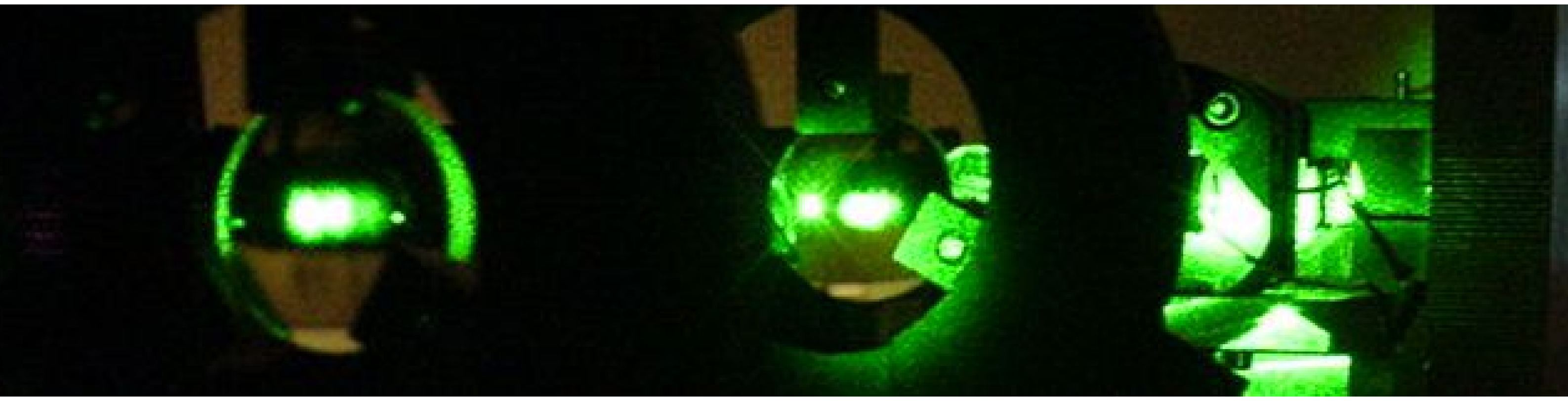
Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute Report 26/2005
Espoo 2005

BIENNIAL REPORT 2003-2004



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

Helsinki University of Technology
Espoo 2005

BIENNIAL REPORT 2003-2004

Editor Ossi Kimmelma

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

Teknillinen korkeakoulu
Sähkö- ja tietoliikennetekniikan osasto
Mittaustekniikan laboratorio

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1 INTRODUCTION

During years 2003-2004 significant changes took place in the organization of the Metrology Research Institute. From the 1st of January 2005 the Metrology Research Institute is operated as a joint laboratory of the Helsinki University of Technology (TKK) and the Centre for Metrology and Accreditation (MIKES). Simultaneously with this change, the undersigned was appointed as the holder of a joint professorship of TKK and MIKES. Furthermore, the microtechnology activities and part of the activities in fiber optics and applied quantum optics moved to the new Micronova building, while the optical radiation measurements, electronic instrumentation and length metrology remained in the Otakaari premises.

Subsequently also the formal organizational structure was changed to correspond the physical location of the activities, effective from 1st of June 2005. Professor Erkki Ikonen was appointed as the head of the Metrology Research Institute continuing at Otakaari and Professor Ilkka Tittonen was appointed as the head of the new unit at Micronova: Optics and Molecular Materials of the Department of Electrical and Communications Engineering.

As described in this biennial report, the two-year period produced very good results in research and teaching. It should especially be mentioned that 17 and 14 Master's degrees were completed in 2003 and 2004, respectively, and 1 and 3 Doctor's degrees in 2003 and 2004. The number of Master's degrees of 2003 is the new record of the Metrology Research Institute.

Erkki Ikonen

2 PERSONNEL

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Franssila Sami	Helsinki University of Technology	+358 9 451 2332
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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute (Mittaustekniikan laboratorio) in 2003 and 2004. Those marked by * are given biennially.

S-108.180	Electronic Measurements and Electromagnetic Compatibility 2 credits (Petri Kärhä, Esa Häkkinen)
S-108.181	Optics 2 credits (Erkki Ikonen, Petri Kärhä)
S-108.186	Microsystem technology 4 credits (Ilkka Tittonen and Sami Franssila)
S-108.187	Laboratory course on microsystems 3 credits (Ilkka Tittonen and Sami Franssila)
S-108.189	Project Work in Measurement Technology 2-5 credits (Erkki Ikonen)
S-108.191	Fundamentals of Measurements Y 2 credits (Mikko Merimaa)
S-108.194	Electronic Instrumentation 3 credits (Pekka Wallin)
S-108.195	Fundamentals of Measurements A 2.5 credits (Mikko Merimaa)
S-108.198	Biological Effects and Measurements of Electromagnetic Fields and Optical Radiation 2 credits (Kari Jokela)
S-108.199	Optical Communications and Optical Instruments 5 credits (Erkki Ikonen, Farshid Manoocheri, Edward Mutafungwa)

S-108.901	Electrical Engineering Project 1-5 credits (Pekka Wallin)
S-108.911	Postgraduate Course in Measurement Technology 7.5 credits (Ilkka Tittonen)
S-108.913	Postgraduate Course in Physics of Measurement* 3 credits (Birger Ståhlberg)
S-108.914	Research Seminar on Measurement Science 1 credit (Erkki Ikonen)

3.2 Degrees

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

Atte Haapalinna, *Characterization Methods for Silicon Photodiode and Silicon Sub-Surface Properties (2004)*

Opponent: Prof. P. Schellekens, Eindhoven University of Technology, The Netherlands

Saulius Nevas, *Characterisation of Materials and Components Using Accurate Spectrophotometric Measurements and Mathematical Modelling (2004)*

Opponent: Dr. Detlev Ristau, Laser Zentrum Hannover, Germany

Goëry Genty, *Supercontinuum generation in microstructured fibers and novel optical measurements techniques (2004)*

Opponent: Prof. David Richardson, ORC, University of Southampton, UK

Harri Mustonen, *Measurement of Epithelial Electrical Passive Parameters and its Application to Study Gastric Defence against Acid and Ulcerogenic Agents (2003)*

Opponent: Prof. Juha Voipio, Department of Biosciences University of Helsinki, Finland

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

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

Ossi Hahtela, *Optical Actuation of a Micromechanical Oscillator (2004)*

Mikko Lehtonen, *Tapered Microstructured Fibers for Efficient Coupling to Photonic Crystal Waveguides (2004)*

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

Ahtee Ville, *Synchronization of Frequency Comb Spacing to an Atomic Clock (2003)*

Antila Jarkko, *Micro-Electromechanical Fourier Transform Interferometer (2003)*

Auromaa Mikko, *Coupled Micromechanical Resonator Structures (2004)*

Drufva Tuukka, *Physical Limitations of Optical Telecommunication Network (in Finnish, 2003)*

Envall Jouni, *Spectral Comparator Facility for Calibrating Ultraviolet Detectors with Low Sensitivity (in Finnish, 2003)*

Federley Kristian, *Testing Development for Outsourced Manufacturing (in Finnish, 2004)*

Forsberg Toni, *Expandable Multiplate Calibration and Trimming Equipment for Acceleration Sensors (in Finnish, 2003)*

Haapanala Sami, *Optical Measurement of Wind from the Movement of Aerosol-Particles (in Finnish, 2004)*

Jankowski Tomasz, *Measurement of Radiation Temperature Using Filter Radiometers (2003)*

Kinnunen Kalle, *Development of a Microprocessor-Based Surveillance System (in Finnish, 2003)*

Klemetti Petri, *Temperature Dependence and Noise of Angular Rate Sensor Element (in Finnish, 2004)*

Lahtinen Juha, *Characterization System for the Performance of Accelerometers (in Finnish, 2004)*

Lamminpää Antti, *Measurement of Nonlinearity of Optical Fiber (2003)*

Marttila Seppo, *Micromechanical Ion Source Made of Silicon and Glass (in Finnish, 2003)*

Niemelä Arto, *Development of Photodiode Measuring Devices and a Sensitive Photodetector (in Finnish, 2003)*

Niinikoski Laura, *Magneto-Optical Trapping of Rubidium Atoms Towards a Gravito-Optical Trap (2004)*

Ojala Panu, *Photonic Crystal Slabs (in Finnish, 2004)*

Pasanen Mikko, *Electromagnetic Compatibility Analysis of an X-ray Device (in Finnish, 2003)*

Pääkkönen Teemu, *Implementation of an Electronic Magnetometer (2003)*

Rantakari Pekka, *Implementation of Micromechanical Oscillator Using CMOS and SOI technologies (in Finnish, 2004)*

Rautkari Tapio, *Multipurpose Calibration Program (in Finnish, 2003)*

Rissanen Anna, *Porous Silica in Micromechanical Applications (2003)*

Savolainen Jari, Integrated *CMOS Sensors for Low-Power Applications (2003)*

Tchere Franck Gustave, *Measurement of Polarization-Mode Dispersion of Optical Fibers (2003)*

Vahala Eero, *Computer Controlled Laser Frequency Stabilization (2003)*

Väisäsvaara Juha, *Charging Effects in Capacitive MEMS (2004)*

Falck Marko, *Design and Verification of Radio Frequency Integrated Circuit Power Amplifiers (2004)*

Valkama Timo, *Implementation of Optical Delay Line for Optical Processing (in Finnish, 2004)*

Manninen Pasi, *Photometric Measurements of Light Emitting Diodes (in Finnish 2004)*

Sutela Lassi, *Evaluation of Measuring Methods for Dissipative Plastic Materials (2004)*

Leskinen Paavo, *Apparatus for Testing Inhomogeneities in Thermocouples (in Finnish, 2004)*

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 2003 – 2004, 101 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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Petri.Karha(at)tkk.fi, Tel. +358-9-451 2289

5 RESEARCH PROJECTS

5.1 Optical Radiation Measurements

Highlights of the years 2003-2004

TKK maintains one of the most accurate realizations of spectral irradiance. In 2003, the effects of correlations in the spectral irradiance measurements were analyzed. The obtained results support the earlier uncertainty calculations. The work gives new knowledge on the propagation of uncertainties in interpolation of spectral data. Highlights also include work on oblique angle thin film measurements. In this project, the transmittance measurement facilities at TKK have been applied to obtain knowledge of optical properties of materials. In 2003, TKK completed a one-year Nordic project on high fiber optic power measurements. Considering the relatively small amount of resources invested, a lot of results were obtained. Finland, Sweden and Denmark all now have facilities for calibrating high fiber optic power levels. The intercomparison arranged demonstrated very satisfactory agreement. TKK has started a research project on photometric properties of LED's. In 2004, research concentrated on luminous intensity measurements of LED's with interesting results on the distance dependence of the measured signals.

Figure 1. Artefacts to be calibrated are numerous. The buoy lantern shown is used in maritime applications and consists of LED's.

Development of absolute scale of spectral diffuse reflectance

A project for the development of an absolute measurement method of spectral diffuse reflectance throughout the wavelength range of 360 – 820 nm was completed in 2003. The new absolute scale of spectral diffuse reflectance will upgrade the earlier-established relative scale at TKK that has been based on direct comparison with transfer standards obtained from the absolute scales of National Research Council (NRC), Canada, and Physikalisch-Technische Bundesanstalt (PTB), Germany. The developed gonioreflectometric measurement facility has been carefully characterized for the uncertainty sources and test measurements have been made. The determined 0/*d* reflectance factors of a set of standards were found to be in agreement with those derived from the earlier scale. The measurement system was also used in the key comparison measurement of spectral diffuse reflectance, CCPR-K5, carried out during 2003. The analysis of the key comparison results is currently in progress. The results of the project were presented in an article published in *Applied Optics* in 2004 and they also made a part of the doctoral dissertation successfully defended in a public examination at TKK in October 2004.

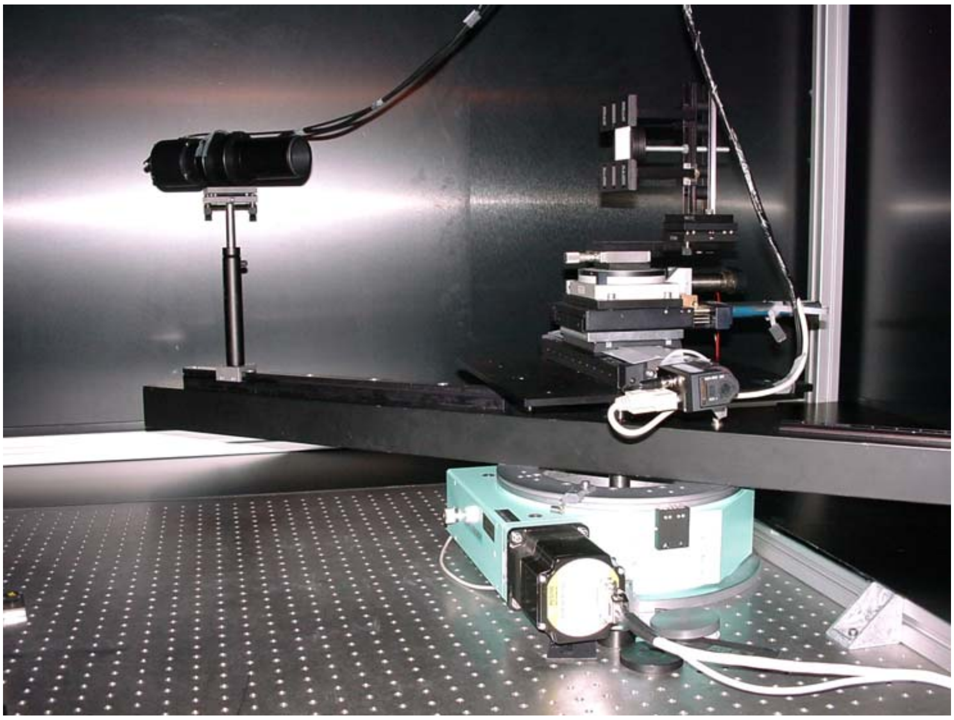

Figure 2. In 2003 TKK completed a development project for an absolute measurement method for diffuse reflectance. The photograph shows the receiver system of the developed gonioreflectometer setup.

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. In 2003 – 2004, a trap detector with GaAsP photodiodes was built and characterized to be used in the UV region. The additional filters needed for the wavelength region 250 nm – 2.5 µm were purchased and characterized. In 2004, Ge diodes were studied to be used as an IR detector. The goal is to build an IR trap detector to be used in the filter radiometer.

Intense UV radiation facility for calibration of radiometers

In the project we have developed a calibration facility for spectral irradiance responsivities of UV meters. The setup consists of a single grating monochromator, a 450-W Xe light source, and apertured reference photodiodes. In 2003, the reference photodiodes were characterized and test measurements were performed on a commercial UVA meter. The results were compared with the earlier spectroradiometric calibration method of the laboratory. A good agreement of the methods was demonstrated. The results were published in the diploma work of Jouni Envall. The setup was further tested in comparison measurements with NIST. In 2004, the stray light properties of the monochromator were studied by measuring the slit scattering function with six laser wavelengths, ranging from 442 nm to 818 nm. The cosine responses of our spectroradiometer and commercial UVA detector were measured in order to calculate corrections due to changes in measurement geometry. A new powerful Hg light source was purchased. A manuscript, describing the results of the project so far, was written and submitted to be published. An international pilot comparison of the scales of UVA irradiance responsivity was started.

Determination of radiation temperature using filter radiometers

In this collaboration project of TKK and the temperature laboratory of MIKES, a new approach to measuring the radiation temperature of a black body radiator is tested. Spectral irradiance of the high precision black body radiator is measured through the limiting set of two apertures in near-IR wavelength region. In 2004 the work was focused on laser-based calibration of filter radiometers for measurements of the freezing temperatures of Cu and Ag.

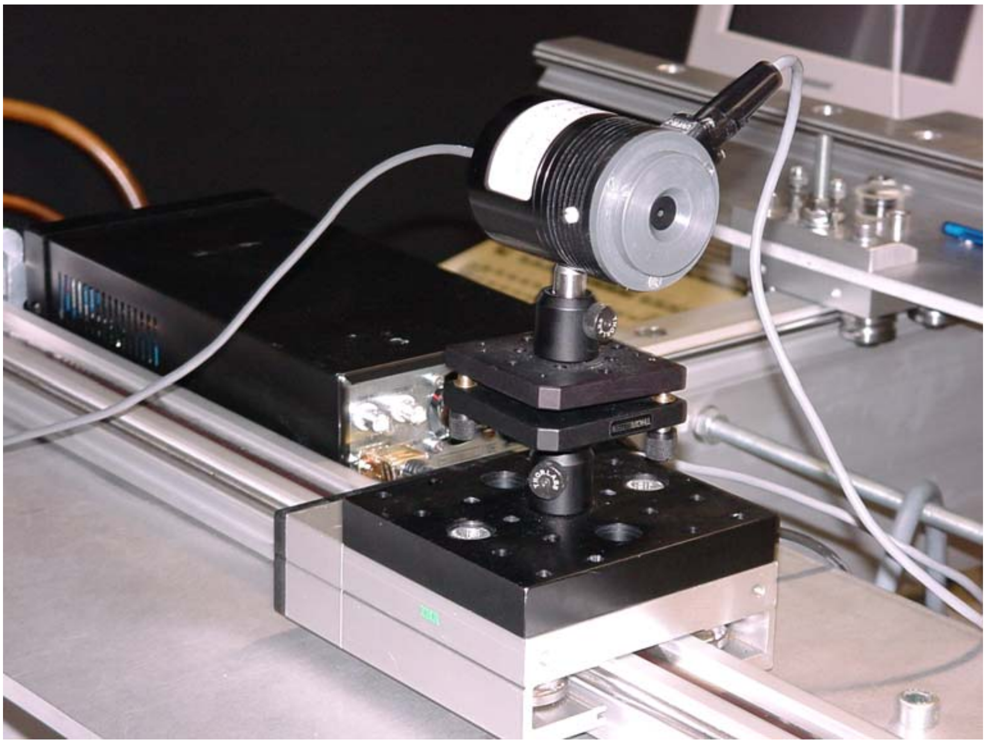

Figure 3. Filter radiometers have an important role in modern radiometry and photometry. TKK is one of the leading experts in this demanding field.

Calibration facility for color displays and colorimeters

The aim of this project is to build a calibration facility for color displays. The calibration facility is intended for measuring the relative spectral radiance of color displays with expanded uncertainty of lower than 0.7 % (k=2). The facility will include a measurement setup around a characterized spectroradiometer, a translation stage, a standard light source, and a characterized color display. In 2003 the project started with experiments using an existing spectroradiometer. In 2004, a diploma thesis work was carried out on the subjects with emphasis on the construction of a setup for characterisation of LCD devices.

High Power Fiber Optic Calibration

In this collaboration project between TKK, SP and DFM, methods for calibrating fiber optic power meters with optical powers in the range 1 – 200 mW were developed and compared. The whole project was completed in 2003. The TKK setup consists of and integrating sphere detector and a 1550-nm laser coupled to an erbium-doped fiber amplifier, EDFA. The obtainable uncertainty is of the order of 1.5 %. The independent setups of the three laboratories were compared. The agreement of the measurements (of the order of 1 %) was well within the uncertainties of the laboratories. In 2004, a manuscript describing the results of the project was written and submitted to be published.

Photometry of Light Emitting Diodes

In this project on LEDs, which started at the beginning of 2004, a measurement setup was built for luminous intensity of LEDs. With LED standard photometer, illuminances produced by LEDs were measured at various distances. Luminous intensities of LEDs were determined from the measured illuminances at different distances. Uncertainty analysis was done for the luminous intensity of a white low power LED. A comparison measurement was done between the photometer used for LED measurements and the reference photometer of the laboratory.

Determination of the diffuser reference plane of photometric and radiometric detector heads

Dome-shaped diffusers are often used in detector heads to improve their cosine response. When measuring with such a detector, the reference plane of the measurement distance is traditionally chosen to be the outermost surface of the diffuser.

A 2-year project to study photometers with dome-shaped diffusers was initiated in 2004. During the first year, a series of measurements were conducted with the reference photometer and commercial luxmeters to determine if any errors occur when the reference plane is chosen as usual. As expected, the actual reference planes were found to be several millimetres inside the diffusers; the higher the diffuser, the larger the difference. If these displacements are not taken into account during the calibrations of the luxmeters, errors of several per cents, greatly exceeding the calibration uncertainties, are obtained in later illuminance measurements.

Measurement results were also compared with a mathematical model of a hemispherical diffuser. The results showed that the theoretical displacements were smaller than the measurements indicated. Therefore, the geometry of the diffuser alone does not explain the phenomenon; apparently at least the material and the internal structure of the detector head have some contribution to the observed displacement.

An article concerning the measurements and analyses was submitted to be published.

5.2 Length Metrology

The lasers and frequency comb that are used for the realization of the definition of the meter are in the MIKES laser laboratory, which is located in the laboratories of the Metrology Research Institute. The stabilized lasers and frequency comb are property of the Centre for Metrology and Accreditation (MIKES).

Iodine-stabilized lasers

The iodine-stabilized He-Ne lasers have been previously developed in collaboration between MIKES and the Metrology Research Institute. These lasers are used regularly in laser frequency calibrations.

The iodine-stabilized lasers (three red He-Ne lasers, two multicolor He-Ne lasers and a frequency-doubled Nd:YAG-laser) have been maintained in qualified conditions. To maintain and improve the reliability of frequency calibrations, iodine-stabilized He-Ne lasers MRI1 and MRI3 were overhauled and the frequency of the portable laser (MRI3) was absolutely measured at BIPM in 2003. After the measurement, the absolute frequency was transferred to the other two red He-Ne lasers (MRI1 and MRI2) through frequency comparisons.

The optics and electronics of the iodine-stabilized Nd:YAG-laser were further developed to achieve better frequency stability, e.g. a new, longer, iodine-cell was installed to the set-up.

Frequency comb

The pump laser for the femtosecond laser oscillator arrived at the very end of year 2002 and the femtosecond laser was transferred to the MIKES laser laboratory. In 2003 the optics and electronics of the optical frequency comb generator were developed and the spectra of various photonic crystal fibers (PCF) were measured. The laser oscillator was used also by the fiber-optics group in characterization of diverse PCFs.

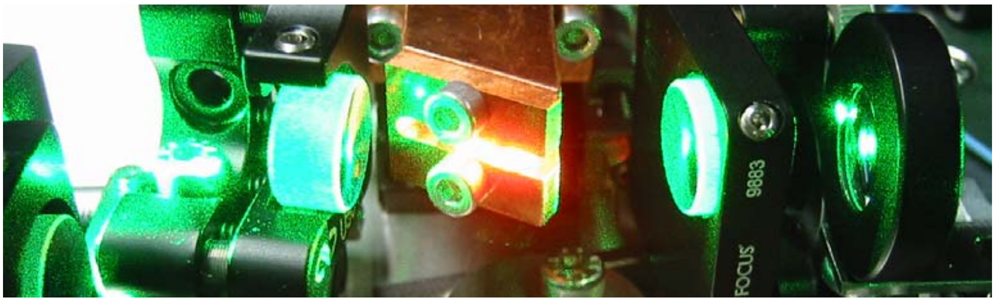

Figure 4. A titanium-sapphire crystal is the gain material of the femtosecond laser. The intense green light from the pump laser provides energy for laser operation.

The MIKES time and frequency section acquired and brought into use two hydrogen masers, which short-term frequency stability greatly exceeds that of a Cs-atomic clock. Consequently, the frequency comb setup was modified to use the self-referencing configuration and all comb frequencies are now directly synthesized from an active hydrogen maser. Currently the operation of the frequency comb is limited by the stability of the hydrogen maser.

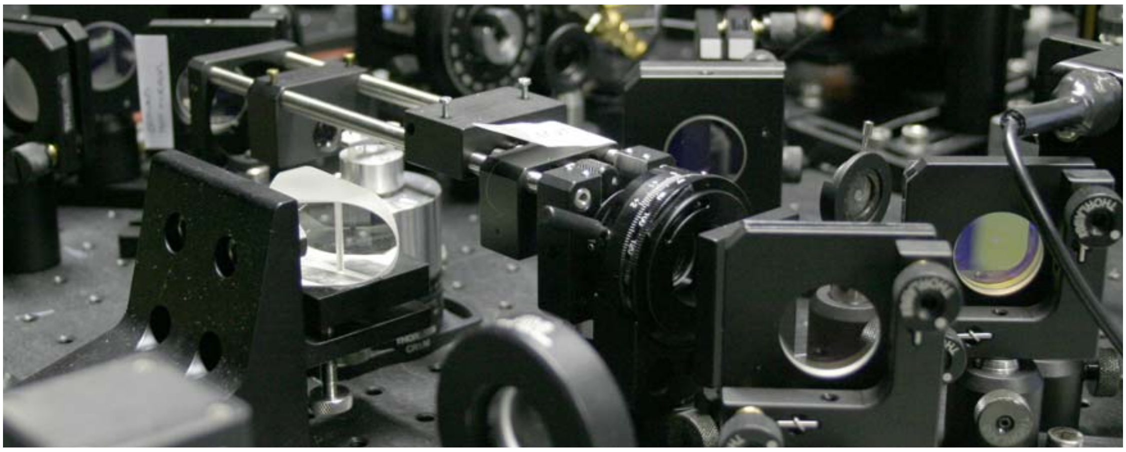

Figure 5. A thin BBO-crystal is used in self-referencing to frequency double part of the frequency comb from infrared to green. The optical path lengths of the two arms of the self-referencing setup are adjusted to be equal with a moveable prism. This is necessary in order to observe interference between short pulses.

An injection-locking set-up was developed for absolute frequency measurements of iodine-stabilized He-Ne lasers at 633 nm. In this set-up a red diode laser is injection locked to the iodine-stabilized He-Ne laser being measured, leading to greatly amplified output power (up to 10 mW). The additional frequency noise caused by injection locking was found to be negligible and the diode laser reliably follows the frequency of the He-Ne laser. Thus, the set-up is valuable asset in absolute frequency measurements of the red He-Ne lasers, which output power would otherwise be insufficient for a beat-frequency measurement with the frequency comb. Furthermore, an iodine spectrometer based on highly stabile transmission grating laser at 633 nm was developed. The spectrometer is suitable for high accuracy measurement of hyperfine spectra around 633 nm, thus allowing absolute frequency assignments of various iodine hyperfine lines.

5.3 Fiber-Optics

Highlights of the Fiber-Optics group

H. Ludvigsen, T. Niemi, G. Genty, J. Tuominen, M. Lehtonen, T. Ritari,
A. Lamminpää, T.C. Franck

The Fiber-Optics group has been involved in various activities in 2003. In particular, a great effort was put into the study of the properties of the novel photonic crystal fibers (PCFs) and applications of these. Many interesting and promising results have been obtained, which will set the basis for PCF-based device with advanced functionalities. Furthermore, the work of the group with temperature tunable silicon etalons has resulted in compact and cost-effective applications for optical telecommunications. Results of the projects described below have also been published in several peer-reviewed journals and international conference proceedings.

For more information see http://metrology.TKK.fi/fiberopticsgroup.

Supercontinuum generated in a highly birefringent PCF

We have investigated the influence of pump laser polarization on the supercontinuum generated in a 5 m long highly birefringent photonic crystal fiber. The supercontinuum was generated in a highly birefringent PCF by launching into the fiber ultra-short pulses from a Ti:Sapphire laser. The laser produces 100 fs pulses with a repetition rate of 80 MHz. The fiber has an elliptical core of dimensions $1.2\times2.4\ \mu m^2$ resulting in two different dispersion profile for the fast and slow principal axis of polarization. The optical spectrum of the SC recorded for three different input polarizations (parallel to the slow and fast axis of the fiber and at 45^o with respect to these axes) is shown in Figure 6 for an average input power of 100 mW.

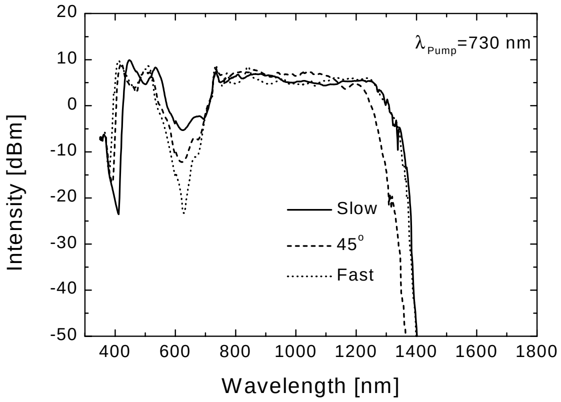

Figure 6. Polarization dependence of the SC.

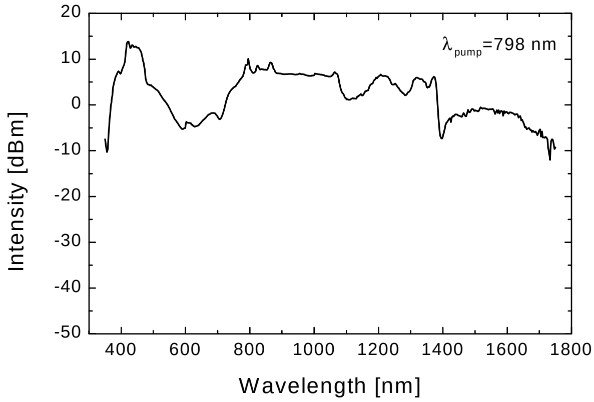

Figure 7. Optimized SC generated along the fast axis of a highly birefringent fiber.

The group-delay difference between the two principal axes of polarization of the fiber was found to be more than 20 ps/m for the visible and IR wavelengths. Consequently, the walk-off distance for 100 fs pulses polarized along the slow and fast axis is less than 1 cm. This means that when light with arbitrary linear polarization is launched into the fiber, the output spectrum is the combination of two independent continua generated separately by the two polarization components. Therefore, the resulting continuum is narrower than in the case of having the polarization of the pump beam parallel to one of the principal axes of the PCF. The observations allowed us to optimize the parameters of the input pulses to obtain an ultra-broad and relatively flat continuum. The pump laser was operated at 798 nm and the polarization was set to be along the slow axis of the fiber. The average power coupled into the PCF was 140 mW. The spectrum of the SC is presented in Figure 7 and extends from 400 to 1700 nm with an amplitude variation of less than 20 dB.

Supercontinuum generation in higher order modes of a PCF

In PCFs, the coupling between the fundamental and higher-order modes has been predicted to be weak due to a large difference in the refractive indices between the different guided modes. We have demonstrated the generation of a supercontinuum whose spectrum is partly divided between fundamental and higher-order modes. The mechanism leading to the continuum generation and the resulting spectrum were found to depend critically on the combination of the excited modes. When pumping the multimode PCF with 200 fs pulses produced by a 80 MHz Ti:Sapphire laser at 860 nm and with 140 mW average input power, we observed the formation of a supercontinuum which extends from 500 to 1300 nm. The wavelengths below 720 nm were found to be in the LP_{11} mode and those above 720 nm in the fundamental mode LP_{01} (see Figure 8). Varying the angle of incidence of the light coupled into the PCF, we were able to excite the degenerate forms of the LP_{11} mode for the wavelengths below 720 nm as shown in Figure 9. For certain angles, a linear combination of the degenerate modes resulting in a ring-shaped mode pattern could be seen. The spectrum measured was not found to significantly depend on the form of the output mode. We were also able to excite a higher order mode as illustrated in Figure 11. The corresponding spectrum, which differs substantially from the spectra measured when exciting the LP_{11} mode is presented in Figure 10. In particular, multimode four-wave mixing with large wavelength separation between the Stokes and anti-Stokes bands is observed. This effect could be for instance advantageously used, e.g., for wavelength conversion. This is in contrast to the results presented in Figure 9 where the interplay between self-phase modulation, Raman scattering and soliton formation leads to the generation of the continuum.

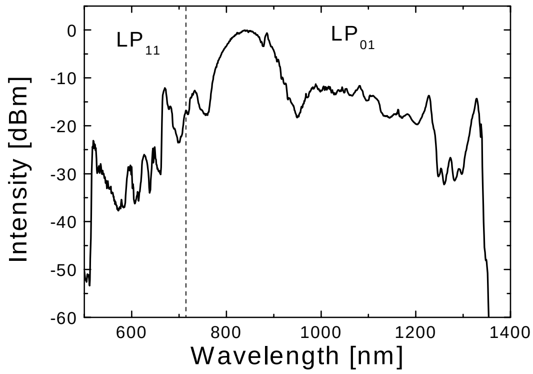

Figure 8. Spectrum of supercontinuum whose spectrum is divided between the LP01 and LP11 modes.

Figure 9. Output modes of the continuum generated in the LP01 and LP11 modes. The pictures were taken using a digital camera.

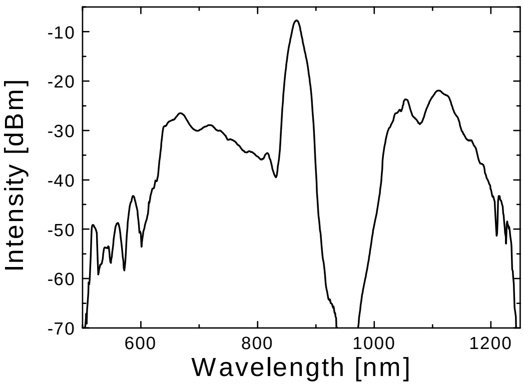

Figure 10. Spectrum of supercontinuum generated in a higher-order mode.

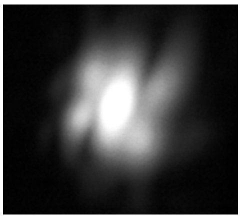

Figure 11. Output mode of the continuum generated in a higher-order mode.

Supercontinuum generation in tapered fibers

We have investigated the possibility of using narrow-core tapered fibers for efficient infrared continuum generation. Extensive simulations and modeling have been performed to obtain the design parameters for generating continua with maximum bandwidth given pump pulse characteristics. An apparatus permitting of tapering standard fibers has been built and successful tapered fibers with a narrow core were demonstrated. Supercontinuum generation at visible and UV wavelengths in this type of fiber was achieved using a Ti:Sapphire laser (rep. rate=80 MHz, pulse duration=200fs) as a pump source. The experimental spectrum recorded at the output of a ~15 mm long tapered fiber with a core diameter <1.5 µm is presented in Figure 12. Further work involves the development of an optical parametric oscillator operating in the range 1400-1700 nm as such a source is a prerequisite for the demonstration of infrared continuum generation in tapered fibers. Numerical simulations shows that the generation of a supercontinuum extending from 1200 to 2200 nm should be possible as is illustrated in Figure 13. This kind of infrared light source could find many applications in, e.g., optical spectroscopy, optical coherent tomography or bio-molecule analysis.

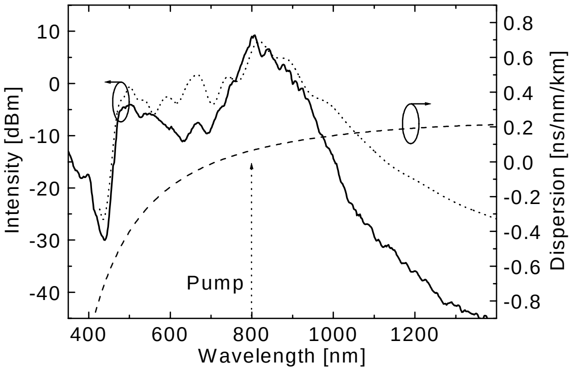

Figure 12. Supercontinuum generated in a 15 mm long tapered fiber. The pump wavelength is located at 800 nm.

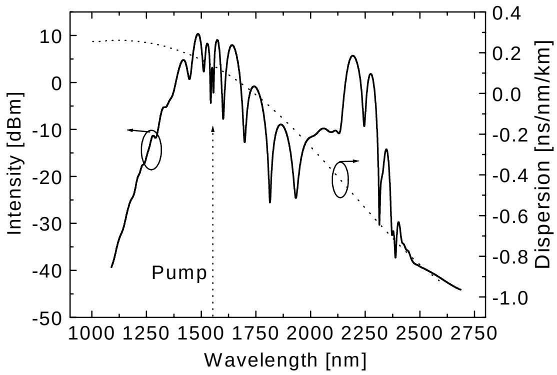

Figure 13. Simulated supercontinuum generated in a 1.4-µm core tapered fiber with pumping at 1550 nm.

Absorption measurements using supercontinuum light

Efficient white-light generation in photonic crystal fibers (PCFs) has recently opened up exciting new possibilities for applications in spectroscopy. We have applied such a broadband source generated in a weakly birefringent MF to measure impurity absorption in an erbium-doped optical fiber. The supercontinuum was generated by launching the 80 MHz pulse train from a mode-locked Ti:Sapphire laser into a 1.5 meter long PCF with a core diameter of 2 µm. As an example, we show in Fig. 1 the absorption measurement on a 5 m long erbium-doped step-index silica fiber. The dashed curve in Figure 14 illustrates the spectrum of the supercontinuum at the output of the PCF and the continuous line the spectrum measured at the output of the doped fiber. Figure 15 shows the doped-fiber absorption spectrum extracted from the measurement. The advantages of the measurement technique include high brightness of the source and efficient coupling of light into the doped fiber.

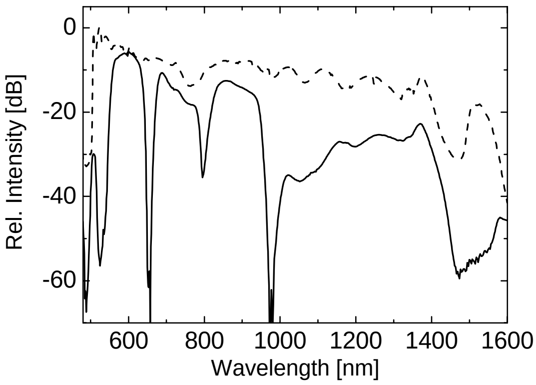

Figure 14. Spectra of generated supercontinuum (dashed line) and output of the doped fiber (solid line).

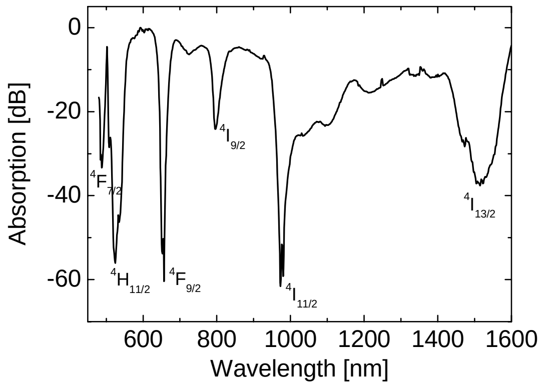

Figure 15. Extracted absorption spectrum of Er3+ ions in the doped silica fiber.

Novel dispersion measurement technique

Dispersion is a crucial parameter of optical fibers as it strongly affects the propagation of light pulses. We have developed a novel and simple technique to characterize the anomalous dispersion of narrow-core and polarization maintaining photonic crystal fibers (PCFs) using short optical pulses from a Ti:Sapphire laser. The technique, based on soliton formation along PCFs, allows for a direct measurement of the dispersion at the desired wavelength from a single pulse. Under the combined effect of nonlinearity and anomalous dispersion, the input pulse changes its shape to a fundamental soliton as it propagates along the fiber. During the reshaping process, a dispersive wave is radiated and the interference between the dispersive wave and the emerging soliton produces oscillations in the measured spectrum (see Figure 16). The phase difference between the two coherent fields depends on both distance and frequency and explains the phenomena observed. The dispersion can then be calculated from this phase difference with a measurement error estimated to be less than 10% (see Figure 17).

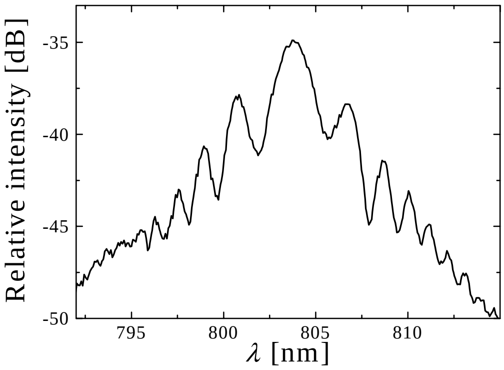

Figure 16. Spectrum at the output of a CF resulting from the interference between the soliton and radiated dispersive wave.

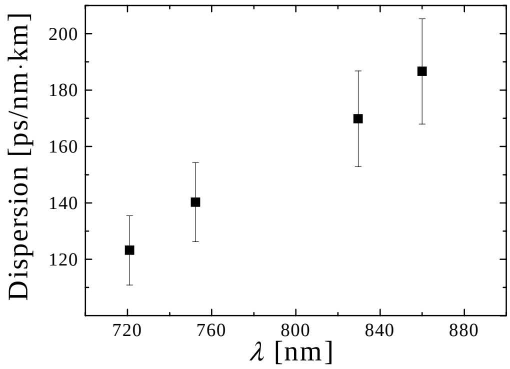

Figure 17. Dispersion of a 1 μm core PCF measured using the spectral modulation technique.

Gas detection using air-guiding photonic bandgap fibers

We have demonstrated that the novel air-guiding photonic band gap fibers (PBFs) can be conveniently employed for gas sensing/detection. In PBFs, more than 98 % of the guided mode energy can propagate in the air regions of the fiber. Therefore, by filling the air holes of a PBF with gas, a significant increase in the overlap between the volume of the gas and the mode field of the light propagating along the fiber can be obtained, thereby reducing considerably the length of fiber needed compared to more traditional designs and increasing the sensitivity of the device. Furthermore, the relatively large core of a PBF (e.g. up to 20 μm) can be filled with gas in a short time, thus improving the response time of the sensor apparatus. Among their other attractive features, PBFs are also highly insensitive to bending, which should allow for the development of compact devices. In our experiments, one end of a 1 m long PBF was spliced to a single-mode fiber to improve the light coupling efficiency. The open end of the PBF was then butt-coupled to a multi-mode fiber using a V-groove and subsequently placed inside a vacuum chamber. The gap between the two fibers was set to ~50 um for efficient filling process. The PBF was purged and filled with gas to a desired pressure. The absorption spectrum was measured using a tunable laser in combination with a wavelength meter and a photodetector. Measurements with a LED and an optical spectrum analyzer were also conducted for comparison. Encouraging results have been obtained for several types of gases: strongly (acetylene/hydrogen cyanide) and weakly (methane/ammonia) absorbing gases. PBFs may find applications in analyzing gas samples using small gas volumes and in remote safety monitoring of reactive or poisonous gases. For gases with weak absorption lines or in low concentration, an increased sensitivity can be obtained by using longer fiber length.

Wavelength and power monitoring in WDM systems

Future dense wavelength division multiplexed (DWDM) channel spacings of 50 and 25 GHz call for highly stable transmitters and accurate means for monitoring the infrared wavelengths and power levels. Continuous characterization of allocated channels, per link channel power levels and channel wavelengths are required to provide dynamic provisioning of DWDM channels. Spectrum analyzers are commonly used for this purpose. They are, however, cumbersome, expensive and need to be replaced by fast, reliable and cost-effective alternatives.

In a joint project with the Photonics Group at VTT/Information Technology, a new device concept for WDM channel monitoring was presented and tested. Our method is based on the labeling of the optical carriers with sub-carriers. A scanning silicon Fabry-Pérot etalon and a sampling scheme are utilized to identify and measure the channels directly from the optical multiplex. The device is capable of measuring up to around 30 channels one at a time, each measurement during around 2 s. The achieved wavelength accuracy was ±5 pm and channel power accuracy was ±0.2 dBm. This device accuracy holds for channel powers down to -40dBm. The proposed device provides fast, reliable and accurate means for monitoring high channel count DWDM networks.

5.4 Microtechnologies

Atom optics

Microscopic traps that mainly utilize evanescent optical fields were studied both theoretically and experimentally. The experimental realization consists of the two major building blocks, the laser setup and the ultra-high-vacuum chamber. The magneto-optical trap was re-established in the end of the year using the totally new UHV system. The theoretical studies show that the final temperature of the evanescent wave laser cooled atoms is an increasing function of the number of atoms in the trap. The phase-space density, on the other hand, shows a well-established minimum. Thus, it becomes possible to optimize the phase-space density by using evanescent wave based traps. This parameter plays a major role in creating of the Bose-Einstein condensate. In addition, various surface-mounted microscopic atom traps were built on an optically transparent substrate. This research is performed by the two research teams: prof. Matti Kaivola and prof. Ilkka Tittonen and the whole activity is being planned to bee moved to new premises at Micronova, which is the TKK Center for Micro and Nanotechnology.

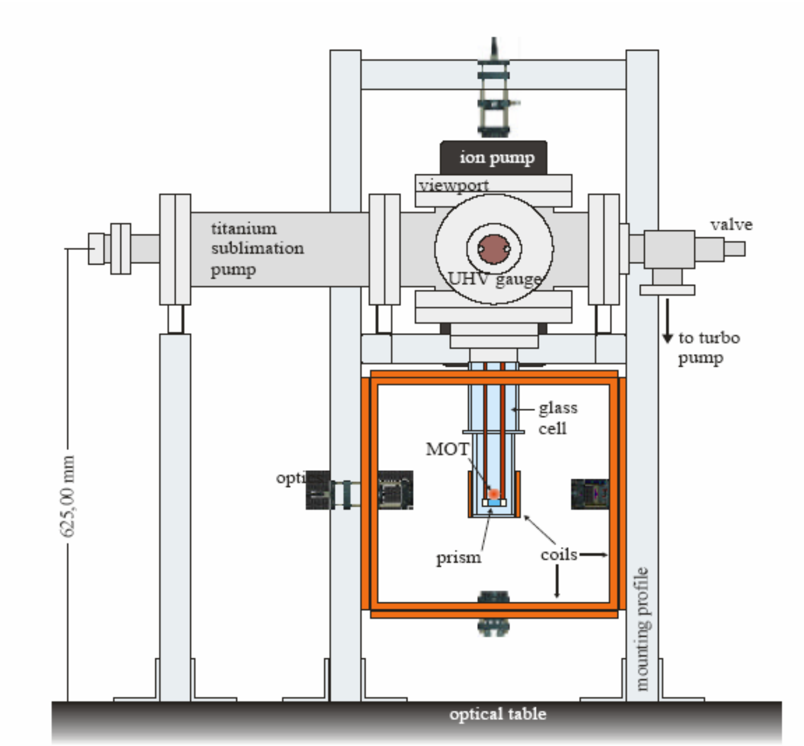

Figure 18. Schematic picture of the atom optics experiment for microtraps.

Microsystems

Microelectromechanical (MEM) resonators are electrostatically excited mechanical resonators that are fabricated usually on SOI (Silicon-On-Insulator) – wafers (Figure 19).

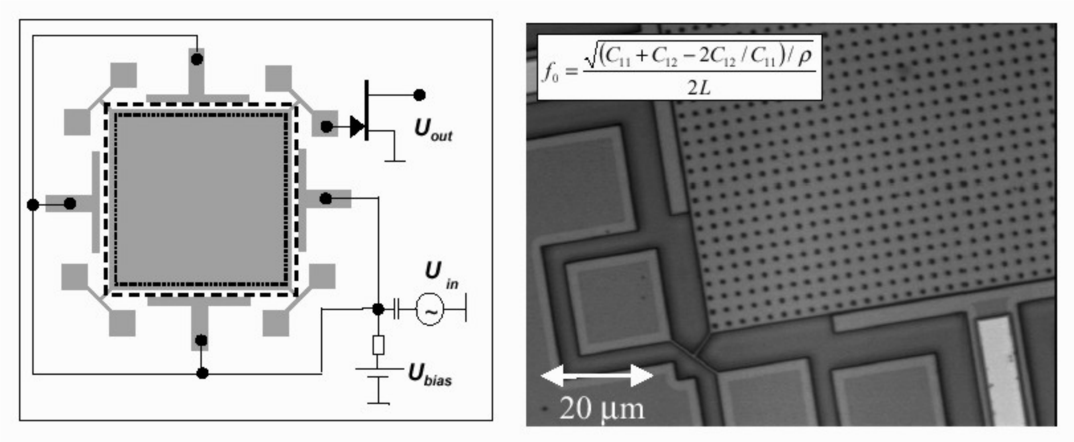

Figure 19. Schematic- and SEM-views of a micromechanical plate-resonator. The SEM-image shows the lower left-hand corner of the device.

We have already demonstrated that micromechanical resonators can compete with quartz crystals in short-term stability. In practice this means, that we have been able to design and fabricate resonators with high enough quality factor and energy storage capability that the oscillators based on these resonators are comparable with quartz-oscillators.

During the last year, we have also been able to demonstrate that the long-term stability of these resonators is sufficient for a frequency-reference operation as long as the resonators are only hermetically packaged.

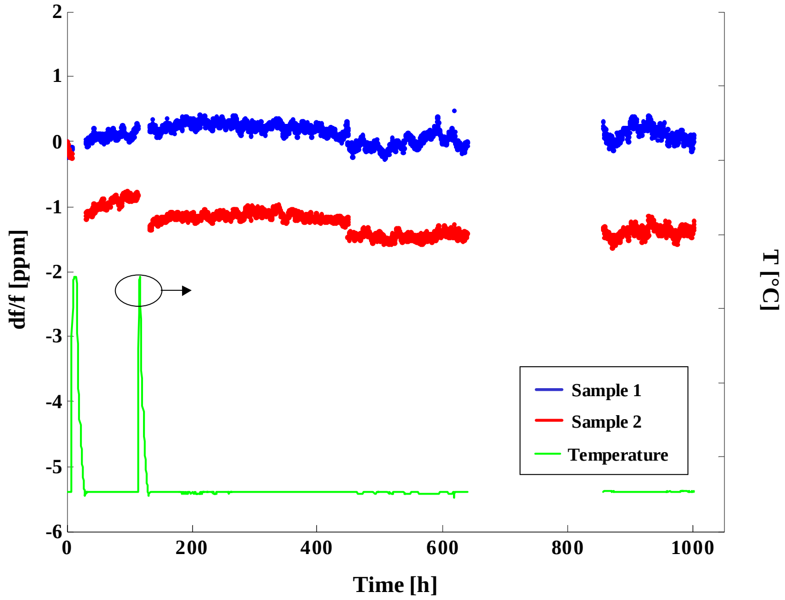

Figure 20. 1000 h follow-up measurement for a packaged micromechanical resonator shows a ppm-level stability in the resonance frequency.

This is an extremely important corner-stone in demonstrating that silicon microresonators provide a serious alternative for quartz crystals in frequency reference applications. These resonators seem to be able to meet even the very strict GSM-specifications and work easily in short-distance communication (BlueTooth, ZigBee etc.) (Figure 20).

In addition to frequency-references, micromechanical resonators offer the possibility to realize other blocks in radio-architectures. By using mechanically coupled resonators, it is possible to develop mechanical delay lines, frequency-mixers and filters that could be the building blocks for the novel close range, low power wireless sensors.

5.5 Applied Quantum Optics

Fabrication of Periodically Poled Crystals Using Electric Field Poling

The light that is induced by a nonlinear process can be summed up constructively by phase matching the input laser field with the one propagating in a medium. One method to perform this is to periodically change the sign of the nonlinear coefficient by physically altering the crystal orientation. This is called quasi-phase-matching (QPM). One dimensionally this poling is already a commercially established technique. Two-dimensional QPM structures were first proposed by Berger [1]. Such structures, referred to as nonlinear photonic crystals (NLPCs), can be created by two dimensional electric field periodical poling in which the crystal orientation of a ferroelectric crystal is reversed by external electric field.

The poling pattern can be done using photolithography. The photoresist functions as an insulator on top of the crystal and an external electric field exceeding the internal coercive field is applied. Short pulses are used so that the crystal pattern would be preserved throughout the crystal. The conductivities between the z and x-y plane have to have several orders of magnitude difference in order to pole without severe domain broadening. The poled pattern can be revealed using anisotropic etching. A microscope picture of a poled 2D crystal is seen in Figure 22.

An advantage of periodic poling is possibility to choose the direction in the crystal which has the greatest nonlinearity in contrast to traditional phase matching in which the angle is determined by crystal refractive index properties. With periodic poling it can be even possible achieve phase matching in the direction that would be traditionally impossible to phasematch. A limitation to periodic poling is the feature size needed for a specific process. This size is determined by the domain broadening (crystal properties) and lithography. The most usual periodically poled devices are crystals for frequency doubling and parametrical oscillators or generators.

The NLP crystals can support multiple conversions in one crystal structure. For example, second, third and fourth harmonic generations have been demonstrated in a single crystal [2]. Nonlinear photonic crystals offer a variety of possibilities but just a few practical demonstrations have been reported.

[1] V. Berger, "Nonlinear Photonic Crystals", Phys. Rev. Lett. 81, 4136-4139 (1998).

[2] N.G.R. Broderick, R.T. Bratfalean, T.M. Monro, D.J. Richardson, C.M. de Sterke, "Temperature and wavelength tuning of second-, third-, and fourth-harmonic generation in a two-dimensional hexagonally poled nonlinear crystal", J. Opt. Soc. Am. B 19, 2263-2272 (2002).

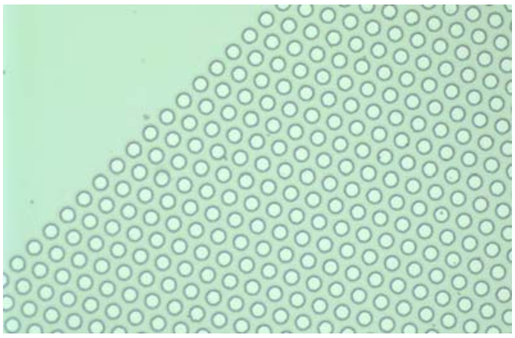

Figure 21. A microscope picture of the two dimensional photoresist structure.

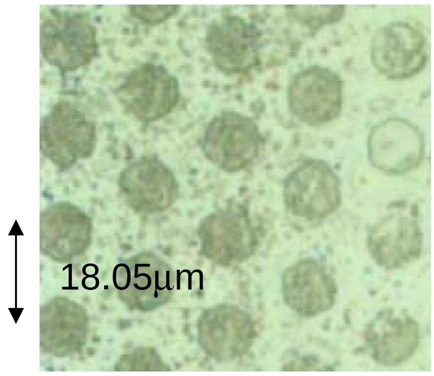

Figure 22. Two dimensional structure close up revealed by etching in HF.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

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

In 2003 the coordinator, NPL, made final measurements on the TKK lamps and the lamps were returned to TKK. Draft A was circulated in December 2004. Draft B is expected in 2005.

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

Draft A was circulated to participants in spring 2003. Draft B is expected in 2005.

CCPR-K2.b International comparison of spectral responsivity in the visible region

The contents of Draft A were discussed in 2003. Final report was published in 2004 [R Goebel et al 2004 *Metrologia* **41** 02004]. The results of TKK are good.

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

TKK measurements were completed in 2004.

CCPR-K3.b.2 Bilateral Comparison of Illuminance Responsivity Scales between the KRISS (Korea) and the TKK (Finland)

Final report was published in 2004 [E Ikonen and J Hovila 2004 *Metrologia* **41** 02003]. TKK acted as the coordinator.

CCPR-K5 International 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.

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

Measurements completed. No progress in 2003 – 2004.

CCPR-S2 International comparison of aperture area measurements

Measurements completed. No progress in 2003 – 2004. Draft A is expected in 2005.

Bilateral comparison of ultraviolet filter radiometers with NIST

In this project, TKK and NIST characterize spectral irradiance responsivities of ultraviolet filter radiometers and the results are compared. In 2003, B. Carol Johnson of NIST visited TKK and all comparison measurements were conducted. The results were in good agreement in the 365 nm wavelength region but deviate in the 250 nm region. The reasons for the deviation are known and studies are being carried out to calculate the corrections needed. In 2004, NIST remeasured the filter radiometer UVFR-4. TKK finished the slit scattering function measurements of the monochromator

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 2004 the final report was accepted for publication [John C. Travis *et al*, Journal of Physical and Chemical Reference Data (in press)]. TKK results indicate good agreement with the consensus average.

EUROMET 666 Intercomparison of Chromatic Dispersion Reference Fibres

The aim of this project is to perform an intercomparison of chromatic dispersion measurements on the most commonly used types of reference fibers (standard, dispersion shifted and non-zero dispersion shifted). In 2003, TKK completed their measurements. Draft A was circulated in 2004.

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

In this one-year project funded by NORDTEST, TKK, SP and DFM developed calibration facilities for fiber optic power in the range 1 – 200 mW. The inter-comparison was arranged at TKK in 2003. The preliminary results indicate good agreement (~1%) of the new realizations. This value is well within uncertainties of the measurements. In 2004, the final report was submitted for publication.

Bilateral comparison of spectral irradiance with METAS

Results of the comparison measurements of two lamps are ready. The deviations between the results are within uncertainties in the wavelength region 290 – 900 nm.

Bilateral comparison of spectral responsivity with METAS

Two trap detectors were measured by TKK and METAS indirectly against cryogenic radiometers at three visible laser wavelengths. Results with one detector (deviations between -0.06% and +0.035%) are within uncertainties. One result with the other detector deviates more than the uncertainties, most likely due to a dust problem.

Bilateral comparison of spectral diffuse reflectance with SPRING Singapore

Measurements at SPRING were completed in 2004. Return measurements at TKK need to be done.

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.

Bilateral comparison of luminous intensity with SP

The luminous intensity scales of TKK and SP were compared in 2003. The results indicate good agreement between the realizations.

Improving the accuracy of ultraviolet radiation measurement

In this project funded by the SMT-programme of the EU, novel filter radiometer techniques developed by TKK were used to compare various ultraviolet calibration facilities in Finland (TKK), France (BNM), and UK (NPL). In 2003, the results were published in Metrologia [P. Kärhä, N. J. Harrison, S. Nevas, W. S. Hartree and I. Abu-Kassem, *Intercomparison of characterization techniques of filter radiometers in the ultraviolet region*, Metrologia 40 (2003) S50-S54]

Bilateral comparison of ultraviolet filter radiometers with BNM-INM

In this project, TKK and BNM-INM characterize spectral irradiance responsivities of ultraviolet filter radiometers and the results are compared. In 2003, TKK conducted their first set of measurements and the filter radiometer was shipped to France. BNM-INM completed their measurements in 2004 and returned the filter radiometer to TKK.

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 2004 preparations for the 6th workshop, in Davos October 2005, were started.

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

XXXIII Estonian Physics Days, Tartu, Estonia, February 14-15, 2003, *Mart Noorma*

XXXVII Annual Conference of the Finnish Physical Society, Helsinki, Finland, March 20 – 22, 2003; *Mikko Lehtonen, Tuomo Ritari, Thomas Lindvall, Mika Koskenvuori, Kaj Nyholm, Pekka Rantakari, Ossi Kimmelma*

EUROMET Photometry and Radiometry Technical Committee meeting, Thessaloniki, Greece, 3-4 April 2003; *Erkki Ikonen*

EGS-AGU-EUG Joint Assembly 2003, Nice, France, April 6 – 9, 2003; *Petri Kärhä*

CREW Workshop & 182. PTB Seminar on Wavelength References for Optical Telecommunications, Braunschweig, Germany, April 10 – 11, 2003, *Jesse Tuominen*

CCPR Working Group on Key Comparisons meeting, BIPM, Paris, 15 June 2003; *Erkki Ikonen*

CCPR Working Group on UV Radiometry meeting, BIPM, Paris, 16 June 2003; *Erkki Ikonen (Chairman)*

CCPR meeting, BIPM, Paris, 17-19 June 2003; *Erkki Ikonen*

Northern Optics 2003, Otaniemi, Espoo, June 16 – 18, 2003; *Petri Kärhä, Hanne Ludvigsen, Ilkka Tittonen, Goëry Genty, Thomas Lindvall, Ossi Hahtela, Tuomo Ritari, Mart Noorma, Saulius Nevas, Tapio Niemi, Jouni Envall, Ossi Kimmelma, Tomasz Jankowski, Miika Heiliö, Mikko Merimaa, Kaj Nyholm, Markku Vainio, Scott Buchter*

ICO Topical Meeting on Polarization Optics, Polvijärvi, June 30 - July 3, 2003; *Ossi Kimmelma, Ossi Hahtela, Miika Heiliö, Markku Vainio*

Eurosensors XVII, Guimares, Portugal, September 21-24, 2003; *Mika Koskenvuori, Pekka Rantakari, Juha Väisäsvaara*

CLEO Europe / EQEC 2003, Munich, Germany, June 22 – 27, 2003; *Thomas Lindvall, Mikko Lehtonen, Tapio Niemi*

ICTON/ESPC, Warsaw, Poland, June 29-July 3, 2003; *H. Ludvigsen*

LEOS Summer Topical Meeting 2003, Vancouver, Canada, July 14-16, 2003; *G. Genty*

ECOC 2003, Rimini, Italy, September 21-25, 2003; *H. Ludvigsen*

Quantum Optics, EuroConference on Cavity QED and Quantum Fluctuations: From Fundamental Concepts to Nano-Technology, Granada, Spain, September 27 – October 2, 2003; *Thomas Lindvall*

Optical Systems Design 2003, organized by SPIE, Saint-Etienne, France, September 29 - October 3, 2003, *Saulius Nevas*

NKT Innovation, Birkerød, Denmark, November 17-19, 2003; *H. Ludvigsen, S.C. Buchter*

COST P11 meeting, Brussels, Belgium, November 24, 2003; *H. Ludvigsen*

Estonian Physics Days 2004, Tartu, Estonia, February 13 - 14, 2004, *Mart Noorma*

N-MERA Workshop (Photometry and Radiometry), Borås, Sweden, March 9 – 10, 2004; *Erkki Ikonen*

N-MERA Seminar, Helsinki, Finland, March 31, 2004; *Erkki Ikonen*

NOG – 2004, Annual Conference of the Nordic Ozone Group, Helsinki, April 14 – 15, 2004; *Petri Kärhä (chairman in one session), Jouni Envall*

EUROMET Technical Committee meeting (Photometry and Radiometry), Turin, Italy, April 22 – 23, 2004; *Erkki Ikonen*

CCPR Working Group on Ultraviolet Radiation Measurements, Gaithersburg, USA, May 10, 2004; *Erkki Ikonen (Chairman)*

CCPR Working Group on Calibration and Measurement Capabilities, Gaithersburg, USA, May 10, 2004; *Erkki Ikonen*

CCPR Working Group on Key Comparisons, Gaithersburg, USA, May 11 –12, 2004; *Erkki Ikonen*

CIE Expert Symposium on LED Light Sources, Tokyo, Japan, June 7 – 8, 2004; *Erkki Ikonen*

CIE Division 2 Technical Committee Meetings and General Meeting, Tokyo, Japan, June 9 – 11, 2004; *Erkki Ikonen*

9th International Symposium on Temperature and Thermal Measurements in Industry and Science (TEMPMEKO 2004) Cavtat, Croatia, June 21–26, 2004 *Mart Noorma*

Ninth Topical Meeting on Optical Interference Coatings (OIC 2004), Loews Ventana Canyon Resort & Spa, Tucson, Arizona, June 27 - July 2, 2004, *Saulius Nevas*

Finnish optics Days 2004, Turku, May 6-7, 2004, *Jari Hovila, Mikko Merimaa, Jouni Envall, Antti Lamminpää, Ville Ahtee, Kaj Nyholm, Markku Vainio, Mart Noorma, Ilkka Tittonen, Miika Heiliö, Ossi Kimmelma*

XXXVIII Annual Confrence of the Finnish Physical Society, Oulu, March 18-20, 2004, *Mikko Merimaa, Ilkka Tittonen, Ossi Kimmelma, Pekka Rantakari, Mika Koskenvuori*

XIX International Conference on Atomic Physics, Rio de Janeiro, Brazil, July 25-30, 2004, *Mikko Merimaa, Thomas Lindvall*

Young Atom Opticians Conference, Innsbruck, Austria, March 13-17, 2004, *Thomas Lindvall*

Eurosensors XVIII, Rome, Italy, September 12-15, 2004, *Mika Koskenvuori, Pekka Rantakari*

6.4 Visits by the Laboratory Personnel

Erkki Ikonen, Hellenic Institute of Metrology, Thessaloniki, Greece, 4 April 2003.

Thomas Lindvall, Sektion Physik der Ludwig-Maximilians-Universität München, June 26, 2003.

Thomas Lindvall, Institute for Experimental Physics, Innsbruck University, June 27-28, 2003.

Mikko Merimaa and *Kaj Nyholm*, Frequency Comb Workshop, BIPM, France, March 13-14, 2003.

Erkki Ikonen, NMIJ/AIST, Tsukuba, Japan, 24 October 2003.

Mikko Merimaa and *Kaj Nyholm*, BIPM, France, November 24-28, 2003.

Saulius Nevas, Thales Angénieux, Saint-Etienne, France, October 3, 2003.

Erkki Ikonen, Physikalisch-Meteorologisches Observatorium Davos, Davos, Switzerland, 4 – 5 February, 2004.

Erkki Ikonen, Technische Universität München, Munich, Germany, 6 – 8 February, 2004.

Erkki Ikonen, Istituto Elettrotecnico Nazionale Galileo Ferraris (IEN), Turin, Italy, 23 April, 2004.

Erkki Ikonen, Stanford Synchrotron Radiation Laboratory, Stanford, USA, 5 – 8 May, 2004.

Erkki Ikonen, Korea Research Institute of Standards and Science, Taejon, Korea, 1 – 6 June, 2004.

Saulius Nevas, The Optical Sciences Center of the University of Arizona, Tucson, July 2, 2004.

Erkki Ikonen, SPRING Singapore, Singapore, 4 – 8 October, 2004.

Petri Kärhä, Metrosert, Tallinn, October 18 – 22, 2004.

6.5 Research Work Abroad

Tapio Niemi, Technical University of Denmark, Copenhagen, Denmark, 1 August – 31 December, 2003.

Tuomo Ritari, Technical University of Denmark, Copenhagen, Denmark, 15 September – 15 November, 2003.

Erkki Ikonen, SPring-8 and RIKEN Harima Institute, Hyogo, Japan, 1 October – 30 November, 2003.

Erkki Ikonen, The Swiss Federal Office of Metrology and Accreditation (METAS), Bern, and Eidgenössische Technische Hochschule Zürich (ETH), Zurich, Switzerland, January 19 – February 18.

6.6 Guest Researchers

Giuliano Granata, University of Rome “La Sapienza,” Italy, August 4 - September 15.

6.7 Visits to the Laboratory

Saba Mylvaganam, Micro Tech, Norway, 3 March 2003.

Dr. Toomas Kubarsepp, Metrosert Ltd, Estonia, 12 March and 8 May 2003.

Mick McLean, Technical Investment Services Ltd, UK, 1 April 2003.

Susan Jones, Scientific Generics Ltd, UK, 1 April, 2003.

Dr. Carol B. Johnson, National Institute of Standards and Technology, USA, May 6 – 9, 2003.

Anne Andersson, SP, Sweden, June 16 – 18, 2003.

Prof. Theodor W. Hänsch, Max-Planck-Institut für Quantenoptik and Sektion Physik der Ludwig-Maximilians-Universität, Germany, June 17, 2003.

Dr. Seung Nam Park, Korea Research Institute of Standards and Science, Republic of Korea, September 14 – 20, 2003.

Dr. Jan C. Petersen (DFM, Denmark) and Anne Andersson (SP, Sweden) October 6– 8, 2003.

Dr. Toomas Kübarsepp, Metrosert Ltd., Tartu, Estonia, January 21, April 1, 2004.

Mr. Leif Liedquist, SP, Sweden, April 13, 2004.

Prof. David Richardson, ORC, University of Southampton, UK, March 12, 2004.

Prof. Mackillo Kira, Philipps University in Marburg, Germany, April 23, 2004.

Ms. Lilli Sooväli, Tartu University, Institute of Chemical Physics, May 31 – June 4, 2004.

Prof. Luca Podesta, University of Rome "La Sapienza," Italy, June 24, 2004.

Dr. Subash Chander Jain, Govt College for Men, Chandigarh, India, June 29, 2004.

Mr. Meelis-Mait Sildoja, Tartu University, Tartu, Estonia, August 25, 2004.

Dr. Makina Yabashi, SPring-8 and Japan Synchrotron Radiation Institute, Mikazuki, Japan, September 2 – 9, 2004.

Prof. Tilman Pfau, Universität Stuttgart, October 8, 2004.

Dr. Detlev Ristau, Laser Zentrum Hannover, Hannover, Germany, October 14 – 15, 2004.

Dr. Toomas Kübarsepp and Mr. Andrei Prokotilov, Metrosert Ltd., Tartu and Tallinn, Estonia, October 20, 2004.

Prof. P.H.J. Schellekens, Eindhoven University of Technology, December 16 – 17, 2004.

7 PUBLICATIONS

7.1 Articles in International Journals

J. Tuominen, T. Niemi, and H. Ludvigsen, "Wavelength reference for optical communications based on a temperature-tunable silicon etalon," *Rev. Sci. Instrum,* **74**, 3620-3623 (2003).

M. Lehtonen, G. Genty, M. Kaivola, and H. Ludvigsen, "Supercontinuum generation in a highly birefringent microstructured fiber," *Appl. Phys. Lett.* **82**, 2197-2199 (2003).

T. Ritari, T. Niemi, M. Wegmuller, N. Gisin, J.R. Folkenberg, A. Pettersson, and H. Ludvigsen, "Polarization-mode dispersion of large mode-area photonic crystal fibers," *Opt. Commun.* **226**, 233-239 (2003).

M. Noorma, P. Toivanen, F. Manoocheri, and E. Ikonen, "Characterization of filter radiometers with wavelength-tunable laser source," *Metrologia* **40**, 220-223 (2003).

P. Kärhä, N. J. Harrison, S. Nevas, W. S. Hartree, and I. Abu-Kassem, "Intercomparison of characterization techniques of filter radiometers in the ultraviolet region," *Metrologia* **40**, S50-S54 (2003).

S. Nevas, F. Manoocheri, and E. Ikonen, "Determination of thin-film parameters from high accuracy measurements of spectral regular transmittance," *Metrologia* **40**, S200-S203 (2003).

P. Kärhä, L. Ylianttila, T. Koskela, K. Jokela, and E. Ikonen, "A portable field calibrator for solar ultraviolet measurements," *Metrologia* **40**, S17-S20 (2003).

L. Ylianttila, K. Jokela, and P. Kärhä, "Ageing of DXW-lamps," *Metrologia* **40**, S120-S123 (2003).

M. Merimaa, T. Lindvall, I. Tittonen, and E. Ikonen, “All-optical atomic clock based on coherent population trapping in ^{85}Rb,” *J. Opt. Soc. Am. B* **20**, 273 (2003).

M. Vainio, M. Merimaa, Y. Sidorin, M. Kuittinen, and E. Ikonen, “Miniaturized transmission grating diode laser at 1.55 μm with a 120 nm tuning range,” *Photonics Technology Letters* **15**, 990 (2003).

K. Nyholm, M. Merimaa, T. Ahola, and A. Lassila, “Frequency stabilization of a diode-pumped Nd:YAG laser at 532 nm to iodine by using third-harmonic technique,” *IEEE Trans. Instrum. Meas.* **52**, 284 (2003).

S. Picard, L. Robertsson, L.-S. Ma, Y. Millerioux, P. Juncar, J.-P. Wallerand, P. Balling, P. Kren, K. Nyholm, M. Merimaa, T. E. Ahola, and F.-L. Hong, “Results from international comparisons at the BIPM providing a world-wide reference network of 127I2 stabilized frequency-doubled Nd:YAG lasers,” *IEEE Trans. Instrum. Meas.* **52**, 236 (2003).

S. Picard, L. Robertsson, L.-S. Ma, K. Nyholm, M. Merimaa, T. E. Ahola, P. Balling, P. Kren, J.-P. Wallerand, “A comparison of 127I2-stabilized frequency-doubled Nd:YAG lasers at the BIPM,” *Applied Optics* **48**, 1019 (2003).

J. Hovila, P. Kärhä, L. Mansner, and E. Ikonen, “Evaluation of calibration methods of a photometer measuring maritime light-emitting diode buoy lanterns,” *Opt. Eng.* **43**, 170-173 (2004).

S. Nevas, F. Manoocheri, E. Ikonen, A. Tikhonravov, M. Kokarev, and M. Trubetskov, “Optical metrology of thin films using high-accuracy spectrophotometric measurements with oblique angles of incidence,” in *Advances in Optical Thin Films*, C. Amra, N. Kaiser, H. A. Macleod, eds., *Proc. SPIE* **5250**, 234-242 (2004).

A. Haapalinna, S. Nevas, and D. Pähler, “Rotational grinding of silicon wafers – – sub-surface damage inspection,” *Materials Sc. and Eng. B* **107**, 321-331 (2004).

S. Nevas, E. Ikonen, P. Kärhä, and T. Kübarsepp, “Effect of correlations in fitting spectral irradiance data,” *Metrologia* **41**, 246-250 (2004).

J. Envall, P. Kärhä, and E. Ikonen, “Measurements of fibre optic power using photodiodes with and without an integrating sphere,” *Metrologia* **41**, 353-358 (2004).

E. Ikonen, "Excess Coincidences of Spontaneous and Stimulated X Rays," *J. Opt. Soc. Am. B* **21**, 1403-1407 (2004).

E. Ikonen and J. Hovila, "Final Report of CCPR-K3.b.2-2004: Bilateral Comparison of Illuminance Responsivity Scales between the KRISS (Korea) and the TKK (Finland)," *Metrologia* **41** Tech. Suppl. 02003 (2004).

S. Nevas, F. Manoocheri, and E. Ikonen, "Gonioreflectometer for measuring spectral diffuse reflectance", *Applied Optics* **43**, 6391-6399 (2004).

J. Hovila, P. Toivanen and E. Ikonen, "Realization of the unit of luminous flux at the TKK using the absolute integrating-sphere method," *Metrologia* **41**, 407-413 (2004).

J. Walewski, K. Nyholm, A. Dreizler, and M. Aldén, "Polarization spectroscopy applied to the detection of trace constituents in sooting combustion", *Appl. Spectros.* **58**, 238–242 (2004).

T. Ritari, M. Wegmuller, M. Legré, N. Gisin, J.R. Folkenberg, M.D. Nielsen, and H. Ludvigsen, "Experimental study of polarization properties of highly birefringent photonic crystal fibers", *Opt. Express* **12**, 5931 (2004).

G. Genty, M. Lehtonen, and H. Ludvigsen, "Effect of cross-phase modulation on supercontinuum generated in microstructured fibers with sub-30 fs pulses", *Opt. Express* **12**, 4614 (2004).

T. Ritari, J. Tuominen, J.C. Petersen, T. Sørensen, T.P. Hansen, H. Simonsen, and H. Ludvigsen, "Gas sensing using air-guiding photonic bandgap fibers", *Opt. Express* **12**, 4080 (2004).

G. Genty, M. Lehtonen, M. Kaivola, and H. Ludvigsen, "Enhanced bandwidth of supercontinuum generated in microstructured fibers", *Opt. Express* **12**, 3471 (2004).

G. Genty, M. Kaivola, K.P. Hansen, and H. Ludvigsen, "Measurement of anomalous dispersion in microstructured fibers using spectral modulation", *Opt. Express* **12**, 929 (2004).

J. Tuominen, M. Söderlund, T. Niemi, M. Leppihalme, and H. Ludvigsen, "Device for simultaneous monitoring of the channel wavelengths and power levels in a DWDM system", *J. Opt. Networking* **3**, 501 (2004).

T. von Lerber, H. Ludvigsen, and A. Romann, "Resonator based measurement technique for quantification of minute birefringence", *Opt. Express* **12**, 1363-1371 (2004).

A. Shevchenko, A. Jaakkola, T. Lindvall, I. Tittonen, and M. Kaivola, "Method for obtaining high phase space density in a surface-mounted atom trap", *Appl. Phys. B* **79**, 367 (2004).

A. Shevchenko, T. Lindvall, I. Tittonen, and M. Kaivola, "Microscopic electro-optical atom trap on an evanescent-wave mirror", *Eur. Phys. J. D* **28**, 273 (2004).

O. Hahtela, K. Nera, and I. Tittonen, "Position measurement of a cavity mirror using polarization spectroscopy", *J. Opt. A: Pure Appl. Opt.* **6**, S115-S120 (2004).

M. Koskenvuori, T. Mattila, A. Häärä, J. Kiihamäki, A. Oja, H. Seppä. and I. Tittonen, "Long-term stability of single-crystal silicon microresonators", *Sensors and Actuators A: Physical* **115**, 23 (2004).

T. Mattila, V. Kaajakari, J. Kiihamäki, A. Oja, H. Kattelus, H. Seppä, M. Koskenvuori, P. Rantakari, and I. Tittonen, "Silicon Micromechanical Resonators for RF-Applications", *Physica Scripta* **T114**, 181 (2004).

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

G. Genty, M. Lehtonen, and H. Ludvigsen, "Route to broadband blue light generation in microstructured fibers", *Opt. Lett.* (in press).

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).

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* (in press).

7.2 International Conference Presentations

M. Koskenvuori, P. Rantakari, J- Väisäsvaara, I. Tittonen, T. Mattila, A. Oja, V. Kaajakari, H. Seppä, H. Kattelus, and J. Kiihamäki: "Active Post-processing method to increase the electro-mechanical coupling in microresonators," in *Book of abstracts, Eurosensors VXII*, Guimarães, Portugal, September, 2003, pp. 675-676.

V. Kaajakari, T. Mattila, A. Oja, H. Kattelus, J. Kiihamäki, M. Koskenvuori, P. Rantakari, I. Tittonen, and H. Seppä: "Square-Extensional Mode Single-Crystal Silicon Micromechanical Resonator," in Proceedings of *Transducers'03*, Boston, June, 2003, pp. 951-954.

P. Kärhä, L. Ylianttila, K. Jokela, and E. Ikonen, "Improvements in dissemination of spectral irradiance calibrations," in *Geophysical Research Abstracts* **5**, Abstract No. EAE03-A-09413, Nice, France (2003).

J. Tuominen, T. Niemi, and H. Ludvigsen, "Wavelength reference based on a silicon etalon," in Proceedings of *CREW Workshop & 182. PTB Seminar*, in Braunschweig, Germany, 10-11 April 2003 (invited talk).

G. Genty, M. Lehtonen, M. Kaivola, H. Ludvigsen, and J. Broeng, "Dispersion measurement using spectral modulation in microstructured fibers," in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper O3.2.

M. Vainio, M. Merimaa, Y. Sidorin, M. Kuittinen, and E. Ikonen, "Widely tunable transmission grating laser for telecommunication applications," in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper O2.1.

T. Jankowski, P. Kärhä, M. Noorma, T. Weckström, L. Uusipaikka and E. Ikonen, "Detector based method for radiation temperature measurements," in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P036.

M. Noorma, P. Kärhä and E. Ikonen, “Instabilities in the areas of precision apertures,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P039.

T. Ritari, T. Niemi, J. R. Folkenberg, and H. Ludvigsen, “Influence of temperature and bending on the polarization properties of microstructured fibers,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P007.

J. Lindberg, T. Setälä, M. Kaivola, G. Genty, and H. Ludvigsen, “Localized function method for modeling microstructured optical fibers,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P054.

S. Nevas, F. Manoocheri, E. Ikonen, A. Tikhonravov, M. Kokarev, and M. Trubetskov, “Optical characterization of thin films using high-accuracy oblique-incidence transmittance measurements,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P022.

J. Envall, P. Kärhä and E. Ikonen, “Development of spectral comparator facility to calibrate ultraviolet detectors with low sensitivity,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P042.

A. Jaakkola, A. Hakola, M. Kaivola, A. Shevchenko, T. Lindvall, and I. Tittonen, “Transparent magnetic microstructures for integrated atom optics,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P041.

T. Lindvall, L. Niinikoski, M. Heiliö, M. Merimaa, A. Shevchenko, M. Kaivola, and I. Tittonen, “Loading technique for surface-mounted atom traps based on a gravito-optical trap,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P068.

A. Shevchenko, S. Buchter, O. Kimmelma, T. Lindvall, I. Tittonen, and M. Kaivola, “Rotating-beam atom trap using a 2D electro-optic scanner,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P073.

M. Merimaa, V. Ahtee, M. Vainio, and K. Nyholm, “Development of a frequency comb generator for precision optical frequency measurements,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P044.

S. Nevas, F. Manoocheri, and E. Ikonen, “Gonioreflectometer for measuring spectral diffuse reflectance,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper PO21.

O. Kimmelma, S. Buchter and I. Tittonen, “Laser frequency doubling using a periodically poled KTP crystal,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P058.

S. Buchter, O. Kimmelma, M. Kaivola and I. Tittonen, “Nonlinear photonic crystals fabricated with electric field poling in lithium niobate,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P071.

S. Buchter, A. Shevchenko, O. Kimmelma, and M. Kaivola, “Two dimensional integrated electro-optic scanner using tandem lithium niobate single crystals,” in Proceedings of *Northern Optics 2003*, in Espoo, Finland, paper P072.

O. Hahtela, K. Nera and I. Tittonen, “Optical interferometry on a mechanical silicon oscillator,” *ICO Topical Meeting on Polarization Optics*, in Polvijärvi, Finland, June 30-July 3, 2003, pp. 166-167.

M. Lehtonen, G. Genty, M. Kaivola, and H. Ludvigsen, “Absorption measurements of doped optical fibers using supercontinuum radiation from a microstructured fiber,” in *Conference on Laser and Electro-Optics (CLEO Europe'03)*, in Munich, Germany, 2003, paper CD3-4-THU.

T. Niemi, G. Genty, M. Lehtonen, and H. Ludvigsen, “Infrared supercontinuum generated in short tapered fiber by pumping around the second zero-dispersion wavelength,” in *Conference on Laser and Electro-Optics (CLEO Europe'03)*, in Munich, Germany, 2003, paper CD3-2-THU.

A. Shevchenko, A. Jaakkola, A. Hakola, M. Kaivola, T. Lindvall, and I. Tittonen, “Microscopic atom traps on an evanescent-wave mirror”, in *Conference on Laser and Electro-Optics (CLEO Europe'03)*, in Munich, Germany, 2003, paper EG5W.

S. Nevas, F. Manoocheri, E. Ikonen, A. Tikhonravov, M. Kokarev, and M. Trubetskov, “Optical metrology of thin films using high-accuracy spectrophotometric measurements with oblique angles of incidence,” in Technical program of *Optical Systems Design 2003*, SPIE, in Saint-Etienne, France, 2003, pp. 5250-30, paper 25.

H. Ludvigsen, G. Genty, M. Lehtonen, T. Ritari, T. Niemi, and M. Kaivola, “Birefringent microstructured fibers: properties and applications,” in Proceedings of *5th International Conference on Transparent Optical Networks/2nd European Symposium on Photonic Crystals (ICTON/ESPC 2003)*, in Warsaw, Poland, paper Tu.C.1, pp. 201-205 (invited talk).

G. Genty, M. Lehtonen, M. Kaivola, and H. Ludvigsen, “Supercontinuum generation under higher-order mode excitation in a microstructured fiber,” in the Proceedings of *LEOS Summer Topical Meeting 2003*, in Vancouver, Canada, 2003, paper TuA4.3.

M. Söderlund, J. Tuominen, T. Niemi, H. Ludvigsen, and M. Leppihalme, “Device concept for monitoring DWDM channels,” in Proceedings of *29th European Conference on Optical Communication and 14th International Conference on Integrated Optics and Optical Fibre Communication (ECOC-IOOC’03)*, in Rimini, Italy, paper We3.2.2.

S. Nevas, A. Lamminpää, F. Manoocheri, and E. Ikonen, “Characterization of thin films based on reflectance and transmittance measurements at oblique angles of incidence,” presented at the *Ninth Topical Meeting on Optical Interference Coatings* (*OIC 2004*), Loews Ventana Canyon Resort & Spa, Tucson, Arizona, June 27 - July 2, WB10.

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T. Ritari, J. Tuominen, J.C. Petersen, T.P. Hansen, and H. Ludvigsen, “Miniature wavelength references based on gas-filled photonic bandgap fibers”, in Proceedings of *the 30th European Conference on Optical Communication (ECOC '04),* in Stockholm, Sweden, 2004, paper Mo3.3.2.

M. Wegmuller, M. Legré, N. Gisin, T. Ritari, H. Ludvigsen, J.R. Folkenberg and K.P. Hansen, “Detailed polarization analysis of birefringent photonic crystal fibers”, in Proceedings of *EPS-QEOD Europhoton Conference - Special Symposium on "Photonic Crystal Fibers and Waveguides”*, in Lausanne, Switzerland, 2004, paper SyA3.

M. Wegmuller, M. Legré, N. Gisin, T. Ritari, H. Ludvigsen, J.R. Folkenberg and K.P. Hansen, “Experimental investigation of wavelength and temperature dependence of phase and group birefringence in photonic crystal fibers”, in Proceedings of *4th European Symposium on Photonic Crystals ESPC 2004/6th International Conference on Transparent Optical Networks ICTON 2004*, in Wroclaw, Poland, 2004, paper We.A2.7.

T. Ritari, H. Ludvigsen, J.C. Petersen, T. Sørensen, A. Bjarklev, and T.P. Hansen, “Gas sensing using air-guiding photonic bandgap fibers”, in Proceedings of *Conference on Lasers & Electro-Optics (CLEO'04)*, in San Francisco, CA, paper CWM1.

S.C. Buchter, M. Kaivola, H. Ludvigsen, and K.P. Hansen, “Miniature supercontinuum laser sources”, in *Conference on Lasers & Electro-Optics (CLEO'04)*, in San Francisco, CA, 2004, paper CTuP58.

S C. Buchter, M. Kaivola, and H. Ludvigsen, “Compact, spectrally smooth, nanosecond infrared continuum source with 700 nm bandwidth”, in *Optical Fiber Communication Conference (OFC 04),* in Los Angeles, CA, US, 2004, paper ThA7.

O. Hahtela, K. Nera, and I. Tittonen, “Position measurement of a moving mirror using polarization spectroscopy”, in Proceedings of *ODIMAP IV, 4th Topical Meeting on Optoelectronic Distance / Displacement Measurements and Applications,* in Oulu, Finland, 2004, p. 322.

A. T. Alastalo, M. Koskenvuori, H. Seppä and J. Dekker, “A Micromechanical Resonating RF Mixer”, *in Prodeecings of 34th European Microwave Conference*, in Amsterdam, The Netherlands (2004).

M. Koskenvuori, T. Mattila, A. Häärä, J. Kiihamäki, P. Rantakari, A. Oja, H. Seppä and I. Tittonen, “Major improvement of long-term stability of SOI-microresonators by encapsulation”, *in Technical Digest of Eurosensors XVIII,* in Rome, Italy (2004) pp. 550-551.

7.3 National Conference Presentations

M. Noorma, P. Kärhä, T. Jankowski, L. Uusipaikka, T. Weckström and E. Ikonen, “Absolute method for radiation temperature measurements,” Estonian Physics Days, Tartu, Estonia, February 14-15, 2003, Annual of *EPS 2002* pp. 68-69.

M. Noorma, P. Kärhä, and E. Ikonen, “Systematic change in areas of the aperture used in optical radiometry,” Estonian Physics Days, Tartu, Estonia, February 14-15, 2003, Annual of *EPS 2002* pp. 74-75.

M. Koskenvuori, P. Rantakari, J- Väisäsvaara, I. Tittonen, T. Mattila, A. Oja, V. Kaajakari, H. Seppä, H. Kattelus, and J. Kiihamäki: “Microresonators with active post-processing gap adjustment,” in *Proceedings of the XXXVII Annual Conference of the Finnish Physical Society*, Helsinki, Finland, March 20 – 22, 2003, Helsinki 2003, paper 07.10.

M. Lehtonen, G. Genty, M. Kaivola, and H. Ludvigsen, “Absorption measurements of doped fibers using supercontinuum radiation,” in *Proceedings of the XXXVII Annual Conference of the Finnish Physical Society*, Helsinki, Finland, March 20 – 22, 2003, paper 363.

T. Ritari, T. Niemi, J.R. Folkenberg, and H. Ludvigsen, “Polarization-mode dispersion of photonic crystal fibers,” in *Proceedings of the XXXVII Annual Conference of the Finnish Physical Society,* Helsinki, Finland, March 20 – 22, 2003, paper 13.7.

T. Niemi, J. Tuominen, M. Lehtonen, G. Genty, and H. Ludvigsen, “Tapered fibers for supercontinuum generation,” in *Proceedings of the XXXVII Annual Conference of the Finnish Physical Society,* Helsinki, Finland, March 20 – 22, 2003, paper 13.10.

J. Lindberg, T. Setälä, M. Kaivola, G. Genty, and H. Ludvigsen, “Vector modal method for modelling microstructured optical fibers,” in *Proceedings of XXXVII Annual Conference of the Finnish Physical Society*, ISBN 952-10-0574-2, Helsinki 2003, paper 13.16.

A. Shevchenko, A. Jaakkola, A. Hakola, T. Lindvall, I. Tittonen, and M. Kaivola, “Novel technique for creating surface-mounted microscopic atom traps,” in *Proceedings of the XXXVII Annual Conference of the Finnish Physical Society*, ISBN 952-10-0574-2, Helsinki, Finland, March 20–22, 2003. p. 375.

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