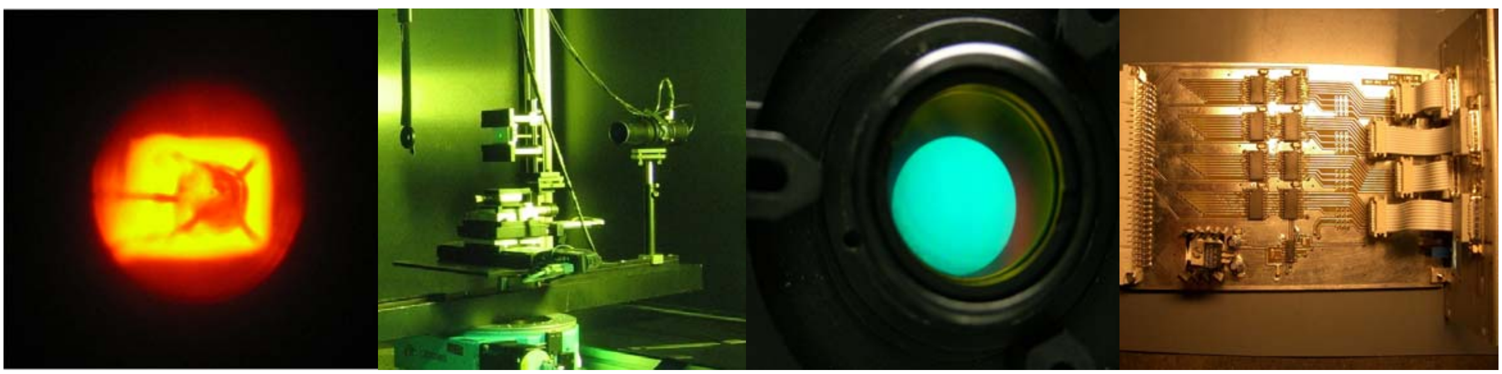
Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute Report 32/2007
Espoo 2007

ANNUAL REPORT 2006



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

Helsinki University of Technology
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Editor Silja Holopainen

Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute

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1 INTRODUCTION

The Metrology Research Institute is one of the units at the Department of Electrical and Communications Engineering of the Helsinki University of Technology (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.

The research highlights of year 2006 include breakthroughs in fiber nonlinearity measurements, in LED illuminance modelling, and in UV aging of materials. The measurement uncertainty of fiber nonlinearity coefficient n_2/A_{eff} was decreased by a factor of three as compared with earlier work. This achievement is based on improved fiber optic power measurements and successful dispersion modelling in the nonlinear fiber. The second breakthrough consists of a new model developed to determine the luminous intensity of LED sources in an unambiguous way over a large distance range. The achieved results are useful in illumination design using LEDs. A set of LED sources with lens packages could be successfully modelled by an equivalent optical arrangement containing just an extended virtual source and an aperture. Thirdly, a table-top device was developed in a TEKES-funded project to measure the wavelength dependence of material aging processes with device characteristics as good as those of earlier room-size setups. The UV radiation levels obtainable exceed the maximum natural solar radiation in Finland by tens of times.

Year 2006 was successful also in relation to teaching activities. Two new courses were realized: First, a special course on measurements of paper industry was organized in the turn of May and June. Over 40 post-graduate students from around the country attended the course. Secondly, a course on virtual instrumentation and computer-aided measurements was initiated in the autumn. In this course, students carry out laboratory exercises where they learn virtual instrumentation, LabView programming and various measurement techniques.

Three doctoral degrees were achieved by the staff members in 2006. This is a very good result which ties for the first place with years 1997 and 2004. The number of M.Sc. degrees was nine in 2006, which is also one of the highest numbers in the history of the Institute.

Erkki Ikonen

2 PERSONNEL

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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute (MIKES TKK Mittaustekniikka) in 2006. Those marked by * are given biennially.

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-108.3030	Virtual Instrumentation 5 credits (Petri Kärhä)
S-108.3110	Optical Communications 5 credits (Farshid Manoocheri)
S-108.3120	Project Work 2-8 credits (Erkki Ikonen, Antti Lamminpää, Tuomas Hieta)
S-108.3130	Project Work in Measurement Science and Technology 2-10 credits (Erkki Ikonen, Antti Lamminpää, Tuomas Hieta)
S-108.3140	Project Work in Optical Technology 2-10 credits (Erkki Ikonen, Antti Lamminpää, Tuomas Hieta)

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)
S-108.4120	Special Course in Measurement Science and Technology: Measurements of Paper Industry* 5 credits (Erkki Ikonen)

Course S-108.3030 Virtual Instrumentation is a new course developed and lectured first time in 2006. In this course, students will carry out laboratory exercises where they learn virtual instrumentation, LabView programming and various measurement techniques. In another teaching related project all furniture and most of the measurement devices used in the student laboratory were modernized.

Figure 1. The student laboratory; under renovation (left) and finished (right).

A special course on measurements of paper industry was organized for the first time in the turn of May and June in 2006. The course was lectured by several experts with both industrial and academic backgrounds. Over 40 post-graduate students from around the country attended the course.

3.2 Degrees

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

Markku Vainio, *Diode Lasers with Optical Feedback and Optical Injection: Applications in Metrology*

Opponent: Dr. Leo Hollberg, NIST, Boulder, USA

Jouni Envall, *Optical Power Measurements: Applications in Fiber Optics and Ultraviolet Radiometry*

Opponent: Prof. Mario Blumthaler, University of Innsbruck, Austria

Antti Lamminpää, *High-Accuracy Characterization of Optical Components: Detectors, Coatings, and Fibers*

Opponent: Dr. Pedro Corredera Guillén, Instituto de Fisica Aplicada, Madrid, Spain

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

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

Tomasz Jankowski, *Measurements of Oxygen Concentration using Tunable Diode Laser Absorption Spectroscopy with Wavelength Modulation*

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

Antti Korhonen, *Apparatus for Calibrating the Squareness Standard on the Rotary Table*

Olli Kivimäki, *Speed Measurement Error Compensation*

Matti Sillantaka, *Driver for an Acousto-Optic Modulator*

Pamela Lindfors, *Characterization and Design Analysis of a Laser Based Excitation Source of a Low Power UV-Spectrometer*

Ilkka Kotamäki, *Study of Display Color Measurement Devices*

Pekka Sipilä, *Calibration Methods for Low Currents*

Juhana Lano, *Facility for Spectral Responsivity Measurements of Infrared Detectors*

Ilari Suorsa, *Low-Level Direct Current Measurement*

Ari Kesänen, *Effective Area of Optical Fiber by Far-Field Scanning*

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 2006, 42 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

Radar measurements

In 2006 the field of electrical instrumentation was expanded in radar measurements. In modern pulsed radars the pulse length can be very short, often less than 100 ns and operating frequencies over 30 GHz are often encountered. This makes measurements very challenging. Conventional measurement devices, e.g. spectrum analyzers, are not suitable for this purpose due to the short pulse length.

A method to measure the short term frequency stability of an oscillator was developed. It is based on a phase detector and a delay line. Frequency fluctuations change the output voltage of the phase detector and these changes are measured using a fast, high-quality multimeter. Using this setup relative frequency changes can be measured with a typical uncertainty of 1.6 Hz using a sampling speed of 100 000 s^{-1}. Results of this work were presented during the European Frequency and Time Forum at PTB premises in Braunschweig, Germany.

Besides frequency, also power and the momentary waveform of the radar pulse are important factors in the research field. Most commercial RF power meters have a very low uncertainty but they are designed to measure CW signal. Therefore some home built RF detectors have been developed and an RF power meter works as a reference when the detectors are calibrated. A fast sampling oscilloscope is used as a display and for data acquisition. Detectors have proven to be fast and accurate in pulse measurements down to at least 20 ns, and results of this work are expected to be published in 2007.

Floor ball goal project

A Finnish company that produces floor ball sticks wanted a device that could measure the speed of a floor ball. The device is intended for marketing purposes and is mostly used at exhibitions and other such events where potential customers can test how fast they can shoot. The device, in the form of a floor ball goal, is shown in action in Figure 2.

Figure 2. Testing the floor ball.

The goal has three parts. The ball is shot through an aluminium frame shown in the middle of Figure 2. The frame has two consecutive infrared gates that detect the ball when it goes through them. The gates are made by placing infrared LEDs and photodiodes to the poles of the goal. The distance between the gates is set to 0.5 meters, so it is easy to calculate the speed when the two signals indicate the time it takes for the ball to travel through the goal. The goal frame has some electronics to amplify and modify the signals and then a microcontroller calculates the result which is shown on a big display. The display also plays different sound effects according to how large is the measured speed. It has six effects and an audio output where a normal stereo amplifier can be plugged and loudspeakers to play the effects. The third part of the goal is not shown in the figure, but it is a grey box that has the power source of the goal inside. It gives power to the LEDs of the goal frame and to the other electronics.

The main purpose of the floor ball goal is not to measure the speed of the ball as precisely as possible, but to be a fancy device that attracts people to the compartment of the company in an exhibition for example. Therefore it was more important to build a device that shows the speed on a big screen and is robust enough to withstand possible blows if some customer would accidentally hit it with a stick. The aluminium frame is very sturdy and it can easily be taken to three parts for transportation. The uncertainty of the speed measurement is approximately ±5%.

At the time of writing the device has been in use for a couple of months and, according to the company that ordered it, it has been a great success. All floor ball players want to come and try their skills and the company gets a lot of good publicity.

Measurement of particle flow in air ducts

In coal-fired power plants, coal is transported in form of powder. This powder moves conveniently in ducts from the storage bin to the powdered-coal burner. There are various methods used for measuring the particle velocity inside the pipes. Many of these methods utilise cross-correlation techniques which makes this application attractive to be used in teaching.

Figure 3. Experimental setup developed for teaching of measurement methods of particle velocities, cross-correlation techniques and virtual instrumentation.

We developed a new laboratory setup to be used in teaching. This setup is presented in Figure 3. The mechanical parts of the setup consist of an air fan and a circular air duct. The lower part of the duct contains a reducer part where the measurements are conducted. Two different measurement techniques are performed here.

The main measurement utilizes two antennas mounted inside the duct. Signals of the antennas are amplified with charge amplifiers. Cross-correlation of these two signals yields the particle velocity. Measurements do not give very good signal to noise ratio for clean air. To simulate coal, some icing sugar and rye flour are added to the duct. For comparison, a simpler measurement based on air pressure difference is also used.

The students use the setup in the course S-108.3030 Virtual Instrumentation to learn LabView programming.

5.2 Optical Radiation Measurements

Metrology of LED light sources

During 2006, Metrology Research institute continued its work in developing luminous intensity model for analysing the behaviour of LED illuminance as a function of distance. The developed model takes into account the geometrical deviations of LEDs from point sources (see Figure 4). Several scientific articles were published on the subject. Work was also carried out to develop measurement methods for flashing light sources. The preliminary results showing the spectral changes of the LEDs during flashing operations are highly interesting.

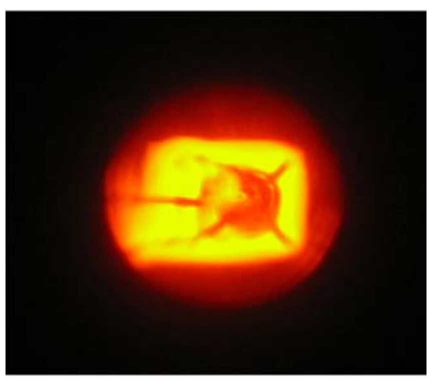

Figure 4. Image of an LED as seen by an observer in the direction of optical axis.

Measurement of oxygen concentration using diode laser spectroscopy

In this project a demonstrator of diode laser spectrometer for oxygen concentration measurements was constructed. The device was developed for the Gasmet Technologies Oy in partial fulfilment for the degree of Licentiate of Technology by Tomasz Jankowski. The oxygen measurement will be implemented as an option in the commercial Gasmet Fourier-transform spectrometer. Fourier-transform spectroscopy is a widely used method for monitoring various exhaust gases, but oxygen has remained outside the set of detectable gases. The main aim of the project was to demonstrate successfully oxygen detection and to verify the superiority of the diode laser spectroscopy as the method for oxygen measurement in combination with Fourier-transform spectroscopy.

The conclusion of the project was that when equipped with the developed module, the Fourier-transform analyzer will become fully capable of monitoring gaseous oxygen concentration independently of any potential presence of water vapor. Besides proving the practicality of the application of diode laser spectroscopy, an important task of the project was to test the behaviour of the tunable laser diode in combination with the multipass cell - an optical element extending the path of the beam by introduction of multiple reflections between its mirrors. A secondary objective of the project was to find the optimal operation parameters for the sensitivity and reliability of the demonstrator and the future commercial module to be built.

Reference spectrometer for infrared detector measurements

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. The Institute has recently moved to expand the spectral range of spectral irradiance scale to cover the UV and near infrared regions. Ongoing projects for spectral irradiance scale will require 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 initiation phase of the project in the year 2006, a facility was developed using a monochromator with two IR gratings (Figure 5). The facility consists of three sections as the light-source / input optics, monochromator, and the comparator / detection system. The coverage of spectral range is for the most part of the 1.1-3.4 µm excluding the atmospheric absorption bands. Measurements have been performed for determining the spectral responsivity of a PbSe and an InAs photodiode using an available pyroelectric radiometer as the reference detector. The uncertainties for the calibration measurements are 1.88 % and 3.32 %, respectively.

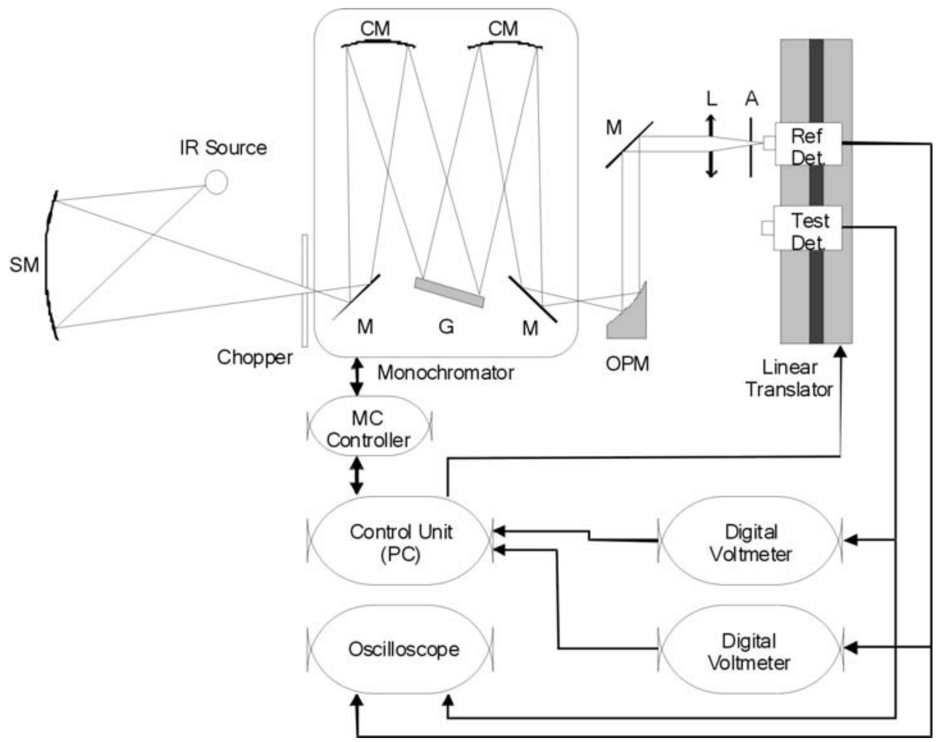

Figure 5. Schematic of the measurement setup. M indicates a flat mirror, SM a spherical mirror, CM a concave mirror, OPM an off-axis parabolic mirror, L a lens, A a variable size aperture and G a diffraction grating.

Goniofluorometer for measuring bispectral luminescent radiance factors

Fluorescence is an important phenomenon which is widely used in several branches of industry like e.g. as a brightening agent in paper industry and a tracer in medical industry. 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 goniofluorometer which uses a bispectral measurement method and goniometric geometries of illumination and viewing in one plane (Figure 6). The fluorometer has been realized by using our existing gonioreflectometer setup. In 2006 the automation of the system has been improved and the instrument was introduced in the 5th Oxford Conference on Spectrometry in Teddington, United Kingdom. Our next objective is to modify the system so that liquid samples can be measured as well. The goal is to reach uncertainty of less than 3 % with a repeatability of better than 1 %.

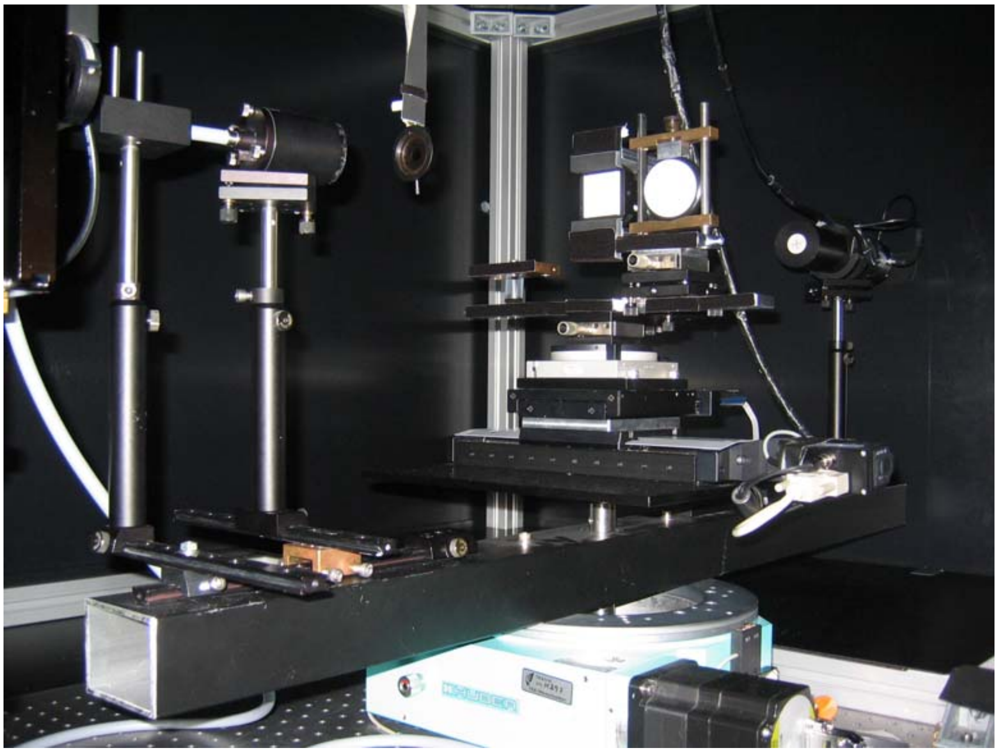

Figure 6. Fluorescence reference instrument. On the left: fluorescence collection lens and fibre guide. Holders for fluorescence sample and a non-fluorescent reference are located on a linear translator and in the background is seen the reference detector for the calibration of the detection system.

Determination of radiation temperature using filter radiometers

In the 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 and linear pyrometer in near-infrared wavelength region. In 2006, one filter radiometer with effective wavelength of 801 nm was calibrated using wavelength-tunable Ti:Sapphire laser. Two dedicated filter radiometers with effective wavelengths of 800 and 900 nm were constructed and their thermodynamic properties were characterized. Thermodynamic temperatures between 1373 K and 1773 K were studied by measuring a variable-temperature black body. The measurements were carried out using a linear pyrometer and four absolutely characterized filter radiometers with effective wavelengths between 600 and 900 nm. The filter radiometer measurements were done in irradiance mode. The results obtained with the pyrometer and the filter radiometers were compared. Before the variable temperature black body measurements, the absolutely characterized filter radiometers were tested on a silver fixed-point cell whose freezing temperature was 1234.93 K. The results will be presented in Tempmeko Conference in 2007.

Facility for spectral ultraviolet aging of materials

Ultraviolet radiation damages materials in many ways - the colour of the objects may change, surfaces may loose gloss, or the mechanical properties may deteriorate. For materials used outdoors, there are various ways to test the UV durability. In this TEKES-funded project (UVEMA), co-ordinated by the Finnish Meteorological Institute, we have developed a facility to measure the wavelength dependence of aging processes of materials (Figure 7). This data will be used in other work packages of the project to improve comparability of out-door ageing tests carried out in various geographic locations.

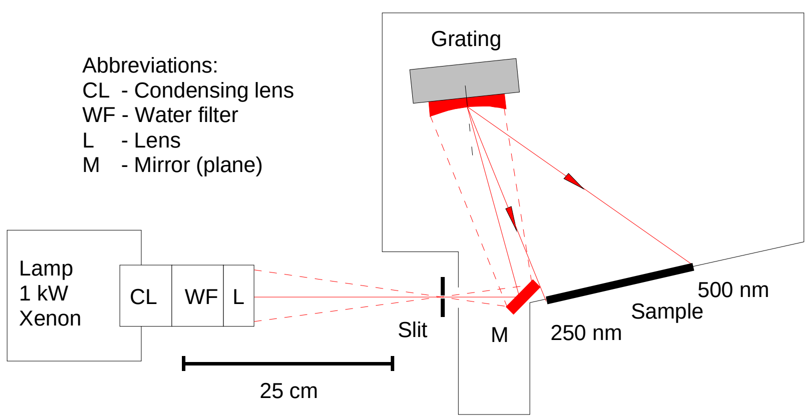

Figure 7. Optical arrangement of the UV ageing facility.

The setup is based on a 1-kW xenon lamp and a flat-field holographic grating. The dispersed UV radiation produced is focused on a sample whose dimensions are 1.5 × 21 cm. Magnitude of the damage on different sample locations can be used to derive the action spectrum of the damage concerned. The radiation levels obtainable exceed the maximum natural solar radiation in Finland by tens of times. Action spectra of typical materials such as plastics can be measured in a few weeks time.

Extension of the wavelength regions of spectral irradiance and radiance

The purpose of this project is to extend the wavelength regions of the spectral irradiance and radiance scales to 200 nm – 2.5 µm. The project has now come to a stage where spectral irradiance measurements cover the spectral region 250 – 1500 nm. In the UV region, a trap detector based on GaP photodiodes is used. In the IR region, a Ge photodiode is used. Comparison measurements with NPL-traceable lamps show good agreement in the visible and IR regions. Figure 8 shows preparation of these comparison measurements.

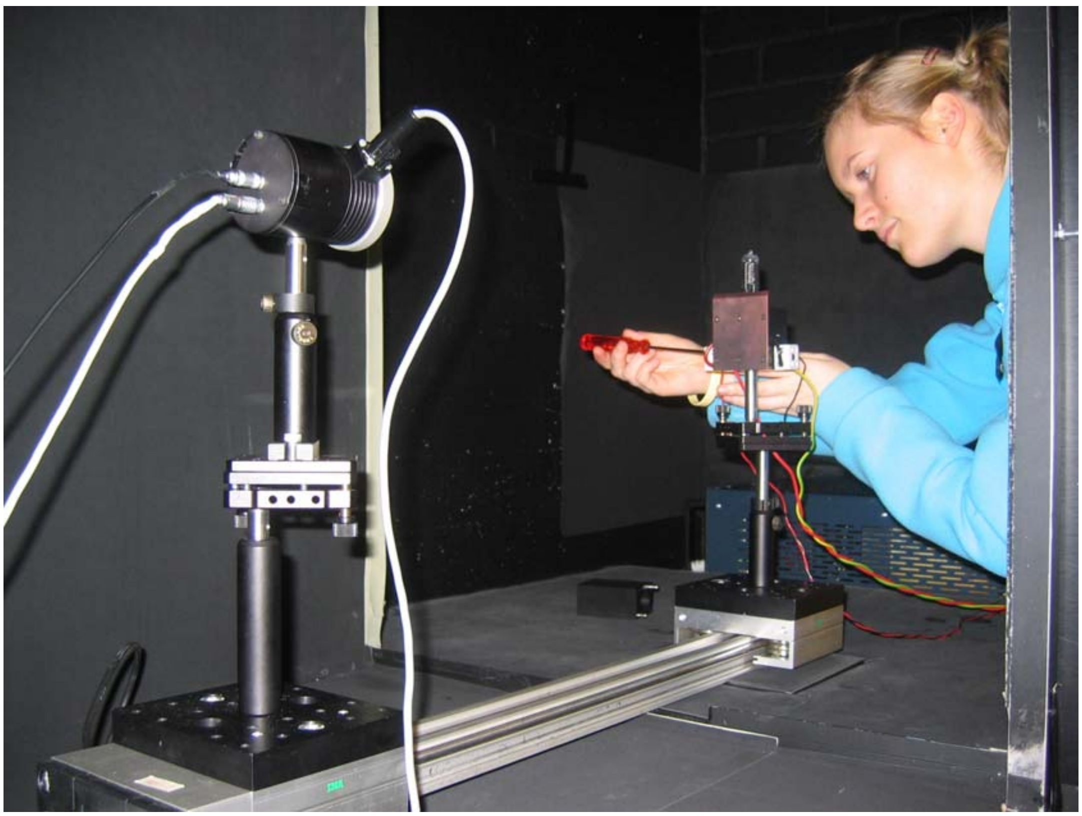

Figure 8. Measurement facility for spectral irradiance. The signal from the lamp is measured at the reference detector in accurately defined solid angle. The wavelength dependence is obtained by using interference filters in front of the detector.

Calibration facility for colour displays and colorimeters

The quality of color displays continues to improve and customers demand higher accuracy in color reproduction. Commercial colorimeters and spectroradiometers are commonly used to measure the chromaticity and luminance of displays. The instruments are typically calibrated at factory using incandescent standard lamps. Such a practice causes errors in determining the color of displays whose spectra are very different from that of the standard lamps. Such measurement errors would significantly degrade the quality control of the display products and the performance of any color management systems. To address the needs for improving and certifying the measurement uncertainties of such color measuring instruments for the Finnish industry, a facility has been developed for spectrometric and colorimetric calibration of displays, colorimeters, and spectroradiometers.

During the year 2006, investigation was carried out regarding the use of a CCD-camera in determining the luminance uniformity of LCD devices using a dedicated laboratory space. Work was also done in developing the low-luminance measurement capability using filters and a sphere-source.

5.3 Fiber Optics

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 refractive index. The intensity dependant 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 applied method for measuring the nonlinear refractive index is continuous self-phase modulation (CW SPM) method. Earlier studies showed that optical power measurement and dispersion were the dominating uncertainty components. With more accurate power measurement and modelling the dispersion, expanded uncertainty was lowered from 6.4 % ($k = 2$) to 2.0 % ($k = 2$) level. Figure 9 illustrates how crucial it is to take the dispersion into account, since otherwise errors up to 3 % may be introduced.

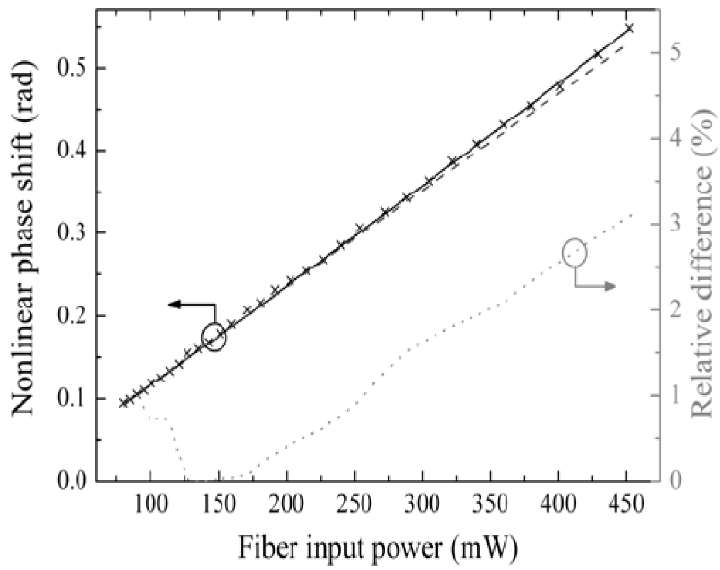

Figure 9. Solid line shows the fit between the simulation and the measured values.

The optical power measurement was made with an integrating sphere detector, capable of handling ~650 mW power levels, needed to determine the nonlinear refractive index accurately. Dispersion analysis required the evaluation of the nonlinear Schrödinger equation. As it has no analytical solution in general case, it had to be evaluated numerically using Split-step Fourier method (SSFM). The developed simulation program can be used to determine the n_2 of various fibers if the dispersion is known.

Supercontinuum generation with fiber laser sources

We have studied through numerical simulations the coherence properties of supercontinuum (SC) generated from fiber laser pumps. For this purpose, parameters typical of such sources and that of appropriate fibers to generate the continuum were used. The results illustrate two general trends. Firstly, for fixed pump wavelength and soliton order N, shorter pulses can propagate over longer distances while still maintaining high coherence. Secondly, for fixed pulse duration and soliton order N, a larger detuning from the zero-dispersion wavelength into the anomalous dispersion region yields a decrease in the propagation distance over which coherence is maintained. Our study can be applied to the optimization of specific experimental conditions (see Figures 10 and 11). For example, considering pulses at 1060 nm of peak power P_0 = 5 kW and duration 200 fs, we have N = 15.8 and L_{fiss} = 22.3 cm, we might expect coherence to be maintained under such conditions over several characteristic fission lengths L_{fiss}. However, we stress that these results assume only quantum-limited input noise, and technical and/or amplified spontaneous emission noise may induce coherence degradation over shorter distances. Nonetheless, our results can be very usefully applied in the initial design of SC experiments where coherence is desired.

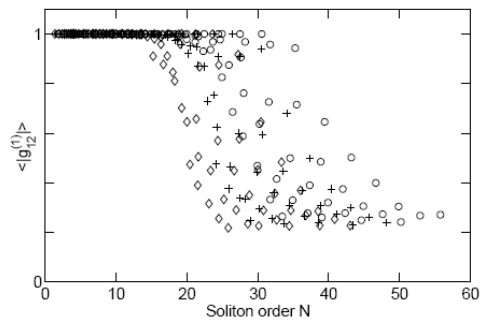

Figure 10. Average coherence of the SC versus soliton order N calculated for pump wavelengths of 1060 (circles), 1070 (cross), and 1080 nm (diamond) and with pulse durations in the range 50–500 fs and peak powers 1–10 kW. Propagation in 25 cm of fiber is considered.

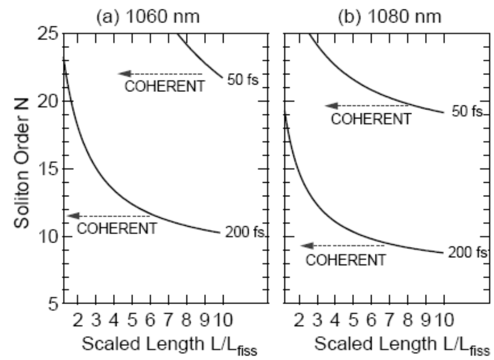

Figure 11. For two different pulse durations and two input wavelengths as indicated, the graph shows the maximum input soliton number N to use for a given normalized propagation distance L/L_{fiss} in order to obtain an average coherence g_{av}>0.95. The regime of coherence is to the left of the plotted lines as indicated by the arrow.

Generalized nonlinear envelope equation for extreme nonlinear broadening

A novel one-dimensional generalized envelope equation (GNEE) to model ultrashort pulse propagation in highly nonlinear waveguides was developed. The GNEE is a powerful concept that integrates dynamical effects on the underlying electric field carrier and allows to model the generation of higher-harmonics frequency components and sub-cycles temporal field structure as a result of nonlinear propagation in a $\chi^{(3)}$ medium. In particular, compared to previous few-cycle envelope equation models, the GNEE explicitly includes a third harmonic term and is valid for regimes where the pulse band-width spans several times the optical carrier frequency, and where the temporal electric field contains structure on a sub-cycle timescale. The validity of the model is confirmed through comparison with the direct numerical integration of Maxwell's equations. Excellent quantitative agreement is obtained, even for extreme cases where nonlinear spectral broadening extends over 10 times the carrier frequency, and the temporal carrier exhibits shock dynamics on a sub-10 attosecond timescale (see Figure 12). The model also reproduces previous experiments where third harmonic has been observed and will allow exploring dynamics of sub-cycles processes.

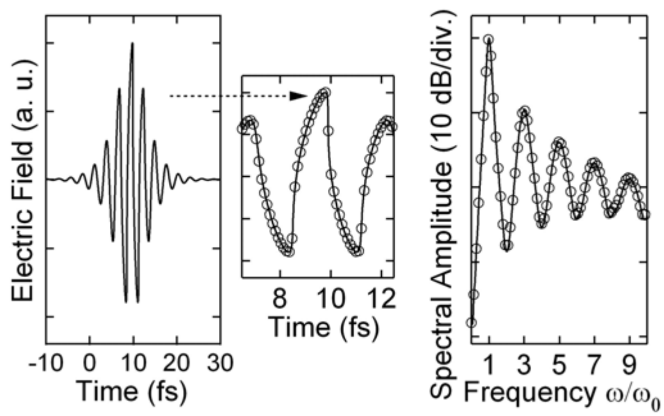

Figure 12. Output field and spectrum from the GNEE (solid line) in a $\chi^{(3)}$ medium. For comparison, the solution of Maxwell's equation is also plotted (circles).

Effective area of optical fiber by far-field scanning

The parameter A_{eff} stands for effective area which defines the spot size of the propagating optical field in a fiber. To get a thorough understanding on light propagation and the concept of effective area, field distribution in optical fibers must be studied through Maxwell's equations.

Effective area of optical fiber can be determined by numerous different methods based on examining the exit-radiation pattern emerging from the fiber end. In this work, A_{eff} was measured with the far-field scanning technique (FFS) standardized by International Telecommunication Union (ITU-T G.650.2). In the measurement setup an InGaAs photodetector was mounted on a high precision rotation stage and the output field of the tested fiber was scanned laterally (Figure 13). To calculate A_{eff} from the measured far-field pattern, the data has to be first converted into the corresponding near-field values using the inverse Hankel transform.

Parameter A_{eff} can also be estimated through another parameter called the mode field diameter (MFD). Calculating A_{eff} through MFD gives slightly faulty results due to applied Gaussian approximation of the optical field. Approximation-induced errors can be corrected by the use of a proper correction factor. This correction factor, denoted by k_{Nam}, was calculated for each measured fiber in addition to MFD and A_{eff}.

Three different types of fibers were measured: standard single-mode fiber (SMF), nonzero dispersion shifted fiber (NZ-DSF), and large effective area fiber NZ-DSF. Measurements were carried out in 1310 nm and 1550 nm wavelength regions. The total expanded uncertainty ($k = 2$) of the constructed measurement setup was found to be about 4 % in determination of A_{eff} and about 2 % in determination of MFD.

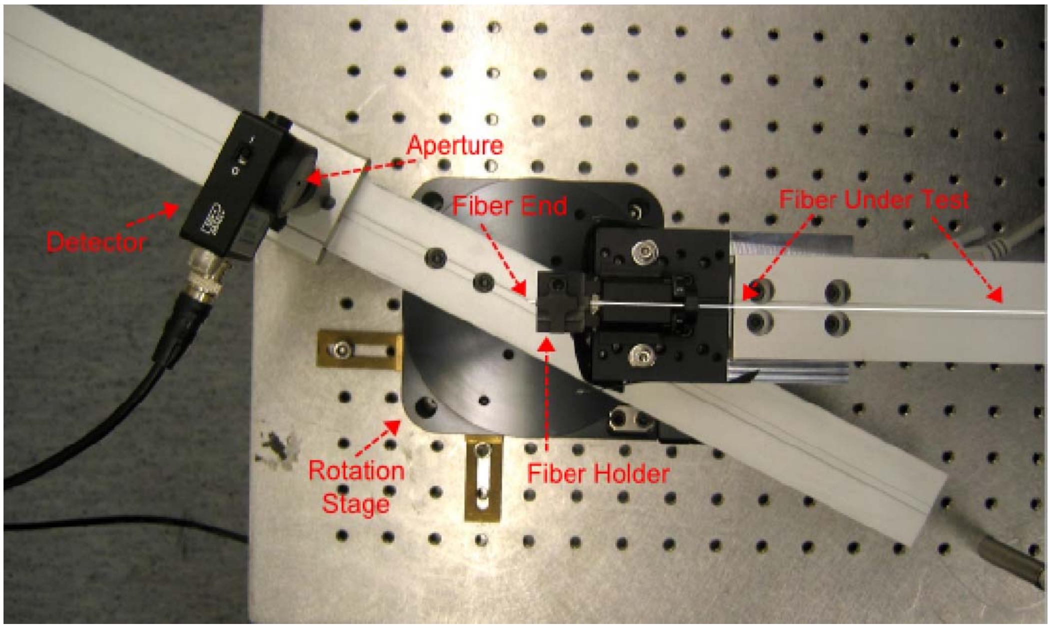

Figure 13. Device using far-field scanning for effective area determination in optical fibre. The fibre is highlighted with white colour to make it visible.

5.4 Applied Quantum Optics

Excess coincidences of x rays from a synchrotron radiation beam line

The study of excess coincidences of x rays has been continued. The results on coincidences of reflected and refracted x rays from a synchrotron radiation beam line have been published (E. Ikonen et al., Phys. Rev. A **74**, 013816, 2006). This work presented, for the first time, such equations which can be applied with different sizes and locations of the coincidence detectors probing the incoming wave front. It can be concluded that the results of coincidence experiments with different measurement conditions are now understood, since the experimental data, including values of the fitted parameters, are in good agreement with theoretical predictions. Another subject of intense research has been multiple coincidences of x rays. For triple coincidences, interesting theoretical predictions have been derived, whose verification may be within the reach of present experimental capabilities. The above results are especially interesting when the future x-ray free electron laser devices become operational. This collaboration project with the SPring-8 facility in Japan is supported financially by the Academy of Finland.

Towards indistinguishable photons from two independent molecules

Reliable single photon sources emitting indistinguishable photons offer powerful tools for exploring quantum mechanical phenomena. 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. In this work, done in collaboration with the Nano-optics group of ETH Zurich, a method for producing indistinguishable photons originating from two independent molecules is studied.

By means of cryogenic laser spectroscopy two fluorescent molecules under distinct microscopes are selected and their lifetime-limited zero-phonon-lines are 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 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.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

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

Draft A-3 is nearly ready to be distributed to the participants in 2007. The changes relative to draft A-2 will hardly affect the overall results.

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

The measurements of the first three groups of participants are completed. The final PTB measurement on the detectors of this round is planned for January 2007. Draft A shall be available later in 2007.

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

The uncertainty budgets have been sent out for review in October 2006, the relative data will be sent in the beginning of 2007. Additional measurements were carried out on samples belonging to the participants as bilateral comparisons. These data will be analysed later and the results will be published separately from the key comparison results. Draft A is expected in 2007

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

Draft A report has been distributed in July 2006. Draft B is expected in 2007.

Supplementary comparison CCPR-S2, aperture area, NIST

Final report was published in 2006. The Metrology Research Institute results are good (see Figure 14). Of nine participants, only the Metrology Research Institute and the National Research Council of Canada had all results within one or two standard deviation limits.

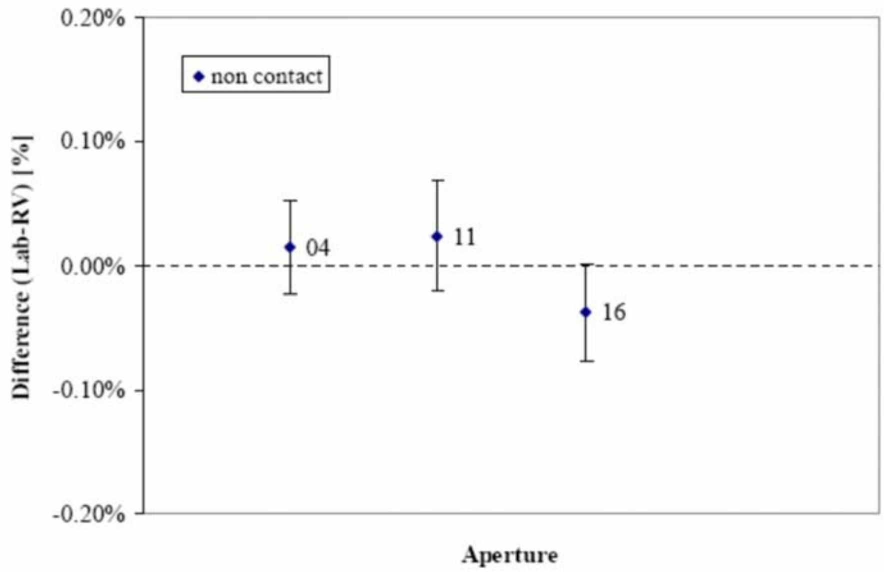

Figure 14. Metrology Research Institute results in aperture area comparison CCPR-S2.

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

Final report was published in 2006. This was a subsequent bilateral comparison which corrected erroneous results of the Metrology Research Institute in the earlier comparison EUROMET-PR.S1. One zero dispersion wavelength result still remained clearly outside 95 % confidence limits.

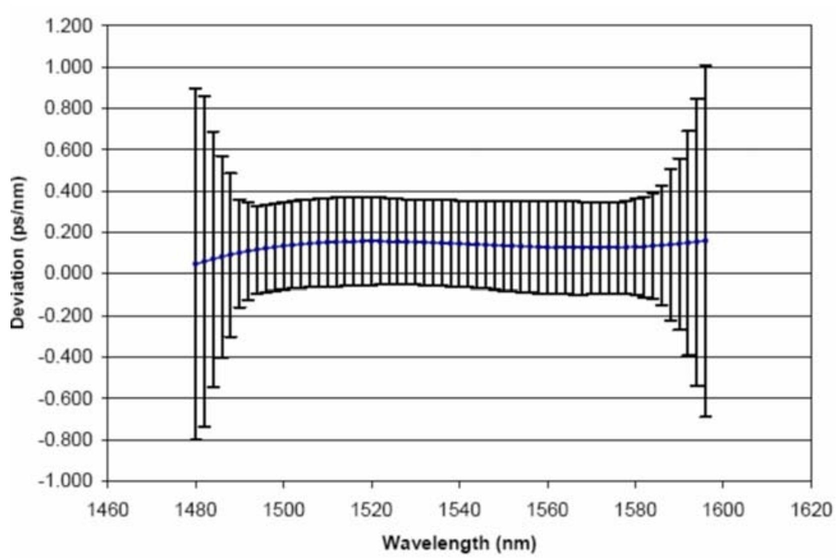

Figure 15. An example of results of the chromatic dispersion comparison.

Comparison methods for UVA irradiance responsivity calibration, piloted by the Metrology Research Institute

A commercial UVA meter was used in the comparison, and each of the five participants was instructed to measure its UVA irradiance responsivity using the exact methodology and equipment that they utilise in their regular work. The results [Envall et al., *Metrologia* **43,** S27-S30 (2006)] were in agreement within ±5 %, which demonstrates a factor of two improvement in the consistency of the results as compared with earlier intercomparisons.

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

Independent methods for measuring the absolute spectral irradiance responsivity of detectors have been compared between calibration facilities at 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 %.

6.2 Thematic Networks

6.2.1 Thematic network for ultraviolet measurements

The Metrology Research Institute is the co-ordinator of the Thematic Network for Ultraviolet Radiation Measurements, which has continued its activities after the EU-funded period. In 2006, the Proceedings of the October 2005 Workshop in Davos were published [P. Kärhä, Ed., *UVNews,* Issue 8, Espoo 2006, 63 p].

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

The XL Annual Conference of the Finnish Physical Society, Tampere, March 9-11, 2006; *Silja Holopainen, Maija Ojanen, Antti Lamminpää, Markku Vainio and Tuomas Hieta*

VIFOM Workshop, Borås, Sweden, March 21-22, 2006; *Erkki Ikonen and Antti Lamminpää*

Estonian Physics Days, Tartu, Estonia, March 21-22, 2006; *Meelis-Mait Sildoja*

20th European Frequency and Time Forum, Braunschweig, Germany, March 27-30, 2006; *Mikko Puranen*

EUROMET Phora TC Meeting, Prague, Czech Republic, April 20-21, 2006; *Erkki Ikonen*

NOG2006, Copenhagen, Denmark, April 27-28, 2006; *Petri Kärhä*

NTNE2006, Nanotechnology in Northern Europe, Helsinki, Finland, May 16-18, 2006; *Pekka Wallin*

IRS 2006, 2nd Microwave and Radar Week, Krakow, Poland, May 24-27, 2006; *Mikko Puranen*

CIE 2nd Expert Symposium on Measurement Uncertainty, Braunschweig, Germany, June 12-13, 2006; *Erkki Ikonen*

Nordic Training Symposium for SSDLs, Stockholm, Sweden, June 13-16, 2006; *Ilari Suorsa*

Northern Optics 2006, Bergen, Norway, June 14-16, 2006; *Pasi Manninen and Ville Ahtee*

CIE Technical Committee meetings, Braunschweig, Germany, June 14-16, 2006; *Erkki Ikonen*

5th Oxford Conference on Spectrometry, London, UK, June 26-28, 2006; *Farshid Manoocheri, Silja Holopainen and Antti Lamminpää*

DFG Excellence Initiative - Application Review Session, Bad Honnef, Germany, July 3-5, 2006; *Erkki Ikonen*

16th Jyväskylä Summer School, Jyväskylä, Finland, July 24-August 11, 2006; *Meelis-Mait Sildoja*

Young Scientist Summer School on Photovoltaics, Valgeranna, Pärnumaa, Estonia, August 21-25, 2006; *Meelis-Mait Sildoja*

New Primary Detector Standards Meeting, Oslo, Norway, September 15, 2006, *Erkki Ikonen*

Innovation 2006, Olostunturi, Finland, September 20-22, 2006*; Pekka Wallin*

Science Autumn School 2006 of Estonian Physical Society, Tartu, Estonia, October 20-22, 2006; *Meelis-Mait Sildoja*

CCPR WG-SP, WG-KC and WG-CMC Meetings, Santiago de Queretaro, Mexico, October 22-24, 2006; *Erkki Ikonen*

CENAM Metrology Symposium, Santiago de Queretaro, Mexico, October 25-27, 2006; *Erkki Ikonen*

Forest-Based Sector Technology Platform in Action, Lahti, Finland, November 22-23, 2006; *Erkki Ikonen*

6.4 Visits by the Laboratory Personnel

Erkki Ikonen, ETH Zurich, Switzerland and PMOD/WRC, Davos, Switzerland, January 20-23, 2006

Erkki Ikonen and Antti Lamminpää, SP, Borås, Sweden, March 22, 2006

Erkki Ikonen, CMI, Prague, Czech Republic, April 19

Erkki Ikonen, Justervesenet, Olso, Norway, September 15, 2006

Erkki Ikonen, NIST, Gaithersburg, USA, October 30-31, 2006

6.5 Research Work Abroad

Ville Ahtee, Eidgenössische Technische Hochschule ETH, Laboratory of Physical Chemistry, Zürich, Switzerland, January 1 - 31, 2006 and December 6 – 12, 2006

Kimmo Ruokolainen, Asian Institute of Technology, Bangkok, Thailand, August 1 - December 31, 2006

Jouni Envall, National Institute of Standards and Technology NIST, Gaithersburg, USA, October 1 - December 31, 2006

Pasi Manninen, National Physical Laboratory NPL, UK, October 1 - December 31, 2006

6.6 Guest Researchers

Francois Romey, France, February 27 – September 8, 2006

6.7 Visits to the Laboratory

Professor Andrew Wallard, BIPM, Paris, January 11, 2006

CTO Hanna Hoffman, Liekki Corporation, Sunnyvale CA, USA, February 20, 2006

Dr. Mart Noorma, NIST, Gaithersburg, USA, February 21, 2006

Dr. Leo Hollberg, NIST, Boulder, USA, March 29-April 1, 2006

Dr. Marek Smid, CMI, Prague, Czech Republic, April 6, 2006

Dr. Leslie Pendrill and Dr. Per-Olof Hedekvist, SP Swedish National Testing and Research Institute, April 27, 2006

Prof. Mario Blumthaler, Medical University of Innsbruck, Austria, June 29- July 2, 2006

Dr. Mart Noorma, Tartu University, Estonia, September 20, 2006

Dr. Toomas Kübarsepp, Metrosert Ltd, Estonia, September 20-21, 2006

Ph.D. Anu Reinart, Tartu Observatory, Tartu, Estonia, November 14, 2006

Research Scientist Silver Lätt, Tartu Observatory/Tartu University, November 29, 2006

Dr. Pedro Corredera Guillén, Instituto de Fisica Aplicada, Madrid, Spain, November 29 – December 2, 2006

7 PUBLICATIONS

7.1 Articles in International Journals

P. Manninen, J. Hovila, L. Seppälä, P. Kärhä, L. Ylianttila and E. Ikonen, "Determination of distance offsets of diffusers for accurate radiometric measurements," *Metrologia* **43,** S120-S124 (2006).

J. Envall, L. Ylianttila, H. Moseley, A. Coleman, M. Durak, P. Kärhä, and E. Ikonen, "Investigation of comparison methods for UVA irradiance responsivity calibration facilities," *Metrologia* **43**, S27-S30 (2006).

A. Lamminpää, M. Noorma, T. Hyyppä, F. Manoocheri, P. Kärhä, and E. Ikonen, "Characterization of germanium photodiodes and trap detector," *Meas. Sci. Technol.* **17**, 908-912 (2006).

J. Envall, P. Kärhä, and E. Ikonen, "Calibration of broadband ultraviolet detectors by measurement of spectral irradiance responsivity," *Rev. Sci. Instrum.* **77**, 063110, 8 pages (2006).

E. Ikonen, M. Yabashi, and T. Ishikawa, "Excess coincidences of reflected and refracted x rays from a synchrotron-radiation beamline," *Phys. Rev.* A **74**, 013816, 8 pages (2006).

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 127I2 at 543 nm," *IEEE Trans. Instrum. Meas.* **55**, 876-880 (2006).

M. Vainio, "Phase-conjugate external-cavity diode laser," *IEEE Photon. Techn. Lett.* **18**, 2047-2049 (2006).

A. Lamminpää, S. Nevas, F. Manoocheri and E. Ikonen, "Characterization of thin films based on reflectance and transmittance measurements at oblique angles of incidence," *Appl. Opt.* **45**, 1392-1396 (2006).

M. Vainio, M. Merimaa and K. Nyholm, "Modulation transfer characteristics of injection-locked diode lasers," *Opt. Commun.* **267**, 455-463 (2006).

M. Merimaa, K. Nyholm, M. Vainio, and A. Lassila, "Traceability of laser frequency calibrations at MIKES," *IEEE Trans. Instrum. Meas.* (in press).

P. Manninen, J. Hovila, P. Kärhä, and E. Ikonen, "Method for analyzing luminous intensity of light-emitting diodes," *Meas. Sci. Technol.* (in press).

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.* (in press).

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* (in press).

7.2 International Conference Presentations

M. Sildoja, T. Kübarsepp, M. Noorma, P. Kärhä, A. Lamminpää, S. Nevas, and E. Ikonen, "Polarization properties of GaAsP trap detectors", in *Proceedings of Estonian Physics Society's Yearbook 2005,* Tallinn, Estonia, March 21-22, 2006, p. 95-96.

M. Puranen, and P. Eskelinen, "Measurement of Short-Term Frequency Stability of Controlled Oscillators", in *Proceedings of 20th European Frequency and Time Forum*, Braunschweig, Germany, March 27-30, 2006, p. 76-79.

P. Kärhä, P. Manninen, J. Hovila, L. Ylianttila, and E. Ikonen, "Distance offset and angular responsivity measurements of UV spectroradiometer diffusers," Annual meeting of the Nordic Ozone Group (NOG), Copenhagen, April 27-28, 2006, in *NOG 2006 Abstracts* (2006).

P. Kärhä and K. Ruokolainen, "Setup for studying the spectral behavior of ageing of materials under intense UV radiation," Annual meeting of the Nordic Ozone Group (NOG), Copenhagen, April 27-28, 2006, in *NOG 2006 Abstracts* (2006).

M. Puranen, P. Eskelinen, J. Ruoskanen, and H. Heikkilä, "Simple 3D Millimetre Clutter Scanner for Field Measurements" in *Proceedings of International Radar Symposium IRS 2006*, 2nd Microwave and Radar Week, Krakow, Poland, May 24-27, 2006, p. 339-342.

S. Nevas, P. Kärhä, and E. Ikonen, "Effect of correlations in fitting spectral irradiance data," in Proceedings of the *2nd CIE Expert Symposium on Measurement Uncertainty*, Braunschweig, Germany, June 12-13, 2006, p. 143-146.

E. Ikonen, J. Hovila, and Seung Nam Park, "Uncertainties in linking bilateral and regional key comparisons to the CCPR key comparison," in Proceedings of the *2nd CIE Expert Expert Symposium on Measurement Uncertainty*, Braunschweig, Germany, June 12-16, 2006, p. 173-177.

P. Manninen, J. Hovila, P. Kärhä, L. Ylianttila, and E. Ikonen, "Distance offset of the effective receiving aperture of a diffuser and its relation to angular responsivity curves", in *Proceedings of Northern Optics 2006*, Bergen, Norway, June 14-16, 2006, p. 125.

P. Manninen, J. Hovila, P. Kärhä, and E. Ikonen, "Analysis of luminous intensity of light emitting diodes with modified inverse square law", in *Proceedings of Northern Optics 2006*, Bergen, Norway, June 14-16, 2006, p. 124.

V. Ahtee, R. Pfab, R. Lettow, A. Renn, E. Ikonen, and V. Sandoghdar, "Towards indistinguishable photons from two independent molecules", in *Proceedings of Northern Optics 2006*, Bergen, Norway, June 14-16, 2006, p. 40.

M. Vainio, "Phase-conjugate external-cavity diode laser," in *Proceedings of Northern Optics 2006,* Bergen, Norway, June 14-16, 2006, p. 70.

A. Andersson, J. Petersen, E. Ikonen, and P.O. Hedekvist, "Virtual institute for fibre optic measurements", in *Proceedings of Northern Optics 2006*, Bergen, Norway, June 14-16, 2006, p. 138.

S. Holopainen, F. Manoocheri, M. Laurila and E. Ikonen "Goniofluorometer for spectral quantum yield measurements", in *5th Oxford Conference on Spectrometry*, London, UK, June 26-28, 2006.

A. Lamminpää, S. Holopainen, F. Manoocheri and E. Ikonen "Effects of aging and degradations on regular transmittance of interference filters", in *5th Oxford Conference on Spectrometry*, London, UK, June 26-28, 2006.

E. Ikonen, P. Manninen, J. Hovila, and P. Kärhä, "Reference plane position and angular responsivity of spectroradiometer diffusers," in Proceedings of *Metrology Symposium 2006*, Queretaro, Mexico, October 25-26, 2006 (CD, 5 p.).

7.3 National Conference Presentations

T. Hieta, A. Lamminpää, and E. Ikonen, "Dispersion analyses and optical power measurement in determination of fiber nonlinearity", in Proceedings of *the XL Annual Conference of the Finnish Physical Society*, Tampere, Finland, March 9-11, 2006, p. 307.

A. Lamminpää, T. Hieta, J. Envall, P. Kärhä, and E. Ikonen, “Scale realization of high fiber optic power”, in Proceedings of *the XL Annual Conference of the Finnish Physical Society*, Tampere, Finland, March 9-11, 2006, p. 314.

S. Holopainen, F. Manoocheri, S. Nevas, and E. Ikonen, “On potential discrepancies between goniometric and sphere-based spectral diffuse reflectance”, in Proceedings of *the XL Annual Conference of the Finnish Physical Society*, Tampere, Finland, March 9-11, 2006, p. 315.

M. Ojanen, M. Merimaa, J. Laasasenaho, T. Melkas, and E. Ikonen, “Measurement of tree diameters using image processing”, in Proceedings of *the XL Annual Conference of the Finnish Physical Society*, Tampere, Finland, March 9-11, 2006, p. 118.

M. Vainio, “Spectral narrowing of a diode laser using phase conjugate feedback”, in Proceedings of *the XL Annual Conference of the Finnish Physical Society*, Tampere, Finland, March 9-11, 2006, p. 291.

7.4 Other Publications

M. Vainio, *Diode Lasers with Optical Feedback and Optical Injection: Applications in Metrology*, TKK Dissertations, Espoo 2006, 57 p.

J. Envall, P. Kärhä, and E. Ikonen, *Calibration of broadband ultraviolet detectors by measurement of spectral irradiance responsivity,* Metrology Research Institute, Helsinki University of Technology, Espoo 2006, Metrology Research Institute Report 30/2006, 17 p.

S. Holopainen (editor), *Annual report 2005*, Metrology Research Institute, Helsinki University of Technology, Espoo 2006, Metrology Research Institute Report 31/2006, 41 p.

J. Envall, *Optical Power Measurements: Applications in Fiber Optics and Ultraviolet Radiometry*, TKK Dissertations, Espoo 2006, 50 p.

E. Ikonen, *Optiikan perusteet,* 4th edition, Espoo 2006, ISBN 951-22-4709-7, 116 p. (in Finnish).

A. Pietiläinen, M. Merimaa, and T. Niemi, *Mittaustekniikan perusteiden laboratoriotyöt*, 13 korjattu painos, Espoo 2006, ISBN 951-22-6737-3, 113 p. (in Finnish).

P. Kärhä, *UVNews,* The official newsletter of the Thematic Network for Ultraviolet Measurements, Issue 8, Espoo 2006, 63 p.

A. Lamminpää, *High-Accuracy Characterization of Optical Components: Detectors, Coatings and Fibers,* TKK Dissertations, Espoo 2006, 57 p.