, and E. Ikonen, "A method for optimizing the cosine response of solar UV diffusers," *J. Geophys. Res.* **118**, 7897–7904 (2013).

J-M. Hirvonen, T. Poikonen, A. Vaskuri, P. Kärhä, and E. Ikonen, "Spectrally adjustable quasi-monochromatic radiance source based on LEDs and its application for measuring spectral responsivity of a luminance meter," *Meas. Sci. Technol.* **24**, 115201 (2013).

M. Sildoja, F. Manoocheri, M. Merimaa, E. Ikonen, I. Müller, L. Werner, J. Gran, T. Kübarsepp, M. Smîd, and M. L. Rastello, "Predictable quantum efficient detector: I. Photodiodes and predicted responsivity," *Metrologia* **50**, 385–394 (2013).

I. Müller, U. Johannsen, U. Linke, L. Socaciu-Siebert, M. Smîd, G. Porrovecchio, M. Sildoja, F. Manoocheri, E. Ikonen, J. Gran, T. Kübarsepp, G. Brida, and L. Werner, "Predictable quantum efficient detector: II. Characterization and confirmed responsivity," *Metrologia* **50**, 395–401 (2013).

E. Puukilainen, O. Ohtonen, T, Lemmettylä, V. Linnamo, B. Hemming, T. Laurila, S. Tapio, M. Räsänen, M. Ritala, M. Leskelä, "Changes in the Cross-Country ski base properties resulting from the ski use," *Sports Eng.* **16**, 229–238 (2013).

M. Sildoja, T. Dönsberg, H. Mäntynen, M. Merimaa, F. Manoocheri, and E. Ikonen, "Use of the predictable quantum efficient detector with light sources of uncontrolled state of polarization," *Meas. Sci. Technol.* **25**, 015203 (2014).

A. Manninen, T. Kääriäinen, T. Parviainen, S. Buchter, M. Heiliö, and T. Laurila, ”Long distance active hyperspectral sensing using high-power near-infrared supercontinuum light source," *Opt. Express* **22**, 7172–7177 (2014).

A. Heikkilä and P. Kärhä, “Photoyellowing revisited: Determination of an action spectrum of newspaper,” *Polym. Degrad. Stab.* **99**, 190–195 (2014).

T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, L. Petroff, and E. Ikonen, “A primary standard of optical power based on induced-junction silicon photodiodes operated at room temperature,” *Metrologia* **51**, 197–202 (2014).

M. Shpak, P. Kärhä, G. Porrovechio, M. Smid, and E. Ikonen, “Luminance meter for photopic and scotopic measurements in the mesopic range,” *Meas. Sci. Technol.* **25**, 095001 (2014).

F. Manoocheri, M. Sildoja, T. Dönsberg, M. Merimaa, and E. Ikonen, “Low-loss photon-to-electron conversion,” *Opt. Rev.* **21**, 320–324 (2014).

H. Baumgartner, A. Vaskuri, P. Kärhä, and E. Ikonen, “A temperature controller for high power light emitting diodes based on resistive heating and liquid cooling,” *Appl. Therm. Eng.* **71**, 317–323 (2014).

T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, L. Petroff, and E. Ikonen, “Primary standard of optical power operating at room temperature,” *EPJ web conf.* **77**, 00012 (2014).

T. Dönsberg, T. Pulli, T. Poikonen, H. Baumgartner, A. Vaskuri, M. Sildoja, F. Manoocheri, P. Kärhä, and E. Ikonen, ”New source and detector technology for the realization of photometric units,” *Metrologia* **51**, S276–S281 (2014).

P. Jaanson, F. Manoocheri, H. Mäntynen, M. Gergely, J.-L. Widlowski, and E. Ikonen, “Gonioreflectometric properties of metal surfaces,” *Metrologia* **51**, S314–S318 (2014).

S. Pourjamal, H. Mäntynen, P. Jaanson, D. Rosu, A. Hertwig, F. Manoocheri, and E. Ikonen, “Characterization of thin film thickness,” *Metrologia* **51**, S302–S308 (2014).

M. L. Rastello, I. P. Degiovanni, A. G. Sinclair, S. Kück, C. J. Chunnilall, G. Porrovecchio, M. Smid, F. Manoocheri, E. Ikonen, T. Kubarsepp, D. Stucki, K. S. Hong, S. K. Kim, A. Tosi, G. Brida, A. Meda, F. Piacentini, P. Traina, A. Al Natsheh, J. Y. Cheung, I. Müller, R. Klein and A. Vaigu, “Metrology for industrial quantum communications: the MIQC project,” *Metrologia* **51**, S267–S275

(2014).

J. I. Peltoniemi, T. Hakala, J. Suomalainen, E. Honkavaara, L. Markelin, M. Gritsevich, J. Eskelinen, P. Jaanson, and E. Ikonen, “Technical notes: A detailed study for the provision of measurement uncertainty and traceability for gonio-spectrometers,” *J. Quant. Spectrosc. Radiat. Transf.* **146**, 376–390 (2014).

7.2 International Conference Presentations

A. Vaskuri, P. Kärhä, H. Baumgartner, J. Oksanen, L. Riuttanen, G. Andor, and E. Ikonen, “Radiometric determination of the junction temperature of light-emitting diodes,” *Proc. CIE Centenary Conference “Towards a New Century of Light,”* Paris, April 15–16, 2013, pp. 308–316. (Talk)

M. Shpak, P. Kärhä, G. Porrovecchio, J.-M. Hirvonen, M. Smid, and E. Ikonen, ”Characterized photopic-scotopic luminance meter for measurements in the mesopic range,” *Proc. CIE Centenary Conference “Towards a New Century of Light,”* Paris, April 15–16, 2013, pp. 601–604. (Poster)

G. Porrovecchio, M. Smid, M. Shpak, P. Kärhä, and E. Ikonen, “Low noise detection system for mesopic and scotopic photometry,” *Proc. CIE Centenary Conference “Towards a New Century of Light,”* Paris, April 15–16, 2013, pp. 605–606. (Poster)

T. Poikonen, T. Pulli, P. Kärhä, and E. Ikonen, “Effect of rotation axis on the value of photometer directional response index f_2,” *Proc. CIE Centenary Conference “Towards a New Century of Light,”* Paris, April 15–16, 2013, pp. 607–610. (Poster)

H. Baumgartner, P. Kärhä, D. Renoux, “Lifetime of LED light sources,” *Conference on Metrology for Solid State Lighting*, NPL, London, April 24–25, 2013. (Talk)

P. Kärhä, A. Vaskuri, H. Baumgartner, G. Andor, and E. Ikonen, “Relationships between junction temperature, forward voltage and spectrum of LEDs,” *Conference on Metrology for Solid State Lighting*, NPL London, April 24–25, 2013. (Talk)

P. Kärhä, H. Baumgartner, D. Renoux, A. Vaskuri, and G. Andor, “Life Time of LED Light Sources,” EMRP SSL Project Workshop for the EURAMET TC-PR, DFM, Copenhagen, February 26, 2013. (Talk)

A. Heikkilä, P. Kärhä, M. Kaunismaa, and H. Lemmetyinen, “Accounting for time and intensity of exposure in deriving action spectra of photo-degradation,” In: Reichert T. (editor): *Natural and Artificial Ageing of Polymers*, 6th European Weathering Symposium 11th – 13th September 2013, Bratislava, Slovak Republic. CEEES Publication No 16, Gesellshaft für Umweltsimulation e.V. GUS, 2013. ISBN 978-3-9813136-8-0, pp. 85–92.

E. Ikonen, “State-of-the-art in radiometry, photometry, photon quantities,” Workshop organized by CCPR WG-SP on *SI units for photometry and radiometry*, Paris, April 22, 2013. (Invited talk)

T. Stevenson, T. Comyn, A. Bell, M. Shpak, P. Weaver, “Electro-optic effects in high temperature, bulk, piezoelectric ceramics,” *Piezo 2013 Electroceramics for End-users VII Conference*, Bourg-Saint-Maurice, March 18, 2013. (Talk)

P. Weaver, T. Correia, P. Woolliams, G. Bartl, T. Quast, T. Stevenson, J. Hameury, P. Klapetek, M. Shpak, T. Schmitz-Kempen, “Electro-thermal coupling and new functional materials technology,” *Piezo 2013 Electroceramics for End-users VII Conference*, Bourg-Saint-Maurice, March 18, 2013. (Poster)

P. Weaver, P. Woolliams, T. Correia, G. Bartl, T. Quast, T. Stevenson, J. Hameury, P. Klapetek, M. Shpak, T. Schmitz-Kempen, “High Temperature Piezoelectric and Electrocaloric Metrology,” *2013 Joint UFFC, EFTF, and PFM Symposium*, Prague, July 21–25, 2013. (Talk)

P. Weaver, P. Woolliams, T. Correia, G. Bartl, T. Quast, T. Stevenson, J. Hameury, P. Klapetek, M. Shpak, T. Schmitz-Kempen, “Metrology of Electro-thermal coupling for new functional materials technology,” *EMRP/EMPIR Open Workshop*, Braunschweig, October 22, 2013. (Talk)

T. Pulli, P. Kärhä, J. Mes, J. Schreder, and E. Ikonen, “Improved Diffusers for Solar UV Measurements,” *UVNet 7th Workshop on Ultraviolet Radiation Measurements*, Davos, August 27–28, 2013. (Talk)

E. Ikonen, F. Manoocheri, M. Sildoja, T. Dönsberg, and M. Merimaa, "Low-Loss Photon-to-Electron Conversion," *Technical Digest of Optics in Engineering Symposium*, Utsunomiya, September 2013, pp. 9–10. (Invited talk)

T. Dönsberg, M. Sildoja, F. Manoocheri, M. Merimaa, L. Petroff, and E. Ikonen, "Primary standard of optical power operating at room temperature," *International Congress of Metrology 2013*, Paris, October 7–10, 2013. (Talk)

E. Woolliams, D. H. Lee, E. Ikonen, "Uncertainty Evaluation for Linking Key Comparisons with the Corresponding CIPM Key Comparison: the CCPR Approach," *Workshop on Key Comparison Data Evaluation*, London, November 6, 2013. (Talk)

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H. Baumgartner, D. Renoux, A. Vaskuri, T. Pulli, T. Poikonen, P. Kärhä, and E. Ikonen, "Lifetime projection of LED light sources," *Proc. Finnish Physics Days 2013*, Espoo, March 11–16, 2013, p. 10.18. (Poster)

J.-M. Hirvonen, T. Poikonen, P. Kärhä, and Erkki Ikonen, "Spectrally Tunable Radiance Source based on LEDs," *Proc. Finnish Physics Days 2013*, Espoo, March 11–16, 2013, p. 10.20. (Poster)

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7.4 Other Publications

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7.5 Awards

Meelis-Mait Sildoja, National contest of students' scientific works 2013 (Estonia), 2. prize in the in the field of natural sciences and technics under the doctoral students category for the doctoral dissertation “Predictable Quantum Efficient Detector”, 2013.

Anna Vaskuri, Masters of Aalto ‘14, Master’s thesis “Multi-Wavelength Setup Based on Lasers for Characterizing Optical Detectors and Materials” was selected for Masters of Aalto ’14 exhibition, which promotes the finest theses of the year from Aalto University.

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