

# BIENNIAL REPORT 2009–2010



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**SCIENCE + TECHNOLOGY** 3/2011

# BIENNIAL REPORT 2009–2010

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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

A series of organizational changes in the host university of the Metrology Research Institute took place during the years 2009–2010. At the end of year 2009 the Helsinki University of Technology (TKK) ceased to be an independent university. TKK was one of the three merging universities in the Helsinki area which now operate under the name Aalto University. From the beginning of 2011, the Institute belongs to the Department of Signal Processing and Acoustics at the Aalto University School of Electrical Engineering. In addition, the Institute is a joint unit of the Aalto University and Centre for Metrology and Accreditation (MIKES) and operates under the Finnish name MIKES-Aalto Mitäustekniikka as the Finnish national standards laboratory for optical quantities.

The Metrology Research Institute has active international collaboration with world leading research units in the wide field of optical radiation measurements. These important research contributions from lighting measurements to applied quantum optics are described in more detail in Sec. 5 of this biennial report. In 2009–2010, significant efforts of the personnel were devoted to participation in the European Metrology Research Program (EMRP). As a result, altogether five new projects have been selected for funding, related to solid state lighting, remote sensing, solar UV, thin film characterizations, and quantum communications. Although the funding level from the EMRP is low, the Institute has demonstrated the depth and breath of its expertise by the number of selected projects, which is larger than for any other European laboratory in the field of optical radiation measurements.

The number of calibration certificates issued in 2009–2010 is 108, which is about the same number as for the period 2007–2008. Four doctoral degrees and sixteen M.Sc. degrees were achieved in 2009–2010. The number of degrees per year is larger than that for the period 2007–2008, partly caused by the 2010 deadline of M.Sc. studies for older students.

Erkki Ikonen

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### 3 TEACHING

#### 3.1 Courses

The following courses were offered by the Metrology Research Institute in 2009–2010. Those marked by \* are given biennially.

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S-108.1010	Fundamentals of Measurements A 4 p (Petri Kärhä)
S-108.1020	Fundamentals of Measurements Y 3 p (Petri Kärhä)
S-108.2010	Electronic Measurements 3 credits (Petri Kärhä)
S-108.2110	Optics 5 credits (Pasi Manninen, Tuomas Hieta, Erkki Ikonen; in 2010 Petri Kärhä)
S-108.3011	Sensors and Measurement Methods 5 credits (Pasi Manninen; since 2011 Maksim Shpak)
S-108.3020	Electromagnetic Compatibility 2 credits (Esa Häkkinen)
S-108.3030	Virtual Instrumentation* 5 credits (Petri Kärhä; Since 2010 Farshid Manoocheri)
S-108.3110	Optical Communications 5 credits (Farshid Manoocheri, Goery Genty)
S-108.3120	Project Work 2-8 credits (Erkki Ikonen, Tuomas Poikonen)
S-108.3130	Project Work in Measurement Science and Technology 2-10 credits (Erkki Ikonen, Tuomas Poikonen)
S-108.3140	Project Work in Optical Technology 2-10 credits (Erkki Ikonen, Tuomas Poikonen)

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S-108.4010	Postgraduate Course in Measurement Technology* 10 credits (Petri Kärhä)
S-108.4020	Research Seminar on Measurement Science 2 credits (Erkki Ikonen; in 2010 Petri Kärhä)
S-108.4110	Biological Effects and Measurements of Electromagnetic Fields and Optical Radiation* 4 credits (Kari Jokela)
S-108.4120	Special Course in Measurement Science and Technology* 2-6 credits (Erkki Ikonen)

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## 3.2 Degrees

### 3.2.1 Doctor of Science (Technology), D.Sc. (Tech.)

Mikko Puranen (2009), *Pulsed Radar Measurements and Related Equipment*  
Opponent: Prof. Mike Underhill, Underhill Research, United Kingdom

Silja Holopainen (2009), *Absolute Measurement Methods for Reflectance and Fluorescence*

Opponent: Prof. Andy Monkman, Durham University, United Kingdom

Maija Ojanen (2010), *Spectral Irradiance and Radiation Temperature Scales*  
Opponent: Dr. Arnold Gaertner, National Research Council of Canada, Canada

Ahtee Ville (2010), *Advanced Applications of Wavelength Tunable Lasers in Metrology and in Fundamental Physics*

Opponent: Prof. Alan Madej, National Research Council of Canada, Canada

### 3.2.2 Licentiate of Science (Technology), Lic.Sc. (Tech.)

Tuomas Poikonen (2010), *Characterization of LED Luminous Flux and Photometer Spectral Responsivity*

### **3.2.3 Master of Science (Technology), M.Sc. (Tech.)**

Kaija Rantoja (2009), *Goniometric Measurements of Liquid Fluorescent Materials*

Petteri Ahonen (2009), *Extension of Spectral Responsivity Scale for Infrared Detectors*

Nicklas Forss (2009), *An Ozone Measurement Device Utilizing a UV-LED Light Source*

Marko Kanto (2009), *Statistical Methods in Integrated Circuit Characterisation (in Finnish)*

Akseli Miranto (2009), *Microelectromechanical Infrared Spectrometer*

Jussi Mäkynen (2009), *A Lightweight Hyperspectral Imager*

Satu Ristiluoma (2010), *Construction of a HeCd-Laser-Based Spontaneous Parametric Down-Conversion Setup*

Jokke Ryyänen (2010), *Calibration System Development for Doppler Speed Radar (in Finnish)*

Jonna Paatelma (2010), *Automation and Characterization of a Goniofluorometer*

Pyry Ekholm (2010), *Measurement and Mapping of Night Sky Pollution (in Finnish)*

Elina Kuisma (2010), *Microelectromechanical Magnetometer for Fusion Reactor Diagnostics*

Risto Malmstedt (2010), *Computer Controlled Testing System for Electrical Safety (in Finnish)*

Jukka Ainali (2010), *Analysis Tool for Monitoring Production of Electronics Using Gage Repeatability and Reproducibility Indices*

Juuso Alanen (2010), *Error Sources in Spectral Irradiance Measurements (in Finnish)*

Jyrki Sippola (2010), *Properties of a New Production Test System Architecture*

Kai Niiranen (2010), *Calibration System for Insulating Glass Gas Concentration Analyzer (in Finnish)*

### **3.2.4 Bachelor of Science (Technology), B.Sc. (Tech.)**

Antti Matinlauri, *Puolisiltamoduulin automaattisen testilaitteen mittaustulosten tilastollisen seurannan toteuttaminen*, Candidate work, TKK, Espoo, 2009, (guided by Petri Kärhä)

Tomi Pulli, *Energiansäästölamppujen valotehokkuuden mittaaminen*, Candidate work, Aalto University, 2010, 34 p. (guided by Tuomas Poikonen)

## 4 NATIONAL STANDARDS LABORATORY

Metrology Research Institute 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 2009, 56 calibration certificates were issued. In 2010, the number of calibration certificates was 52. 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) tkk.fi, Tel. +358-9-470 22289, 050-596 8469

## 5 RESEARCH PROJECTS

### 5.1 Electrical Instrumentation

#### *LED driver and temperature controller*

In 2010, a new linear current driver and temperature controller were designed and constructed for optical measurements of LEDs (see Figure 1). A modular internal design was chosen for easy servicing. All connections and circuits are protected for short circuits. A thermal fuse is used for protecting the electronics, in case the operating temperature of the unit gets too high. The device has two current ranges, 0–200 mA for low-power LEDs, and 0–2 A for high-power LEDs with precisions of 1  $\mu\text{A}$  and 10  $\mu\text{A}$ , respectively. The main components of the current source are an instrumentation amplifier measuring over a precision shunt resistor, an I-controller and a high current voltage buffer. The time constant of the controller can be selected from 0.2 Hz to 560 kHz. External modulation can be used from DC-operation to fairly short pulses, if needed.



Figure 1. The new LED driver and temperature controller.

The temperature of the LED-holders is measured with an AD590JF temperature transducer and is adjusted with a Peltier element driven by a PI-controller. The temperature can be set in the range of 10–70  $^{\circ}\text{C}$  with a precision of 0.1  $^{\circ}\text{C}$ . The

control parameters, such as speed and maximum power of the Peltier drive can be fine-tuned for different Peltier elements and LED holders of different sizes. The PI-control parameters for low- and high-power LEDs can be adjusted individually using the trimmers inside the device. For switching between control circuits and operating modes, both conventional and semiconductor relays are used.

## 5.2 Optical Radiation Measurements

### *Improvements in LED luminous flux setup*

The integrating sphere setup of LED luminous flux was further improved in 2009 by a new LED holder and baffle design (see Figure 2). The original baffles and the LED holder of the sphere were replaced with our custom-made parts. The size of the new baffles was optimized to be as small as possible to reduce unnecessary screening, while maintaining the functionality. The design of the LED holder was also revised. The holder was equipped with an aluminum cone head to reduce absorption of the backward emission of LEDs. The new baffle, which is needed in the total luminous flux measurements, is now fixed to the holder and can be detached from the sphere together with the holder. These design changes clearly improve the spatial responsivity of the measurement setup.



Figure 2. New custom parts of the LED luminous flux sphere.

The SRDF (Spatial Resonivity Distribution Function) of the sphere was scanned in partial flux geometry using a green collimated LED and a rotation stage in the center of the 50-mm entrance aperture of the sphere. The scanning was conducted before and after the modifications, in both vertical and horizontal directions covering a measurement angle of  $\pm 60^\circ$ . With the new baffles, variation of less than  $\pm 1.5\%$  in the SRDF was obtained in the area, where the light does not illuminate the baffles directly. This is a vast improvement compared to the old design, which resulted in variation of more than  $\pm 5\%$  in the SRDF. Spatial correction factors were simulated for LEDs having varying angular distributions. The results of the study show that the correction is needed only for LEDs having angular spread larger than  $\pm 40^\circ$  or significant minor beams. Expanded uncertainty ( $k = 2$ ) of the improved measurement setup varies between 1.2 % and 4.6 % depending on the measurement geometry, color, and the angular spread of the test LED light beam. A paper of the measurement setup has been published [T. Poikonen, P. Manninen, P. Kärhä, and E. Ikonen, Multifunctional Integrating Sphere Setup for Luminous Flux Measurements of Light Emitting Diodes, *Rev. Sci. Instrum.* **81**, 023102 (2010)].

In some cases, it is more reasonable to measure the optical power of LEDs instead of luminous flux. This is especially true for such single-color LEDs, of which emission spectra are close to the edges of the  $V(\lambda)$ -function, and are not used for general lighting. In 2010, the integrating sphere setup was calibrated for spectral radiant flux using a spectroradiometer. This allows measurement of LEDs without photometric weighting. On the other hand, the weighting can be calculated afterwards from the spectral data if needed. The calibration of the measurement setup was tested by measuring radiant flux of a UV-LED of type HERO HUVL370-510. The measured radiant flux differs only 1.7 % of the minimum specified value reported by the manufacturer.

#### *Metrology for solid state lighting (EMRP SSL)*

Metrology for Solid State Lighting (EMRP SSL) is a three year project funded by the European Metrology Research Program (EMRP). The project coordinated by VSL (the Netherlands) was started on May 1, 2010. Project participants include altogether 17 European National Standards Laboratories.

This project develops new measurement techniques for lamps and luminaires based on LEDs. The research is conducted as collaboration between the Euro-

pean National Standards Laboratories. Solid state lamps differ from traditional incandescent lamps significantly, e.g., from geometrical and spectral points of view. Power consumption is significantly reduced, but the shape of the drive current differs from sinusoidal, which complicates luminous efficacy measurements.

Metrology Research Institute develops a new type of two-channel luminance meter for reliable measurements of low light levels. In this so-called mesopic region, the human vision is adapted somewhere between the photopic and the scotopic visions. We also measure spectra of various LED lamps, and develop a method for determining the junction temperature of an LED from its spectrum. The ultimate goal is to study whether the method could be used to estimate the life time expectancy of solid state lamps.

#### *EMRP SSL: A setup for measuring luminous efficacy*

Luminous efficacy, defined as the luminous flux produced by a lamp divided by its electrical power, is an essential quantity in determining the energy consumption of light sources. Measurement of luminous efficacy for solid state lamps is a complicated task. Luminous flux setups have typically been characterized for incandescent light sources only. Color corrections and geometrical corrections need to be redefined for all solid state lamps to be measured. Luminous efficacy also requires electrical power to be measured. In the EMRP SSL project, there will be an intercomparison of facilities that the National Standards Laboratories have for measuring luminous efficacies. As comparison artifacts, a selection of solid state light sources will be used.

In 2010, we built and tested a setup for measuring luminous efficacies of solid state lamps. The setup is based on our 1.65-m integrating sphere that was slightly modified and characterized (see Figure 3). The electrical wiring was renewed and a new lamp holder was constructed to allow operation of 230 V AC lamps. A programmable AC power supply was acquired for regulating the voltage for driving the test lamps. In addition to the basic 230 V and 50 Hz operation, the voltage and frequency can be adjusted for characterizing the lamp performance under varying power line conditions. A digital power meter was obtained for monitoring various parameters of the AC-input, such as voltage, current, frequency, and power factor. Frequencies up to 100 kHz are taken into account in the power measurements.

Various incandescent-, halogen-, CFL- and LED-lamps with E27 screw base were studied after a 100-h burn-in period. A new calibration method of the integrating sphere system was also tested. The luminous responsivity of the integrating sphere photometer was measured only once with an empty lamp holder, to minimize the burn time of the external standard lamp. Self-absorption corrections of the test lamps were determined using a halogen lamp in the auxiliary port of the sphere. The study revealed large variations in the luminous efficacy values between different LED-lamps suggesting that the structures of LED lamps may differ drastically from each other. In the case of LED-lamps, the measured luminous efficacies varied between 25 and 58 lm/W. The setup and its test measurements have been reported in a candidate work [T. Pulli, *Energiansäästölamppujen valotehokkuuden mittaaminen*].



Figure 3. Preparing an LED-lamp for luminous efficacy measurement.

### *EMRP SSL: Life time expectancy of solid state light sources*

In LEDs, junction temperature  $T_j$  is an essential parameter. The life time of an LED is greatly influenced by  $T_j$  – the higher the temperature, the shorter the life time. On the other hand,  $T_j$  also affects the spectrum of the LED. Known effects include broadening and shifting of the peak wavelength and change of the white/blue ratio in the case of white LEDs.

We assume that by measuring the spectrum of a solid state lamp, one can calculate  $T_j$  from the spectrum and predict the life time to some extent. The overall life time is of course influenced by other factors as well, but it is worthwhile to study this one effect. To build a model, that allows estimating the life time, various measurements are needed. The effect of the temperature on the life time of LEDs and lamps needs to be studied. Spectra need to be studied in order to find features that most reliably give the temperature. A lamp typically consists of various LEDs. It thus needs to be studied whether measurement of a lamp gives useful information on the single LEDs.

In 2010, we have been studying the lamp markets and mapped out possibilities to obtain solid state lamps, and the LEDs they consist of, to be studied in the project. Figure 4 shows examples of lamps studied.



Figure 4. A selection of solid state lamps with E27 base.

### *EMRP SSL: A two-channel mesopic luminance meter*

Solid state light sources offer large potential of saving energy in road lighting. However, present LEDs are rather directive, and new street luminaires produce narrower light beams than the earlier luminaires based on metalhalide, mercury and sodium lamps. This complicates the use solid state lamps, as the distances between the lamp posts need to be shortened. Such a change requires more effort than just replacing the luminaires.

Introducing new lamp posts is costly, thus savings may be acquired by more accurate measurements. In dusk conditions, human eye adapts. The vision gradually turns from photopic to scotopic when lighting is dimmed. In practice this means that the sensitivity of the eye shifts to bluer wavelengths to get optimal use of the light. Photopic and scotopic sensitivities are well defined and recently CIE has established recommendations for the mesopic region in between. The mesopic region lies within luminance levels of  $0.001\text{--}10\text{ cd}\cdot\text{m}^2$ .

In 2010, we have designed a two-channel luminance meter capable of measuring mesopic luminances (Figure 5). The device is based on combination of scotopic and photopic channels, into which the dim light is guided with focusing optics and a beam splitter. The signals produced by the photodiodes are of the order of picoamperes. They will be amplified with special amplifiers built by the Czech Metrology Institute. The project will continue with building and characterising the device in 2011.

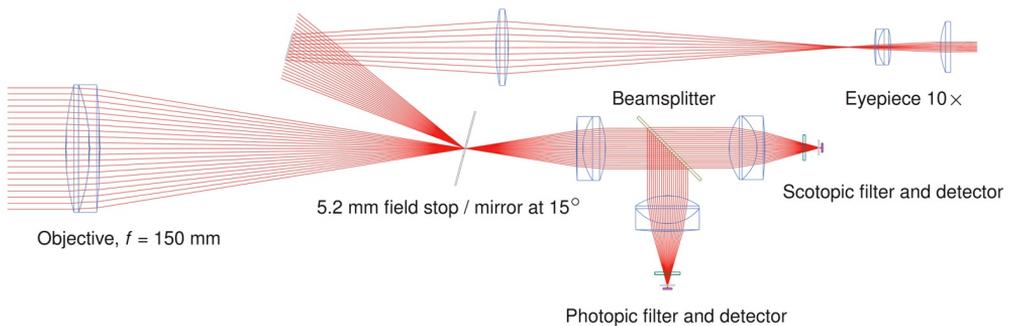


Figure 5. Optical layout of the two-channel mesopic luminance meter.

### *Spectral radiance source*

In 2010, a survey for building a spectrally tunable radiance source began. One of the key ideas was to use LEDs for producing the monochromatic output instead of using a broadband source and a monochromator. When ready, the setup can be used for calibrations of spectral responsivity of luminance meters and  $r,g,b$  color functions of cameras. Such calibrations are occasionally asked by customers. Mostly single-color high-power LEDs were selected for covering the visible wavelength range. Such wavelengths, which cannot be achieved with single-

color LEDs, are produced using combinations of white LEDs and optical filters. The output of the radiance source can be made uniform by using either Teflon sheets or an integrating sphere, or a combination of these two. Test measurements were done with a high-power LED and one or two diffuser plates at varying geometries. The tests showed that the spatial uniformity on the last diffuser plate was not sufficient for the purpose. A uniform output could be achieved if the diffuser plates were combined with an absorption mask fitted for compensating the angular intensity distribution of the LED. However, due to the reason that the different colors of the source have to be made using LEDs with varying angular spreads, fitting of a separate absorption mask for each color would be needed. Therefore, an integrating sphere is used for the final setup. The LED color will be changed by a large rotating heatsink, on which the LEDs and filters are mounted.

#### *Uncertainty analysis of photometer quality factor $f_1'$*

Quality factor  $f_1'$  quantifies the spectral matching of photometers with the  $V(\lambda)$  function. We have studied the applicability of random and biased error models for determining the uncertainty of  $f_1'$  using Monte Carlo simulations and real spectral responsivity data of two photometers. In the case of filtered detectors, the wavelength uncertainty of the spectral responsivity measurement with a monochromator may cause a large biased error contribution to the relative spectral responsivity  $s_{\text{rel}}(\lambda)$  of the photometer, in addition to true random uncertainty components. The results show that the random error model alone underestimates the uncertainty of  $f_1'$ . The real effect of the biased uncertainty components, such as that due to the wavelength scale, on the uncertainty of  $f_1'$  can be evaluated only with the biased error model.

It was also found that the uncertainty of  $f_1'$  can be highly sensitive to fine details of the spectral responsivity data when the biased error model is used. Lower uncertainties of  $f_1'$  are obtained with spectral responsivity data, which cross the  $V(\lambda)$  curve at several wavelengths. The results of Monte Carlo simulations with the biased error model for this type of spectral responsivity data approach the simulation results obtained with the random error model. Due to the absolute value integrand in the definition of  $f_1'$ , Monte Carlo simulations may produce mean values of the probability distribution of  $f_1'$  that are higher than the nominal value of  $f_1'$  calculated using the nominal spectral responsivity of the photometer.

A practical interpretation of this result is that the estimate of  $f_1'$  is given by the nominal value which is accompanied by a skewed probability distribution of  $f_1'$  where the mean does not necessarily coincide with the nominal value of  $f_1'$ . Also, in practice the shift from the nominal value is small as compared with the uncertainty of  $f_1'$  when the biased uncertainty components dominate. Spectral responsivity data and Monte Carlo simulation results for two photometers are shown in Figure 6. A paper of the study has been published [T. Poikonen, P. Kärhä, P Manninen, F. Manoocheri and E. Ikonen, Uncertainty Analysis of Photometer Quality Factor  $f_1'$ , *Metrologia* **46**, 75–80 (2009)].

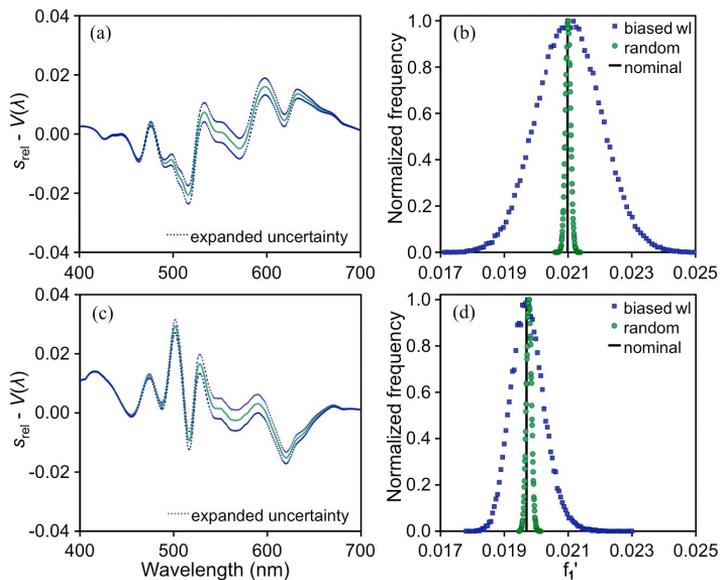


Figure 6. Deviation  $s_{\text{rel}}(\lambda) - V(\lambda)$  and absolute expanded uncertainty ( $k = 2$ ) of the relative spectral responsivity (a) for photometer 1 and (c) for photometer 2. Probability distributions of  $f_1'$  for (b) photometer 1 and (d) photometer 2.

In 2010, research was started to formulate a new general mathematical method for Monte Carlo simulations for uncertainty estimation of spectral measurements.

### *Measurements of photometer directional responsivity*

Photometers are often equipped with diffusing input optics in order to obtain a good cosine response. The CIE directional response index  $f_2$  quantifies the matching of the directional response of a photometer with the cosine function.

The measurement of the directional response is done by measuring a small light source at a relatively large distance and rotating the photometer in order to change the direction of light incident on the acceptance area of the photometer.

In 2010, the directional responses of three photometers were measured at the Metrology Research Institute and at METAS, in order to compare the resulting responsivities and  $f_2$  values. The uncertainties of the  $f_2$  values are simulated using Monte Carlo analysis. The preliminary results show that the  $f_2$  values of the three photometers are within a range of 1.26–4.65 %. The final results will be published during 2011.

### *Measurement of LED luminance*

Applicability of the method of effective luminous intensity to the determination of the LED luminance was studied in 2009. Illuminances from a few directional LEDs in variable distances were measured by an illuminance meter (Figure 7). From this measurement data, the effective luminous intensity, size, and location of the virtual source of the LEDs could be analyzed. The effective LED luminance was then obtained as a ratio of the effective luminous intensity to the area of the emitting surface of the virtual source. To verify the applicability of the method, the luminance distributions of the LEDs were measured by a luminance meter with narrow measurement angle. The average luminances were calculated from the luminance distributions measured. The agreement between the methods was typically within 5 %. The method of effective luminous intensity works best for the directional LEDs having flat-top-type luminance distributions. Such LEDs are also important from the point of view of eye safety.

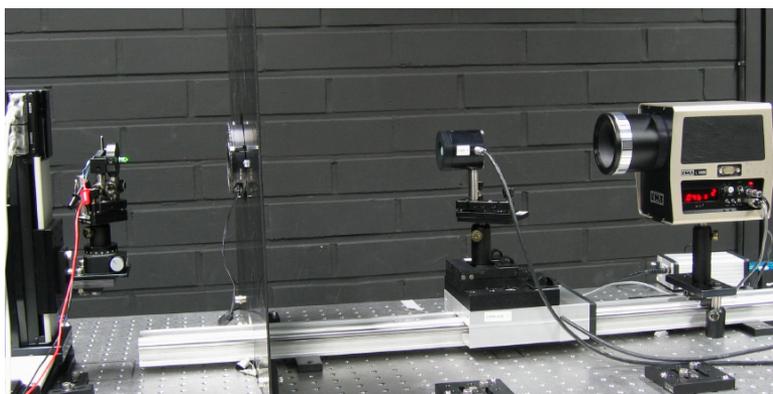


Figure 7. The measurement setup for determination of LED luminance.

### *Spectral irradiance model for 1 kW tungsten halogen lamps*

We have developed a physical model for the spectral irradiance of 1-kW tungsten halogen incandescent lamps for the wavelength range 340–850 nm. The model consists of the Planck’s radiation law, published values for the emissivity of tungsten, and a residual spectral correction function taking into account unknown factors of the lamp (Figure 8).

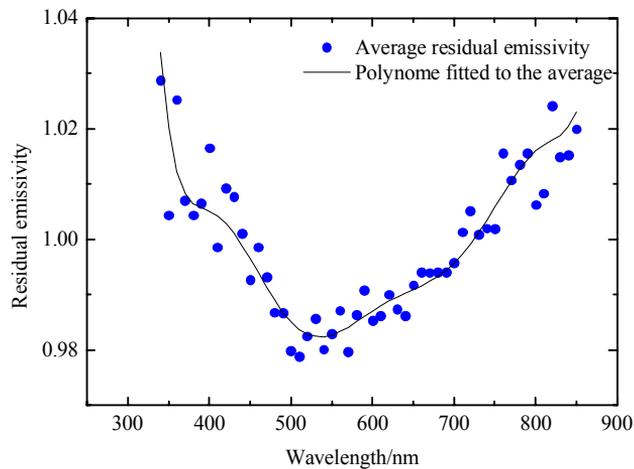


Figure 8. Averaged measured residual emissivity and an 8th degree polynomial fitted to the average.

The correction function was determined by measuring the spectra of an FEL type incandescent lamp at different temperatures. The model was tested with 1-kW tungsten halogen lamps of types FEL and DXW. Comparisons with measurements of two national standards laboratories (MIKES/Aalto and NPL) indicate that the model can account for the spectral irradiance values of lamps with an agreement better than 1 % throughout the spectral region studied.

The spectral irradiance of a lamp can be predicted with an expanded uncertainty of 2.6 % if the color temperature and illuminance values for the lamp are known with expanded uncertainties of 20 K and 2 %, respectively. Using resistance measurements at room temperature and at burning temperature, the temperature of the filament may be obtained by using the known temperature dependence of the resistance of tungsten. The results have been published [M. Ojanen, P. Kärhä, and E. Ikonen, Spectral Irradiance Model for Tungsten Halogen Lamps in 340-850 nm Wavelength Range, *Appl. Opt.* **49**, 880–886 (2010)].

### *Radiation temperature measurements*

Preparations for the development of the lower temperature measurement facility (500–850 °C) were continued. Linear pyrometer of type LP3 was calibrated, and it was used to characterize a new copper fixed point cell and a sodium heatpipe, which were purchased in spring 2009. The single-diode Si filter radiometers with nominal wavelengths of 800 and 900 nm and a new electrometer were used to measure the temperature of the sodium heatpipe in spring 2010. Significant differences between readings were observed at low temperatures. A difference of up to 25 °C was observed between the radiometers and a pyrometer, and up to 12 °C between two radiometers. The source of these errors has not been found yet.

### *Temperature measurements of silicon microbridge emitters*

Microbridges are miniature suspended structures fabricated in silicon. Microbridges can be used as wideband light sources when heated by passing a current through them. We investigated the behavior of the microbridge by measuring its emitted spectrum and determining the temperature from Planck's radiation law. The emissivity was modeled with thin-film Fresnel equations. Temperatures of 500–1100 °C were obtained from the measured spectra at different levels of applied power. The range is limited by the sensitivity of the detectors at lower power levels, and by the stability of the bridge at higher levels. Results of the optical measurements were compared with contact temperature measurements in collaboration with the Department of Micro and Nanosciences of Aalto University. Contact measurements were made with a microthermocouple in the same temperature range, and the results of the two methods agree within 100 K. A paper on the results of the study has been published [M. Shpak, L. Sainiemi, M. Ojanen, P. Kärhä, M. Heinonen, S. Franssila, and E. Ikonen, Optical Temperature Measurements of Silicon Microbridge Emitters, *Appl. Opt.* **49**, 1489–1493 (2010)].

To model the emissivity, knowledge about optical properties of highly doped silicon at high temperatures is needed. It was obtained by measuring the radiance of a bulk sample heated in the furnace to a known temperature, and calculating refractive indices as a function of wavelength. In 2010, this work was presented at a TEMPMEKO & ISHM conference in Slovenia [M. Shpak, P. Kärhä, M. Ojanen, E. Ikonen and M. Heinonen, Optical Temperature Measurement Method

for Glowing Microcomponents, *Int. J. Thermophys.* **31**, 1762–1770 (2010)].

The work will be continued in 2011, when the aim is to extend the measurements to a variety of doping levels and temperatures of the silicon samples.

### *Spectroscopic measurement of air temperature*

The refractive index of air for interferometric length measurements is conventionally calculated from parameters of ambient air using Edlén equations or their modified versions. These equations require an accurate knowledge of ambient conditions and especially the temperature of air. For example, to reach an uncertainty of  $10^{-7}$  in the refractive index, the air temperature has to be known within 100 mK. This does not necessarily cause problems in stable laboratory environment. However, for measurements outdoors or in industrial environment, variations in temperature can be very rapid and local temperature gradients can cause significant error if not taken into account. Moreover, if the required distance is long, the temperature over the whole measurement path can be impractical or impossible to determine at sufficient temporal or spatial resolution by conventional temperature sensors.

The developed method based on molecular spectroscopy of oxygen allows both lateral spatial and temporal overlap of the temperature measurement with the actual distance measurement. Temperature measurement using spectroscopy is based on the line intensity ratio of two oxygen absorption lines, previously applied for measurements of high temperature in flames. The oxygen absorption band at 762 nm is a convenient choice for two-line thermometry since the line strengths are practical for short- and long-distance measurements and suitable distributed feedback lasers are commercially available. Measurements carried out on a 67-m path at MIKES at ambient conditions demonstrate that the RMS noise of 22 mK near 293 K using 60 s measurement time can be achieved. The work was presented at a TEMPMEKO & ISHM conference in Slovenia [T. Hieta and M. Merimaa, Spectroscopic Measurement of Air Temperature, *Int. J. Thermophys.* **31**, 1710–1718 (2010)].

### *Uncertainty evaluation for linking a bilateral comparison with the corresponding CIPM key comparison*

A method for evaluating the uncertainty in linking a bilateral key comparison to another key comparison with several participants is presented theoretically and demonstrated with an actual comparison. Equations are derived for the uncertainties of the unilateral and mutual degrees of equivalence for the linked participant in the bilateral comparison. One of the main conclusions is that the uncertainty components related to uncorrelated effects in the measurements of the linking participant dominates the additional uncertainty due to the linking process. This finding is of special importance if participants with low uncertainties need to seek linkage to the key comparison reference value via bilateral or regional key comparisons. As a practical example, the results are applied to a bilateral comparison of the spectral irradiance scales of the Metrology Research Institute (Finland) and NIMT (Thailand) in the spectral range from 290 nm to 900 nm.

### *Testing a multi-wavelength filter radiometer at near infrared wavelengths*

The performance of an automatic multi-wavelength filter radiometer (MWFR) of the National Metrology Centre (NMC, Singapore) has been evaluated using a three-element InGaAs trap detector and nine narrow-band interference filters from NMC and from the Metrology Research Institute in a joint experiment conducted by researchers from both labs. Comparison measurements of detector spectral responsivity and filter spectral regular transmittance in the same wavelength range were also carried out. The maximum relative deviation of the measured photocurrent using MWFR and of the calculated photocurrent using known spectral irradiance values from a standard lamp was less than 1.8 % with an expanded uncertainty of 1.9 % ( $k = 2$ ). From the promising results obtained in this [Y.J. Liu, G. Xu, X.B. Huang, F. Manoocheri, E. Ikonen, submitted to *Light and Engineering* (2010)] and in earlier work [Y. J. Liu, G. Xu, M. Ojanen, and E. Ikonen, *Metrologia* **46**, S181 (2009)], it is concluded that a direct realisation of the spectral irradiance scale in the wavelength range of 300 nm to 1600 nm is possible using the MWFR.

### *Goniofluorometer for characterization of fluorescent materials*

A goniofluorometer can characterize the angular behaviour of fluorescence emission from various materials. The device can also measure the luminescent radiance factors in the wavelength range of 250–800 nm. Such measurements are needed so that the colour of a fluorescent specimen can be determined for a desired source and observer. Part of the research work has been devoted to investigations on possible non-Lambertian behaviour of the opaque fluorescent standard materials. Also extensive measurements of the fluorescence spectra of several well known fluorophores such as fluorescein, rhodamine 101, and quinine sulphate as liquid samples have been performed and reported. The work in developing methods for determination of fluorescent quantum yield is ongoing. There are also difficulties in traceable calibration of commercially available fluorometers used in various industries. To address this issue we have initiated the development of a calibration method using well known fluorophore liquid solutions with spectral and quantum efficiency traceability to our measurements using the gonio-fluorometer facility. For this purpose a luminescence spectrometer type LS 55 manufactured by Perkin Elmer is used.

### *Detector responsivity at infrared*

The development of the infrared spectrometer facility is nearly complete for accommodating accurate measurement of spectral power responsivity in the wavelength range from 0.7  $\mu\text{m}$  to 15  $\mu\text{m}$ . The measurements performed with the facility are traceable via a reference pyroelectric detector to the scale of optical power maintained by the laboratory. The uncertainty of the measurements depends on the spectral range and the device under test among other factors. At present, the best measurement uncertainty is about 4 % with components arising from measurement repeatability, linearity and spatial uniformity of reference detector, wavelength scale, and ambient condition of the measurement compartment.

### *Predictable Quantum Efficient Detector*

To replace the present primary standard of optical power – the cryogenic radiometer – and to possibly redefine the SI base unit of luminous intensity in terms of photon flux, a solid state based detector called Predictable Quantum Efficient Detector (PQED) is under development within the EMRP (European Metrology

Research Programme) joint research project Quantum Candela (see [www.quantumcandela.org](http://www.quantumcandela.org)). The goal is to construct an optical detector capable of measuring the flux of visible monochromatic radiation with the relative uncertainty of 1 ppm. Such a low uncertainty is theoretically achieved using custom-made silicon photodiodes with close to 100% quantum efficiency. Instead of a regular p-n junction, these diodes use an induced junction obtained via natural inversion layer occurring in thermally oxidized p-type silicon. When completed, the detector involves two high-efficiency photodiodes in a light-trapping configuration (Figure 9) to minimize the reflectance losses. In addition, the diodes are cooled down to cryogenic temperature and reverse biased to fulfill the conditions of the high collection efficiency. In this project Aalto University is a collaborator supported financially by the Academy of Finland and MIKES is responsible for building the detector.

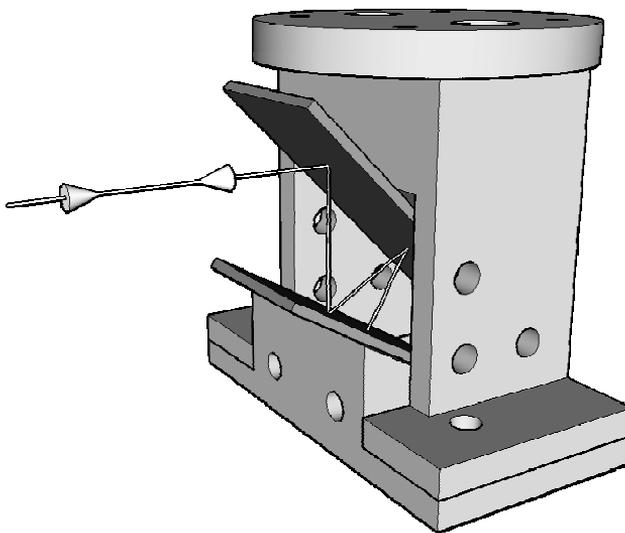


Figure 9. Laser beam travelling between two PQED photodiodes placed into a custom designed copper holder. The metal holder is required for good thermal conductivity. The diodes are misplaced for clear vision. In reality they are entirely inside the holder.

In 2009, a test PQED was built using the first set of photodiodes made by VTT. This prototype was measured against a reference standard trap detector with the uncertainty of 500 ppm at the wavelength of 488 nm. A set of responsivity non-uniformity and non-linearity measurements of single diodes was performed by partner institute PTB to study the quality of the diodes. These results showed

that external quantum efficiency close to 1 may be achievable. Surface smoothness measurements of the diodes were performed by MIKES. In 2010, a second set of photodiodes was manufactured by VTT exploiting some improvements over the first round diodes. For example, an additional contact behind the diode was added. The diode holders were redesigned to implement the changes of the diodes and to reduce the total size of the light-trapping structure. A few diodes were sent to PTB to study their non-uniformity and non-linearity and the dependence of their responsivity on temperature and bias voltage.

### *Optical identification of plastics*

The motivation for this preliminary study was to map out possibilities for future research projects on remote sensing of polymeric materials for recycling purposes. There is a growing need for accurate and fast optical identification of chemicals for plastics recycling automation. Two most promising technologies are Fourier-transform spectroscopy (FTIR) and laser induced plasma spectroscopy (LIPS).

FTIR is based on interferometric measurements of the spectral reflectances of materials. The measured interferogram is converted to an absorption spectrum using Fourier transform. Different chemical bonds of organic polymers can be identified from the absorption spectrum.

LIPS is based on an energetic laser pulse which is shot to the material under study. A few micrograms of material turn into plasma for some nanoseconds. This plasma radiates bright visible light which is measured with a fast spectrometer. The emission spectrum exposes unique excitation wavelengths of the elements involved. This makes LIPS useful for identifying chemical elements.

### *Effects of UV radiation on materials 2 (UVEMA-2)*

This two-year project funded by TEKES was a continuation of an earlier project. The work was carried out in collaboration with the Finnish Meteorological Institute, Tampere University of Technology and several industrial partners. The role of the Metrology Research Institute was to build an improved version of a device that can be used for studying the effect of wavelength on the UV ageing of materials.

The improved device (Figure 10), as its predecessor, is based on a concave flat-field holographic grating and a 1-kW Xe-lamp. The major improvements are:

1. The sample can be heated up to 80 °C to accelerate the ageing.
2. The output spectrum is limited to wavelengths 280–420 nm to avoid problems associated with higher order diffraction.
3. There is an additional sample port for the zero order diffraction.

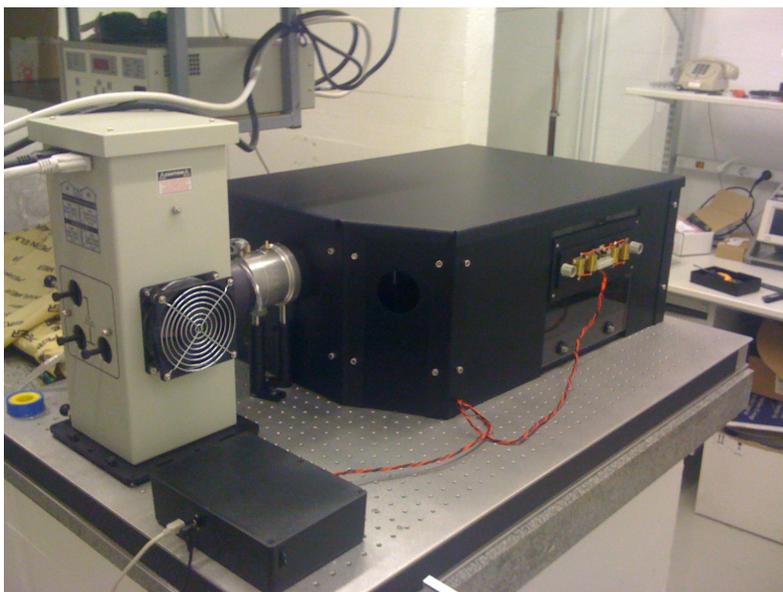


Figure 10. The new ageing facility. Light of the 1-kW Xe-lamp (left) is coupled into the spectrograph inside the black box. The components on the front surface of the box include a heater attached on the sample to heat it up to 80 °C. The zero-order diffraction comes out of the spectrograph through the round opening.

During 2009–2010, the device was assembled and thoroughly tested. The performance is comparable to the first prototype. The output power is slightly reduced due to the increased dispersion needed to meet the reduced wavelength region. Test measurements show that the heating works and does really accelerate the ageing (Figure 11). However, it was noted that in some cases the heating also changes the action spectrum. The channel containing the zero-order diffraction was a slight disappointment. This channel contains very little UV and thus samples attached to it age slower than anticipated.

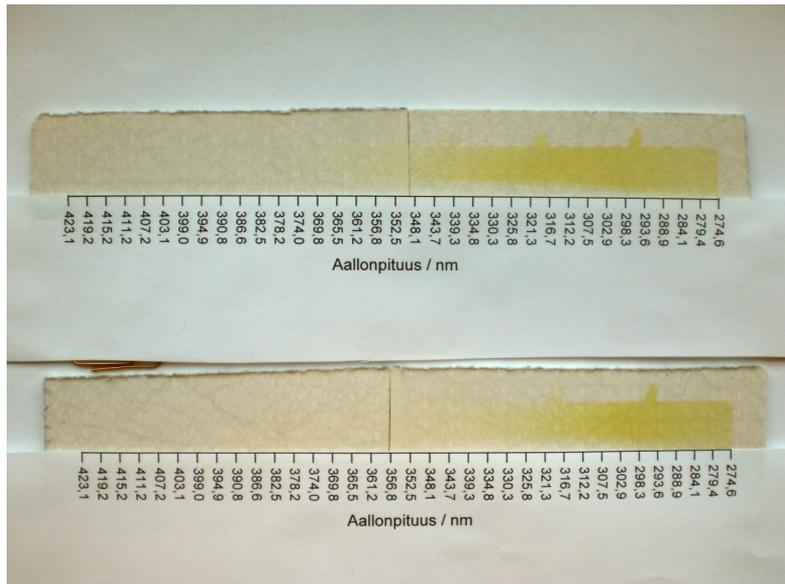


Figure 11. Aged polymer samples. The time for ageing has been the same for both samples, but the upper sample has been heated up to 70 °C. It is clearly seen that the ageing has been significantly accelerated.

### 5.3 Applied Quantum Optics

#### *New developments of single-photon sources*

There have been significant recent advances in radiometry in the development of single-photon sources and single-photon detectors, associated with such technologies as quantum computing and quantum cryptography. The acceptance of these new quantum-based technologies requires improved traceability and reliability of measurements at the level of a few photons as described in a recent review article [J. C. Zwinkels, E. Ikonen, N. P. Fox, G. Ulm and M. L. Rastello, Photometry, Radiometry and "the Candela": Evolution in the Classical and Quantum World, *Metrologia* **47**, R15–R32 (2010)] written as CCPR collaboration, with financial support from the Academy of Finland as an appropriation to Senior Scientist.

Researchers from the Metrology Research Institute have contributed to the work at ETH Zurich [V. Ahtee, R. Lettow, R. Pfab, A. Renn, E. Ikonen, S. Götzinger, V. Sandoghdar, Molecules as Sources for Indistinguishable Single Photons, *Journal of Modern Optics* **56**, 161–166 (2009)], where two-photon interference

has been demonstrated using two remote single molecules as bright solid-state sources of indistinguishable photons. By varying the transition frequency and spectral width of one molecule, the effect of photon distinguishability could be tuned. The work resulted in a concluding publication in 2010 [R. Lettow, Y. L. A. Rezus, A. Renn, G. Zumofen, E. Ikonen, S. Götzinger, and V. Sandoghdar, Quantum Interference of Tunably Indistinguishable Photons from Remote Organic Molecules, *Phys. Rev. Lett.* **104**, 123605 (2010)].

In a related work, a room-temperature single-photon source based on a single organic molecule with record photon count rates exceeding 48 MHz was reported. By designing the refractive index of the medium around the molecule, it is possible to collect 95.5% of the emitted photons emitted into a 120° cone. Because this extraction efficiency is insensitive to design parameters, the photon emission rate can be reliably predicted. Such a single-photon source holds great promise as a new primary intensity standard in the pW range and below [K.-G. Lee, X. Chen, H. Eghlidi, E. Ikonen, S. Götzinger and V. Sandoghdar, A Predictable Bright Single-Photon Source, *Proceedings of the CIE Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry* (Bern, Switzerland, 2010) pp. 60–61].

### *Coherence of radiation as studied by multiple coincidences of photons and particles*

Analogies between the coherence properties of photon and particle radiation are studied with the aim of applying the results obtained in quantum optics to heavy ion collisions. In particular, multiple coherent source components for particle correlation experiments are considered with partially coherent pion radiation produced by heavy-ion collisions. If the partial coherence in pion radiation will ever be conclusively demonstrated, the source properties producing this radiation become under study. The work contributes to the understanding of properties of such particle radiation. The conventional analysis, which assumes one coherent source current, is extended to cover the case of multiple coherent source currents. Theoretical calculations on the relation between two- and three-pion correlators give some evidence, when compared with experimental data, for the existence of multiple coherent components in heavy-ion collisions. In 2009–2010, these results were presented in particle collision conferences with financial support from the Academy of Finland as an appropriation to Senior Scientist

[E. Ikonen, Multiple Coherent Components in Heavy-Ion Collisions, *Proceedings of the XXth Hadron Collider Physics Symposium*, Eds. E. Auge and S. Bertolucci (Proceedings of Science, Trieste 2010) PoS(HCP2009)079, 3 p; E. Ikonen, Multiple Coherent Components in Relativistic Heavy-Ion Collisions, *Hadron 2009: Proceedings of the XIII International Conference on Hadron Spectroscopy*, Eds. V. Crede, P. Eugenio, and A. Ostrovidov (AIP Conference Proceedings Volume 1257, New York 2010) pp. 800–803].

## 6 INTERNATIONAL CO-OPERATION

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

### 6.1 International Comparison Measurements

#### **Key comparison CCPR-K2.a, spectral responsivity 900–1600 nm, pilot NIST**

The final report for the CCPR-K2.a, spectral responsivity at 900 nm–1600 nm, was approved in November 2009 and has been published in the *Metrologia Technical Supplement* [S. W. Brown *et al.*, *Metrologia* **47**, 02002 (2010)] and in the key comparison database (KCDB). The results of MIKES are well in agreement with the reference value of the key comparison.

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

The measurements are complete and the pre-Draft A process is finished. Draft A is expected in April 2011.

#### **Key comparison CCPR-K5, spectral diffuse reflectance, pilot NIST**

Draft A-2 in the form of Draft B has been prepared. The extended bilateral comparison results are also being analyzed.

#### **Key comparison EURAMET.PR-K6, spectral regular transmittance, pilot LNE**

MIKES acts as one of the seven EURAMET link laboratories in this regional key comparison to be linked to CCPR-K6. The measurement results from the year 2000 of CCPR-K6 were used for the linkage. The final report has been published in the KCDB.

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

MIKES and pilot measurements of four transfer standard lamps of luminous intensity were completed during 2008. The return measurements by MIKES were made in 2009.

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

MIKES measurements of four transfer standard lamps of luminous flux were completed during 2008. The pilot measurements and return measurements by MIKES were made in 2009.

### **Supplementary regional comparisons APMP.PR-S3.a, APMP.PR-S3.b, and APMP.PR-S3.c, LED related quantities, pilot KRISS**

The measured quantities in these comparisons include the CIE averaged luminous intensity  $B$ , total luminous flux, and chromaticity coordinates  $x$ ,  $y$  of LEDs. The MIKES measurements were completed during 2008. The draft A is expected in February 2011.

### **Bilateral comparison of spectral diffuse reflectance**

A comparison between the absolute gonireflectometric scales at the Metrology Research Institute and the Physikalisch-Technische Bundesanstalt (PTB) has been accomplished. Six different reflection standards were measured for their  $0:45^\circ$  spectral radiance factors between 250 nm and 1650 nm in 10 nm intervals. Also, the  $0:d$  reflectance factor between 400 nm and 1600 nm in 100 nm intervals was determined from the gonimetric reflectance measurements over polar angles with subsequent integration within the hemisphere above the sample. For all but one opal glass sample OG1, the differences between the results were within the expanded uncertainty of the comparison ranging from 0.6 % to 2.7 % up to 1400 nm wavelength. It was found that the significant level of translucency of OG1 is the main cause of discrepancies in the results. A full report of the results has been published in *Applied Optics* **48**, 2947–2957 (2009).

### **Bilateral comparison of spectral regular reflectance at infrared wavelengths**

A comparison between the absolute regular reflectance scales of the Metrology Research Institute and of the Physikalisch-Technische Bundesanstalt (PTB) has been performed in the wavelength range 1000–2500 nm at 50 nm intervals. Two mirrors, aluminium and gold, were used for the measurements at incident angles of about  $6^\circ$ . PTB measured reflectance for the wavelengths of 1400 nm, 1700 nm, 2000 nm, 2200 nm and 2500 nm. The differences between the results were within the expanded uncertainty of the comparison ranging from 0.2 % to

0.5 %. The results of the comparison are presented in Figure 12 for the Aluminium mirror and in Figure 13 for the Gold mirror.

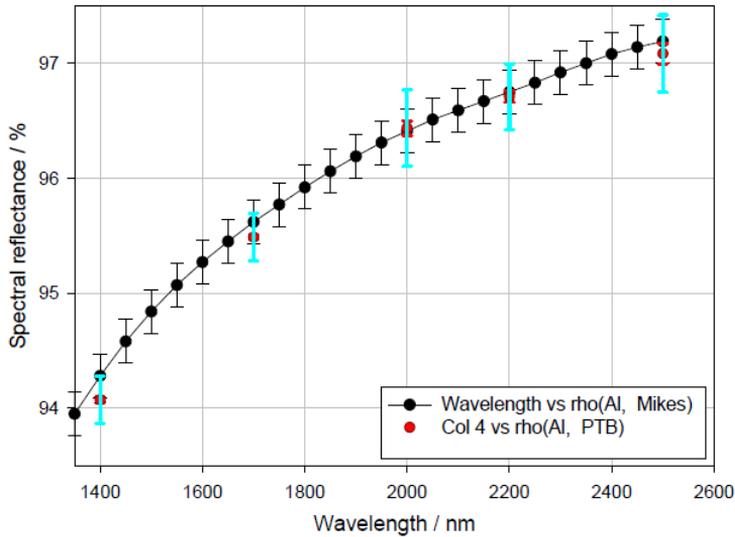


Figure 12. Results of spectral reflectance comparison for the PF-20-03-G01 Aluminium mirror. Black – MIKES results, red – PTB results (statistical uncertainties only,  $k = 2$ ), cyan – PTB results (statistical and systematic uncertainties,  $k = 2$ ).

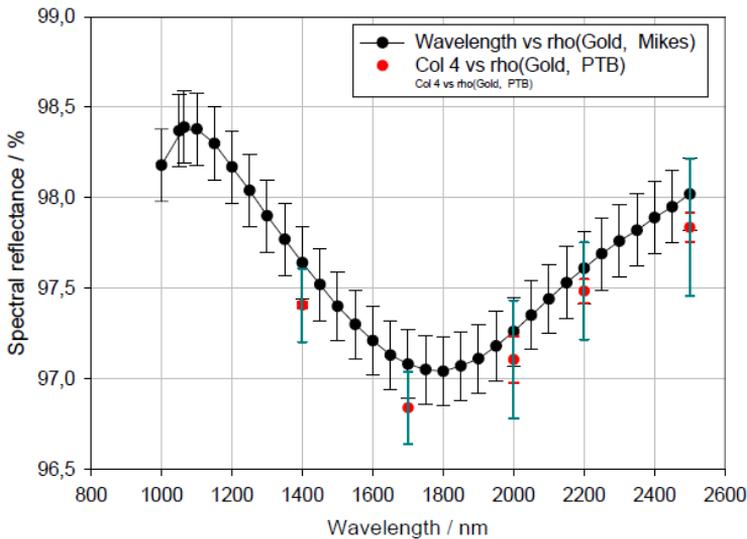


Figure 13. Results of spectral reflectance comparison for the PF-20-03-M01 Gold mirror. Black – MIKES results, red – PTB results (statistical uncertainties only,  $k = 2$ ), cyan – PTB results (statistical and systematic uncertainties,  $k = 2$ ).

### **Bilateral comparison in radiation temperature**

The radiation temperature scales of PTB and MIKES were compared in the range of 1570 – 2770 K using four filter radiometers of MIKES, one filter radiometer of PTB, and linear radiation thermometers of both MIKES and PTB. The agreement was partial: Two filter radiometers and the linear radiation thermometer of MIKES agreed with the equipment of PTB, while two filter radiometers deviated from the other equipment. The results of the comparison have been published in *Measurement* **43**, 183–189 (2010).

### **Trilateral comparison of fiber optic power**

In 2009, MIKES took part in a trilateral comparison measurement of fiber optic power with the accredited laboratory of NEMKO as the pilot. The results published in May 2010 show good agreement between the three participants MIKES, Nemko Finland, and Nemko SpA Italy. A fibre optic power meter was calibrated by each institute at 1310 and 1550 nm wavelengths, at the power levels of -10 and -30 dBm. At 1310 nm, the deviation of Mikes from the reference value was  $(0.07 \pm 0.09)$  dBm, and at 1550 nm it was  $(0.10 \pm 0.09)$  dBm. The quoted uncertainty is that reported by MIKES and it does not take into account the higher uncertainty of other participants.

### **Bilateral comparison of illuminance responsivity**

In 2010, the photometric scales of MIKES and NIMT (Thailand) were compared by measuring the illuminance responsivities of two photometer heads of NIMT. The differences between the measurement results were within the expanded uncertainties ranging from 0.40 % to 0.89 %.

### **Bilateral comparison of luminous efficacy of LED-lamps**

In 2010, a comparison of luminous efficacy measurements of LED-lamps was agreed with NIMT. MIKES completed the measurements during fall 2010. The lamps are to be sent to NIMT for measurements in the beginning of 2011.

### **Bilateral comparisons on detector spectral responsivity and filter spectral regular transmittance**

Bilateral comparisons with the National Metrology Centre (NMC, Singapore) on

detector spectral responsivity and on filter spectral transmittance in the wavelength range 1000–1600 nm were carried out. Relative deviations between measured spectral responsivities were less than 1 %. These values are well within the expanded uncertainty of 1.6 % ( $k = 2$ ) of NMC. From these results and from the degree of equivalence (DoE) of MIKES presented in the final report of CCPR-K2.a-2003, we derived the DoE of NMC relative to the key comparison reference value, using the uncorrelated uncertainty of 0.6 % ( $k = 2$ ) of MIKES in these comparisons. In the comparison of the spectral transmittance of band-pass filters, the relative deviations of the measured peak values were less than 0.36 %, which is within the standard uncertainty of the filter transmittance measurements. For the three filters with center wavelengths of 1100 nm, 1300 nm, and 1500 nm, wavelength scale differences NMC–MIKES of 0.54 nm, 0.44 nm, and 0.20 nm were observed. The reason for the wavelength shifts is not clear and further study is needed to resolve their origin, but it is worth emphasizing that for a tungsten halogen lamp and an InGaAs trap detector the integrated filter radiometer signal differences caused by the wavelength scale differences are only –0.020 %, 0.015 %, and 0.015 %, respectively. The filter radiometer measurements have usually one to two orders of magnitude higher uncertainties.

## 6.2 Conferences and Meetings

iMERA+ Regenmed JRP meeting, Turin, Italy, January 14–17, 2009; *Farshid Manoocheri*

EMRP Committee meeting, Turin, Italy, March 3–5, 2009; *Erkki Ikonen*

Green Lighting Event 2009, Frankfurt, Germany, March 24–26, 2009; *Erkki Ikonen*

iMERA+ Candela JRP meeting, Sofia, Bulgaria, April 22, 2009; *Erkki Ikonen, Farshid Manoocheri*

EURAMET TC Phora meeting, Sofia, Bulgaria, April 22–24, 2009; *Erkki Ikonen, Farshid Manoocheri*

Interreg proposal preparation meeting, Tallinn, Estonia, May 13, 2009; *Erkki Ikonen*

CIE Light and Lighting Conference, Hungary, Budapest, May 26–29, 2009; *Erkki Ikonen, Pasi Manninen, and Tuomas Poikonen*

CIE TC meetings and Division 2 meeting, Budapest, Hungary, May 31–June 3, 2009; *Erkki Ikonen and Pasi Manninen*

EURAMET General Assembly, Malta, June 9–10, 2009; *Erkki Ikonen*

EMRP Committee meeting, Malta, June 10–11, 2009; *Erkki Ikonen*

NPL Optical Technologies Workshop, London, UK, June 16–19, 2009; *Tuomas Poikonen*

International Metrology Congress, Paris, France, June 22–25, 2009; *Erkki Ikonen*

EMRP Sub-Committee meeting, Ajaccio, France, July 21–24, 2009; *Erkki Ikonen*

The 5<sup>th</sup> International Summer School “New Frontiers in Optical Technologies,” Tampere, Finland, August 10–14, 2009; *Meelis Sildoja, Maksim Shpak, and Tuomas Hieta*

Northern Optics 2009 Conference, Vilnius, Lithuania, August 26–28, 2009; *Erkki Ikonen*

OIE 2009, the Eighth Japan-Finland Joint Symposium on Optics in Engineering, Tokyo, Japan, September 2–5, 2009; *Erkki Ikonen*

Preparation meeting of EMRP SSL project, Delft, The Netherlands, September 8–9, 2009; *Petri Kärhä*

iMERA+ Candela JRP meeting, Turin, Italy, September 8–12, 2009; *Farshid Manoocheri, Erkki Ikonen*

EURAMET TC Phora additional meeting, Paris, France, September 14, 2009; *Erkki Ikonen*

CCPR WG-SP TG-4 meeting, Paris, France, September 14, 2009; *Erkki Ikonen*

CCPR WG-KC meeting, Paris, France, September 15, 2009; *Erkki Ikonen*

CCPR WG-CMC meeting and WG-SP meeting, Paris, France, September 16, 2009; *Erkki Ikonen*

CCPR meeting, Paris, France, September 17–18, 2009; *Erkki Ikonen*

CCPR WG-KC TG - RMO Linking meeting, Paris, France, September 18, 2009; *Erkki Ikonen*

OFMC 2009 Conference, London, UK, September 16–18, 2009; *Tuomas Hieta*

BIPM Worksop of Physiological Quantities and SI Units, France, Paris, November 15–17, 2009; *Erkki Ikonen*

Hadron Collider Physics Symposium, Evian, France, November 17–20, 2009; *Erkki Ikonen*

EMRP Proposal Review Conference, Berlin, Germany, November 25–26, 2009; *Erkki Ikonen*

EMRP Sub-Committee meeting, Berlin, Germany, November 26, 2009; *Erkki Ikonen*

EMRP Committee meeting, Berlin, Germany, November 27, 2009; *Erkki Ikonen*

iMERA+ Regenmed JRP meeting, London, UK, November 26–27, 2009; *Farshid Manoocheri*

Hadron 2009 Conference, Tallahassee, Florida, USA, November 29 – December 4, 2009; *Erkki Ikonen*

Metromet - 6th International Conference on Industrial Dimensional Metrology, Spain, Bilbao, February 24–27, 2010; *Erkki Ikonen*

CIE Lighting Quality & Energy Efficiency Conference, Vienna, Austria, March 14–17, 2010; *Erkki Ikonen*

EURAMET TC Phora EMRP preparation meeting, Vienna, Austria, March 16, 2010; *Erkki Ikonen*

WMO-BIPM Workshop: Measurement Challenges for Global Observation Systems for Climate Change, Monitoring, Traceability, Stability and Uncertainty, Geneva, Switzerland, March 30–April 1, 2010; *Erkki Ikonen*

EMRP Sub-Committee meeting, Brussels, Belgium, May 2–5, 2010; *Erkki Ikonen*

iMERA+ Candela JRP meeting, Berlin, Germany, May 10–11; *Farshid Manoocheri and Erkki Ikonen*

EURAMET General Assembly, Lissabon, Portugal, May 25–27, 2010; *Erkki Ikonen*

EMRP Committee meeting, Lissabon, Portugal, May 27–28, 2010; *Erkki Ikonen*

Joint International Symposium on Temperature, Humidity, Moisture and Thermal Measurements in Industry and Science - TEMPMEKO & ISHM 2010, Portoroz, Slovenia, May 30 – June 5, 2010; *Tuomas Hieta and Maksim Shpak*

Blackbody Users Group (BBUG) Meeting, June 10, 2010, Portoroz, Slovenia; *Maksim Shpak*

Kick-off meeting of the EMRP project ENG05, Metrology for Solid State Lighting, Delft, The Netherlands, June 2–3, 2010; *Petri Kärhä*

Summer School of Exact Sciences, Tostamaa, Estonia, June 18–21, 2010; *Meelis Sildoja*

EURAMET Phora TC meeting, Berlin, Germany, June 21–24, 2010; *Erkki Ikonen*

EMRP Partnering Conference 2010 – TP Industry - Dimensional metrology, PTB, Berlin, Germany, June 29–30, 2010; *Farshid Manoocheri*

EMRP Partnering Conference 2010 – TP Environment, PTB, Berlin, Germany, July 1–2, 2010; *Petri Kärhä and Farshid Manoocheri*

EMRP Partnering Conference 2010 – TP Industry - Optical metrology, NPL, London, United Kingdom, July 5–6, 2010; *Erkki Ikonen, Farshid Manoocheri, and Petri Kärhä*

CCPR WG-SP TG - Fiber optics meeting, NPL, London, United Kingdom, July 6, 2010; *Erkki Ikonen*

CCPR WG-KC TG - RMO Linkage meeting, NPL, London, United Kingdom, July 7, 2010; *Erkki Ikonen*

CCPR WG-SP meeting, NPL, London, United Kingdom, July 8, 2010; *Erkki Ikonen*

CCPR WG-KC meeting, NPL, London, United Kingdom, July 9, 2010; *Erkki Ikonen*

The 20<sup>th</sup> International Jyväskylä Summer School, Jyväskylä, Finland, August 8–14, 2010; *Meelis Sildoja*

EMRP Partnering meeting of project IND18, NPL, London, United Kingdom, August 17, 2010; *Farshid Manoocheri*

CIE Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry, Bern, Switzerland, 30–31 August 2010; *Erkki Ikonen and Tuomas Poikonen*

CIE TC meetings and Division 2 meeting, Bern, Switzerland, September 1–3, 2010; *Erkki Ikonen and Tuomas Poikonen*

EMRP Partnering meetings of projects ENV09 and IND25, Bern, Switzerland, September 3–7, 2010; *Petri Kärhä*

WPCF2010: The Sixth Workshop on Particle Correlations and Femtoscopy, Kiev, Ukraine, September 14–18, 2010; *Erkki Ikonen*

iMERA+ Candela JRP meeting, Tartu, Estonia, September 26–28, 2010; *Meelis Sildoja, Farshid Manoocheri, and Erkki Ikonen*

EMRP Partnering meeting of project IND26, Tartu, Estonia, September 28, 2010; *Meelis Sildoja, Farshid Manoocheri, and Erkki Ikonen*

Metrology Symposium 2010, Queretaro, Mexico, October 27–29, 2010; *Erkki Ikonen*

EMRP Proposal Review Conference, Budapest, Hungary, November 22–25, 2010; *Erkki Ikonen*

EMRP Sub-Committee meeting, Berlin, Germany, November 29, 2010; *Erkki Ikonen*

EMRP Committee meeting, Berlin, Germany, November 29–30, 2010; *Erkki Ikonen*

### **6.3 Visits by the Laboratory Personnel**

*Erkki Ikonen, Petri Kärhä, Farshid Manoocheri, Silja Holopainen, Maija Ojanen, Tuomas Poikonen, Meelis-Mait Sildoja, Maksim Shpak, Antti Kunnas, Timo Dönsberg, Jarkko Koski and Prasad Thakur*, Research Group Development Day and visit to Tartu University, Estonia, May 14–15, 2009

*Erkki Ikonen*, NMIJ, Tsukuba, Japan, September 2, 2009

*Erkki Ikonen*, SPring-8, Hyogo, Japan, September 7, 2009

*Erkki Ikonen*, PTB, Braunschweig, Germany, October 23, 2009

*Erkki Ikonen*, Ohio State University, Columbus, Ohio, USA, December 7, 2009

*Maija Ojanen*, LNE, Paris, France, December 18, 2009

*Erkki Ikonen*, Indian Institute of Technology, Mumbai, India, January 8–9, 2010

*Erkki Ikonen*, National Institute of Metrology, Thailand (NIMT), Bangkok, January 22, 2010

*Erkki Ikonen*, Physikalisch-Meteorologisches Observatorium Davos, Switzerland, February 4–5, 2010

*Erkki Ikonen*, CERN, Geneva, Switzerland, February 9, 2010

*Erkki Ikonen*, FIAS Frankfurt Institute of Advanced Studies, Goethe University, Frankfurt, Germany, February 23, 2010

*Erkki Ikonen*, Metrology Light Source, PTB Berlin, Germany, March 1–2, 2010

*Farshid Manoocheri*, PTB Berlin, Germany, June 28–29, 2010

*Erkki Ikonen*, PTB Berlin, Germany, October 18, 2010

*Erkki Ikonen*, Centro Nacional de Metrologia (CENAM), Queretaro, Mexico, October 25–26, 2010

*Erkki Ikonen*, MKEH, Budapest, Hungary, November 24, 2010

#### **6.4 Research Work Abroad**

*Silja Holopainen*, PTB, Braunschweig, Germany, January 1 – April 30, 2009

*Farshid Manoocheri*, Measurements for the Quantum Candela project, PTB, Berlin, Germany, April 2–9, 2009

*Maija Ojanen*, LNE Laboratoire national de métrologie et d'essais, France, June 1 – December 31, 2010

*Erkki Ikonen*, Agency for Science, Technology and Research (A\*STAR), National Metrology Centre (NMC), Singapore, January 10–21, 2010

*Erkki Ikonen*, ETH Zurich, Switzerland, February 8–11 and March 22–29, 2010

*Meelis Sildoja*, Measurements for the Quantum Candela project, PTB, Berlin, Germany, November 15–19, 2010

#### **6.5 Guest Researchers**

*Julie Dahl*, Justervesenet, Norway, August 3–21, 2009

*Dr. Soontorn Chanyawadee*, NIMT, Thailand, August 7–28, 2010

*Rattana Chuenchom*, NIMT, Thailand, August 7–28, 2010

## **6.6 Visits to the Laboratory**

*Dr. Jouni Envall*, Tartu Observatory, Estonia, February 3–6, 2009

*Ilmar Ansko*, Tartu Observatory, Estonia, February 3–6, 2009

*Joel Kuusk*, Tartu Observatory, Estonia, February 3–6, 2009

*Dr. Toomas Kübarsepp*, Metrosert, Estonia, February 5, 2009

*Prof. Mike Underhill*, Underhill Research Ltd, United Kingdom, March 24–25, 2009

*Dr. Jouni Envall*, Tartu Observatory, Estonia, June 9–10, 2009

*Prof. Andy Monkman*, Durham University, United Kingdom, June 16–17, 2009

*Dr. Giorgio Brida*, INRIM, Italy, August 20, 2009

*Dr. Jarle Gran*, Justervesenet, Norway, August 20, 2009

*Dr. Marek Smid*, CMI, Czech Republic, August 20, 2009

*Dr. Lutz Werner*, PTB, Germany, August 20, 2009

*Stian Samset Hoem*, Justervesenet, Norway, August 20, 2009

*Dr. Ingmar Muller*, PTB, Germany, August 20, 2009

*Dr. Toomas Kübarsepp*, Metrosert, Estonia, August 20, 2009

*Anne Anderson*, SP, Sweden, August 24, 2009

*Priit Jaanson*, Metrosert, Estonia, August 24, 2009

*Lukasz Litwiniuk*, GUM, Poland, November 24, 2009

*Dr. Arnold Gaertner*, National Research Council of Canada, Canada, May 20–26, 2010

*Veronika Besser, Christoph Rödiger, and Jerome Jacquin, European Patent Office, Germany, June 7, 2010*

*Dr. Toomas Kübarsepp, Metrosert, Estonia, August 10, 2010*

*Dr. Yuanjie Liu, NMC, Singapore, August 27–29, 2010*

*E.W.D. van der Ham, VSL, The Netherlands, Alicia Pons, CSIC, Spain, Paola Iacomussi, INRIM, Italy, Georgy Andor, MKEH, Hungary, Daren Lock, University of Surrey, United Kingdom, Armin Sperling, PTB, Germany, Simon Hall, NPL, United Kingdom, Dominique Renoux, LNE, France, November 4, 2010.*

*Prof. Grega Bizjak, University of Ljubljana, Slovenia, November 15, 2010*

*Dr. Jouni Envall, Tartu Observatory, Estonia, November 19, 2010*

*Prof. Alan Madej, National Research Council of Canada, Canada, November 17–21, 2010*

## 7 PUBLICATIONS

### 7.1 Articles in International Journals

A. Heikkilä, P. Kärhä, A. Tanskanen, M. Kaunismaa, T. Koskela, J. Kaurola, T. Ture, and S. Syrjälä, “Characterizing a UV chamber with mercury lamps for assessment of comparability to natural UV conditions,” *Polymer Testing* **28**, 57–65 (2009).

V. Ahtee, R. Lettow, R. Pfab, A. Renn, E. Ikonen, S. Götzinger, V. Sandoghdar, “Molecules as sources for indistinguishable single photons,” *Journal of Modern Optics* **56**, 161–166 (2009).

T. Poikonen, P. Kärhä, P. Manninen, F. Manoocheri and E. Ikonen, “Uncertainty analysis of photometer quality factor  $f_1$ ’,” *Metrologia* **46**, 75–80 (2009).

M. Sildoja, F. Manoocheri and E. Ikonen, “Reflectance calculations for predictable quantum efficient detector,” *Metrologia* **46**, S151–S154 (2009).

M. Ojanen, M. Shpak, P. Kärhä, R. Leecharoen, and E. Ikonen, “Report of the Spectral Irradiance Comparison EURAMET.PR-K1.a.1 between MIKES (Finland) and NIMT (Thailand),” *Metrologia* **44**, Tech. Suppl. 02001, 16 pages (2009).

Y. J. Liu, G. Xu, M. Ojanen, and E. Ikonen, “Spectral irradiance comparison using a multi-wavelength filter radiometer,” *Metrologia* **46**, S181–S185 (2009).

T. Hieta and E. Ikonen, “Measurement of Erbium-doped fiber nonlinearity using continuous-wave self-phase modulation method,” *IEEE/OSA Journal of Lightwave Technology* **27**, 2977–2982 (2009).

T. Widmaier, T. Salmela, P. Kuosmanen, J. Juhanko, P. Kärhä, and J. Uusimäki, “Reducing thickness variation of hot rolled steel strip by non-circular backup roll geometry,” *Ironmaking and Steelmaking* **36**, 133–140 (2009).

S. Holopainen, F. Manoocheri, E. Ikonen, K.-O. Hauer, and A. Höpe, “Comparison measurements of 0.45 radiance factor and goniometrically determined diffuse reflectance,” *Applied Optics* **48**, 2947–2957 (2009).

S. Holopainen, F. Manoocheri and E. Ikonen, “Non-Lambertian behaviour of fluorescence emission from solid amorphous material,” *Metrologia* **46**, S197–S201 (2009).

M. Ojanen, M. Shpak, P. Kärhä, R. Leecharoen, and E. Ikonen, “Uncertainty evaluation for linking a bilateral comparison with the corresponding CIPM key comparison,” *Metrologia* **46**, 397–403 (2009).

P. Manninen, T. Koskela, L. Ylianttila, P. Kärhä, and E. Ikonen, “Estimation of the optical receiving plane positions of solar spectroradiometers with spherical diffusers on the basis of spatial responsivity data,” *Opt. Lett.* **34**, 3241–3243 (2009).

T. Hieta, M. Vainio, C. Moser, and E. Ikonen, “External-cavity lasers based on a volume holographic grating at normal incidence for spectroscopy in the visible range,” *Optics Communications* **282**, 3119–3123 (2009).

M. Ojanen, P. Kärhä and E. Ikonen: “Spectral irradiance model for tungsten halogen lamps in 340-850 nm wavelength range,” *Appl. Opt.* **49**, 880-886 (2010).

R. Lettow, Y. L. A. Rezus, A. Renn, G. Zumofen, E. Ikonen, S. Götzinger, V. Sandoghdar, “Quantum Interference of Tunably Indistinguishable Photons from Remote Organic Molecules,” *Phys. Rev. Lett.* **104**, 123605, 4 pages (2010).

M. Ojanen, K. Anhalt, J. Hartmann, S. Schiller, T. Weckström, P. Kärhä, M. Heinonen and E. Ikonen, “Comparison of the radiation temperature scales between MIKES and PTB,” *Measurement* **43**, 183–189 (2010).

T. Poikonen, P. Manninen, P. Kärhä, and E. Ikonen, “Multifunctional integrating sphere setup for luminous flux measurements of light emitting diodes,” *Rev. Sci. Instrum.* **81**, 023102 (2010).

M. Shpak, L. Sainiemi, M. Ojanen, P. Kärhä, M. Heinonen, S. Franssila, and E. Ikonen, “Optical temperature measurements of silicon microbridge emitters,” *Appl. Opt.* **49**, 1489–1493 (2010).

E. Ikonen, “Coherence of Radiation as Studied by Multiple Coincidences of Photons and Particles,” *Optical Review* **17**, 239–247 (2010).

J. C. Zwinkels, E. Ikonen, N. P. Fox, G. Ulm and M. L. Rastello, "Photometry, Radiometry and "the Candela": Evolution in the Classical and Quantum World," *Metrologia* **47**, R15–R32 (2010).

M. Shpak, P. Kärhä, M. Ojanen, E. Ikonen and M. Heinonen, "Optical temperature measurement method for glowing microcomponents," *Int. J. Thermophys.* **31**, 1762–1770 (2010).

T. Hieta and M. Merimaa, "Spectroscopic measurement of air temperature," *Int. J. Thermophys.* **31**, 1710–1718 (2010).

L. Sainiemi, A. Shah, V. Jokinen, M. Shpak, S. Aura and S. Franssila, "Nonreflecting silicon and polymer surfaces by plasma etching and replication," *Adv. Mater.* (in press).

P. Kärhä, A. Heikkilä, K. Ruokolainen, and M. Kaunismaa, "A novel facility for ageing materials with narrow-band UV radiation exposure," *Rev. Sci. Instrum.* (in press).

## **7.2 International Conference Presentations**

E. Ikonen, T. Poikonen, P. Kärhä, and P. Manninen, "Determination of LED luminance and radiance from effective intensity," *Proceedings of the CIE Light and Lighting Conference*, Budapest, Hungary, May 27–29, 2009, pp. 174–175 (poster).

T. Poikonen, P. Kärhä, P. Manninen, and E. Ikonen, "A multifunctional setup for measurement of LED luminous flux based on integrating sphere method," *Proceedings of the CIE Light and Lighting Conference*, Budapest, Hungary, May 27–29, 2009, pp. 115–116 (poster with short oral introduction).

P. Manninen, "Influence of duty cycle on properties of a phosphor-converted white LED," *Proceedings of the CIE Light and Lighting Conference*, Budapest, Hungary, May 27–29, 2009, pp. 200–201 (poster).

E. Ikonen "Silicon photodiodes as efficient detectors of light," *Proceedings of the Northern Optics 2009 Conference*, Vilnius, Lithuania, August 26–28, 2009, p. 30 (invited talk).

E. Ikonen, A. Haapalinna, M. Sildoja and F. Manoocheri, “Photon-to-electron converter with 1 ppm quantum deficiency,” *Proceedings of the Northern Optics 2009 Conference*, Vilnius, Lithuania, August 26–28, 2009, p. 114 (poster).

E. Ikonen, “Coherence of radiation as studied by multiple coincidences of photons and particles,” *Technical Digest of the OIE’09 Eighth Japan-Finland Joint Symposium on Optics in Engineering*, Tokyo, Japan, September 3–5, 2009, p. 19 (plenary talk).

P. Manninen, T. Koskela, L. Ylianttila, P. Kärhä, and E. Ikonen, “Imperfections in UV diffusers: practical consequences,” *12<sup>th</sup> Biennial WMO-GAW Brewer Users Group Meeting*, Aosta, Italy, 20–26 September 2009 (poster).

A. Heikkilä, S. Kazadzis, O. Tolonen-Kivimäki, O. Meinander, A. Lindfors, K. Lakkala, T. Koskela, J. Kaurola, A. Sormanen, P. Kärhä, A. Naula-Iltanen, S. Syrjäälä, M. Kaunismaa, J. Juhola, T. Ture, U. Feister, N. Kouremeti, A. Bais, J.M.Vilaplana, J.J. Rodriguez, C. Guirado, E. Cuevas, and J. Koskinen, “Effects of terrestrial UV radiation on selected outdoor materials: an interdisciplinary approach.” *Proc. SPIE 7462*, 74620G (2009) (poster).

A. Heikkilä, P. Kärhä, K. Ruokolainen, J. Juhola, M. Kaunismaa, and T. Ture, “A new facility for ageing materials with spectrally resolved UV radiation,” *Natural and Artificial Ageing of Polymers, 4<sup>th</sup> European Weathering Symposium*, Ed. T. Reichert, Gesellschaft für Umweltsimulation e.V. GUS, CEEES Publication No 11, September 16–18, 2009 (talk).

T. Hieta and E. Ikonen, “Measurement of Erbium-doped fiber nonlinearity using continuous-wave self-phase modulation method,” *Optical Fiber Measurement Conference 2009*, Teddington, UK, September 16–18, 2009 (talk).

E. Ikonen, “Multiple coherent components in relativistic heavy-ion collisions,” *Hadron Collider Physics Symposium 2009*, Evian, France, November 17–20, 2009 (poster).

E. Ikonen, “Multiple coherent components in relativistic heavy-ion collisions,” *Hadron 2009 Conference*, Tallahassee, Florida, USA, November 29–December 4, 2009 (talk).

E. Ikonen, “Interferometric length measurements,” *Metromet - 6th International Conference on Industrial Dimensional Metrology*, Bilbao, Spain, February 24–26, 2010 (tutorial talk).

E. Ikonen, T. Poikonen, P. Manninen, and P. Kärhä, “An integrating sphere setup for measurement of LED luminous flux,” *Abstracts of the CIE Lighting Quality & Energy Efficiency Conference*, (Vienna, March 2010) pp. 235–237 (talk).

M. Shpak, P. Kärhä, M. Ojanen, E. Ikonen and M. Heinonen, “Optical temperature measurement method for glowing microcomponents,” *Joint International Symposium on Temperature, Humidity, Moisture and Thermal Measurements in Industry and Science - TEMPMEKO & ISHM 2010*, Portorož, Slovenia, May 30–Jun 5, 2010 (talk).

T. Hieta and M. Merimaa, “Spectroscopic measurement of air temperature,” *Joint International Symposium on Temperature, Humidity, Moisture and Thermal Measurements in Industry and Science - TEMPMEKO & ISHM 2010*, Portorož, Slovenia, May 30–Jun 5, 2010 (poster).

K.-G. Lee, X. Chen, H. Eghlidi, E. Ikonen, S. Götzinger and V. Sandoghdar, “A predictable bright single-photon source,” *Proceedings of the CIE Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry* (Bern, Switzerland, August 2010) pp. 60–61 (talk).

Y. J. Liu, G. Xu, X. B. Huang, F. Manoocheri, and E. Ikonen, “Application of InGaAs trap detector in the multiwavelength filter radiometer for spectral irradiance measurement,” *Proceedings of the CIE Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry* (Bern, Switzerland, August 2010) pp. 94–98 (poster).

T. Poikonen, P. Blattner, and E. Ikonen, “Measurements of photometer directional response index  $f_2$  at MIKES and at METAS,” *Proceedings of the CIE Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry* (Bern, Switzerland, August 2010) p. 129 (poster).

E. Ikonen, “Three-pion correlations for studying partial coherence in nuclear collisions,” *WPCF2010: The Sixth Workshop on Particle Correlations and Femtoscopy*, Kiev, Ukraine, September 14–18, 2010 (talk).

E. Ikonen, A. Haapalinna, M. Sildoja, and F. Manoocheri, “Photon-to-electron converter with 1 ppm quantum deficiency,” *Proceedings of Metrology Symposium 2010*, (Queretaro, Mexico, October 2010) CD, 2 p. (invited talk).

E. Ikonen, “Multiple coherent components in heavy-ion collisions,” *Proceedings of the XXth Hadron Collider Physics Symposium*, Eds. E. Auge and S. Bertolucci (Proceedings of Science, Trieste 2010) PoS(HCP2009)079, 3 p (poster).

E. Ikonen, “Multiple coherent components in relativistic heavy-ion collisions,” *Hadron 2009: Proceedings of the XIII International Conference on Hadron Spectroscopy*, Eds. V. Crede, P. Eugenio, and A. Ostrovidov (AIP Conference Proceedings Volume 1257, New York 2010) pp. 800–803 (talk).

### 7.3 National Conference Presentations

E. Ikonen, “Multiple coherent components in relativistic heavy-ion collisions,” *Proceedings of the XLIII annual conference of the Finnish Physical Society*, Espoo, Finland, March 12–14, 2009, p. 133 (poster).

T. Poikonen, P. Kärhä, P. Manninen, F. Manoocheri, and E. Ikonen, “Applicability of random and biased error models in uncertainty evaluation of photometer quality factor  $f_1'$ ,” *Proceedings of the XLIII annual conference of the Finnish Physical Society*, Espoo, Finland, March 12–14, 2009, p. 256 (poster).

M. Shpak, M. Ojanen, P. Kärhä, E. Ikonen, M. Heinonen and T. Weckström, “Optical temperature measurement of miniature silicon emitters,” *Proceedings of the XLIII annual conference of the Finnish Physical Society*, Espoo, Finland, March 12–14, 2009, p. 285 (poster).

T. Ture, M. Kaunismaa, A. Sormanen, K. Ruokolainen, P. Kärhä, A. Naula-Iltanen, J. Juhola, J. Hakkarainen, S. Syrjälä, O. Kivimäki-Tolonen, O. Meinander, J. Kaurola, T. Koskela, A. Lindfors, A. Tanskanen, A. Heikkilä, and J. Koskinen, “Effects of UV radiation on materials,” *Scientific Day 2009 of Tekes Functional Materials workshop*, April 1, 2009, Espoo, Finland (talk).

A. Heikkilä, S. Syrjälä, P. Kärhä, A. Sormanen, A. Naula-Iltanen, M. Kaunis-  
maa, T. Ture, and J. Koskinen, “UVEMA2 - UV radiation effects on materials,”  
Tekes Annual Seminar “*Driving innovation with nanotechnology and functional  
materials in Finland*”, May 27–28, 2009, Helsinki, Finland (poster).

P. Jaanson, F. Manoocheri, and E. Ikonen, “A new method for validation of  
commercial fluorescence spectrometers”, *Optics Days*, Tampere, Finland, May  
6–7, 2010, p. 82 (poster).

J.-M. Hirvonen, P. Manninen, and E. Ikonen, “LED-based light source for spec-  
tral radiance responsivity measurements of colorimeters and luminance meters”,  
*Optics Days*, Tampere, Finland, May 6–7, 2010, p. 81 (poster).

T. Hyvönen, M. Ojanen, P. Kärhä, and E. Ikonen, “Prospects in online optical  
identification of polymeric materials – future of recycling”, *Optics Days*, Tam-  
pere, Finland, May 6–7, 2010, p. 84 (poster).

M. Ojanen, P. Kärhä, and E. Ikonen, “Spectral irradiance model for tungsten ha-  
logen lamps in 340 – 850 nm wavelength range”, *Optics Days*, Tampere,  
Finland, May 6–7, 2010, p. 39 (poster).

#### **7.4 Other Publications**

A. Pietiläinen, M. Merimaa, T. Niemi, P. Kärhä, and M. Ojanen, *Mittaustekniikan perusteiden laboratoriotyöt*, 16. korjattu painos, Espoo 2009, ISBN 951-22-6737-3, 118 p. (in Finnish).

A. Pietiläinen, M. Merimaa, T. Niemi, P. Kärhä, M. Ojanen and M. Shpak, *Mittaustekniikan perusteiden laboratoriotyöt*, 17. korjattu painos, Espoo 2010, ISBN 978-952-60-3324-2, 125 p. (in Finnish).



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