Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute Report 31/2006
Espoo 2006

ANNUAL REPORT 2005

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

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Metrology Research Institute Report 31/2006
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Editor Silja Holopainen

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Department of Electrical and Communications Engineering
Metrology Research Institute

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Picaset Oy
Helsinki 2006

CONTENTS

1 INTRODUCTION

The Metrology Research Institute is one of the units at the Department of Electrical and Communications Engineering of TKK. It is operated as a joint laboratory of TKK and MIKES (Centre for Metrology and Accreditation). The research work of the Institute consists of electronic instrumentation, optical radiation measurements, fiber optics, and laser applications. In 2005, significant achievements were made in all these fields of research. Below are given just a few examples. These and other achievements are described in more detail in the Research Projects section of this Annual Report.

In optical radiation measurements, a significant new feature was found in experiments using diffuser-based measurement heads with spectro-radiometers: The displacement of the effective receiving plane of the diffuser from the assumed position may lead to large measurement errors if the spectroradiometer is calibrated and used at different distances from the radiation source. Furthermore, the upgrading of our gonioreflectometer optics for spectral diffuse reflectance measurements revealed an important uncertainty contribution due to scattering in the measurement beam, which may explain most of the differences between sphere-based and gonioreflectometer-based results reported by other research groups. Although our previous and new scattering corrections differ by a factor of five, the reflectance results remain unchanged yielding increased confidence on the measured spectral diffuse reflectance.

As an example of laser applications, an optical amplifier at 633 nm was developed for femtosecond frequency comb measurements. The device utilizes injection locking of a diode laser in order to facilitate frequency measurements of iodine-stabilized He-Ne lasers, which are the most widely used optical frequency standards.

The Metrology Research Institute provides calibration services for external customers resulting in 45 certificates in 2005. The reliability of the calibration work is based on international comparison measurements which the laboratory participates on a regular basis. For example, the results of CCPR-K1.a key comparison of spectral irradiance measurements were published in 2005, with results showing the applicability of our primary filter radiometer method in the near-UV and visible wavelength ranges.

Erkki Ikonen

2 PERSONNEL

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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute in 2005.

S-108.1010	Fundamentals of Measurements A 4 credits (Petri Kärhä)
S-108.1020	Fundamentals of Measurements Y 3 credits (Petri Kärhä)
S-108.2010	Electronic Measurements 3 credits (Petri Kärhä)
S-108.2110	Optics 5 credits (Erkki Ikonen)
S-108.3010	Electronic Instrumentation 5 credits (Pekka Wallin)
S-108.3020	Electromagnetic Compatibility 2 credits (Esa Häkkinen)
S-108.3110	Optical Communications and Optical Instruments 5 credits (Erkki Ikonen, Farshid Manoocheri)
S-108.3120	Project Work 2-8 credits (Erkki Ikonen, Antti Lamminpää)
S-108.4010	Postgraduate Course in Measurement Technology 10 credits (Petri Kärhä)
S-108.4020	Research Seminar on Measurement Science and Technology 2 credits (Erkki Ikonen)
S-108.4110	Biological Effects and Measurements of Electromagnetic Fields and Optical Radiation 4 credits (Kari Jokela)

3.2 Degrees

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

Mart Noorma, *Development of Detectors and Calibration Methods for Spectral Irradiance and Radiometric Temperature Measurements*

Opponent: Prof. Jürgen Metzdorf, PTB, Braunschweig, Germany

Jari Hovila, *New Measurement Standards and Methods for Photometry and Radiometry*

Opponent: Dr. Georg Sauter, PTB, Braunschweig, Germany

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

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

Jouni Envall, *National Standard for Fiber Optic Power*

Markku Vainio, *Stable Transmission-Grating Diode Laser for Iodine Spectroscopy*

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

Mikko Puranen, *Design and Implementation of Fiber-Optic Transmitter and Receiver for Radio Frequency Signal* (in Finnish)

Tuomas Hyyppä, *Characterization of Germanium Photodetectors*

Mikko Valle, *Storage Area Network Extension Using Synchronous Digital Hierarchy Technologies*

Juho Huitu, *Calibration System for Accelerometers* (in Finnish)

Juha Nieminen, *Characterization of Liquid Crystal Display Devices*

Tuomas Hieta, *Dispersion Analysis and Optical Power Measurement in Determination of Fiber Nonlinearity*

Maija Ojanen, *Measurement of a Tree Diameter using Image Processing* (in Finnish)

Marko Laurila, *Characterization of a CCD-Based Spectrometer for Fluorescence Measurements*

4 NATIONAL STANDARDS LABORATORY

Metrology Research Institute is the Finnish national standards laboratory for the measurements of optical quantities. The institute was 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 2005, 45 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.

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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5 RESEARCH PROJECTS

5.1 Electronic Instrumentation

Design and implementation of radio frequency devices

Electronic design is important element in nearly all of our projects. Different kinds of devices are needed, for example, in controlling optical instruments. A good example of this is a laser diode driver, which can be seen in Figure 1. This device is used as optical transmitter for low power analog RF-signal. Long-term stability of the injection current is excellent, deviation less than 5 µA. Noise factor is also very low. Intended frequency range for the laser driver is 1.5 – 2.0 GHz. Driver is controlled by PIC-microcontroller, which are used in quite many electrical applications of our projects.

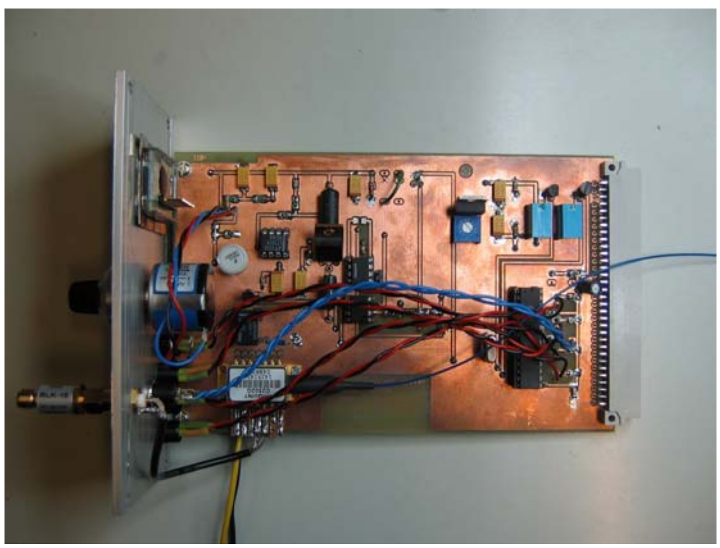

Figure 1. Current driver for laser diode. Driver is controlled by a microcontroller, it has RF input and adjustable injection current. The output of the laser is coupled to a single mode fibre.

Also a temperature controller and an optical receiver were built to be used with the current driver. Temperature controllers are vital to ensure proper operation of a laser diode. Our latest design, used with the laser diode presented before, has temperature stability of 0.5 mK.

Recently RF-electronics have become more and more important in our research. This requires good equipment for testing and also skilled researchers, since in the microwave region non-idealities of the components are significant. Small surface mounted components must be used, and also material of the circuit board must be chosen carefully. Transmission line is also a critical part of the RF-system. In Figure 2, an amplifier for 5.5 GHz region is shown. The amplifier is built on a two-sided Teflon-based circuit board, and 50-ohm microstrips are used as transmission lines.

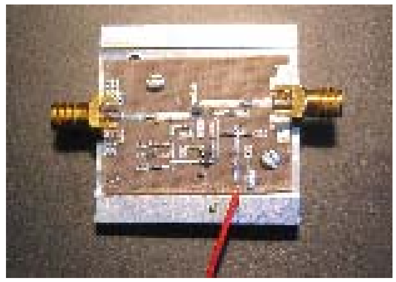

Figure 2. RF-amplifier for 5.5 GHz frequency region. The amplifier is based on a HEMT-transistor, and it is built on a circuit board made of Teflon. Surface mounted components are used to minimize non-idealities. The transmission line is a 50-Ω microstrip.

Calibration of current-to-voltage converters for radiometric applications at picoampere level

Filter radiometers are increasing their popularity in modern photometry and radiometry. At the Metrology Research Institute they have been successfully used in spectral irradiance, illuminance and radiation temperature measurements. One major limitation of extending the use of filter radiometers has been the measurement of the photocurrent. Measuring spectral irradiance in the ultraviolet region or measuring relatively low temperatures results in photocurrents that are in the picoampere range. To reduce the uncertainties of ultraviolet and temperature measurements, we have developed together with MIKES a calibration method for the picoampere range based on the constant-voltage method.

In the constant-voltage method for current calibrations a precise voltage, U, is applied over a precise resistor, R, and the current, I, determined by the classical Ohm's law, is measured (Figure 3). The accuracy of the method is determined in practice by the accuracy of the resistor and the stability of the current-to-voltage converter, as accurate voltage generators are easy to obtain. The main advantage of this method is its simplicity. However, with this method a trade-off for the accuracy has to be made as compared to methods based on capacitive components. Also, there are difficulties with the use of resistive components, such as their long term stability and voltage dependence.

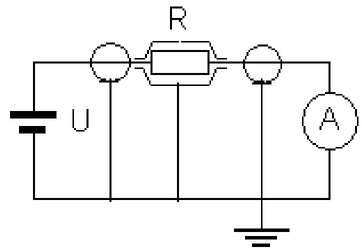

Figure 3. Schematic diagram of the current calibration setup based on the constant-voltage method. The applied voltage *U* over the resistor *R* generates a current which is measured with the current-to-voltage converter, *A*.

The setup consists of a Fluke 5440B/AF (max. output 1000 V) voltage calibrator and a resistor set from 10 GΩ to 100 TΩ. The resistors are characterized in a ladder type sequence starting from a known standard resistor of 1 GΩ (Figure 4). In addition, the resistors have been characterized for voltage dependence, stability, and temperature dependence. The setup has been tested for calibrations of a Keithley 6157 electrometer and two current-to-voltage converters from Vinculum.

Figure 4. The 9331S-series resistor (left) and the 65206-series resistor (middle) are used in the calibrations. The P4030 1 GΩ standard resistor (right) provides traceability for the other resistors.

With the setup one can achieve precise currents between 1 pA and 100 nA. The achievable uncertainties (k = 2) at the current levels of 1 pA, 10 pA and 100 pA are 3800, 460, and 150 ppm, respectively. With the lowest calibrated current values the 1/f-noise becomes the limiting factor for the accuracy of the characterization. The temperature drift component of the 1/f-noise is minimized by using a temperature stabilized environment (23 ºC ± 0.025 ºC) for the resistor and the meter. A 1/f noise value of 2 fA has been measured at current levels of 1 pA and 10 pA.

5.2 Optical Radiation Measurements

Effects of UV radiation on materials (UVEMA)

The Metrology Research Institute participates in a materials testing project which started in 2005. The work is organized as a four-year project which is coordinated by the Finnish Meteorological Institute (FMI) and mainly funded by TEKES. Other participants are Tampere University of Technology, Elastopoli Oy and the following industrial partners: Oy All-Plast Ab, Exel Oyj, MacGregor (FIN) Oy and Nokian Tyres plc.

The Metrology Research Institute is responsible for building a UV-aging device which can be used to measure materials' activation spectra. During summer 2005, a tentative experimental setup was built and tested. This demo device is presented in Figure 5. The setup is based on a monochromator which was modified to give the whole UV spectrum into its exit plane. A couple of test materials were irradiated and the obtained activation spectra were compared with the corresponding activation spectra found in literature. Based on this demo setup the final UV-aging device was designed and the parts needed were ordered.

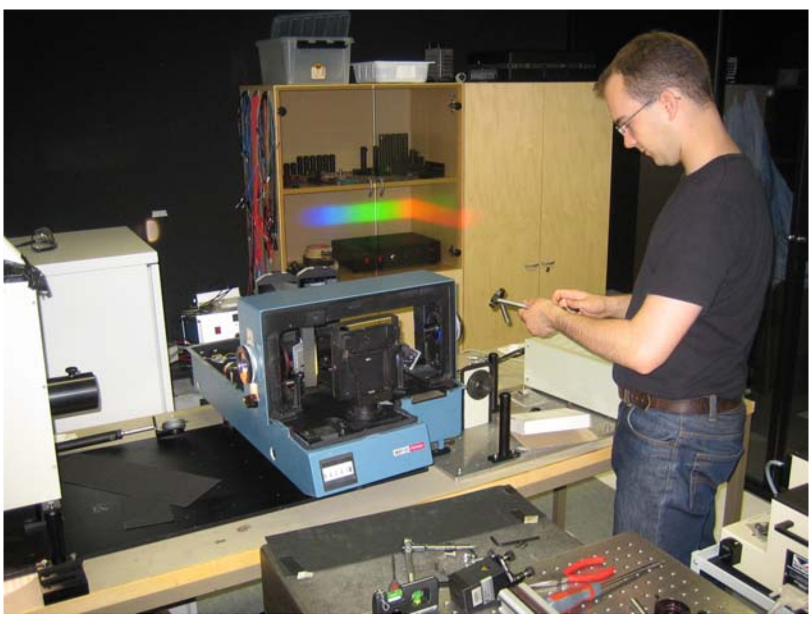

Figure 5. Experimental setup for UV-aging device.

On potential discrepancies between goniometric and sphere-based spectral diffuse reflectance

The absolute scales of spectral diffuse reflectance are mainly based on integrating-sphere techniques. An alternative approach to these techniques is angular integration of gonioreflectometric measurement results. The gonioreflectometer-based methods are becoming more popular among National Metrology Institutes for the measurement and realization of absolute scale of spectral diffuse reflectance. However, some discrepancies between the gonioreflectometric and the integrating-sphere based methods have been reported thus raising questions about the origin of the deviations.

As a result of recent modifications in the light source system of our gonioreflectometer, the spatial properties of the measurement beam were improved. The most important outcome was a significant reduction in the applied correction necessary to account for the effects of light scattered about the main beam. The correction dropped from about -1.1 % to -0.2 % and became wavelength independent as can be seen in Figure 6.

The agreement of the spectral diffuse reflectance values measured before and after the modifications is very good and we believe that scattering of light about the main beam has been properly accounted for. Furthermore, this effect might be one of the reasons for the discrepancies reported previously between measurements based on gonioreflectometric and integrating-sphere techniques. Considering the magnitude of the correction required before the modifications, it is obvious that definite errors will occur if scattered light is not taken into account when designing and characterizing a gonioreflectometer.

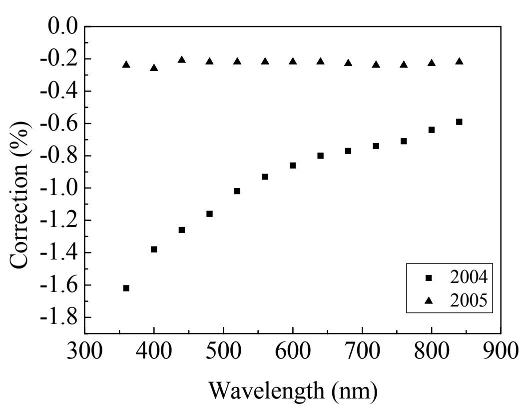

Figure 6. Correction for the scattered light in the old (2004) and the new (2005) setups.

Gonio-fluorometer for spectral quantum yield measurements

The existing fluorometers are typically based on fixed measurement geometry of illumination and viewing. There are needs for characterization of fluorescent materials used as transfer standards in a variety of measurement geometries. We have built a gonio-fluorometer which uses the bispectral measurement method and goniometric geometries of illumination and viewing in one plane (Figure 7). The fluorometer has been realized by using our existing gonioreflectometer setup. Our measurement system can also be used for determination of material appearance under illumination with any spectral power distribution in the wavelength range of 240 – 830 nm. We are able to measure the absolute value of spectral quantum yield of different fluorescent artefacts traceable to diffuse reflectance and spectral responsivity calibration.

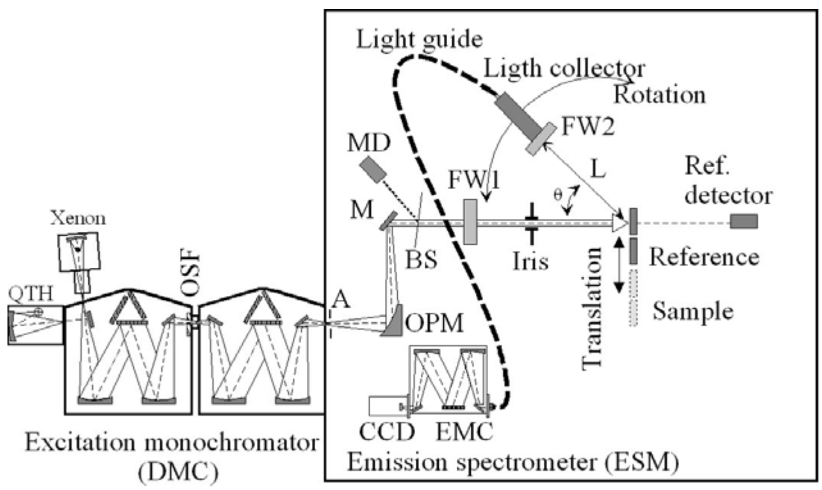

Figure 7. Schematic of the gonio-fluorometer setup: QTH, quartz-tungsten halogen lamp; Xenon, xenon lamp; DMC, double monochromator; OSF, order sorting filter; A, aperture; OPM, off-axis parabolic mirror; M, flat mirror; BS, beam splitter; MD, monitor detector; FW1, FW2, polarizer and filter wheel; L, distance between sample and light collector; EMC, emission monochromator; CCD, CCD detector.

Investigation of comparison methods for UVA irradiance responsivity calibration facilities

In the project we have developed a calibration facility for spectral irradiance responsivity of UV meters. The setup consists of a single grating monochromator, a 450-W Xe light source, and apertured reference photodiodes.

In 2005, an international pilot comparison was organised, in order to compare the scales of UVA irradiance responsivity of five European institutes. The participants were the Metrology Research Institute of Helsinki University of Technology (TKK, working as the pilot laboratory), Radiation and Nuclear Safety Authority (STUK, Finland), Photobiology Unit of the University of Dundee (United Kingdom), Medical Physics Laboratory of Guys & St Thomas Hospital (United Kingdom), and National Metrology Institute of Turkey (TUBITAK-UME). In this pilot comparison, a novel method was introduced to compare the results of different laboratories. This method enabled direct comparison between laboratories utilising different calibration methods and radiation sources. A commercial UVA meter (Figure 8) was used in the comparison, and each laboratory was instructed to measure its UVA irradiance responsivity, using the exact methodology and equipment that they utilise in their regular work. The pilot then calculated individual reference values for each laboratory, based on the earlier measured spectral irradiance responsivity and cosine response of the detector. The reference values differed from each other, due to the different methods and sources used.

Figure 8. The UVA meter used in the pilot comparison.

Finally, the results were analysed in such a way, that none of the laboratories, including the pilot, was given a special status. The final results are shown in Figure 9. The results were in agreement within ±5 %, which demonstrates a factor of two improvement in the consistency of the results as compared with earlier intercomparisons. The results were reported in UVNet Workshop, held in Davos, Switzerland in October. In addition, the results will be published in the NEWRAD 2005 special edition of Metrologia

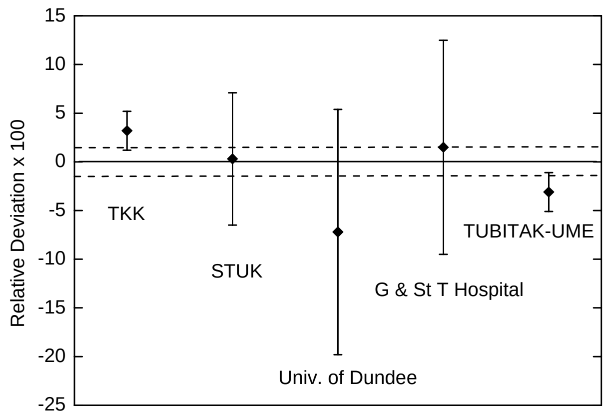

Figure 9. Results of the comparison, given as the relative deviation from the reference value. The error bars indicate the measurement uncertainties (*k=2*) specified by each laboratory. The dashed lines denote the uncertainty (*k=2*) of the reference value.

Characterization of germanium photodiodes and trap detector for near-infrared wavelength region

In order to extend the Finnish national scale of spectral irradiance to the near infrared wavelength region, we have developed new detectors based on germanium (Ge) photodiodes, which have sufficiently high responsivity between 900 and 1650 nm. In this work, we have characterized Ge photodiodes and a trap detector (Figure 10), which consists of three Ge photodiodes. Our results show that to some extent the large area Ge photodiodes provide a cost-effective alternative for indium gallium arsenide (InGaAs) photodiodes of similar diameters.

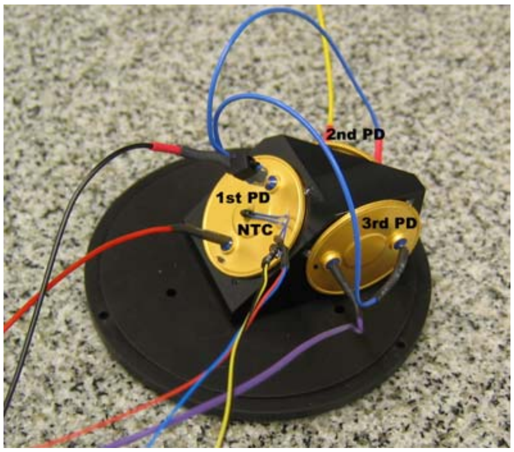

Figure 10. The body part of the trap detector, where the photodiodes and the NTC temperature sensor are marked. Light enters to the trap from the direction of the table.

The Ge photodetectors are characterized in terms of spectral responsivity, spatial uniformity, and spectral reflectance. The effects of temperature, polarization and low shunt resistance on the responsivity measurements are studied as well. We analyze also the anti-reflection coating of the photodiodes based on the reflectance measurements at oblique angles of incidence.

In addition to the characterization process of two Ge photodetectors, this study contains two important findings. First, the reflectance of the Ge trap detector is analyzed extensively for the very first time. Second, the spatial uniformity of the Ge photodiodes has improved tremendously over the last five years and it is now found to be at the level of ~0.1 %. The results will be published in the journal Measurement Science and Technology.

Analysis of luminous intensity of LEDs

The modified inverse-square law method for determination of the luminous intensity of light emitting diodes (LEDs) was tested for several LEDs with different packages and lenses (Figure 11). The analysis takes into account location and the size of an LED source. The results were very consistent regardless of an LED type. It was also noticed that the effective size of an LED source is a function of the size of the light beam of the LED.

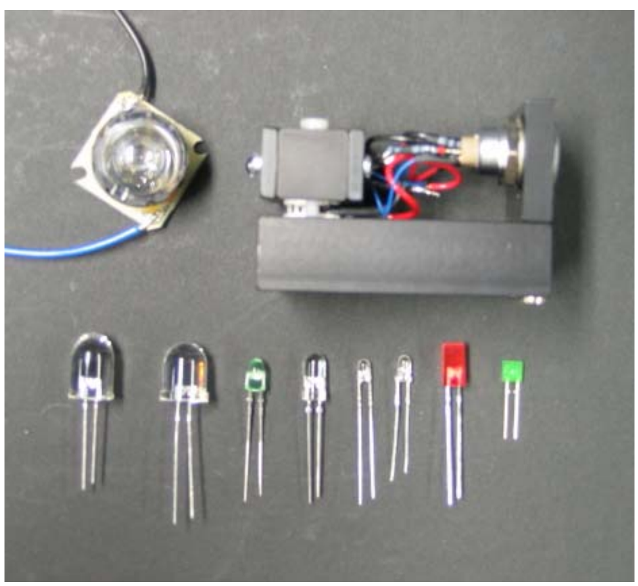

Figure 11. Part of tested LEDs.

Determination of distance offsets of diffusers for accurate radiometric measurements

Distance offsets of the effective aperture planes of four spectroradiometer diffusers (Figure 12) were determined at four wavelengths. The offset found was spectrally varying as well as the angular responses of the diffusers. Also, clear correlation between the angular response and the distance offset of diffusers at different wavelengths occurred. A surprising result of this work was that the unknown reference plane position of some diffusers used commonly in solar UV measurements may cause a calibration error as large as 2.5 %. The results were reported in the NEWRAD 2005 Conference and they will also be published in the NEWRAD special edition of Metrologia.

Figure 12. Studied spectroradiometer diffusers (from left to right): Bentham D3, Bentham D7, Bentham D5, and Schreder J1002-01 diffuser.

Determination of radiation temperature using filter radiometers

In this collaboration project of the Metrology Research Institute and the temperature laboratory of MIKES, a new approach for measuring the radiation temperature of a black body radiator is tested. Spectral irradiance of the high precision black-body is measured with absolutely characterized filter radiometers in near-IR wavelength region. In 2005 the work was focused on extending the measurement range towards lower temperatures. For this purpose the measurement accuracy of picoampere scale currents was improved and a Ge-diode based filter radiometer was tested. The freezing temperature of Al (660.32 ºC) was measured. A comparison of laser based calibration methods for filter radiometers with the National Institute of Standards and Technology (NIST) in the USA was started.

5.3 Fiber Optics

Extension of fiber optic power measurements up to 650 mW

In the applications related to fiber amplifiers, accurate determination of high fiber optic power can be essential. Therefore, we have extended our measurement capabilities to cover optical power up to 650 mW. Also the evaluation of the measurement uncertainty of fiber nonlinear coefficient shows that the determination of the fiber optic power is the most significant uncertainty component in these measurements. As a fiber optic power reference, we use Spectralon-coated integrating sphere detector with fiber adapter and an InGaAs photodiode. The power responsivity of the sphere detector is traceable to cryogenic absolute radiometer. The total expanded uncertainty ($k = 2$) for fiber optic power below 100 mW is 0.9 % and for the higher power up to 650 mW it is 1.3 %.

Chromatic fiber dispersion and wavelength

Chromatic dispersion of optical fibers and chirp set limits for the data rate and transmission distance. We performed a subsequent bilateral-comparison related to EUROMET 666 Supplementary comparison coordinated by METAS in order to confirm the reliability of our chromatic fiber dispersion measurements. Measurements of fiber dispersion are performed using a conventional phase-shift method.

Another improvement in the field of fiber optic measurements was the construction of a new measurement scheme for the wavelength measurements. The widely spread use of lasers has also created a need for an accurate method to determine laser wavelengths. In order to do this, an interferometric wavelength meter was calibrated against well-known reference laser wavelengths at TKK and MIKES. This wavelength meter then stores the calibration and can be easily used to calibrate customer instruments.

Dispersion analysis and optical power measurement in determination of fiber nonlinearity

The ever growing need of transmission capacity in optical networks demands high optical power levels and dense wavelength spacing. Due to these facts, the total light intensity inside the fiber becomes high and therefore nonlinear effects become important. Nonlinear effects are caused by the intensity dependence of the refractive index. The intensity dependent part of the refractive index is called nonlinear refractive index (n_2). Although the nonlinear refractive index can be omitted when using low power levels, it has to be taken into account when the intensities of numerous wavelength division multiplexing signals are summed.

The most frequently applied method for measuring the nonlinear refractive index is continuous self-phase modulation (CW SPM) method. Earlier studies showed that optical power measurement and fiber dispersion were the dominating uncertainty components. With more accurate power measurement and modelling of the dispersion, expanded uncertainty can be lowered from 6.4 % to 2.0 % (k = 2) level. Figure 13 presents our CW SPM measurement setup. Red colour indicates improvements from the previous setup.

The power measurement was made with an integrating sphere detector, capable of handling ~650 mW power levels, needed to determine the nonlinear refractive index accurately. The dispersion analysis required the evaluation of the nonlinear Schrödinger equation. As it has no general analytical solution, it had to be evaluated numerically using Split-step Fourier method (SSFM). SSFM was implemented using Matlab®.

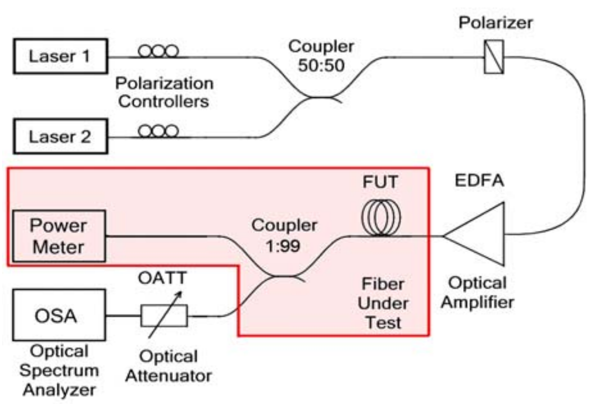

Figure 13. CW SPM measurement setup

5.4 Length Metrology

Measurement of tree diameters using image processing

The purpose of the forest evaluation is to gather information for forest planning. Thus, information on the quantity and quality of wood is needed. Nowadays common methods used for measurement of tree diameters are measurement tapes and scissors. However, there is a demand for a more powerful, measurer-independent landscape measurement device. At present the best measurement results are obtained by measuring each tree independently, which is time consuming and expensive.

In this work a prototype was developed for remote measurement of tree diameters, which would give measurer-independent measurement results in a minimal time. The prototype is based on a line laser of 633-nm wavelength, digital camera and image processing. The laser line is formed with a diode laser and an adjustable lens system. The measurer takes a photograph of the line which is superimposed on the tree trunk (Figure 14). The image is then automatically transferred to PC and the laser line is separated from the surrounding image. The distance is measured simultaneously with a laser distance meter. With the aid of distance and focal length information of the camera, the diameter of the tree is calculated. The device is planned for measuring trees at distances between 1 and 15 m on an experimental plot, while maintaining the measurement uncertainty of the tree diameter below ± 5 mm. The calibration of the device is done with cylinders of known diameters. After necessary calibration corrections, the experimental results prove that the method achieves the specified uncertainty in laboratory conditions.

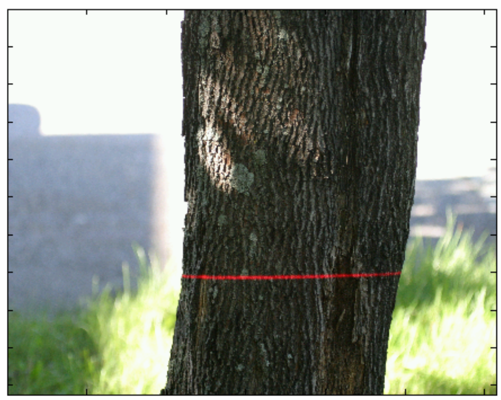

Figure 14. Red laser line superimposed on a tree trunk

Frequency comb generator for calibration of stabilized lasers at MIKES

An optical frequency comb generator for absolute frequency calibrations of metrological lasers has been constructed for MIKES in a collaboration project. The comb generator is referenced to a hydrogen maser, which is part of the MIKES time standards that also participate in the keeping of the international time scale. The frequency comb is used to measure the absolute frequencies of iodine stabilized lasers, which are subsequently used as secondary standards for calibration of e.g. Zeeman-stabilized lasers.

The repetition rate and carrier-envelope offset (CEO) of the MIKES frequency comb are synthesized from the hydrogen maser to achieve good short-term stability and short integration times when measuring low-noise laser frequency standards. The repetition rate is controlled using essentially similar approach as in S. A. Diddams et al., Phys. Rev. Lett. 84, 5102-5105 (2000), while the CEO frequency control is based on the self-referencing technique, which requires an octave spanning comb.

The spectrum of a commercial mode-locked Ti:S-laser (Gigaoptics Gigajet 20) spans the full octave, when broadened in a non-linear microstructured fiber (Crystal fibre NL- 2.0-740). The self-referencing setup is conventional and utilizes the high and low frequency ends of the frequency comb: the low frequency end of the comb is frequency doubled in a thin BBO-crystal to overlap with the original high-frequency part, thus making the CEO beat-note signal measurable with a photodiode. The frequency of the CEO beat note depends on the operational parameters of the laser and, due to relatively low SNR, must be filtered for reliable counting and phase-locking. This is achieved by mixing the CEO signal to an intermediate frequency, which is subsequently band-pass filtered and phase-locked to the hydrogen maser by adjusting the Ti:S-laser pump power.

Frequency measurements of various iodine-stabilized lasers have been performed with the MIKES frequency comb generator. The results are consistent and agree well with the CIPM recommended values. The frequency comb generator, ensemble of atomic clocks, and iodine-stabilized lasers allow completely independent realization of the definition of the meter at MIKES with direct traceability to the SI-second.

Diode laser systems with optical injection

Techniques and instruments for the purposes of spectroscopy and length metrology have been developed based on diode laser injection locking. The research includes a detailed theoretical and experimental study of the modulation transfer properties of injection locked diode lasers. In particular, suppression of intensity modulation and reproduction of the frequency modulation have been considered in terms of master-slave detuning. In addition to metrology and spectroscopy, the results of the study are of practical importance in designing of injection-locked diode laser systems for optical communications, where both intensity modulation and frequency modulation are commonly used.

An example of a newly developed measurement instrument that utilizes laser injection locking is an iodine spectrometer for absolute frequency measurements of various iodine absorption lines. Another practical application is an optical amplifier, which has been developed in order to facilitate frequency measurements of iodine-stabilized He-Ne lasers, which are the most widely used optical frequency standards for the practical realization of the definition of the meter. The amplifier has been used, together with MIKES frequency comb generator, to measure the absolute frequency of an iodine-stabilized He-Ne laser at 633 nm (Figure 15). The measured frequency differs from the CIPM recommendation by less than 0.2 kHz and is in very good agreement with previously reported results. The results were published in the journal Applied Physics B.

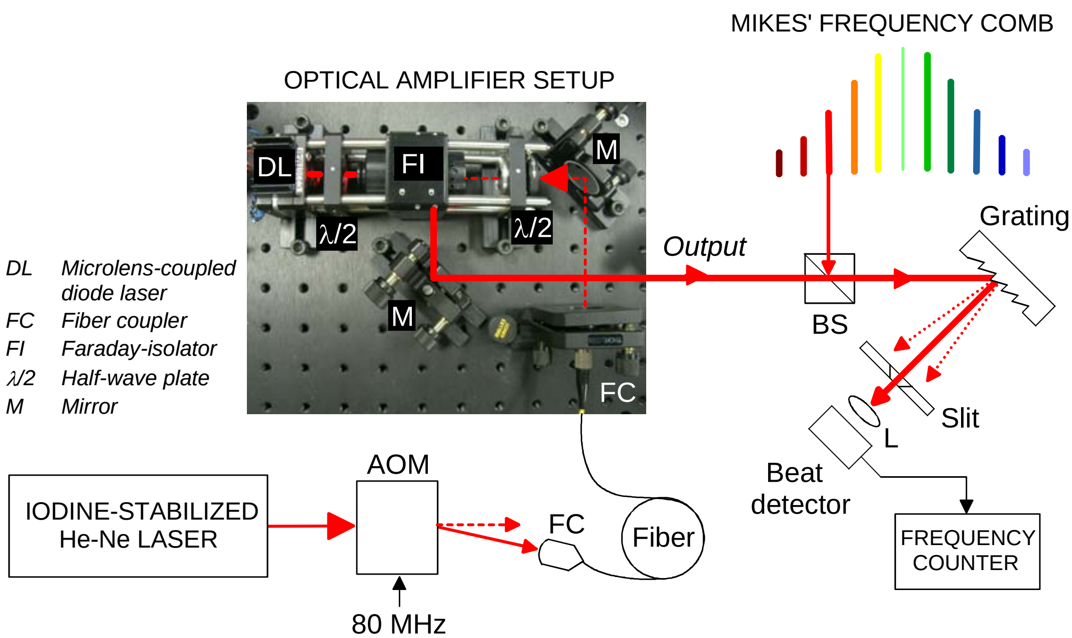

Figure 15. Principle of the setup used in absolute frequency determination of an iodine-stabilized 633-nm Helium-Neon laser (MRI3). The laser output is amplified in the injection-locking setup before directing it to beat frequency comparison with the MIKES frequency comb.

Diode lasers with phase-conjugate optical feedback

Diode lasers are widely used tools in many applications of atom physics, spectroscopy, and optical communications. To make a laser operate in a single longitudinal mode and to obtain sufficiently narrow linewidth, diode lasers subjected to external optical feedback from a diffraction grating are commonly used. Although the spectral properties of such external-cavity diode lasers (ECDL) are greatly improved compared to solitary diode lasers, their operation is typically very sensitive to temperature variations and mechanical drifts. Since both the longitudinal and transversal mode selection of an ECDL is very sensitive to alignment of the feedback element, careful design and stabilization of the laser structure is needed for reliable long-term operation and repeatability.

To relax the need of precise alignment of the optical feedback element, possibility of using phase-conjugate feedback instead of conventional optical feedback for improving diode laser spectral properties has been studied. The first results show very stable operation of a diode laser subjected to phase-conjugate feedback from a photorefractive $BaTiO_3$:Ce crystal. The constructed setup is the first demonstration of successful phase-conjugation using an antireflection coated diode laser without any additional mirrors or diffusers. Also, the measured inherent linewidth (25 kHz) and frequency stability ($1.5 \cdot 10^{-8}$ at 100 s) are the best values reported for a phase-conjugated diode laser.

5.5 Applied Quantum Optics

Towards indistinguishable photons from two independent molecules

Reliable single photon sources emitting indistinguishable photons offer powerful tools for exploring quantum mechanical phenomena. They are also needed as basic elements for optical quantum computing.

Traditional techniques for such a device have utilized the parametric down-conversion process which generates correlated photon pairs. Recently it has been shown that single quantum dots, single trapped atoms, and single molecules can be used as true sources for identical single photons. However, so far all the experiments have been restricted to one single emitter. In this work carried out with the Nano-optics group of ETH Zürich, we propose a method for producing indistinguishable photons originating from two independent sources.

By means of cryogenic laser spectroscopy two fluorescent molecules under distinct microscopes will be selected and their lifetime-limited zero-phonon-lines will be Stark shifted to match each other in frequency. Vibronic excitation scheme with a pulsed laser source will allow observation of synchronized zero-phonon-line emission of the molecules. The indistinguishability of the photons will be confirmed by Hong-Ou-Mandel interferometry.

Our preliminary results indicate that single molecules are promising candidates for multiple sources of indistinguishable photons. Achieving this would greatly help developing applications in the field of quantum optics. The work of the Metrology Research Institute in this project is supported by the Academy of Finland.

Excess coincidences of reflected and refracted X rays from a synchrotron radiation beamline

Characterization of coherence properties of x rays is important for many applications of hard synchrotron radiation. Such information is available from measurements of intensity correlation of radiation which can be observed in photon counting experiments as excess number of coincidences relative to the random background. Most of the earlier measurements on excess coincidences of hard x rays have been carried out in an experimental arrangement, where the width of a slit in front of the detectors measuring coincidences is varied. In this type of experiments, very wide slits are needed in order to reduce the excess coincidences down to the background level. Such behaviour can be understood in terms of incomplete averaging of sinusoidal interference patterns, when patterns with very long periods are present.

The utilization of intensity correlation of electromagnetic radiation in astronomical experiments has been traditionally called as intensity interferometry. In the initial demonstration of the intensity correlation effect in the 1950's with visible light, Hanbury Brown and Twiss used a mercury arc lamp and a beam splitter, which divided the light on two detectors. This allowed the detectors to probe different parts of the incoming wavefront and determination of intensity correlation as a function of the transverse distance between the measurement positions. A decaying shape of the intensity correlation curve was observed reaching the background level with a relatively short separation of the detectors.

Thus it is of interest to test the beam splitter configuration for hard-x-ray intensity correlation measurements, taking advantage of the recent improvements in experimental facilities and understanding of the experimental conditions. In this work are presented, for the first time, such equations which can be applied with different sizes and locations of the coincidence detectors probing the incoming wavefront. Two different setups are used for the coincidence measurements with a silicon crystal in Laue geometry as a beam splitting element. The effective detector positions are scanned either perpendicular to the scattering plane in vertical direction or parallel to the scattering plane in horizontal direction. For vertical scans, the derived equations neatly reproduce the new kind of experimental curve shapes and give consistent results for the fitting parameters describing the size of the source and the amplitude of the excess coincidence effect. For horizontal scans in the scattering plane, the results can be understood on the basis of angular spread of the reflected and refracted x-rays.

It can be concluded that the results of coincidence experiments with different scanning conditions are now understood, since the experimental data, including values of the fitted parameters, are in good agreement with theoretical predictions. The results of this work may be useful for the future x-ray free electron laser beam diagnostics in vertical and horizontal directions. This collaboration project with the SPring-8 facility in Japan is supported financially by the Academy of Finland.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

CCPR-K1.a International key comparison of spectral irradiance in the wavelength region 250 - 2500 nm

In 2005 the final report was published. The results of TKK are good in the wavelength range 290-900 nm used in the comparison. Results of TKK (labelled as HUT) at 450 nm are shown in Figure 16.

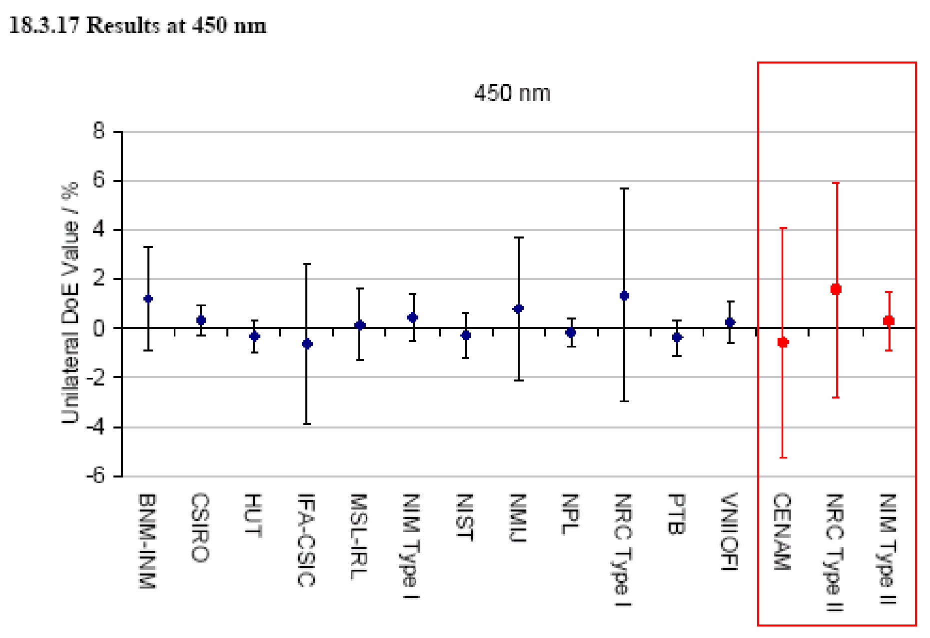

Figure 16. Results of an international key comparison on spectral irradiance at 450 nm.

CCPR-K2.a International key comparison of spectral responsivity in the wavelength region 900 - 1600 nm

Draft A-2 was circulated to participants in 2005. Draft B is expected in 2006.

CCPR-K2.c International key comparison of spectral responsivity in the wavelength region 200 – 400 nm

TKK measurements were completed in 2004. Draft A is expected in 2007.

CCPR-K5 International key comparison of spectral diffuse reflectance in the wavelength region 360 - 830 nm

The key comparison piloted by NIST is on diffuse reflectance measurements of Spectralon and tile samples in the wavelength region from 360 nm to 820 nm. In 2003 TKK completed their first set of measurements. Results were submitted in 2004. Draft A is expected in 2006-2007.

CCPR-K6 International key comparison of regular spectral transmittance in the wavelength region 380 - 1000 nm

Measurements completed. No progress in 2005.

CCPR-S2 International comparison of aperture area measurements

Draft A was circulated to participants in 2005.

Bilateral comparison of ultraviolet filter radiometers with NIST

In this project, TKK and NIST characterized spectral irradiance responsivities of ultraviolet filter radiometers and the results are compared. The results were published in the proceedings of NEWRAD 2005 conference and had a good agreement at 365 nm wavelength.

Multilateral comparison of wavelength scales with NIST

The comparison was piloted by NIST and NPL in the wavelength region of 220-1700 nm. A dilute acidic holmium oxide solution and a solid wavelength calibration filter were used as samples. In 2003 TKK conducted their measurements. In 2005 the final report was published [John C. Travis *et al*, Journal of Physical and Chemical Reference Data, **34**, 41-56 (2005)]. TKK results indicate good agreement with the consensus average.

EUROMET 666 Supplementary comparison of Chromatic Dispersion Reference Fibres

Final report was published in 2005. TKK results showed a deviation from the comparison reference value. The measurements of a subsequent bilateral comparison were carried out in 2005 with METAS acting as the pilot of this comparison.

Trilateral comparison of high fibre optic power calibrations with SP and DFM

In this project funded by NORDTEST, the participants TKK, SP and DFM developed calibration facilities for fiber optic power in the range 1 – 200 mW. The intercomparison was arranged at TKK in 2003. The results indicate good agreement (~1 %) of the new realizations. This value is well within uncertainties of the measurements. In 2005, the final report was published [J. Envall et al, *Appl. Opt.* **44**, 5013-5017 (2005)].

Bilateral comparison of spectral diffuse reflectance with SPRING Singapore

Measurements at SPRING were completed in 2004. Return measurements at TKK were made in 2005 and the results were published in the NEWRAD 2005 proceedings. The agreement between the results was good.

Bilateral comparison of aperture area and luminous responsivity measurements with KRISS

In 2003, TKK conducted their measurements of this bilateral comparison. The artefacts were transported to Korea. The results were discussed in 2004-2005 and published in the NEWRAD 2005 proceedings. The agreement between the results was approximately within the expanded uncertainties ($k=2$).

6.2 Thematic Networks

6.2.1 Thematic Network for Ultraviolet Measurements

TKK is the co-ordinator of the Thematic Network for Ultraviolet Measurements, which has continued its activities after the EU-funded period. In October 2005 the 6th workshop was arranged in Davos, Switzerland, as a satellite activity of the NEWRAD 2005 Conference.

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

Second Photonics and Laser Symposium PALS 2005, Kajaani, February 23-25, 2005; *Erkki Ikonen*

XXXIX Annual Conference of the Finnish Physical Society, Espoo, March 17-19, 2005; *Erkki Ikonen, Petri Kärhä, Kaj Nyholm, Jouni Envall, Antti Lamminpää, Pasi Manninen, Markku Vainio and Silja Holopainen*

Opto-Ireland 2005, Dublin, Ireland, April 4 – 5, 2005; *Markku Vainio*

EUROMET PHORA Technical Committee meeting, Belgrade, Serbia-Montenegro, April 24-26; *Erkki Ikonen*

Optics Days, Jyväskylä, May 12-13, 2005; *Erkki Ikonen, Farshid Manoocheri, Mikko Merimaa, Kaj Nyholm, Antti Lamminpää, Markku Vainio and Meelis-Mait Sildoja*

CIE Division 2 Working Group and Division meetings, Leon, Spain, May 16-18, 2005; *Erkki Ikonen*

12th International Metrology Congress, Lyon, France, June 20-23, 2005; *Mikko Merimaa*

5th International Conference on Tunable Diode Laser Spectroscopy, Florence, Italy, July 11 – 15, 2005; *Markku Vainio*

SUM 2005 IEEE LEOS Summer Topical Meeting, San Diego, USA, July 25-27, 2005; *Mikko Merimaa*

Summer School of Consumer Optics, University of Joensuu, August 8-12, 2005; *Jari Hovila, Antti Lamminpää and Silja Holopainen*

Summer School of New Frontiers in Optical Technologies, Tampere, August 19, 2005; *Kaj Nyholm, Mikko Merimaa and Markku Vainio*

2005 NCSLI Workshop & Symposium, Advances in Science and Technology – Their Impact on Metrology, Washington D.C., USA, August 7-11, 2005; *Mart Noorma*

OFMC 2005 Conference for Measurement for Optical Fibres and Optoelectronics, NPL Teddington, United Kingdom, September 21-23, 2005; *Antti Lamminpää*

9th International Conference on New Developments and Applications in Optical Radiometry NEWRAD 2005, Davos, Switzerland, October 16-19, 2005; *Erkki Ikonen, Petri Kärhä, Farshid Manoocheri, Jouni Envall, Jari Hovila, Antti Lamminpää, Mart Noorma and Saulius Nevas*

6th Workshop on Ultraviolet Radiation Measurements, Davos, Switzerland, October 20-21, 2005; *Petri Kärhä, Farshid Manoocheri, Jari Hovila, Antti Lamminpää, Saulius Nevas, and Jouni Envall*

iMERA meeting, Ljubjana, Slovenia, October 20, 2005; *Erkki Ikonen*

CCPR WG-KC, WG-CMC, WG-UV meetings, CCPR meeting and iMERA PHORA meeting, Paris, France, October 23-27, 2005; *Erkki Ikonen*

Metrology Research Seminar, MIKES, Espoo, Finland, November 17-18, 2005; *Erkki Ikonen, Petri Kärhä, Farshid Manoocheri*

6.4 Visits by the Laboratory Personnel

Erkki Ikonen, ETH Zurich, Switzerland, April 27, 2005

Erkki Ikonen, University of Oslo, Norway, June 27-29, 2005

Mikko Merimaa, Bureau International des Poids et Mesures BIPM, Paris France, September 12-14, 2005

Petri Kärhä, Farshid Manoocheri, Jari Hovila, Antti Lamminpää, Saulius Nevas, and Jouni Envall, Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center, Davos Switzerland, October 21, 2005

Petri Kärhä, Measurepolis, Kajaani, Finland, October 28, 2005

Petri Kärhä, Nmi-VSL, Delft, the Netherlands, November 15-16, 2005

6.5 Research Work Abroad

Mart Noorma, National Insitute of Standards and Technology NIST, Gaithersburg, USA, March 1 – December 31, 2005

Saulius Nevas, Laser Zentrum, Hannover, Germany, June 1- December 31, 2005

Ville Ahtee, Eidgenössische Technische Hochschule ETH, Laboratory of Physical Chemistry, Zürich, Switzerland, January 10 – June 30, 2005 and October 1 – December 31, 2005

Juha Nieminen, Universitat Politècnica de Catalunya, Spain, January 1–June 30, 2005

Pekka Sipilä, Czech Technical University, Prague, Czech Republic, September 1 – December 31, 2005

6.6 Guest Researchers

Meelis-Mait Sildoja, Tartu University, Tartu, Estonia, March 7-25, 2005 and July 5-6, 2005

Toomas Kübarsepp, Metrosert Ltd, Estonia, August 22-25, 2005

6.7 Visits to the Laboratory

Ain Noormägi, Andres Martma, Metrosert Ltd, Estonia, February 1, 2005

Anne Andersson SP Swedish National Testing and Research Institute, Sweden, February 14-15, 2005

Dr. Jan Petersen, DFM Danish Institute for Fundamental Metrology, Denmark, February 14, 2005

Dr. Theo Theocharous, NPL National Physical Laboratory, UK, April 8, 2005

Enno Saluvee, Eesti Energia AS, *Ingrid Tavits*, Ministry of Economic Affairs and Communications, *Viktor Krutob*, Estonian Accreditation Centre, *Mait Palts*, Estonian Chamber of Commerce and Industry, *Zigmontas Strepaitis*, OÜ Balteco Mööbel, Estonia, April 15, 2005

Maidu Nanits, Tallinn University of Technology, Estonia, 15 May, 2005

Andre Prokotilov, Metrosert Ltd, Estonia, June 21, 2005

Prof. Jürgen Metzdorf, Physikalisch-Technische Bundesanstalt PTB, Germany, 5-7 July, 2005

Dr. Toomas Kübarsepp, Metrosert Ltd, Estonia, January 11-12, February 1, June 21, July 6 and November 8, 2005

Prof. Tilman Pfau, University of Stuttgard, Germany, August 22, 2005

Dr. Steven Cundiff, NIST National Institute of Standards and Technology, USA, August 22, 2005

Dr. Nigel Fox, NPL National Physical Laboratory, UK, November 17, 2005

Dr. Georg Sauter, Physikalisch-Technische Bundesanstalt PTB, Germany, December 8-10, 2005

7 PUBLICATIONS

7.1 Articles in International Journals

M. Noorma, P. Kärhä, A. Lamminpää, S. Nevas, and E. Ikonen, "Characterization of GaAsP trap detector for radiometric measurements in ultraviolet wavelength range," *Rev. Sci. Instrum.* **76**, 033110 (2005).

A. Lamminpää, T. Niemi, E. Ikonen, P. Marttila, and H. Ludvigsen, "Effects of dispersion on nonlinearity measurement of optical fibers", *Opt. Fiber Technol.* **11**, 278-285 (2005).

J. C. Travis, J. C. Acosta, G. Andor, J. Bastie, P. Blattner, C. J. Chunnilall, S. C. Crosson, D. L. Duewer, E. A. Early, F. Hengstberger, C-S. Kim, L. Liedquist, F. Manoocheri, F. Mercader, A. Mito, L.A.G. Monard, S. Nevas, M. Nilsson, M. Noël, A. Corróns Rodriguez, A. Ruíz, A. Schirmacher, M. V. Smith, G. Valencia, N. van Tonder, J. Zwinkels, "Intrinsic wavelength standard absorption bands in holmium oxide solution for UV/visible molecular absorption spectrophotometry," *Journal of Physical and Chemical Reference Data* **34**, 41-56 (2005).

M. Puranen, P. Eskelinen, and P. Kärhä, "Fiber-optic radar calibration", *IEEE Aerospace and Electronic Systems Magazine* **20**, 30-33 (2005).

M. Vainio, M. Merimaa, and E. Ikonen, "Iodine spectrometer based on a 633-nm transmission-grating diode laser," *Meas. Sci. Technol.* **16**, 1305-1311 (2005).

J. Hovila, M. Mustonen, P. Kärhä, E. Ikonen, "Determination of the diffuser reference plane for accurate illuminance responsivity calibrations," *Appl. Opt.* **44**, 5894-5898 (2005).

J. Envall, A. Andersson, J. C. Petersen and P.Kärhä, "Realization of the scale of high fiber optic power at three national standards laboratories", *Appl. Opt.* **44**, 5013-5017 (2005).

M. Vainio, M. Merimaa, and K. Nyholm, "Optical amplifier for femtosecond frequency comb measurements near 633 nm", *Appl. Phys. B* **81**, 1053-1057 (2005).

L.-S. Ma, S. Picard, M. Zucco, J.-M. Chartier, L. Robertsson, P. Balling, P. Kren, J. Qian, Z. Liu, Ch. Shi, M. V. Alonso, G. Xu, S. L. Tan, K. Nyholm, J. Henningsen, J. Hald, and R. Windeler, "First absolute frequency measurements of the R(12) 26–0 and R(106) 28–0 transitions in $^{127}I_2$ at 543 nm", *IEEE Trans. Instrum. Meas.* (in press).

A. Lamminpää, S. Nevas, F. Manoocheri and E. Ikonen, "Characterization of thin films based on reflectance and transmittance measurements at oblique angles of incidence", Accepted for publication in *Appl. Opt.*, Feature Issue Optical Interference Coatings (2005).

7.2 International Conference Presentations

M. Noorma, P. Kärhä, T. Jankowski, F. Manoocheri, T. Weckström, L. Uusipaikka, and E. Ikonen, "Absolute detector-based radiometric temperature scale", *in the Proceedings of TEMPMEKO 2004*, Cavtat, Croatia, June 21-26, 2004, p 101-106. (published in 2005)

E. Ikonen, "Excess coincidences of photons", in Proceedings of *Photonics and Laser Symposium PALS 2005*, Kajaani, Finland, February 23-25, 2005; *Erkki Ikonen* (invited)

M. Vainio, M. Merimaa, K. Nyholm, and E.Ikonen, "External-cavity diode laser based spectrometer for absolute determination of iodine lines around 633 nm", in *Opto-Ireland 2005*, Dublin, Ireland, April 4-5, 2005, Proc. of SPIE Vol. 5826, p. 331.

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M. Merimaa, K. Nyholm, and M. Vainio, "MIKES frequency comb generator and absolute frequency measurements of iodine-stabilized lasers", in Proceedings of *12th International Metrology Congress*, Lyon, France, June 20-23, 2005 (CD, 3 p.)

M. Vainio, M. Merimaa, and K. Nyholm, "Use of injection locking for reducing optical feedback effects and residual amplitude modulation in wavelength modulation spectroscopy", in Proceedings of *5th International Conference on Tunable Diode Laser Spectroscopy*, Florence, Italy, July 11-15, 2005, p. 100.

M. Merimaa, K. Nyholm, and M. Vainio "Frequency Comb Generator for Calibration of Laser Frequency Standards", in Proceedings of *SUM 2005 IEEE LEOS Summer Topical Meeting,* San Diego, USA, July 23-30, 2005, p. 33-34.

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A. Lamminpää, T. Niemi, J. Envall, H. Ludvigsen, P. Marttila, and E. Ikonen, "Uncertainty contributions related to dispersion and power measurement in determination of fiber nonlinearity using continuous-wave self-phase modulation", in Proceedings of *OFMC 2005*, London, UK, September 21-23, 2005, p. 63-67.

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P. Kärhä, P. Manninen, J. Hovila, L. Seppälä and E. Ikonen “Determination of luminous intensity of light-emitting diodes with modified inverse-square law”, in Proceedings of *9th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2005)*, Davos, Switzerland, October 17–19, 2005, p. 211-212.

M. Noorma, S. Mekhontsev, V. Khromchenko, A. Gura, M. Litorja, B. Tsai, and L. Hanssen, “Transfer standard pyrometers for radiance temperature measurements below the freezing temperature of silver at NIST ”, in Proceedings of *9th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD 2005)*, Davos, Switzerland, October 17–19, 2005, p. 313-314.

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