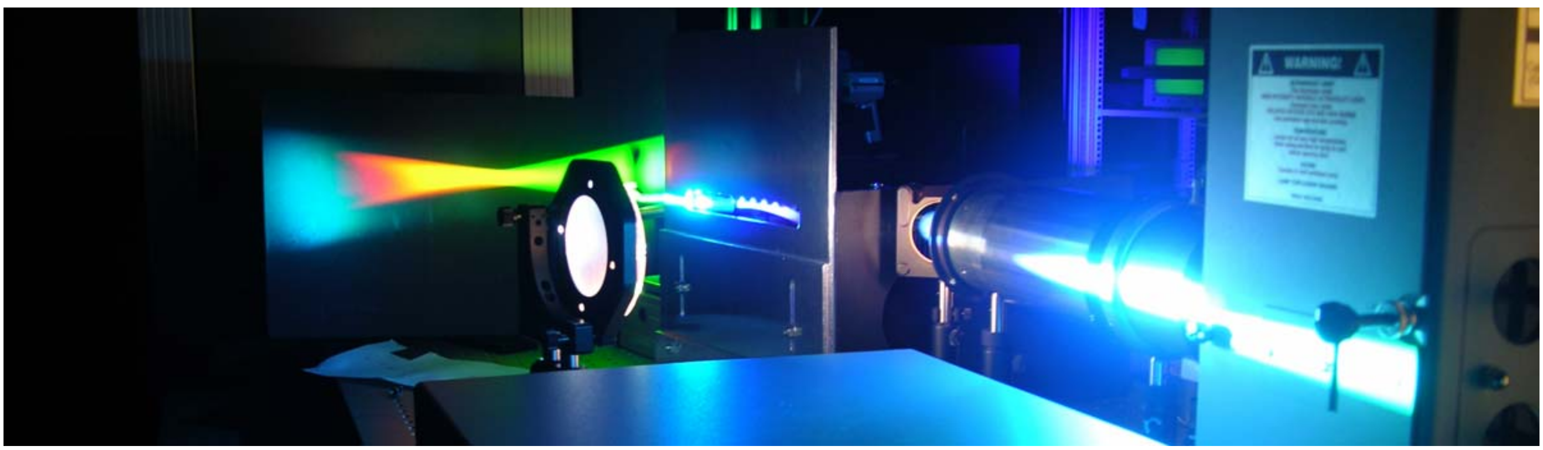
Helsinki University of Technology
Faculty of Electronics, Communications and Automation
Metrology Research Institute Report 33/2008
Espoo 2008

ANNUAL REPORT 2007



TEKNILLINEN KORKEAKOULU
TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY
TECHNISCHE UNIVERSITÄT HELSINKI
UNIVERSITE DE TECHNOLOGIE D'HELSINKI

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Editor Silja Holopainen

Helsinki University of Technology
Faculty of Electronics, Communications and Automation
Metrology Research Institute

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1 INTRODUCTION

The Metrology Research Institute is a joint laboratory of Helsinki University of Technology (TKK) and Centre for Metrology and Accreditation (MIKES). The Finnish name of the Institute is MIKES TKK Mittaustekniikka and its research areas consist of electronic instrumentation, optical radiation measurements, fiber optics, and laser applications. A very wide range of topics is covered from magnetic interference to fluorescent materials and quantum computers.

During 2007, much effort was devoted to development of the European Metrology Research Program (EMRP). The researchers contributed to preparation of Expressions of Interest and the subsequent formulation of Joint Research Project proposals in collaboration with MIKES. Finally it was rewarding to find out that two projects were selected for funding, one in Targeted Program "Health" and one in "Grand Challenges on Fundamental Metrology".

Another positive development during 2007 was that publications of the staff members included high-quality journals, like Applied Physics Letters (APL), Optics Express, and Physical Review A (Rapid Communications). For example, in the APL work behaviour of LEDs under pulse-width modulation was studied. The measurement results indicated a blue shift of the peak wavelength and bandwidth narrowing for the studied LEDs as the width of the pulse was decreased. This and other research works are described in more detail in Sec. 5 of this Annual Report.

In the electronic instrumentation work, an improved version was developed of the floor ball speed measurement device. The electronics and software were completely redesigned to a more simplified form, allowing construction of two new devices. One of them has been used, with great success, during visits of high-school students at the TKK.

One doctoral degree and 7 M.Sc. degrees were achieved in 2007. After the record year of 2006, these are quite satisfactory numbers.

Erkki Ikonen

2 PERSONNEL

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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute (Mittaustekniikan laboratorio) in 2007. Those marked by * are given biennially.

S-108.1010	Fundamentals of Measurements A 4 cr (Petri Kärhä)
S-108.1020	Fundamentals of Measurements Y 3 cr (Petri Kärhä)
S-108.2010	Electronic Measurements 3 cr (Petri Kärhä)
S-108.2110	Optics 5 cr (Erkki Ikonen)
S-108.3010	Electronic Instrumentation 5 cr (Pasi Manninen)
S-108.3020	Electromagnetic Compatibility 2 cr (Esa Häkkinen)
S-108.3030	Virtual Instrumentation* 5 cr (Petri Kärhä)
S-108.3110	Optical Communications 5 cr (Farshid Manoocheri, Goery Genty)
S-108.3120	Project Work 2-8 cr (Erkki Ikonen, Tuomas Hieta)
S-108.3130	Project Work in Measurement Science and Technology 2-10 cr (Erkki Ikonen, Tuomas Hieta)

S-108.3140	Project Work in Optical Technology 2-10 cr (Erkki Ikonen, Tuomas Hieta)
S-108.4010	Postgraduate Course in Measurement Technology 10 cr (Petri Kärhä)
S-108.4020	Research Seminar on Measurement Science and Technology 2 cr (Erkki Ikonen)
S-108.4110	Biological Effects and Measurements of Electromagnetic Fields and Optical Radiation 4 cr (Kari Jokela)
S-108.4120	Special Course in Measurement Science and Technology* 2-6 cr (Erkki Ikonen)

3.2 Degrees

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

Björn Hemming, *Measurement Traceability and Uncertainty in Machine Vision Applications*

Opponents: Professor Leonardo De Chiffre and Professor Heikki Tikka

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

The Licentiate degree is an intermediate degree between M.Sc. and D.Sc.

Mikko Puranen, *Measuring Concepts and Their Uncertainties in Pulsed Radar Experiments*

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

Kimmo Ruokolainen, *Facility for Spectral Ultraviolet Aging of Materials*

Heikki Koivula, *Measurement System for Microwave Power Sensors*

Liisa Ollikka, *Extension of the Wavelength Range of Spectral Irradiance Measurements*

Antti Viitanen, *Test System for the Analysis of Temperature Dependences within an Angular Rate Sensor*

Tuomas Poikonen, *Luminous Flux Measurement of Light Emitting Diodes*

Markku Valkonen, *Development of Dry-Nitrogen-Purged Spectrometer for Infrared Wavelength Region*

Aarni Iho, *Laser Diffractometer for Grating Pitch Characterization with Picometer-Level Uncertainty*

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

Juha Peltonen, *Suodatinradiometrin termodynaaminen suunnittelu*

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 2007, 40 calibration certificates were issued. 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 in Finland.

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/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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5 RESEARCH PROJECTS

5.1 Electronic Instrumentation

Measurement of the speed of a floor ball

In 2006 a Finnish company ordered a device that could measure accurately the speed of a floor ball. The company didn't want to use a traditional radar system because of its lack of accuracy, so a measurement system was developed which comprises two infrared gates with a 0.5 meter distance between them. Externally the measurement system resembles a floor ball goal. The measured speed is shown on a large LED display and a sound effect corresponding to the speed is played. The goal has been attracting youngsters to the company's stand at floor ball tournaments and other exhibitions.

In 2007, the company ordered a second goal setup. The new version (Figure 1) works according to the same principle, but the electronics and software were completely redesigned to a more simplified form, allowing construction of two new devices. The new version comprises only two units, a display unit and a goal frame. The display unit has only one power supply for the whole setup and most of the electronics are put inside it. The goal frame includes infrared gates and a very sensitive amplifier to boost up the weak signal into TTL level. In this version the speed is calculated with our own software, so we also managed to somewhat improve the measurement accuracy.

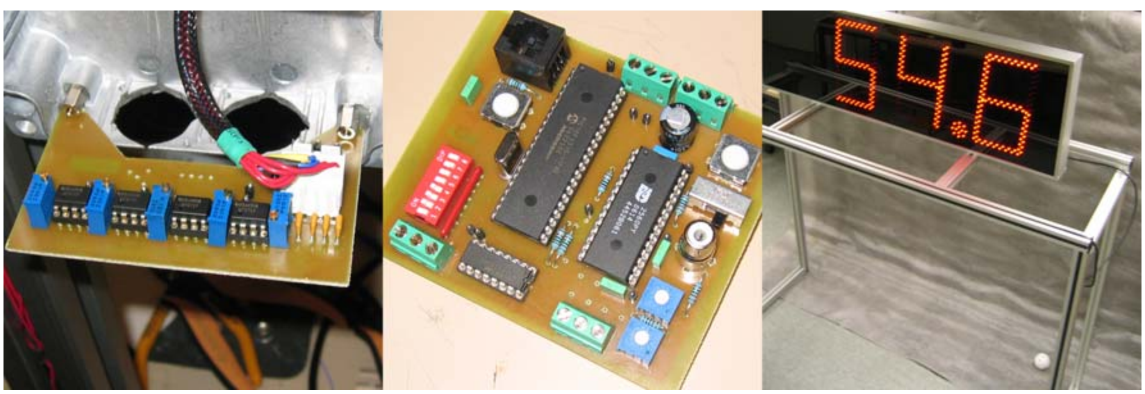

Figure 1. From the left, an amplifier placed in the goal frame, the mother board inside the display unit and the goal frame and the display.

Logarithmic measuring amplifier

A temperature display including a logarithmic measuring amplifier was designed and built for measurements of light emitting diodes (LEDs). The temperature of the studied LED is stabilized using a temperature controller unit and a temperature stabilizer which has a built-in NTC thermistor and a thermoelectric module. Earlier, an additional temperature sensor was used for measuring the LED temperature. The new measuring amplifier integrates with the temperature controller unit and measures the voltage of the thermistor which is built in the temperature stabilizer. The voltage of the thermistor is exponential as a function of the temperature and needs to be linearized in order to drive a linear display. For this reason, a logarithmic measuring amplifier was built. The amplifier has several gain and offset stages for adjusting the logarithmic function. Because another temperature sensor is no longer needed, the system is more compact and easier to use.

Simple active method for reducing magnetic interference in a thermoelectrically cooled photomultiplier tube

We have developed a simple modification for thermoelectrically cooled photomultiplier tube (PMT) assemblies that eliminates the magnetic interference between the Peltier element and the PMT (Figure 2). An active compensation is accomplished by forming current loops of the wires of the Peltier element and placing them in such a way that they eliminate the interfering magnetic field.

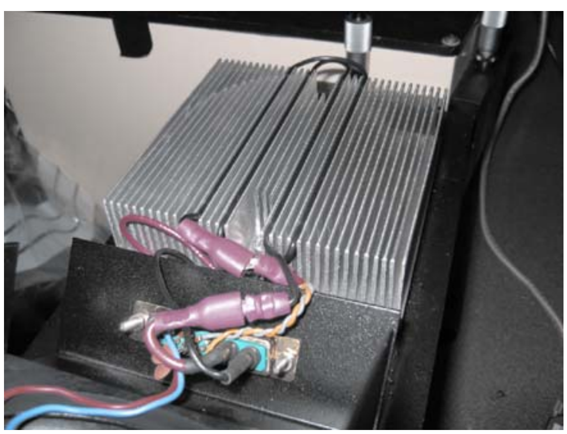

Figure 2. Modification of the current leads of the Peltier element. The positive current lead forms two loops that are placed in such an orientation that the magnetic field produced compensates for the magnetic field produced by the Peltier element.

It has been demonstrated that the improved system reduces measurement errors of the order of 1 % to the level of noise at 0.07 % (Figure 3).

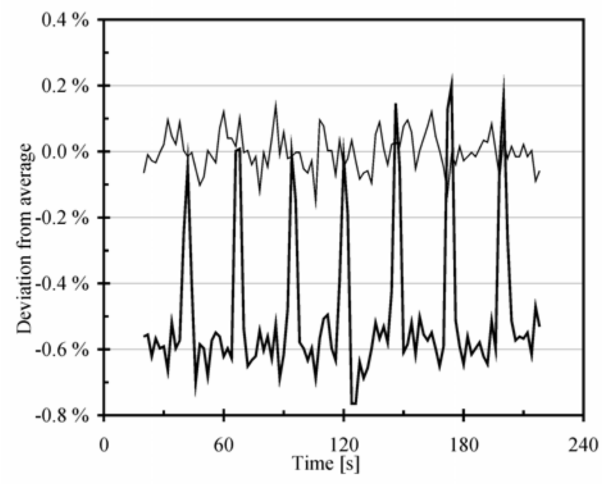

Figure 3. Measurement results on a 1-kW incandescent lamp before (thick line) and after (thin line) the modification. Stationary wavelength of 600 nm was measured at 2-s intervals. The photomultiplier tube was cooled in both measurements down to -20 °C and allowed to stabilize, so that the pulse-width modulated interference was present.

Radar measurements

In 2007, research in radar measurements was continued. In modern radars, short pulse length - often less than 100 ns - and high operating frequency set some limits in using conventional measurement devices.

New setup for frequency measurements of radar pulses was developed. It was modified from the earlier version, which was based on a phase detector. The new setup uses a separate oscillator as a frequency reference and is capable to detect frequency differences of 200 kHz, when the pulse length is 100 ns.

Also instrumentation radar was designed and built. It is used mainly on foliage attenuation measurements. It operates in Ka-band, and employs a very short, 17 ns pulse. Results of this work will be published in 2008.

5.2 Optical Radiation Measurements

Reducing reflectance in custom made photodiodes

A method is proposed to reduce the reflectance from a custom-made silicon photodiode with thick oxide layer. Increasing the oxide coating thickness to a value much bigger than typical thickness (25-30 nm) will lead to a situation where destructive interference for *p*-polarized reflected beam occurs simultaneously at multiple wavelengths. It is due to the periodic behaviour of the reflectance as a function of the oxide thickness (Figure 4). Wavelengths 453.5 nm, 488.1 nm (Ar+), 528.5 nm, 576.0 nm, 633.0 nm (HeNe), 703.0 nm and 790 nm (Ti:Sapphire) reach low reflectance with the photodiode oxide layer thickness of 2907 nm. The incident angles for all the wavelengths are rather similar and correspond to the Brewster angles for vacuum-silicon interface.

This mechanism allows developing a single photodetector where losses due to reflection are minimized at several commonly used laser lines.

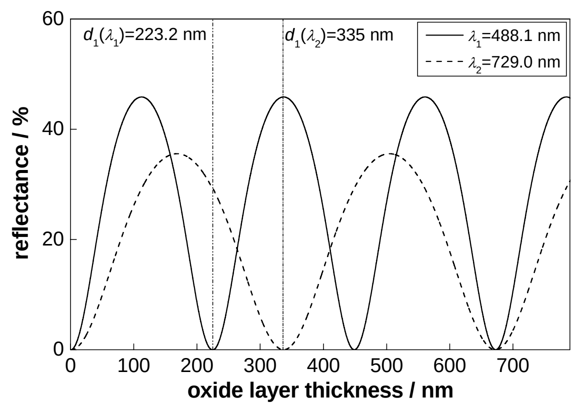

Figure 4. Reflectance from a silicon photodiode as a function of oxide layer thickness. Incident p-polarized beams are arriving to the photodiode at Brewster angles.

Behaviour of LEDs under pulse-width modulation dimming

During 2007, as a part of light emitting diode (LED) project, spectral and thermal behaviours of three AlGaInP LEDs were studied when controlling their brightness with pulse-width modulation (PWM). In the work, variations in the peak wavelength and band width of the emission spectrum of the studied LEDs with different colours under PWM dimming were investigated as well as changes in their junction and charge carrier temperatures. The measurement results indicated the blueshift of the peak wavelength and the bandwidth narrowing for the studied LEDs as the width of the pulse was decreased. Also, the junction temperature and carrier temperature of the studied LEDs linearly rose with increasing duty cycle. Perceivable changes in colour of AlGaInP LEDs under the PWM scheme were observed.

Luminous flux measurement of light emitting diodes

A setup was designed, built and characterized for luminous flux measurements of Light Emitting Diodes (LEDs). The measurement setup is based on the CIE 127 standard and uses an integrating sphere method. Both the total luminous flux and the partial LED flux of low or high power LEDs can be measured using the same 30-cm integrating sphere. In addition to a detector port and an auxiliary LED port, the integrating sphere has only one entrance port, in contrast to other designs which have an additional port for the total luminous flux measurement. The measurement setup was calibrated and test measurements were conducted using two white LEDs. The expanded uncertainties (k=2) for the measurement setup vary between 0.5 % and 2.2 % depending on the measurement mode and the properties of the tested LED. The measurement uncertainty is comparable to those of the measurement setups developed in other metrology institutes. The measurement setup is fully functional and can be used for calibrating standard LEDs for customers and for further research of LEDs. Figure 5 shows the inner surface of the integrating sphere in a self-absorption measurement of a test LED.

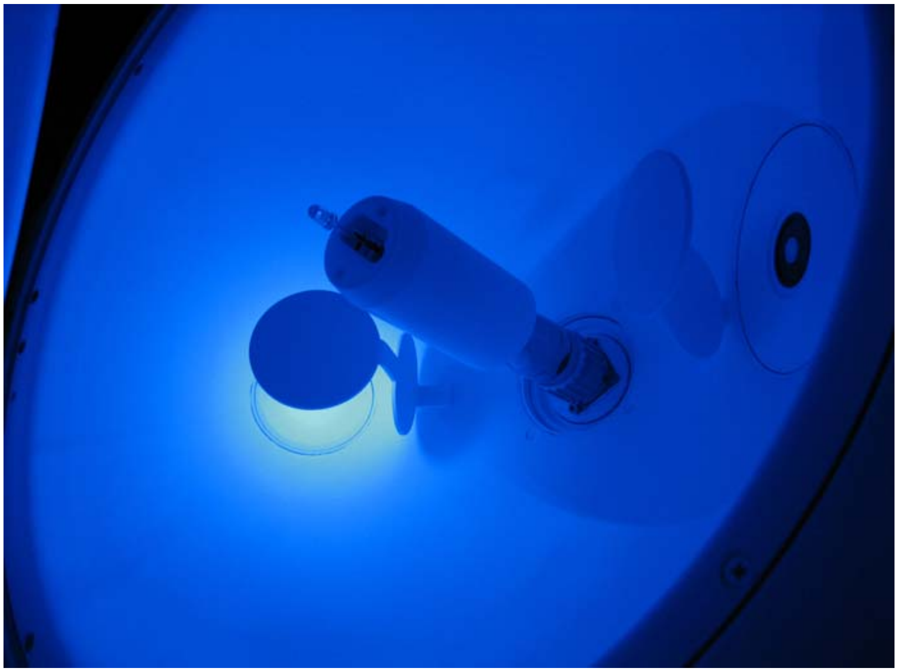

Figure 5. Self-absorption measurement of a white low power test LED. A blue auxiliary LED was used for illuminating the integrating sphere.

Improving the accuracy of linear pyrometer measurements and comparison of the radiation temperature scales between PTB and MIKES

Methods for improving the extrapolated radiation temperature measurements above the metallic fixed points using linear pyrometers were compared. Four different methods for obtaining the effective wavelength were studied. These include direct measurement of the spectral responsivity of the pyrometer, comparison of two measured pyrometer signals at known temperatures, comparison against a narrow-band filter radiometer operating as an irradiance mode transfer pyrometer, and calculating the effective wavelength using reliable intercomparison data. The improvements obtained using the methods are estimated by comparing the results with extrapolation using the Sakuma-Hattori method and analysis using Planck's law with the nominal wavelength (651 nm) of the pyrometer tested. Experimental results of the study are based on a large set of intercomparison data resulting from a recent temperature intercomparison between the PTB (Germany) and the MIKES (Finland) in the range of 1570 K to 2770 K. The measurement artifacts include a high temperature black body, a strip lamp used as an ITS-90 reference, two linear pyrometers and various irradiance-mode filter radiometers. It was shown that improper understanding of the pyrometer properties may lead to systematic measurement errors up to several Kelvins. With careful analysis, uncertainties of the order of 1 K are obtainable.

Comparison of detector-based spectral irradiance scales using NIR lasers

Spectral irradiance measurements using filter radiometers are needed for radiometric temperature determinations. Independent laser-based calibration facilities at the Metrology Research Institute, Finland, and the National Institute of Standards and Technology (NIST), United States, used for the realization of the detector-based spectral irradiance scale have been compared in the near-infrared (NIR) region. The results of the comparison of the laser-based facilities were compared to the spectral irradiance scale obtained with the NIST monochromator-based calibration facility. The comparison was carried out by calibrating a narrow-bandwidth filter radiometer on each facility. The results of the comparison showed agreement between the integrated responsivities of the radiometer within 0.1 %, well within the standard uncertainty of the comparison. The work also covers the study of out-of-band responsivity measurements and the ageing properties of the filter radiometer used. The results give additional evidence on the suitability of lasers as sources for the realization of absolute spectral irradiance scales in the NIR region enabling, e.g. the development of the radiometric temperature scales with lower uncertainties.

Extension of the wavelength range of spectral irradiance measurements

The wavelength range of spectral irradiance measurements was extended to 250 – 290 nm in the ultraviolet region and to 900 – 1500 nm in the near infrared region. GaAsP trap detector and ultraviolet filters were used in the ultraviolet region, and Ge detector and infrared filters were used in the near infrared region. In the visible region Si trap detector was used. Three FEL-type standard lamps (Figure 6) calibrated by NPL were measured with all three filter radiometers. As a result the spectral irradiance could be measured for the first time in the wavelengths 260 nm, 980 nm, 1100 nm, 1300 nm and 1500 nm and the wavelength range of spectral irradiance was extended to 250 – 1500 nm region. The expanded uncertainty (k=2) is 2.8 % in the ultraviolet region and 3.0 % in the infrared region. The comparison with NPL indicates that we are measuring an average of 2.5 % higher spectral irradiance values than NPL in the ultraviolet region. The deviation between spectral irradiances is less than 4.7 % in the near infrared region, but in the visible region the differences are only in the range of 0.5 %.

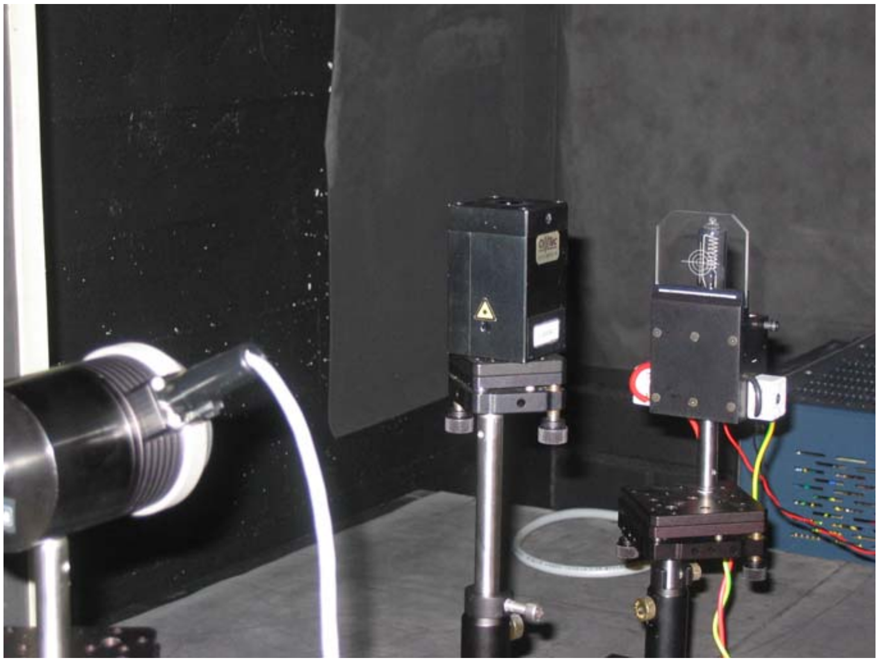

Figure 6. Aligning the detector and the lamp to the same optical axis using a two-output laser source.

Goniofluorometer for characterization of fluorescent materials

The colour of a fluorescent specimen depends on the illuminating source and the observer. It can be calculated for the desired source and observer with the help of the source and observer independent bispectral radiance factors. We have characterized our goniofluorometer for measuring bispectral luminescent radiance factors in the wavelength range of 250 – 800 nm. In 2007 we purchased a new monochromator for the excitation system to improve the accuracy and reliability of the instrument. We are currently characterizing the excitation system with the monochromator. We have also purchased components for building a sample holder for liquid samples. The purpose is to have holders that can hold both liquid and solid samples and improve the sample holder system so that incident angles can be varied from 0° to 90°. Presently we are limited to the viewing angles between 0° – 8°.

Detector responsivity at infrared

Many radiometric applications require the determination of the spectral radiant power responsivity function of infrared (IR) detectors. Applications of IR detectors in various fields such as thermal imaging, night vision and surveillance, low temperature measurements, and testing of micromechanical devices have brought demanding requirements for accurate calibration of infrared standard detectors. Accurate measurement of spectral power responsivity in the visible spectral region has been a service provided by the Metrology Research Institute for several years. We have recently moved to expand the spectral range of spectral irradiance scale to cover the UV and near infrared regions. The extension of wavelength range for spectral irradiance scale requires the availability of a spectral power responsivity of utilised detectors in the range from 0.9 µm to 2.5 µm. Recently, spectral responsivity calibration capability has been extended from 0.2 µm out to 1.7 µm.

In the year 2007, three cabinets equipped with dry Nitrogen purging system were built (Figure 7) for measuring spectral power responsivity of detectors in the wavelength range from 1.1 µm to 3.1 µm, including the atmospheric absorption bands. Several working reference detectors were developed with the possibility of mounting them onto an integrating sphere. In addition, integrating sphere detectors were utilised for measurement of relative diffuse transmittance of paper samples in the near infrared spectral range in order to study their water content.

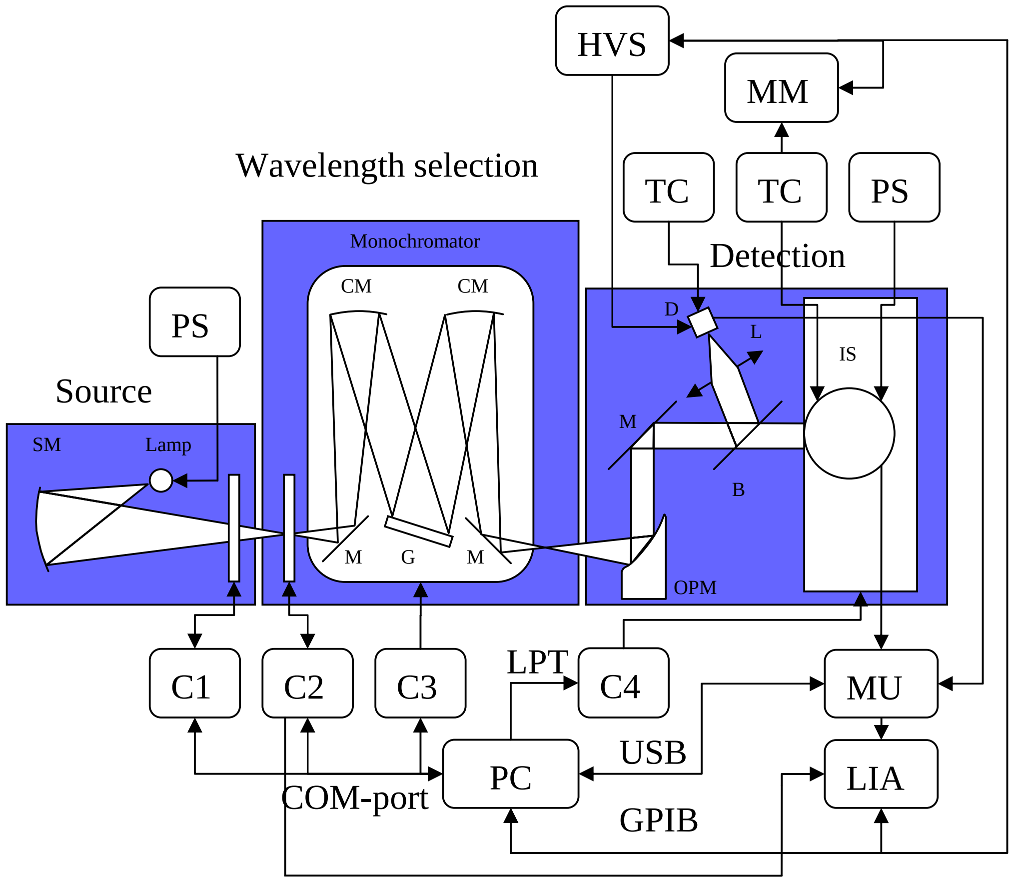

Figure 7. Schematic of the measurement setup for spectral power responsivity and for relative diffuse transmittance at near infrared wavelengths. The colored parts are filled with dry nitrogen.

Spectral emissivity model for tungsten-halogen lamps

Spectral irradiance measurement with a filter radiometer requires prior knowledge of the object's emissivity. The tungsten filament of a lamp has an emissivity which is wavelength and temperature dependent. The method of irradiance measurement currently in use at the Metrology Research Institute is based on a complex error minimization algorithm, where the emissivity of the source is modeled with a polynomial using linear regression. To simplify the algorithm, a fixed spectral emissivity model for tungsten lamps was tested, which was obtained using spectral irradiance data of three NPL calibrated 1 kW lamps. Results differ significantly from the spectral emissivity values for tungsten found in literature. The difference is wavelength dependent and it is up to 20 % over a broad spectral range. Possible physical explanations include losses in halogen gas and quartz glass, impurities in tungsten filament and surface preparation.

Effects of UV radiation on MAterials (UVEMA).

In this two-year project in collaboration with Finnish Meteorological Institute, Tampere University of Technology and several industrial partners, the Metrology Research Institute built a device that can be used for studying the effect of wavelength on the UV ageing of materials. The device is based on a concave flat-field holographic grating that disperses the radiation collected from a 1-kW Xe-lamp, and images it onto a sample plane. The device causes noticeable damage to newspaper in hours. Plastic samples age in a matter of days so that the action spectrum can be defined.

Figure 8. Fine-tuning of the radiator setup in the Observatory of Jokioinen. On the right, one can see the Xe-lamp in its housing and on the left, a water cooler used to circulate the water in the heat absorbing filter.

During 2007 the device was finalized and delivered to the customer (Figure 8). Thorough measurements were conducted to ensure that the alignment of the setup did not change in the transfer. The device is to be operated by technicians so detailed operating instructions were produced.

5.3 Fiber-Optics

Highly coherent supercontinuum generation in dispersion increasing fibers

Supercontinuum (SC) generation has attracted considerable interest in the past few years primarily due to the rapid development of photonic crystal fibers and the many important applications in pure and applied optics. These studies have led to renewed interest in SC generation in other fiber types such as highly nonlinear fibers or dispersion-decreasing fibers (DDFs). Significantly, detailed previous studies have suggested that fibers with longitudinally varying dispersion could be advantageous in generating flatter and broader SC spectra compared to fibers with uniform longitudinal dispersion. In particular, fibers with a decreasing dispersion profile were found to produce uniform and wide SC with a high degree of coherence useful for pulse compression applications. On the other hand, the case where the dispersion increases with propagation has received little attention. In this work, we have shown that, with appropriate design, dispersion-increasing fibers (DIFs) may be even more advantageous to generate highly coherent SC with large bandwidths along very short lengths of fiber, which could prove to be very useful for pulse compression applications. Figure ***9*** illustrates the SC generated by launching 0.5 ps pulses (FWHM) with 28 kW peak power into the fiber with a dispersion profile as in Figure 9. These parameters correspond to an input soliton number *N*=30. The generated SC spans nearly one optical octave at the -20 dB bandwidth, although there are relatively large variations in the spectral amplitude.

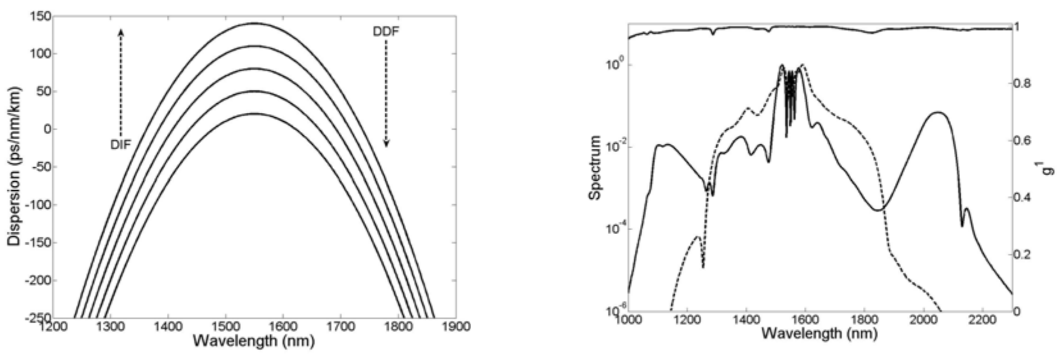

Figure 9. (a) Varying dispersion profile used for the simulations. The dispersion at the pump wavelength increases from 20 ps/nm·km to 140 ps/nm·km for the DIF and vice-versa for the DFF and (b) SC generated along the DIF and associated coherence (solid line). For comparison, the SC generated along the same fiber used as a DDF is plotted as a dash line.

Dynamics of harmonic generation in highly nonlinear silica nanowires

Pulse propagation in highly nonlinear waveguides has been dramatically stimulated by the development of sub-wavelength dimension nanowires made of silica or highly nonlinear glass. The elevated nonlinearity that can be attained in such nanowires allows for the generation of ultra broadband highly coherent light sources, and pulse compression approaching a single optical cycle. Recent theoretical studies have also investigated the generation of third and higher-order harmonic generation in nanowires, in the context of modeling carrier self-steepening and shock development using simulations based on a new generalized nonlinear envelope equation [G. Genty *et al. Opt. Express* **15**, 5382-5387 (2007)]. We have extended this work and studied the detailed propagation dynamics of ultrashort pulse propagation and harmonic generation in fused silica nanowires under fully realistic conditions, including the presence of input pulse noise (Figure 10). A particular result that we found is that for conditions of simultaneous pump spectral broadening and third harmonic generation, the spectral amplitude can be intrinsically sensitive to carrier-envelope offset phase (CEO). This suggests a particularly simple and straightforward approach to CEO phase stabilization based on spectral amplitude control, obviating the need for more complex self-referencing techniques.

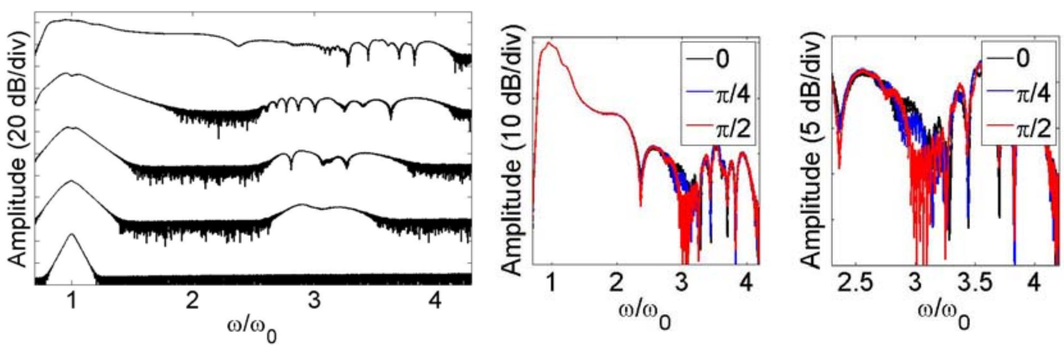

Figure 10. (a) Simulated Spectral intensity profiles shown at selected distances of 1060 nm pulses in a 600 nm diameter fused silica nanowire. Length=0.5 mm, input pulse duration=30 fs, pulse peak power=150 kW. (b) Spectrum generated in 0.5 mm of a 600 nm diameter fused silica nanowire for various CEO values with expanded view of the third harmonic spectral components. (color online http://metrology.hut.fi/cgi-bin/index.cgi?publications)

Determination of Er-doped active fiber nonlinearity

Nonlinear effects are caused by the intensity dependence of refractive index. The intensity dependent part of the refractive index is called nonlinear refractive index (n_2). Generally nonlinear effects can be omitted when using low power levels, but become important when fiber lengths are increased and/or power is high. In the case of Er-doped fiber, the fiber length is usually short, but power levels can reach over 100 mW levels.

As in the case of standard fibers, the power measurement is also crucial in determination of the nonlinearity of Er-doped fibers. Dispersion is not that critical because of the short length, but other phenomena such as spectral hole burning (SHB), varying gain and amplified spontaneous emission (ASE) may considerably increase the measurement uncertainty.

Continuous-wave self-phase-modulation methodology can be applied to Er-fibers as well, but the fiber lengths have to be considerably shorter. In our studies, it was shown that less than 10 meters is an optimal length for the fiber (Figure 11). ASE and power transfer off the signal wavelength become distorting. On the other hand, if the fiber is very short, the uncertainty of the nonlinearities induced from the fixed components (EDFA, pigtails & coupler) dominate.

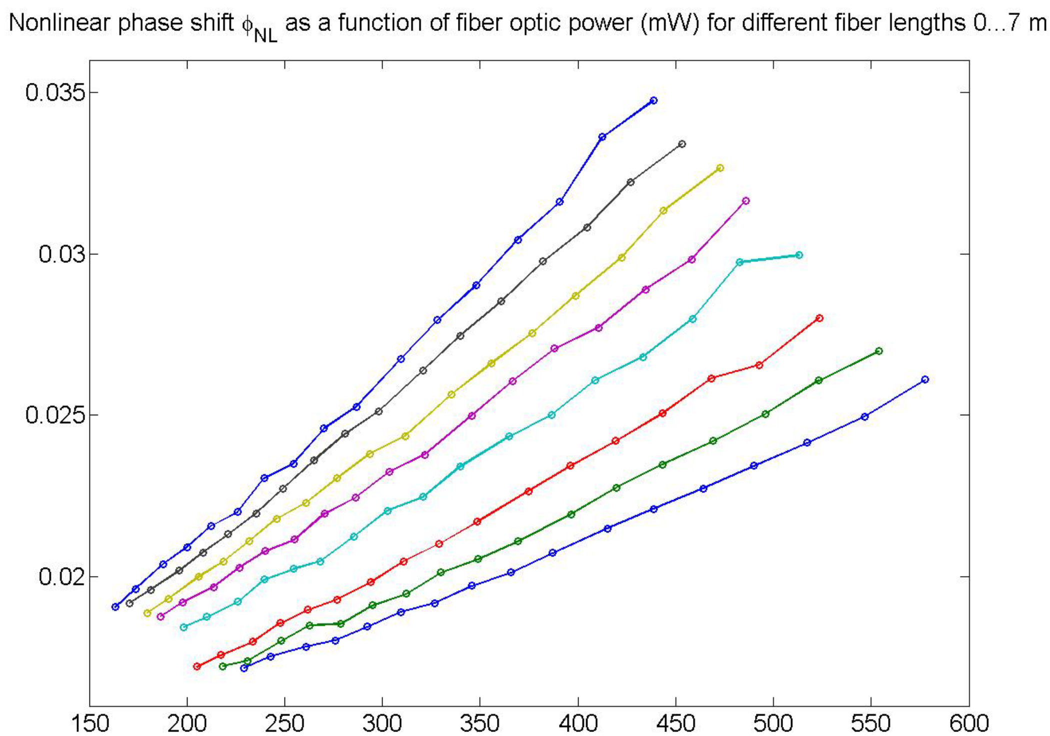

Figure 11. Nonlinear phase shift (deduced from sidebands) as a function of fiber optic power. By setting 0 m (lowest line) as the reference, nonlinear coefficient can be determined from the difference of the slopes.

5.4 Applied Quantum Optics

Triple coincidences of x-ray photons

The intensities of x-ray sources have increased dramatically during the development of modern high-energy synchrotron radiation facilities. This development has allowed experimental studies on spatial and temporal properties of x-ray sources by excess coincidences of two photons. Even more intense sources are anticipated when the new x-ray free-electron lasers (XFELs) become operational. For the XFEL, multiple-photons can be observed in very small detector areas in a single-shot measurement. Features of multiple photon coincidences are thus interesting at orders higher than two, including consideration of the feasibility of observing such x-ray coincidences at presently available synchrotron radiation facilities.

The process that leads to emission of x rays from a synchrotron radiation source can be regarded as a collision of the bunch of electrons and the electromagnetic field of a storage-ring insertion device, such as an undulator. This type of process has been thoroughly analyzed in connection with nuclear collisions. Instead of photons, nuclear collisions mainly produce pions, kaons, and other particles, for which three-pion coincidences have been studied recently in heavy ion accelerators. Furthermore, it has been argued that three-particle coincidences provide additional information which is not accessible by two-particle measurements.

We have studied the basic theory of triple coincidences of x-ray photons from a synchrotron radiation source [E. Ikonen and S. Holopainen, *Phys. Rev*. A **76**, 031801(R), (2007)]. The analysis reveals a genuine combination of three radiation fields in the third-order intensity correlation function, which is a special characteristic of triple coincidences. It is further shown that experimental observation of the triple coincidences, including the characteristic three-field effect, is feasible with operational parameters achievable at the SPring-8 synchrotron radiation facility in Japan. Although three-pion correlations are much studied in high-energy physics, the triple coincidences of x-ray photons require a dedicated analysis to reveal their special features and tentative applications. This project is supported financially by the Academy of Finland.

Molecules as sources for indistinguishable single photons

In a collaboration project with ETH Zurich, triggered generation of indistinguishable photons was achieved by solid-state single-photon sources in two separate cryogenic laser scanning microscopes. Organic fluorescent molecules were used as emitters and investigated by means of high resolution laser spectroscopy. Continuous-wave photon correlation measurements on individual molecules proved the isolation of single quantum systems [R. Lettow, *et al*. *Opt. Express* **15**, 15842 (2007)]. By using frequency selective pulsed excitation of the molecule and efficient spectral filtering of its emission, triggered Fourier-limited single photons were produced. In a further step, local electric fields were applied to match the emission wavelengths of two different molecules via Stark effect. Identical single photons are indispensable for the realization of various quantum information processing schemes proposed. The solid-state approach presented in this work prepares the way towards the integration of multiple bright sources of single photons on a single chip (Figure 12). The work of the Metrology Research Institute in this project is supported financially by the Academy of Finland.

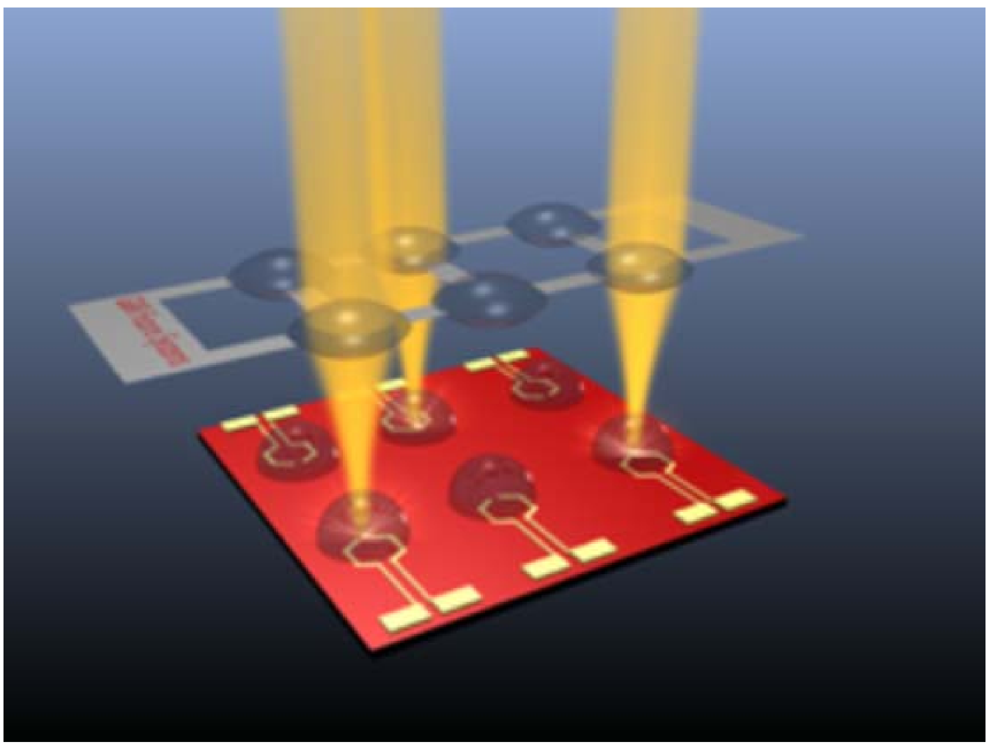

Figure 12. Schematics of multiple single-photon sources on a single chip where molecules are individually addressable by laser beams focused by aspheric lens and solid immersion lens combinations. Electrodes can be used to shift the emission wavelength of each single-photon source independently (Figure from V. Ahtee, R. Lettow, R. Pfab, A. Renn, E. Ikonen, S. Götzinger, and V. Sandoghdar, “Molecules as Sources for Indistinguishable Single Photons,” submitted to Journal of Modern Optics).

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

The Metrology Research Institute is a joint laboratory of Helsinki University of Technology (TKK) and Centre for Metrology and Accreditation (MIKES). The Metrology Research Institute participates in official key and supplementary comparisons under the name MIKES.

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

Draft A-3 is yet to be completed due to workload of the NIST staff member. The changes relative to Draft A-2 will be very small, hardly noticeable on the plots.

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

Part of the measurements was still in progress in 2007. For one participant, two PtSi photodiodes were damaged twice during the comparison. The last measurements by this participant were to be completed in July 2007. All results should be received by October 2007. Draft A is expected in April 2008.

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

Pre-Draft A process was completed during 2007. It is hoped to distribute Draft A early 2008. The data of additional comparisons with some of the participants will be analyzed later and the results will be published separately.

Key comparison CCPR-K6, spectral regular transmittance, pilot LNE

Draft A-3 has been distributed in 2007. Draft B is expected in 2008.

Supplementary comparison CCPR-S2, aperture area, pilot NIST

Final report was published in Metrologia Technical Supplement in 2007: *Metrologia* **44**, Tech. Suppl. 02002, 84 pages.

Chromatic dispersion comparison EUROMET-PR.S1.1 (bilateral with METAS)

Final report was published in Metrologia Technical Supplement in 2007: *Metrologia* **44**, Tech. Suppl. 02003, 12 pages.

Bilateral key comparison EURAMET-K1.a.1, spectral irradiance, pilot MIKES

Three spectral irradiance standard lamps were calibrated in the wavelength range 290 – 900 nm by the pilot and by the National Institute of Metrology Thailand (NIMT). The repeat measurements of the pilot and reporting of the results will be carried out in 2008.

Spectral irradiance comparison with SPRING Singapore using filter radiometers

A new method of comparing spectral irradiance scales was studied. The TKK spectral irradiance lamp was calibrated against the SPRING spectral irradiance scale embodied by the filter radiometers (Figure 13).

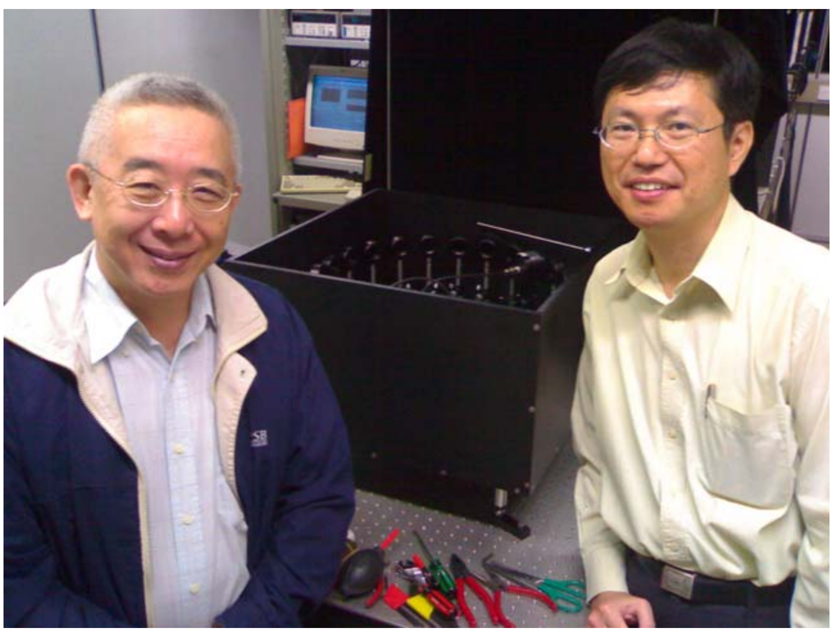

Figure 13. Dr. Gan Xu and Dr. Yuanjie Liu (right) in front of the SPRING filter radiometer consisting of rotating filters and a trap detector. The black-walled lamp enclosure is seen behind the filter wheel container.

Comparison of absolute spectral irradiance responsivity measurement techniques using wavelength-tuneable lasers

Independent methods for measuring the absolute spectral irradiance responsivity of detectors have been compared between the Metrology Research Institute and the National Institute of Standards and Technology (NIST), USA. The results of the comparison demonstrate agreement at the uncertainty level of less than 0.1 % and are published in *Appl. Optics* **46**, 4228-4236 (2007).

Comparison of the radiation temperature scales

The radiation temperature scales of PTB and MIKES were compared in the range of 1570 K to 2770 K at Physikalisch-Technische Bundesanstalt (PTB), Germany. The measurement artifact was a high temperature black body, and a strip lamp was used as an ITS-90 reference. The measurement equipment consisted of four filter radiometers from TKK, one filter radiometer from PTB and linear pyrometers from MIKES and PTB. The results of filter radiometers agree within *k*=2 uncertainty limits between the scales (Figure 14). The average difference to ITS-90 of the linear pyrometer from MIKES was -0.28 K and the standard deviation was 0.52 K. For the linear pyrometer from PTB, the average difference was 0.18 K and the standard deviation 0.36 K.

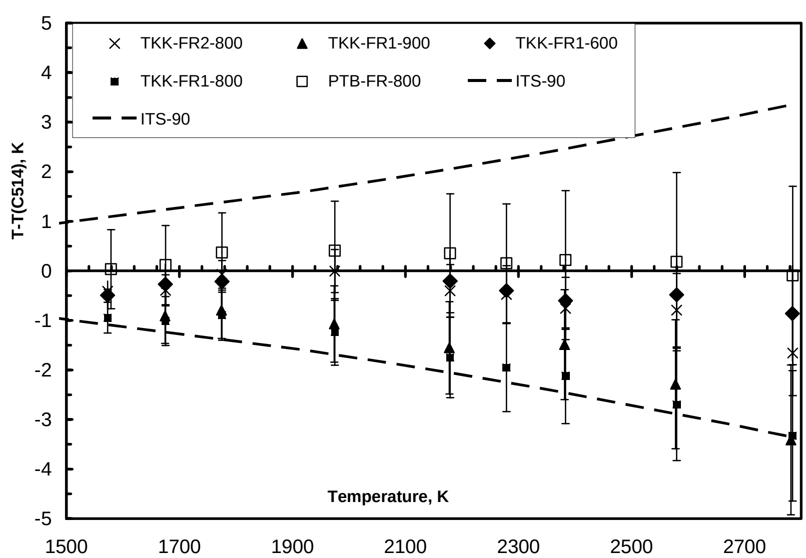

Figure 14. Filter radiometer measurement results and their differences to the ITS-90 reference. The dashed lines represent the expanded uncertainty (*k*=2) of the ITS-90 reference.

6.2 Thematic Networks

6.2.1 Thematic network for ultraviolet measurements

The Metrology Research Institute is the coordinator of the Thematic Network for Ultraviolet Radiation Measurements, which has continued its activities after the EU-funded period. In 2007, the Network had no activities.

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

EURAMET e.V. Inaugural Meeting, Berlin, Germany, January 11, 2007; *Erkki Ikonen*

European Metrology Research Programme (EMRP) Committee Meeting, Berlin, Germany, January 12, 2007; *Erkki Ikonen*

Nonlinear Effects in Photonic Materials, Berlin, Germany, March 11–14, 2007; *Goery Genty*

Physics Days 2007, XLI Annual Conference of the Finnish Physical Society, Tallinn, Estonia, March 15–18, 2007; *Petri Kärhä, Goery Genty, Silja Holopainen, Meelis-Mait Sildoja and Tuomas Hieta*

EUROMET Phora TC meeting, Bucharest, Romania, April 18–19, 2007; *Erkki Ikonen*

Tempmeko 2007, Lake Louise, Canada, May 21–25, 2007; *Maija Ojanen and Ville Ahtee*

EFTF2007 Conference, Geneva, Switzerland, May 27 – June 1, 2007; *Mikko Puranen*

Science Summer School 2007 of Estonian Physical Society, Tartu, Estonia, June 15–17, 2007; *Meelis-Mait Sildoja*

CCPR and CCPR WG-KC, WG-CMC, WG-UV (Chair), WG-SP meetings, Paris, France, June 17–21, 2007; *Erkki Ikonen*

Meeting on EURAMET Phora Joint Research Projects, Paris, France, June 19, 2007; *Erkki Ikonen*

Conference on Lasers and Electro-Optics, Munich, Germany, June 17–23, 2007; *Goery Genty*

CIE Session 2007, Beijing, China, July 4–7, 2007; *Erkki Ikonen and Farshid Manoocheri*

CIE Technical Committee meetings and CIE Division 2 meeting, Beijing, China, July 9–12, 2007; *Erkki Ikonen and Farshid Manoocheri*

EMRP Call 2007 TP Health Facilitation meeting, NPL, Teddington, UK, July 20, 2007; *Farshid Manoocheri*

EMRP Candela Joint Research Project preparation meeting, Espoo, Finland, August 2–3, 2007; *Erkki Ikonen, Farshid Manoocheri, Petri Kärhä, Ville Ahtee*

4th International Summer School "New Frontiers in Optical Technologies", Tampere, Finland, August 13–17, 2007; *Tuomas Hieta*

17th Jyväskylä Summer School, August 18–17, 2007; *Meelis-Mait Sildoja*

SPW 2007, Single-Photon Workshop 2007, Torino, Italy, September 25–29, 2007; *Ville Ahtee*

European Metrology Research Programme (EMRP) Committee Meeting, Paris, France, October 3–4, 2007; *Erkki Ikonen*

OFMC 2007, London, UK, October 14–17, 2007; *Tuomas Hieta*

EMRP Review Conference, Paris, France, October 24–25, 2007; *Erkki Ikonen*

EMRP Committee meeting, Paris, France, October 26, 2007; *Erkki Ikonen*

6.4 Visits by the Laboratory Personnel

Erkki Ikonen, BESSY II and Metrology Light Source (MLS), Berlin, Germany, January 11, 2007

Erkki Ikonen, National Metrology Institute of Australia (NMIA), Sydney, Australia, January 26 – February 2, 2007

Erkki Ikonen, National Institute of Metrology Thailand (NIMT), Bangkok, Thailand, February 3–6, 2007

Maija Ojanen, PTB, Berlin, Germany, March 5–9, 2007

Mikko Puranen, CNC, Hallstadt, Germany, March 21–25, 2007

Farshid Manoocheri and Silja Holopainen, BAM and PTB, Berlin and Braunschweig, Germany, April 23–26, 2007

Maija Ojanen, NRC, Canada, May 25, 2007

Erkki Ikonen, SPring-8, Harima, Japan, July 1–4, 2007

Tuomas Hieta, NPL, Teddington, UK, October 17, 2007

Erkki Ikonen, LNE-INM, Paris, France, October 24, 2007

Erkki Ikonen, National Institute of Metrology Thailand (NIMT), Bangkok, Thailand, October 31 – November 4, 2007

Erkki Ikonen, SPRING Singapore, November 5–17, 2007

Ville Ahtee, ETH Zürich, December 13–15, 2007

6.5 Research Work Abroad

Kimmo Ruokolainen, Asian Institute of Technology, Bangkok, Thailand, January 2007

Pasi Manninen, National Physical Laboratory NPL, UK, January 1 – March 31, 2007

Jouni Envall, NIST, USA, January 1 – October 30, 2007

6.6 Visits to the Laboratory

Dr. Toomas Kübarsepp and Mr. Andrei Prokotilov, Metrosert Ltd, Estonia, February 20, 2007

Dr. Toomas Kübarsepp, Metrosert Ltd, Estonia, May 13, 2007, June 7–8, 2007 and October 9, 2007

Dr. Mart Noorma, Tartu University, Estonia, June 7–8, 2007

Dr. Julian Gröbner, PMOD/WRC, Switzerland**,** June 20, 2007

Dr. Maria Luisa Rastello (IEN, Italy)*, Dr. Giorgio Brida* (IEN, Italy)*, Malcolm White* (NPL, UK)*, Dr. Jessica Cheung* (NPL, UK)*, Dr. Stefan Kück* (PTB, Germany)*, Dr. Marek Smid* (CMI, Czech Republic)*,* August 3, 2007

Mr. Wolfgang Dähn, Gigahertz Optik, Germany, September 3, 2007

Mr. Lukasz Litwiniuk, National Metrology Institute of Poland, October 29–31, 2007

Professor Leonardo De Chiffre, Technical University of Denmark, December 16–18, 2007

7 PUBLICATIONS

7.1 Articles in International Journals

P. Manninen, J. Hovila, P. Kärhä, and E. Ikonen, ”Method for analysing luminous intensity of light-emitting diodes,” *Meas. Sci. Technol.* **18**, 223-229 (2007).

A. Lamminpää, T. Hieta, J. Envall and E. Ikonen, “Reliable determination of optical fiber nonlinearity using dispersion simulations and improved power measurements,” *Journal of Lightwave Technology* **25**, 527-532 (2007).

G. Genty, S. Coen, and J.M. Dudley, “Fiber supercontinuum sources,” *J. Opt. Soc. Am. B* **24**, 1771-1785 (2007), invited paper.

G. Genty, P. Kinsler, B. Kibler, and J. M. Dudley, “Nonlinear envelope equation modelling of sub-cycle dynamics and harmonic generation in nonlinear waveguides,” *Opt. Express* **15**, 5382-5387 (2007).

S. Holopainen, F. Manoocheri, S. Nevas and E. Ikonen, “Effect of light scattering from source optics in goniometric diffuse reflectance measurements,” *Metrologia* **44**, 167-170 (2007).

M. Merimaa, K. Nyholm, M. Vainio, and A. Lassila, “Traceability of laser frequency calibrations at MIKES,” *IEEE Trans. Instrum. Meas.* **56**, 500-504 (2007).

V. Ahtee, S. W. Brown, T. C. Larason, K. R. Lykke, E. Ikonen, and M. Noorma, “Comparison of absolute spectral irradiance responsivity measurement techniques using wavelength-tunable lasers,” *Appl. Optics* **46**, 4228-4236 (2007).

R. Lettow, V. Ahtee, R. Pfab, A. Renn, E. Ikonen, S. Götzinger, V. Sandoghdar, “Realization of Two Fourier-Limited Solid-State Single-Photon Sources,” *Opt. Express* **15**, 15842-15847 (2007).

B. Hemming, M. Noorma, and E. Ikonen, “Measurement of Aperture Areas Using an Optical Coordinate Measuring Machine,” *International Journal of Optomechatronics* **1**, 297-311 (2007).

E. Ikonen and S. Holopainen, ”Triple Coincidences of X-Ray Photons,” *Phys. Rev. A* **76**, 031801 (Rapid Communication), 4 pages (2007).

E. Ikonen, P. Manninen, and P. Kärhä, “Modeling Distance Dependence of LED Illuminance,” *Light & Engineering* **15**, 57-61 (2007).

A. Heikkilä, A. Tanskanen, P. Kärhä, and K. Hanhi, “Adjusting timing of weathering test to account for seasonal variations in UV exposure,” *Polym. Degrad. Stab.* **92**, 675-683 (2007).

P. Manninen and P. Orreveteläinen, “On spectral and thermal behaviors of AlGaInP light-emitting diodes under pulse-width modulation,” *Appl. Phys. Lett.* **91,** 181121, 3 pages (2007).

M. Litorja, J. Fowler, J. Hartmann, N. Fox, M. Stock, A. Razet, B. Khlevnoy, E. Ikonen, M. Machacs, and K. Doytchinov, “Final report on the CCPR-S2 supplementary comparison of area measurements of apertures for radiometry,” *Metrologia* **44**, Tech. Suppl. 02002, 84 pages (2007).

J. Morel and A. Lamminpää, “Final report of EUROMET-PR.S1.1: Bilateral intercomparison on measurements of chromatic dispersion reference fibres between METAS (Switzerland) and MIKES (Finland),” *Metrologia* **44**, Tech. Suppl. 02003, 12 pages (2007).

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: Products and Applications* (in press).

A. G. Nasibulin, A. Ollikainen, A. S. Anisimov, D. P. Brown, P. V. Pikhitsa, S. Holopainen, J. S. Penttilä, P. Helistö, J. Ruokolainen, M. Choi and E. I. Kauppinen, ”Integration of single-walled carbon nanotubes into polymer films by thermo-compression,” *Chemical Engineering Journal* (in press).

M. Sildoja, F. Manoocheri and E. Ikonen, “Reducing photodiode reflectance by Brewster-angle operation”, *Metrologia* (in press).

S. Holopainen, F. Manoocheri and E. Ikonen, “Goniofluorometer for characterization of fluorescent materials”, *Applied Optics* (in press).

7.2 International Conference Presentations

G. Genty, “Beyond supercontinuum generation in photonic crystal fiber: extreme nonlinear broadening”, in *Proceedings of Nonlinear Effects in Photonic Materials*, Berlin, Germany, March 11-14, 2007 (invited talk).

J. M. Dudley, G. Genty, S. Coen, B. Kibler, and P. K. Kinsler, “From supercontinuum generation to carrier shocks: consequences of SPM in ultrafast pulse propagation in photonic crystal fiber”, in *Joint Symposium on Self-Phase Modulation in Its 40th Year, Conference on Laser and Electro-Optics (CLEO 2007)*, Baltimore, USA, May 6-11 2007 (invited talk).

M. Ojanen, M. Noorma, V. Ahtee, T. Weckström, P. Kärhä, and E. Ikonen “Filter radiometers as a tool for quality assurance of temperature measurements with linear pyrometers” in *Proceedings of Tempmeko 2007*, Lake Louise, Canada, May 21-25, 2007 (oral).

V. Ahtee, S.W. Brown, T.C. Larason, M. Ojanen, K.R. Lykke, and E. Ikonen, and M. Noorma “Comparison of detector-based spectral irradiance scales using lasers at TKK and at NIST” in *Proceedings of Tempmeko 2007*, Lake Louise, Canada, May 21-25, 2007 (oral).

G. Genty, “Generalized envelope equation for studying sub-cycle dynamics and multiple-harmonic spectral broadening in highly nonlinear waveguides”, in *Proceedings of Conference on Lasers and Electro-Optics Europe (CLEO Europe’2007)*, Munich, Germany, June 17-22, 2007 (oral).

E. Ikonen, P. Manninen, and P. Kärhä, “Modeling distance dependence of LED illuminance” in *Proceedings of CIE2007*, Beijing, China, July 4-12, 2007, p. D2.6-D2.9 (oral).

G. Genty, “Highly coherent supercontinuum generation in dispersion increasing fibers”, in *Proceedings of the Seventh Finnish-Japanese Joint Symposium on Optics in Engineering*, Tampere, August 8-10, 2007 (poster).

G. Genty, “Highly coherent supercontinuum generation in dispersion increasing fibers”, in *Proceedings of Nonlinear Photonics*, Quebec city, Canada, September 2-6, 2007 (oral).

A. Heikkilä, A. Tanskanen, A. Lindfors, P. Kärhä, and S. Syrjälä, “Quantification of material exposure to ultraviolet radiation,” In: Reichert T. (ed.) *Natural and Artificial Ageing of Polymers*, 3rd European Weathering Symposium, Krakow, Poland, September 12-14, 2007. CEEES Publication No. 8 2007, pp. 461-470 (poster).

V. Ahtee, R. Lettow, S. Götzinger, G. Wrigge, R. Pfab, A. Renn, E. Ikonen, and V. Sandhogar, “Towards indistinguishable photons from two independent molecules” in *Proceedings of SPW 2007*, Single-Photon Workshop 2007, Torino, Italy, September 25-29, 2007, p. 111 (poster).

T. Hieta, A. Lamminpää and E. Ikonen, "High-accuracy determination of fiber nonlinearity using dispersion analysis and improved power measurement", in Conference Digest of 8th Optical Fiber Measurement Conference (OFMC 2007), pp. 19-22, London, UK, 15-17 October, 2007 (oral).

7.3 National Conference Presentations

G. Genty, J.M. Dudley, B. Kibler, and P.K. Kinsler, “Generalized nonlinear envelope equation for extreme nonlinear broadening”, in *Proceedings of the XLI Annual Conference of the Finnish Physical Society*, Tallinn, Estonia, March 15-18, 2007, p 304 (poster).

P. Kärhä, K. Ruokolainen, and A. Heikkilä, “Facility for spectral ultraviolet aging of materials,” in *Proceedings of the XLI Annual Conference of the Finnish Physical Society*, Tallinn, Estonia, March 15-18, 2007, p. 286 (poster).

T. Hieta, A. Lamminpää, and E. Ikonen, “High-accuracy determination of fiber nonlinearity using dispersion analysis and improved power measurement”, in *Proceedings of the XLI Annual Conference of the Finnish Physical Society*, Tallinn, Estonia, March 15-18, 2007, p 305 (poster).

A. Kesänen, A. Lamminpää, T. Hieta, and E. Ikonen, “Effective area of optical fiber using far-field scanning”, in *Proceedings of the XLI Annual Conference of the Finnish Physical Society*, Tallinn, Estonia, March 15-18, 2007, p 307 (poster).

S. Holopainen, F. Manoocheri, and E. Ikonen, “Goniofluorometer for measuring bispectral luminescent radiance factors”, in *Proceedings of the XLI Annual Conference of the Finnish Physical Society*, Tallinn, Estonia, March 15-18, 2007, p 292 (poster).

M. Sildoja, F. Manoocheri, and E. Ikonen, “High laser power measurement facility”, in *Proceedings of the XLI Annual Conference of the Finnish Physical Society*, Tallinn, Estonia, March 15-18, 2007, p 226 (poster).

7.4 Other Publications

S. Holopainen (editor), *Annual report 2006*, Metrology Research Institute, Helsinki University of Technology, Espoo 2007, Metrology Research Institute Report 32/2007, 37 p.

A. Peltonen, M. Merimaa, T. Niemi, P. Kärhä, and M. Ojanen, *Mittaustekniikan perusteiden laboratoriotyöt*, 14 korjattu painos, Espoo 2007, ISBN 951-22-6737-3, 124 p. (in Finnish).

HELSINKI UNIVERSITY OF TECHNOLOGY
METROLOGY RESEARCH INSTITUTE REPORT SERIES

HUT-MRI-R23/2004	S. Nevas, F. Manoocheri, and E. Ikonen, Gonioreflectometer for measuring spectral diffuse reflectance.
HUT-MRI-R24/2005	M. Noorma, V. Ahtee, A. Lamminpää, P. Kärhä, F. Manoocheri, T. Weckström, and E. Ikonen, Radiometric temperature measurements with absolutely characterized filter radiometers in irradiance mode.
HUT-MRI-R25/2005	M. Noorma, Development of detectors and calibration methods for spectral irradiance and radiometric temperature measurements.
HUT-MRI-R26/2005	O. Kimmelma (editor), Biennial report 2003-2004.
HUT-MRI-R27/2005	S. Nevas, S. Holopainen, F. Manoocheri, E. Ikonen, Y. Liu, T. H. Lang, and G. Xu, Comparison measurements of spectral diffuse reflectance.
HUT-MRI-R28/2005	Petri Kärhä, Jaakko Hollmen, Satu Karling, Jaakko Kujala, Petri Kuosmanen, Janne Lindqvist, Opinnäytetyön ohjaus Teknillisessä korkeakoulussa.
HUT-MRI-R29/2005	Markku Vainio, Mikko Merimaa, Kaj Nyholm, Modulation transfer characteristics of injection-locked diode lasers.
HUT-MRI-R30/2006	J. Envall, P. Kärhä, and E. Ikonen, Calibration of broadband ultraviolet detectors by measurement of spectral irradiance responsivity.
HUT-MRI-R31/2006	S. Holopainen (editor), Annual report 2005.
TKK-MRI-R32/2007	S. Holopainen (editor), Annual report 2006.
TKK-MRI-R33/2008	S. Holopainen (editor), Annual report 2007.

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