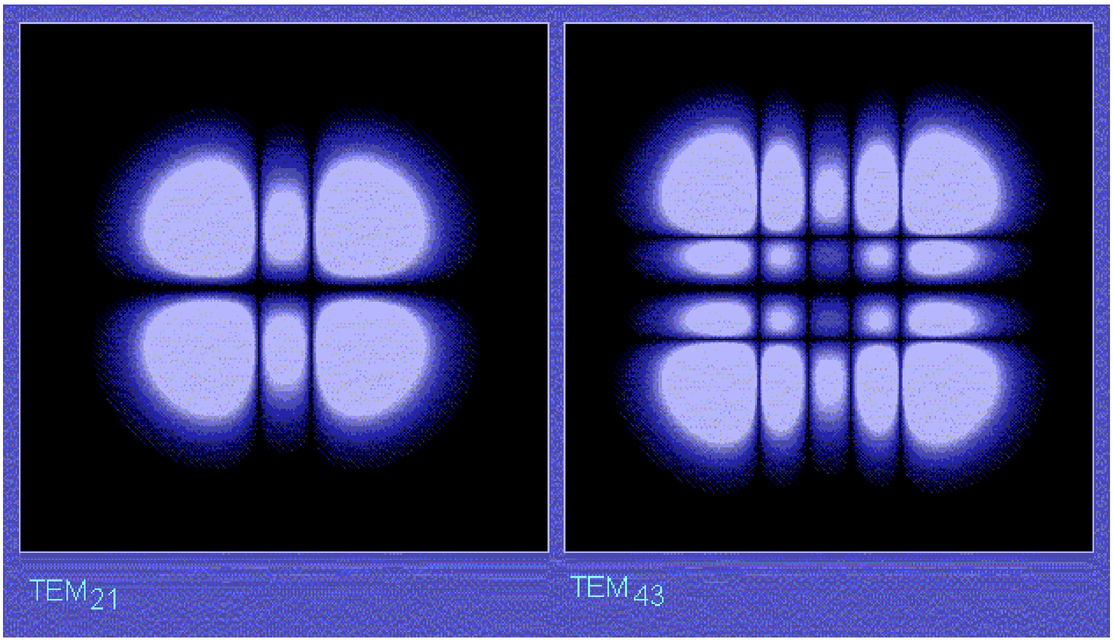
Helsinki University of Technology Department of Electrical and Communications Engineering
Metrology Research Institute Report 16/2000
Espoo 2000

ANNUAL REPORT 1999



TEKNILLINEN KORKEAKOULU
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HELSINKI UNIVERSITY OF TECHNOLOGY
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Helsinki University of Technology
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Editor Ilkka Tittonen

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Department of Electrical and Communications Engineering

Metrology Research Institute

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CONTENTS

1 INTRODUCTION

The Metrology Research Institute has a thirty-year background in metrology starting with applications in electrical measurement technology. Today, the Institute is the *National Standards Laboratory* for optical quantities. It carries out research and development work related to measurement of light, characterization of optical properties of materials, and to the use of lasers for measurement applications. A significant number of projects are related to optical communications and to silicon technology.

In 1999 the Metrology Research Institute continued expanding the activities especially in the fields of fibre optics applicable to optical telecommunications, diode laser applications and microtechnologies. Many young research assistants started their career during the year 1999 in the laboratory.

The Institute is active in post-graduate education and is a partner in four *National Graduate Schools*; Electronics, Telecommunications and Automation (GETA), Modern Optics and Photonics, Electronic Materials and Manufacture Technology Techniques, and Silicon Technology and Microsystems.

The Institute is an active participant within the EU Research Programmes. Petri Kärhä became the work package manager in a new project *Improving the Accuracy of Ultraviolet Radiation Measurements.* A significant effort was put on this project in which high-accuracy filter radiometers are constructed for the spectral band of interest in solar UV measurements. Hanne Ludvigsen became the Finnish coordinator in the COST Action 265 on *Measurement Techniques for Active and Passive Fibres to support Future Telecommunications Standardisation*.

An international arrangement on mutual recognition of national measurement standards and of calibration and measurement certificates (MRA) was signed in October 1999. The technical content of the MRA is based on comparison measurements and all national metrology institutes have experienced the enormous growth in the number of planned and on-going comparisons. The MRA will lead to a public database that includes the mutually recognised measurement capabilities. The analysis of the measurement capabilities is on the responsibility of the regional metrology organisations. The Metrology Research Institute is presently holding the rapporteur position of the Photometry and Radiometry group of EUROMET (European collaboration in measurement standards) and has thus carried out a significant amount of work related to analysis of the measurement capabilities of the European national metrology institutes.

Erkki Ikonen

Staff of the Metrology Research Institute.

2 PERSONNEL

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3 TEACHING

3.1 COURSES

The following courses were offered by the Metrology Research Institute (Mittaustekniikan laboratorio) in 1999. Those marked by * are given biennally.

S-108.180 Electronic Measurements and Electromagnetic Compatibility
2 credits (Petri Kärhä, Esa Häkkinen, Hannu Talvitie)

S-108.181 Optics
2 credits (Erkki Ikonen)

S-108.183 Micromechanics
4 credits (Ilkka Tittonen and Sami Franssila)

S-108.184 Computer-based Measurements
2 credits (Kristian Lahti)

S-108.189 Project Work in Measurement Technology
2-5 credits (Pekka Wallin)

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)

S-108.901 Electrical Engineering Project
1-5 credits (Pekka Wallin)

S-108.903 Fourier Transforms in Measurements*
4 credits (Jyrki Kauppinen)

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 in Technology, D.Sc. (Tech.)

Martti Heinonen: National basis for traceability in humidity measurements

Opponent: Dr. Peter Huang, National Institute of Standards and Technology, NIST, USA

Toomas Kübarsepp: Optical radiometry using silicon photodetectors

Opponent: Professor Wolfgang Heering, University of Karlsruhe, Germany

3.2.2 Master of Science in Technology, M.Sc. (Tech.)

Anssi Ikonen: Development of a sensor for illuminance measurements of night sky

Ville Nurmiainen: Micromechanical earthquake sensor calibration and testing setup

Tommi Linna: Sensor for soil moisture content

Janne Simola: GSM short message in test and measurement applications

Tuomas Lamminmäki: Implementation of a high-Q RF-resonator by silicon micromechanics

José R. Casado Domínguez: An absolute frequency reference for WDM communication systems

4 MEASUREMENT SERVICE

The 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 is entitled to give official calibration certificates on the optical quantities listed in the following tables.

The demand for calibrations of the optical quantities is in continuous growth in Finland. During 1999, 37 calibration certificates were issued. There are also two accredited calibration laboratories in the field of optical quantities. The calibration services are mainly used by the Finnish industry and various research organisations.

The institute offers also other measurement services and consultation in the field of measurement technology. Various memberships in international organisations ensure that the laboratory can also influence e.g. international standardisation so that it takes into account the national needs.

4.1 FACILITIES

The Metrology Research Institute performs its calibration measurements under a strict quality system approved by MIKES. The uncertainties and the traceability of the quantities are guaranteed by the quality system that fulfils the requirements of standards EN45001 and ISO Guide 25.

4.1.1 Calibration of optical power meters

Optical power meters and coherent radiation sources can be calibrated against the reference equipment listed in Table 1. For the most precise optical power measurements, the cryogenic absolute radiometer is used. This device forms the basis for the traceability for most optical quantities. The use of the highest accuracy is rather limited in wavelength and signal level. A practical transfer standard for optical power is a trap detector, which is directly traceable to the cryogenic absolute radiometer. For higher power levels and extended wavelength range, a pyroelectric detector is used. In addition to the calibration of meters, spatial responsivity and linearity of the detectors can be characterised.

Table 1. Measurement ranges and uncertainties for optical power measurements.

Quantity	Measurement range	Wavelength range	Relative uncertainty (k=2)	Equipment
Optical power	0,1 - 0,5 mW	543,5 nm, 633 nm 457 nm…514 nm (several laser lines)	5×10^{-4}	Cryogenic radiometer
	10 nW - 1 mW	250 nm - 920 nm	0,1 % - 0,8 %	Trap detector
	10 µW - 10 W	250 nm - 16 µm	2 % - 10 %	Pyroelectric detector

4.1.2 Photometric calibrations

Photometric calibrations are based on a reference photometer, the calibration of which is traceable to the cryogenic radiometer. Using the reference photometer, units for illuminance, luminous intensity and luminance may be realised. Photometric calibrations are performed on a 4,5-m long optical bench enclosed in a light-tight enclosure. Stable photometric lamps and an integrating sphere source are used as light sources.

Table 2. Measurement ranges and uncertainties for the photometric calibrations.

Quantity	Measurement range	Relative uncertainty (k=2)
Luminous intensity	10 - 10 000 cd	0,3 %
Illuminance	10 - 2 000 lx	0,2 % - 0,5 %
Luminance	5 - 40 000 cd m^{-2}	0,8 %

4.1.3 Spectrophotometric calibrations

Spectrophotometric calibrations are carried out using a reference spectrometer facility that is based on a single grating monochromator. By changing the grating of the monochromator, a wide wavelength region from ultraviolet (250 nm) to near infrared (1700 nm) is covered. Spectral transmittance of filters up to 10 cm in diameter can be measured. By using a special accessory, measurements of spectral reflectance can be carried out. The spectral responsivity of photodetectors can also be calibrated with the reference spectrometer.

A commercial spectrophotometer (Perkin Elmer Lambda 900) is also being used as a transfer standard instrument for the measurements of regular spectral transmittance. The instrument provides transmittance calibrations of a range of optical components traceable to the reference spectrometer. The performance of the instrument has been tested by internal quality control and comparison measurements for the visible spectral range. In the near future, the instrument will provide an extension of the wavelength range of calibrations to 185-3300 nm.

Table 3. Measurement ranges and uncertainties for transmittance, reflectance and spectral responsivity measurements.

Quantity	Measurement range	Wavelength range	Relative uncertainty (*k*=2)
Transmittance	0,0005 - 1 0,0001 - 1 0,0005 - 1	250 - 380 nm 380 - 920 nm 920 - 1700 nm	0,1 % - 1 % 0,05 % - 0,5 % 0,1 % - 1 %
Spectral reflectance	0,05 - 1 0,01 - 1	250 - 380 nm 380 - 1000 nm	0,5 % - 5 % 0,3 %-3 %
Spectral responsivity	>0,01 A/W	250 - 380 nm 380 - 920 nm 920 - 1700 nm	1 % 0,5 % 4 %

4.1.4 Calibration of spectroradiometric quantities

Spectroradiometric calibrations are based on a filter radiometer very similar to the reference photometer used in photometric calibrations. This unique filter radiometer utilises 13 interference filters that cover a wide spectral range from near-UV to the near-IR. By measuring a lamp using all the filters, the spectral irradiance of the lamp may be obtained. Such characterised lamps can be used as standards of spectral irradiance when calibrating spectroradiometers. The spectrum may also be used to calculate the colour temperature and the colour co-ordinates of the lamp with high accuracy. When used in combination with the integrating sphere source used in luminance measurements, spectral radiance may be calibrated.

Table 4. Measurement ranges and uncertainties for spectroradiometric quantities.

Quantity	Measurement range	Wavelength range	Relative uncertainty (*k*=2)
Spectral irradiance	10 pW mm^{-2} nm^{-1} - 500 μW mm^{-2} nm^{-1}	290 - 380 nm 380 - 900 nm	1,1 % - 2,8 % 0,6 % - 1,1 %
Spectral radiance	5 μW m^{-2} sr^{-1} nm^{-1} - 6 W m^{-2} sr^{-1} nm^{-1}	290 - 900 nm	1,0 %

Colour co-ordinates (x, y)	0 - 1		0,1 %
Colour temperature	1 000 K - 3 500 K		0,15 %

4.1.5 Optical wavelength

Optical wavelength is an important quantity in many fields such as telecommunications. The laboratory has a purpose-built FFT-wavemeter that can be used for such calibrations. The traceability of the calibrations is obtained from MIKES that maintains the national standards of optical frequency in collaboration with the Metrology Research Institute.

Table 5. Measurement ranges and uncertainties for the optical wavelength measurements.

Quantity	Measurement range	Relative uncertainty (k=2)
Optical wavelength	400 nm - 1,55 µm	10^{-8}

5 RESEARCH PROJECTS

5.1 PHOTOMETRY AND RADIOMETRY

5.1.1 Absolute spectral irradiance measurements in UV-VIS-NIR

T. Kübarsepp, P. Kärhä, F. Manoocheri and S. Nevas

The detector-based realisation of spectral irradiance scale is in continuous development at our laboratory. In 1999, we have further improved the methods for absolute measurements of spectral irradiance of sources with continuous output spectrum in a wide wavelength region from 290-900 nm. In the measurements, we use a compact filter radiometer, which is constructed of a silicon-based trap detector, a precision aperture and a set of thirteen interchangeable band-pass filters. The construction allows all the components to be separately characterised which, in our laboratory conditions, yields accurate responsivity values of the complete radiometer.

The measurements of spectral irradiance have been extended to 290-nm wavelength by taking into use a new filter with the peak transmittance at 285 nm. The characterisation of the silicon trap detector is improved by implementing a new physically meaningful model of the responsivity in the near UV. The spectral irradiance values are currently derived separately for UV and VIS-NIR wavelength regions. The resulting expanded uncertainty ($k=2$) for the lamp irradiance varies between 2,6 % at 290 nm and 0,7 % at 900 nm (Fig. 1a).

The performance of our method has been tested by measuring the values of the spectral irradiance of lamps traceable to National Institute of Standards and Technology (NIST), USA and in a direct intercomparison with Physikalisch-Technische Bundesanstalt (PTB), Germany. The results of the comparisons show good agreement of our measured values with those of both NIST and PTB within uncertainties quoted (Fig. 1a).

The long-term reproducibility of the measurements has been studied by measuring the spectral irradiance of an FEL-type lamp which is traceable to NIST at UV wavelengths. The results indicate that the reproducibility is better than 0,5 % within one year (Fig. 1b).

The excellent agreement achieved in intercomparison measurements and high level of reproducibility demonstrate the applicability of our developed method for absolute spectral irradiance measurements at high level of accuracy.

a) *b)*

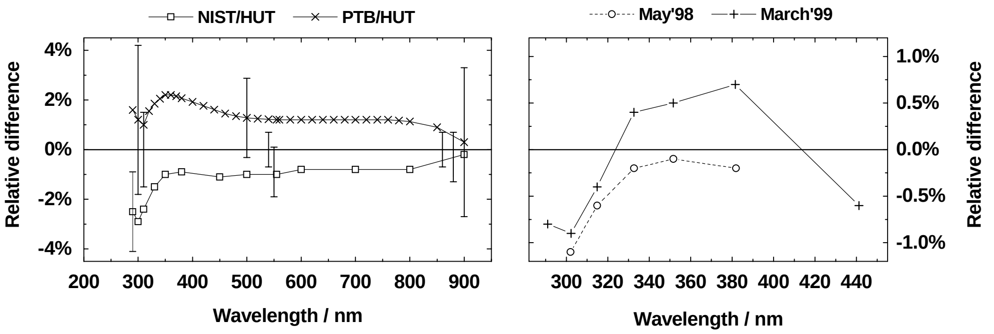


Figure 1. Results of intercomparison measurements and the reproducibility of the realisation of spectral irradiance scale at HUT. Relative differences between the spectral irradiance values a) measured by HUT and given by NIST (empty squares) and by PTB (crosses), bars indicate the level of measurement uncertainties (k=2); b) given by NIST and those of obtained from the measurement results in May 1998 (empty circles) and in March 1999 (plus signs) by using the lamp F-434.

5.1.2 Improving the accuracy of UV radiation measurement

P. Kärhä, T. Kübarsepp and N. Harrison (NPL, UK)

HUT is a participant in a EU-funded project "Improving the Accuracy of Ultraviolet Radiation Measurement" (SMT4-CT98-2242). This three-year project was formulated in 1998 to address the requirement from the European ultraviolet measurement community for higher accuracy UV radiation scales, improved transfer standards for the dissemination of UV scales, and for improved instrumentation and methods for the measurement of UV radiation. The project is co-ordinated by the National Physical Laboratory (NPL, UK).

The objectives of the project are firstly to investigate detectors, filters and other optical components for use in the ultraviolet with the objective of achieving UV irradiance measurements with an uncertainty of between 0,1 % and 1 %. Secondly, to establish and compare ultraviolet spectral responsivity scales using new transfer standards, improving base UV scale uncertainties to between 0,1 % and 0,3 %. Thirdly, to apply the knowledge and techniques developed during the project to improve measurement of solar UV radiation. The final objective is to develop an enhanced intense UV irradiance meter with improved stability for a demanding industrial application capable of achieving an accuracy of 2 %.

The project is divided into five work packages (WP). WP1 will target the development and evaluation UV filter radiometers for spectral irradiance measurements. This will also involve investigating the agreement in UV filter radiometer calibration between different NMIs using different calibration techniques. Three different techniques for establishing UV spectral responsivity scales using cryogenic radiometers will be compared and evaluated in WP2. The selection of suitable detectors to act as UV spectral responsivity transfer standards is an important part of this work package. Improving the industrial measurement of intense UV irradiance is the subject of WP3. The objective is to develop and evaluate an intense UV irradiance meter for industrial applications. WP4 aims to construct a portable calibrator for solar ultraviolet monitoring spectroradiometers. The fifth and final work package is primarily concerned with administration and dissemination of the results. HUT is involved in WP1 and in charge of WP4.

In WP1, HUT has constructed nine UV filter radiometers based on silicon trap detectors, interference filters stabilised with Peltier-cooling, and precision apertures. These filter radiometers have been characterised and sent to UK and France for the local national standards laboratories to be characterised.

Comparison of the calibration results will give indication about the suitability of filter radiometers to realise and disseminate UV scales. HUT has also characterised six filter radiometers built by NPL. These filter radiometers utilise slightly different techniques, e.g. GaAsP photodiodes, which should yield better results in UV because of their solar blindness.

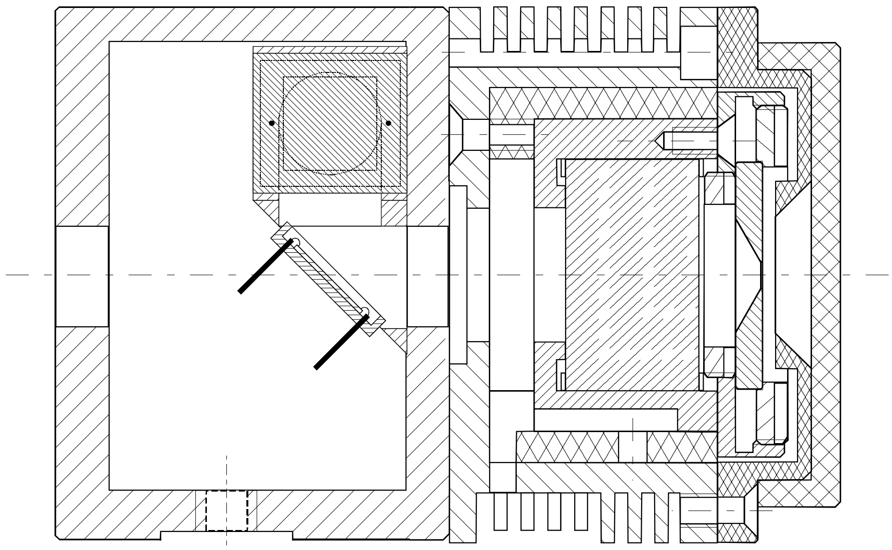


Figure 2. Cross-sectional view of the trap-based filter radiometer designed and constructed at HUT.

In WP4, HUT has collaborated with STUK, Radiation Protection Authority to construct a portable detector-stabilised solar UV calibrator. HUT's task has been the co-ordination of the work package and the development of the stabilising filter radiometers.

5.1.3 Development of the lumen realization

J. Hovila, K. Lahti, P. Toivanen and E. Vahala

High-accuracy measurements of luminous flux are widely needed by the lighting industry and research institutes. Luminous flux (unit lm) is a photometric quantity that describes the total emitted power of a light source as it is seen by a human eye. It is usually measured by a substitution method, where a standard lamp and a lamp to be calibrated are placed inside an integrating sphere and detector signals are compared. However, this requires an accurate standard lamp, which is normally characterised by measuring the spatial power distribution with a goniophotometer. This characterisation method has many disadvantages, including long measurement time and the need for high-accuracy positioners.

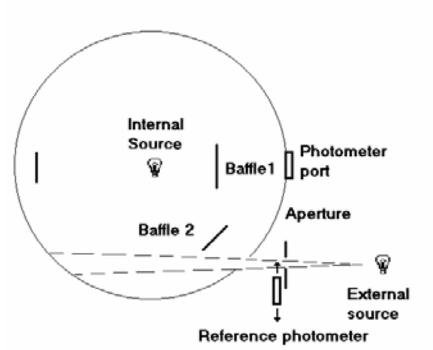


Figure 3 Set-up for the luminous flux measurement using the absolute integrating sphere method.

A large integrating sphere (diameter 65 inches) was purchased in 1999 as a part of the new calibration and measurement system for luminous flux using the absolute integrating sphere method [1],[2], where no standard lamps are needed. The sphere is coated with barium sulphate paint which has a reflectivity of approximately 98 % in the visible region. The measurement set-up is presented in Fig. 3.

In the absolute integrating sphere method, the luminous flux of the external source is obtained by measuring the illuminance within the calibrated aperture by the reference photometer. The signal of the photometer attached to the sphere is measured for both the external and internal source. The luminous flux of the internal source is calculated from the ratio of the signals.

Some corrections have to be made to eliminate the errors caused by the spatial nonuniformity of the sphere surface and the spectral differences of the light sources. Additional correction factors are needed due to the illuminance nonuniformity at the aperture plane and due to unequal incidences of light on the sphere surface.

The preliminary expanded uncertainty of our measurement system is 0,72 %. Three luminous flux standard lamps were measured after characterisation of the measurement system. The average difference of the measured values as compared with the reported values was -0,64 %.

The measurement set-up is going through some modifications to improve the repeatability but will be fully operational by the end of 2000. More accurate uncertainty analysis will be then available. The first international comparison of luminous flux standard lamps is scheduled to be in June.

[1] Y. Ohno, “Detector Based Luminous-flux Calibration Using the Absolute Integrating Sphere Method”, *Metrologia*, 1998, **35**, 473-478.

[2] K. Lahti, J. Hovila, P. Toivanen, E. Vahala, I. Tittonen, E. Ikonen, “Realisation of the Luminous Flux Unit Using a LED Scanner for the Absolute Integrating Sphere Method”, submitted.

5.1.4 Luminance and spectral radiance

P. Toivanen, J. Hovila and P. Kärhä

The realisations of the units of luminance and spectral radiance are based on an integrating sphere light source, a photometer and a spectroradiometer. The integrating sphere is illuminated by two tungsten halogen lamps with tuneable luminous flux level. The luminous responsivity of the photometer is traceable to the unit of illuminance. The spectral irradiance responsivity of the spectroradiometer is traceable to the unit of spectral irradiance. The luminance value at the aperture plane of the integrating sphere is obtained from the measured luminous intensity value and the known area of the output aperture of the sphere. The unit of spectral radiance is realised by measuring the relative spectral irradiance distribution of the light source. The spectral radiance at the aperture plane of the integrating sphere is then calculated from the measured luminance and the relative spectral irradiance values.

A new method was developed to determine the spatial non-uniformity of the output of the integrating sphere, which is one of the main uncertainty components in the realisation of the unit of luminance. The spatial non-uniformity was determined by scanning a laser beam within the aperture area. Both lamps of the integrating sphere source were replaced by large area photodiodes (18×18 mm^2). Since the path of the light is reversible, the changes in the signals of the photodiodes should correspond to the spatial non-uniformity in the output of the integrating sphere.

The dynamic range of the luminance calibration is from 250 to 40 000 cd/m^2. The realisation is independent on any standard materials, avoiding thus the uncertainty related to the ageing of the materials. The combined standard uncertainty of the realisation (0,36 %) is approximately five times lower than that obtainable with the methods based on standard materials, but still higher than that obtainable with the methods based on black-body radiators. However, the realisation is straightforward and relatively inexpensive to establish as compared with those based on black bodies.

The uncertainty of the unit of spectral radiance is mostly caused by the properties of the spectroradiometer, leading thus to significant wavelength dependence. The standard uncertainty of the unit of the spectral radiance is shown in Figure 4. At the wavelength range from 410 nm to 730 nm the relative standard uncertainty is below 0,5 %, being comparable to other methods for realising the unit of spectral radiance. At shorter and longer wavelength regions, the uncertainty increases rapidly. The uncertainty levels could be decreased by improving the spectroradiometer. For the long wavelength region, the lamps of the integrating sphere source may also be changed.

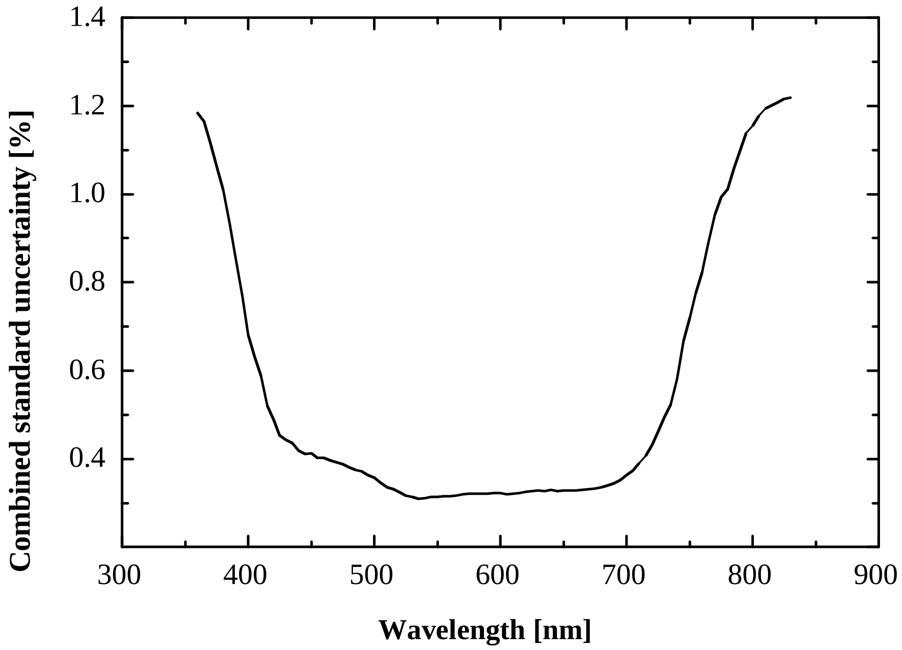


Figure 4. Combined standard uncertainty of the unit of spectral radiance as a function of wavelength.

5.1.5 Relative scale of spectral diffuse reflectance

S. Nevas and F. Manoocheri

Diffuse reflectance measurements are needed in many fields, including accurate colourimetry and heat transfer. Paper industry needs calibration of diffuse reflectance transfer standards, mainly used as reference in measurements of whiteness of paper.

The developed facility can provide diffuse reflectance calibrations of a range of standards traceable to an absolute scale. The performance of the facility will be tested in a CCPR key comparison. At present, the facility can measure diffuse spectral reflectance of white samples in the wavelength range 360 - 830 nm. The facility is based on an integrating sphere and the measurements are relative to reference standards from an absolute scale. The measurements can be made in the geometries of illumination view of 8°/diffuse, 8°/total, and 0°/diffuse. The facility is used in conjunction with the reference spectrometer to benefit from the available optics and automated equipment. The expanded uncertainty in the measurement of optical quality samples is less than 0,5 % (2σ) in the visible spectral range.

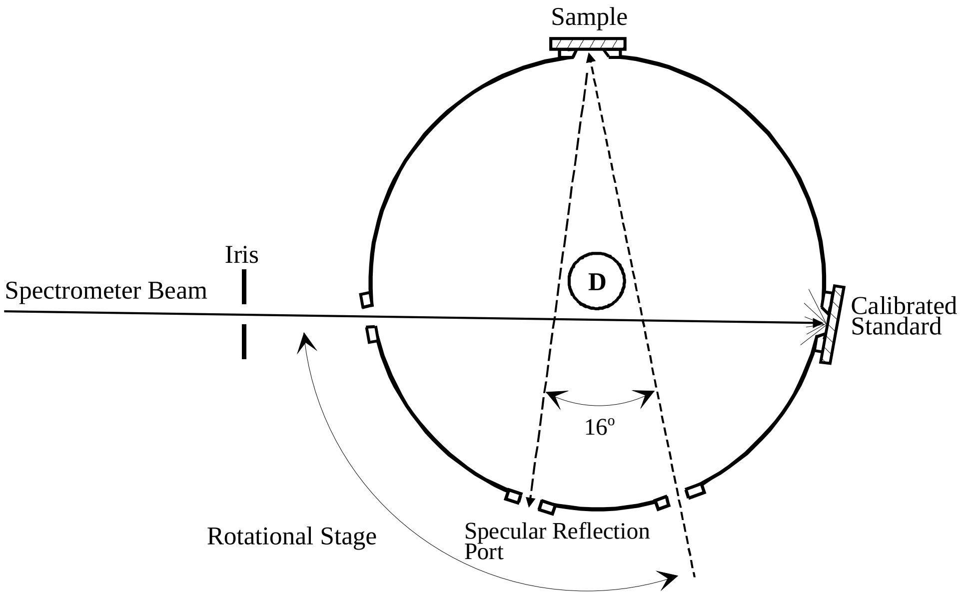


Figure 5. Top view of the averaging sphere in the setup for measurement of spectral diffuse reflectance. (D: Silicon detector on sphere wall). Interchangeable sample and reference holders cal also be used at 8 degrees to achieve 0°/diffuse degrees geometry.

Using a rotational stage, the sample and the calibrated standard are alternately illuminated by the spectrometer beam. Specular reflection exit port enables measurements with the specular component excluded (8°/diffuse geometry) from the reflected radiation. The detector views a specific portion of the sphere surface. The diffuse reflectance of the sample can be determined by the ratio of the detector signals obtained during the sample and the standard illumination.

5.1.6 Calibration setup for fibre-optic power meters

P. Kärhä and T. Ahola

Calibration of fibre-optic power is one of the basic calibrations needed in telecommunications industry. It is needed e.g. for accurate power measurements and measurements of transfer losses in fibres.

In 1999, HUT started to develop a calibration facility for fibre-optic power. The system will be applicable for measurements in 1310 nm and 1550 nm wavelengths. The target accuracy is 1,5 %. The project will be extended to cover 850 nm as well.

During the first year of the project, the electronics for the lasers were developed, built, and tested. Also, the InGaAs detectors to be utilised were purchased and the mechanics for them were built. Next year, the project will continue with characterisation of the detectors, implementation of the optics, and test calibrations.

5.2 LENGTH METROLOGY

5.2.1 External cavity diode laser with a transmission grating

M. Merimaa, P. Laakkonen[1], M. Kuittinen[1], I. Tittonen and E. Ikonen,
[1]University of Joensuu

Diode lasers are widely used in experiments in optical and atomic physics and increasingly in spectroscopy and frequency stabilization. Their small size, high power, low price and simple operation account for their popularity, but they nevertheless have their drawbacks. Poor tunability, large linewidth and operation on multiple longitudinal modes mainly restrict the usability of solitary diode lasers. It is widely known that these properties can be improved by operating the diode laser in a longer external cavity which provides frequency selective optical feedback.

A traditional external-cavity diode laser is based on a reflective diffraction grating in the Littrow configuration as shown in Fig. 6 (a). A significant improvement can be obtained by using a transmittive grating, as shown in Fig. 6 (b), as it totally removes the problem of turning the output beam while tuning the laser wavelength, which is a major drawback in the reflection geometry. Transmittive gratings have not been used before due to the difficulty of obtaining 15 - 20 % diffraction back to the laser without significant power loss to other diffraction orders or reflections. A novel external-cavity diode laser based on a low-loss transmission diffraction grating has been constructed. The grating has been designed and manufactured at the Physics Department of the University of Joensuu.

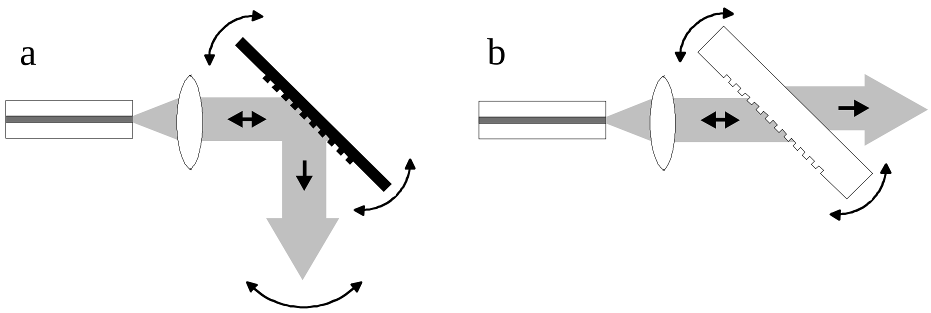


Figure 6. External-cavity lasers. The traditional reflection geometry (a) and the novel transmission geometry (b). Note that in (b) the output beam direction does not change.

The mechanical structure of the laser is shown in Figure 7. The optical length of the cavity is 25 mm, yielding free spectral range of 6 GHz, which is enough to give robust single mode operation. The laser source is an AR-coated 15 mW laser diode (SDL-7501). The transmission grating is fabricated onto a SiO_2 substrate with electron beam lithography and reactive ion etching. The grating is coated with a TiO_2 layer using vacuum evaporation. The grating transmits 74 % of the power, diffracts 17 % back to the laser and only 9 % of the power is lost. These experimental values compare favorably to the theoretical calculations which give 17,3 % diffraction and 74,6 % transmission.

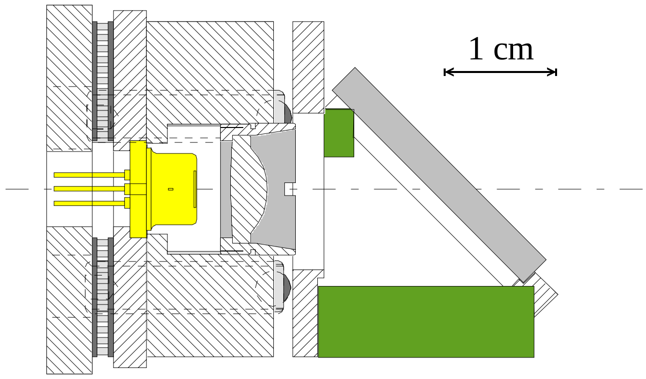


Figure 7. Mechanical structure of the external-cavity laser based on a transmission grating.

When the laser is properly adjusted, the differential efficiency is as high as 0,4 mW/mA and the laser can be operated at powers up to 10 mW. The total tuning range of the laser is ±4 nm around 632 nm with a continuous tuning range of 18 GHz. The spectral purity of the laser is very good; the linewidth is 30 kHz and the sidemode suppression is 35 dB. The laser intensity noise is nearly shot noise limited at high frequencies.

The results prove that the transmission configuration provides excellent performance without the problem of directional variation of the output beam. The transmission configuration is also suitable for making extremely compact external-cavity lasers.

5.2.2 Iodine-stabilized diode lasers

M. Merimaa, P. Kokkonen, K. Nyholm and E. Ikonen

A portable (32 cm × 13 cm × 6 cm) laser frequency standard has been constructed by frequency stabilizing an external-cavity diode laser at 633 nm to the I_2-Doppler free absorption. The compact structure is achieved by using a novel transmission grating to construct a highly compact external-cavity laser with an excellent passive frequency stability.

In our earlier portable frequency standard (35 cm × 8 cm × 6 cm) we have used weak optical feedback from a closely mounted microlens to improve the spectral properties of a solitary diode laser. However, the sensitivity to optical feedback, large linewidth and weak sidemode suppression limits the laser stability to $\sim 2\times10^{-12}$ and the day-to-day repeatability to $\sim 5\times10^{-11}$. This motivates the study of other laser sources that could be used in portable frequency standards. Compact external-cavity lasers are usually based on a reflective grating in the Littrow configuration. However, the Littrow reflection geometry is hampered by the output beam directional variation while tuning the laser. A significant improvement can be obtained by using a transmittive grating as it removes the problem of output beam directional variation. For this purpose we have designed a external-cavity based on a novel low loss transmission grating.

The Doppler-free spectrum is detected using saturated absorption in an external iodine cell using collinear geometry. The experimental setup can be seen in Figure 8.

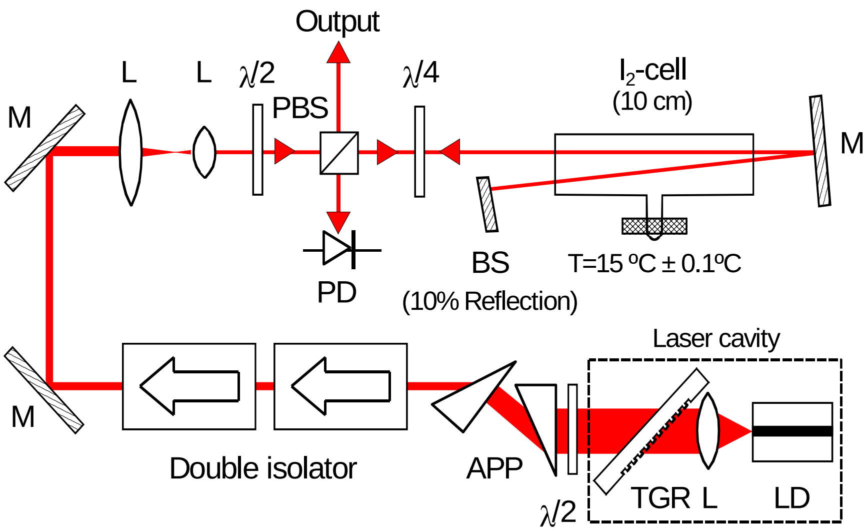


Figure 8. Experimental setup. (LD = laser diode, L = lens, TGR = transmission grating, λ/2 = half-wave plate, APP = anamorphic prism pair, M = mirror, PBS = polarising beamsplitter, λ/4 = quarter-wave plate, BS = beamsplitter, and PD = photodetector.)

The highly elliptical output beam of the external-cavity laser is first shaped with an anamorphic prism pair and then directed through an optical isolator. In order to achieve sufficient intensity inside the iodine cell the beam diameter is further reduced to ~0,6 mm by a telescope. The one-way saturating power inside the cell is 6 mW and 10 % of the saturated power is reflected back as a probe beam and it is detected with a photodiode. All optics in the setup are antireflection coated including the facets of the iodine cell to reduce optical feedback and power losses.

Frequency locking is implemented with a lock-in amplifier using standard third harmonic technique. The output of the lock-in amplifier is used as an error signal in a PI-controller and the control and modulation signals affect the laser frequency via piezoelectric transducers. Modulation frequency (1f) of 10 kHz and detection frequency (3f) of 30 kHz are used in the lock-in amplifier. The laser has been successfully locked to the hyperfine components of iodine P(33) 6-3 transition, but the detailed evaluation of the laser frequency stability and repeatability has not been carried out yet. However, better performance than what has been achieved with our earlier portable frequency standard can be expected.

5.3 FIBRE-OPTIC MEASUREMENTS

5.3.1 Characterization of WDM components

T. Niemi, M. Uusimaa, G. Genty and H. Ludvigsen

Wavelength-division multiplexing (WDM) has enabled a considerable increase in the bandwidth of fibre optic communications systems. Transmission of more than 200 channels in a single fibre has already been reported. The technology, however, requires new and more complex components and thus a full and reliable characterization of such devices is needed.

We have built a measurement setup for characterization of different filters such as fibre Bragg gratings (FBGs) and multiplexers/demultiplexers. The setup is based on the well-known phase shift method, which is an established method for performing high-accuracy measurements of the amplitude and the group delay characteristics. The dispersion of the component is obtained from the group delay by differentiation with respect to wavelength. The accuracy to resolve the fine structure of the group delay, however, depends critically on the modulation frequency used in the measurements. The choice of the modulation frequency is a trade off between the desired accuracy of the method and the resolution of the phase measurement.

We have studied the accuracy of the method in resolving dense group delay ripples that are present in chirped FBGs. The FBG we used is 20 cm long with a bandwidth of 2 nm and a nominal dispersion of –660 ps/nm. The example of the measured group delay for different modulation frequencies is given in Fig. 9. Comparison between the measured amplitude of the ripple and the amplitude calculated using an analytical model with sinusoidal variation of the ripple amplitude is given in Fig. 10. According to the model the measured amplitude of sinusoidal ripple follows a sinc-function. It is clearly seen from both of the figures that the ripple is effectively averaged out when the modulation frequency approaches a multiple of half a period of the ripple. This model gives a means for estimating the accuracy of the group-delay ripple measurements for the selected modulation frequency.

The work has been financially supported by the Academy of Finland and TEKES.

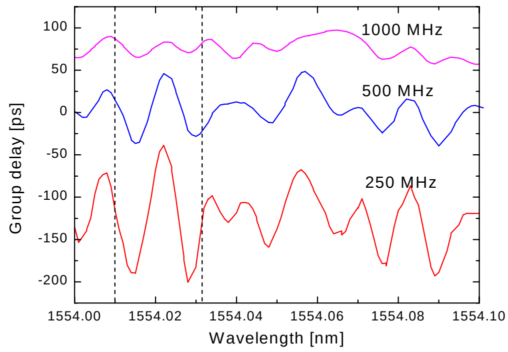


Figure 9. Group delay measured for three different modulation frequencies.

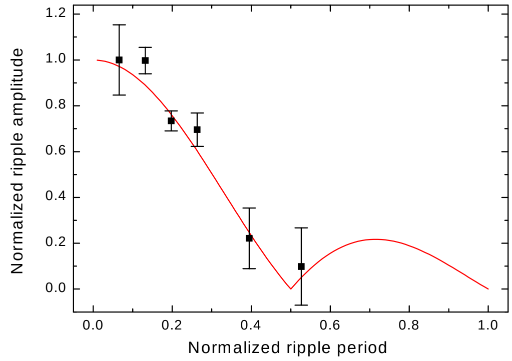


Figure 10. Comparison between the measured and estimated ripple amplitudes.

5.3.2 Dispersion compensation in analog link

T. Niemi, M. Uusimaa, G. Genty and H. Ludvigsen

The high quality of fibre-optic links has increased the performance of the CATV network. The improvements made in external modulation of DFB-lasers have enabled transmission of analog television signals in an optical fibre. However, two main problems are encountered in long-haul CATV distribution systems: the creation of distortion as a result of the interactions between chromatic dispersion and nonlinearity of the refractive index of optical fibre and limitation for maximum transmitted optical power due to Brillouin scattering.

We have studied the compensation of chromatic dispersion and nonlinearity induced effects in analog CATV links by using novel components such as fibre Bragg gratings (FBGs) and dispersion compensating fibres (DCFs). A typical design of a fibre-optic CATV link is depicted in Fig. 11. A continuous wave laser operating at 1554 nm is externally modulated with a Mach-Zehnder (MZ) interferometer. A phase-modulator inserted before the MZ-interferometer is used to suppress Brillouin scattering. An erbium doped fibre amplifier (EDFA) is placed in front of the single-mode fibre (SMF) to ensure a sufficient power level of the signal at the receiver. The composite triple beat (CTB) and composite second-order (CSO) distortions are the principal undesirable effects. Both were studied using a standard CATV transmitter including 42 carriers.

Measurements were performed for a link with 75 km of SMF and two EDFAs. The link was also simulated with the commercial simulation tool Gigabit Optical Link Designer (*GOLD*). We found that the use of a DCF allows CSO and CTB to be maintained at reasonable levels and that the quality of the received signal depends on the position of the DCF in the link. The transmission length of the CATV link could be increased beyond 100 km when DCF was used. Measurement and simulation results for a CATV link having 75 km of SMF are given in Fig. 12. The reference measurement was done without any dispersion compensating components. It can be seen that the DCF degreases the distortion level. The FBG did not perform well but it degraded the signal quality. The problem was identified to be related to the ripple in the group delay of the linearly chirped fibre grating.

The work has been financially supported by TEKES.

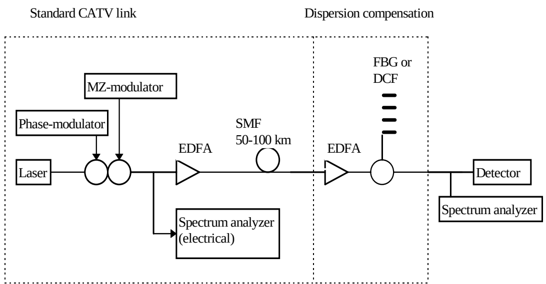


Figure 11. Outline of a typical CATV long-haul transmission link.

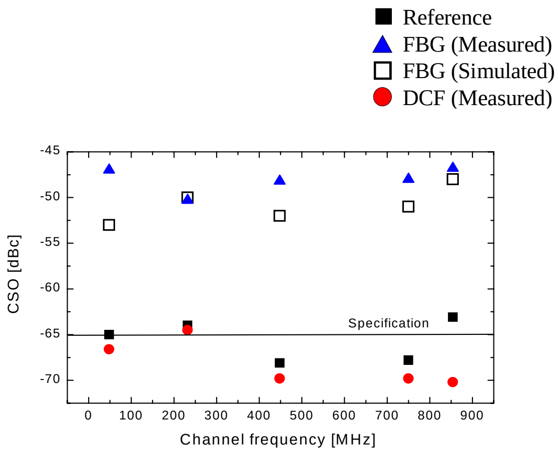


Figure 12. Measurement and simulation results for a CATV link with 75 km of fibre.

5.3.3 Linewidth measurements of a grating-cavity laser

G. Genty, A. Dupart, T. Laukkanen, M. Kaivola[1] and H. Ludvigsen
[1]HUT, Materials Physics Laboratory

In the case of strong optical feedback, the behavior of the linewidth of an external cavity laser depends on the fine-tuning of the grating dispersion curve relative to the Fabry-Pérot modes of the external cavity [1]. We have investigated experimentally the dependence of the linewidth of a grating-feedback cavity laser on this parameter.

The laser linewidth was measured by applying a self-homodyne technique with a delay line shorter than the coherence length of the laser. Figure 13 shows an outline of the experimental setup. The delay fibre is 60 m long, corresponding to a time delay of 0,3 μs. The linewidth of the ECL was measured as a function of the tuning of the grating orientation over a range corresponding to a 9 GHz change of the oscillation frequency of the laser. A conversion of the PZT voltage to the tuning of the laser frequency was deduced from the known 2 GHz *FSR* of the monitoring Fabry-Pérot interferometer. A theoretical spectrum based on a white-noise model for the phase fluctuations of the laser was fitted to the measured data using a least-squares method keeping the linewidth as a free parameter. The linewidth variations versus the shift of the oscillation frequency are plotted in Fig. 14 [2]. The linewidth evolution clearly follows the mode structure of the external cavity and shows substantial variation within one external cavity mode. The linewidth can vary by as much as 100 kHz over a range of 1,8 GHz, which was measured to be the frequency interval between the hops of the external cavity mode. This is slightly more than the *FSR* of the external cavity. The discrepancy is due to the fact that the rotation of the grating is actually coupled to a small translation resulting in a tiny change of the external cavity length.

This work has been financially supported by the Academy of Finland.

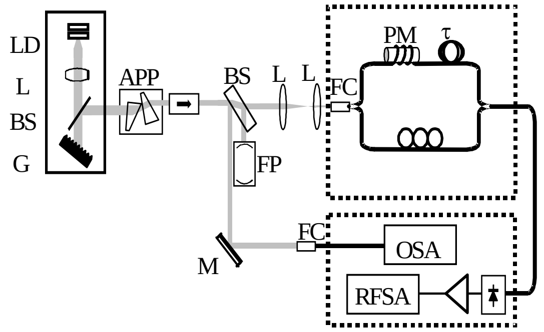


Figure 13. Linewidth measurement setup. G: grating, L: lens, LD: laser diode, APP: anamorphic prisms, BS: beam splitter, M: mirror, FC: fibre collimator, FP: Fabry-Pérot interferometer, OSA: optical spectrum analyzer

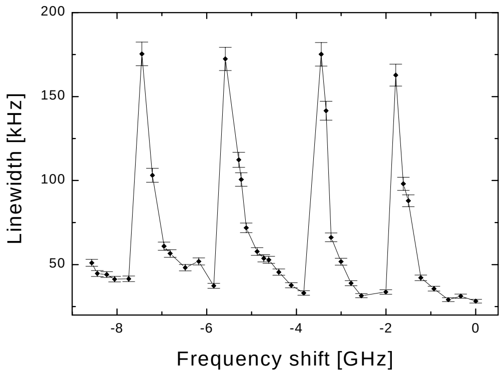


Figure 14 .Variations of the linewidth of an ECL measured over a range of external-cavity modes.

[1] G. Genty, A. Gröhn, H. Talvitie, M. Kaivola, and H. Ludvigsen, “Analysis of the linewidth of a GaAlAs laser with optical feedback from a grating”, submitted for publication.

[2] G. Genty, M. Kaivola and H. Ludvigsen, “Measurements of linewidth variation within one external cavity mode of a grating-cavity laser”, CPEM 2000, Sydney, Australia, May 7-11, 2000.

5.3.4 Tunable micro-filter for use in DWDM-systems

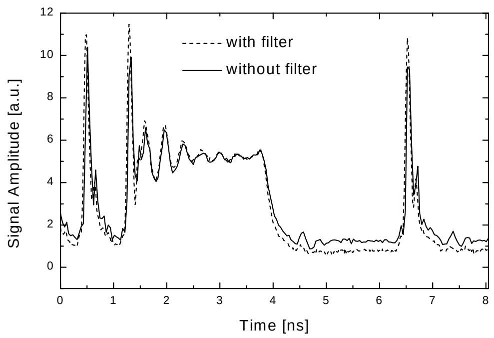
M. Uusimaa, T. Niemi, S.Tammela[1], T. Kajava[2], M. Kaivola[2] and H. Ludvigsen
[1]VTT Electronics, Microelectronics
[2]HUT, Department of Engineering Physics and Mathematics

Frequency chirping of a directly modulated DFB laser degrades the transmitted signal and causes dispersion penalty in a cost-effectively realized optical DWDM network. In this work, a temperature-tunable filter made of silicon was developed for simultaneous wavelength monitoring and spectral filtering of the transmitter output to reduce the fibre induced dispersion effects [1]. We have earlier demonstrated a similar device concept for time-resolved frequency chirp measurements [2].

The Fabry-Perot filter was fabricated by depositing two dielectric mirrors on a double-side polished silicon wafer with a thickness of 400 μm. The reflectivity of the mirrors is 66 % and the free spectral range of the etalon is 110 GHz. In addition, two integrated thin-film resistors on the surface of the wafer allow simple control of the transmission properties of the chip by temperature tuning and a simultaneous wavelength monitoring of the transmitter.

We tested the filter by placing it after a directly modulated DWDM transmitter operating at a bit-rate of 2,5 Gbit/s. The operation point of the Fabry-Perot filter was chosen at 50 % of the transmission maximum by temperature tuning. The accuracy of the measured linear relation between the sensor resistance of the thin-film resistor and the transmission wavelength is better than 2 pm. It indicates that the wavelength drift of the transmitter can be reliably monitored with the micro-filter.

The time traces with and without the filter after transmission through 350 km of fibre are shown in Fig. 15. The filter improves the quality of the signal having adiabatic frequency chirp mainly by improving its extinction ratio. An improvement of the dispersion penalty by 1,5 dB at the BER level of 10^{-9} was achieved (Fig. 16).



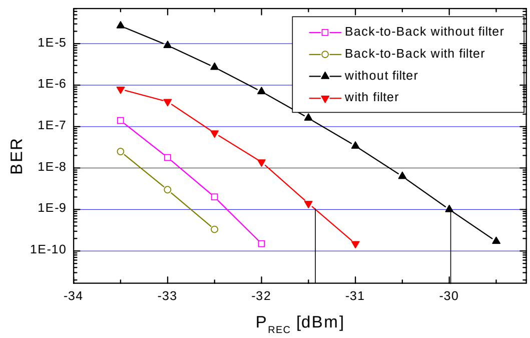


Figure 15. Signals with and without the filter after 350 km of fibre.

Figure 16. BER measurements with 350 km of fibre.

This work has been financially supported by TEKES. Nokia Networks is acknowledged for the loan of equipment.

[1] T. Niemi, M. Uusimaa, S. Tammela, P. Heimala, T. Kajava, M. Kaivola and H. Ludvigsen, "Simultaneous spectral filtering and wavelength monitoring of a DWDM transmitter using a tunable Fabry-Perot filter", OFC 2000, Baltimore, Maryland, March 5-10, 2000.

[2] T. Niemi, S. Tammela, T. Kajava, M. Kaivola, and H. Ludvigsen, "Temperature-tunable silicon-wafer for frequency chirp measurements", Microwave and Optical Technol. Lett. 20 (1999) 190.

5.3.5 Absolute frequency reference for WDM-systems

M. Merimaa, J. Casado, T. Niemi and H. Ludvigsen

During the last few years the interest in wavelength division multiplexing (WDM) in the 1,55 μm wavelength range has been growing. This has been due to the excellent performance of optical fibres and the availability of compact optical amplifiers at this wavelength. Because of the increased bandwidth demand and the limited gain range of the Er-doped optical amplifier, the channel spacing in WDM systems has been diminishing. This requires increasingly accurate wavelength measurements to ensure reliable operation and world-wide interconnectivity.

To make a frequency standard for accurate wavelength measurements, we have frequency stabilized a commercial telecommunications laser to the linear absorption spectrum of ^{13}C-acetylene ($^{13}C_2H_2$). The ^{13}C-acetylene molecule has more than hundred absorption lines in the wavelength region between 1,552 μm and 1,518 μm, making it a suitable absolute frequency reference for our purpose.

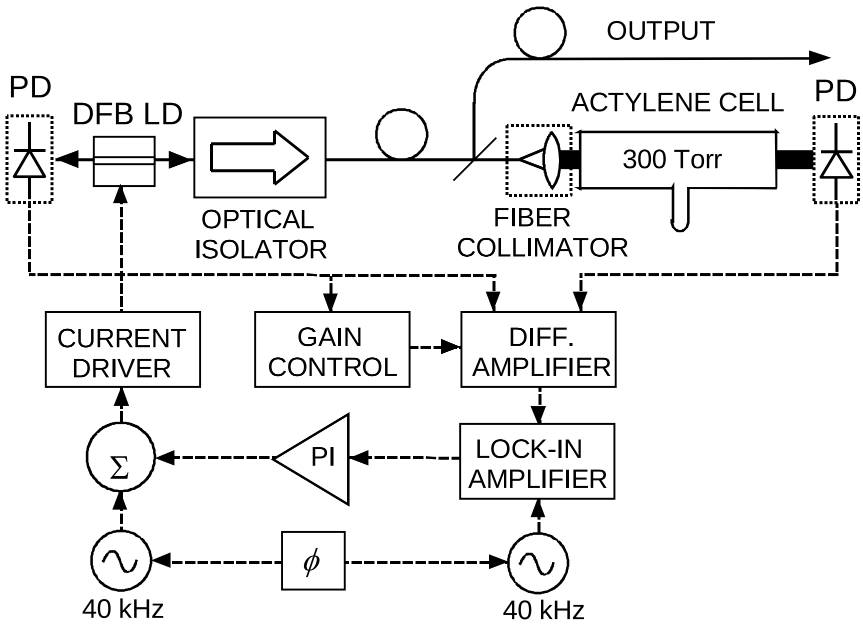


Figure 17. Experimental setup for frequency stabilization.

The experimental setup is schematically shown in Fig. 17. The laser source is a 2-mW single mode DFB diode laser (Alcatel 1915 LMI), operating at around 1,55 μm. The frequency stabilization is based on observing linear absorption of a frequency modulated laser beam in a 5 cm long acetylene cell using lock-in technique. The output of the lock-in amplifier provides a zero crossing at the center frequency of an absorption line and is used as an error signal for the PI-controller. The PI-controller adjusts the laser frequency via injection current.

The monitoring photodiode of the laser is used to subtract the intensity modulation that is caused when the laser frequency is modulated via injection current.

The laser diode can be tuned between 1,5435 μm and 1,5455 μm, in which range there are four strong absorption lines, P(18)-P(21), of the combination band ($\nu_1 + \nu_3$) and several weaker absorption lines. The laser has been successfully locked to the strong absorption lines. The line P(18) is the best choice for a frequency reference as it is the strongest of the available lines and there are no weaker lines in the immediate vicinity. It is also only 0,1 nm from the ITU standard fibre-optic telecommunication channel 42.

This work has been financially supported by TEKES.

5.4 MICROTECHNOLOGIES

5.4.1 Micromechanical resonators for RF-applications

T. Lamminmäki, K. Ruokonen, K. Nera, K. Lahti and I. Tittonen

The partners in the RF-MEMS project are the Metrology Research Institute, VTT/Automation, VTT/Electronics, Nokia Research Center, VTI Hamlin, TEKES and the Finnish Academy.

The rapidly developing telecommunication systems are setting increasing requirements for RF-components in performance, size, cost and integrability. Micromechanical resonators have emerged as a promising technique to meet these demands. Micromechanical high frequency resonators have usually been fabricated by surface micromechanics, which can be integrated with ICs. In addition, poly-Si provides flexibility in geometry, anchoring and number of structural layers. However, polycrystalline silicon has non-optimal intrinsic quality factor and it is typically processed at high temperatures, which develops stress gradients in film layers due to mismatches in thermal expansion coefficients.

To overcome these problems, single crystal silicon is selected as the basic resonator material. Single crystal silicon is fully elastic up to the fracture point resulting in minimal hysteresis in the normal temperature area. It has very high intrinsic Q-factor (up to $6 \cdot 10^5$ at room temperature) and the strength of single-crystal silicon is comparable to that of steel. There has been some effort to integrate single-crystal silicon micromechanical resonators on standard wafers, but using RFIC (Radio Frequency Integrated Circuit) single-crystal silicon-oninsulator (SOI) wafers integration is easier to implement. Single-crystal SOI-wafers are very useful material for mechanical RF-resonator applications because SOI has become strategic for low-power, battery-operated portable systems and large-scale integrated logic and memory circuits with sub-half micron features. In addition many integrated micromechanical SOI-CMOS-sensors and integrated dipole antennas have been presented.

The fabrication of micromechanical SOI-resonators operating at high frequencies, fulfilling simultaneously the strict noise performance specifications, remains challenging. Accurate modelling of the resonator structures is required to allow the design of components with the desired properties. Analytic modeling of micromechanical capacitively actuated resonators is complex, since the resonators are described by dynamic, non-linear equations coupling electric and mechanical energy domains.

In this example we have used finite element modeling which provides a very flexible tool for simulation of both mechanical and electrostatical behavior of electromechanical microresonator. With same method very complex geometries can be modelled and optimised. Based on the FEM-calculated mechanical parameters, a equivalent electrical circuit model is used for simulation of resonator dynamic response. Comparison between measured and simulated results shows good agreement indicating reliability of the modeling approach.

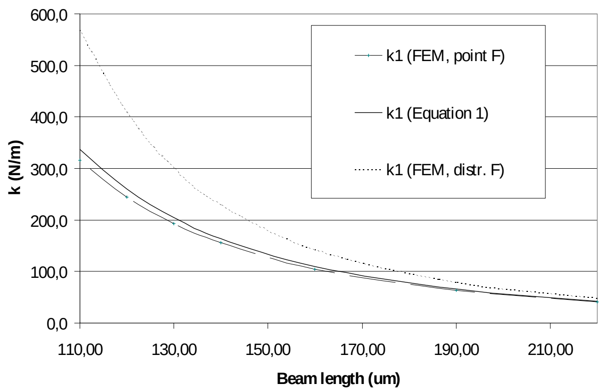


Figure 18. Spring constant k of a bridge resonator as the length of the bridge is varied.

Finite element method (FEM) has been used to calculate the mechanical parameters for a clamped-clamped beam micromechanical resonators. The calculated values are used in creating equivalent electrical circuit model for the resonator structures, including effects due to mechanical non-linearity. Good agreement is found between the measured and simulated resonator frequency responses. Q-value of the order of 30000 has been extracted for 1,5 MHz clamped-clamped SOI-resonator.

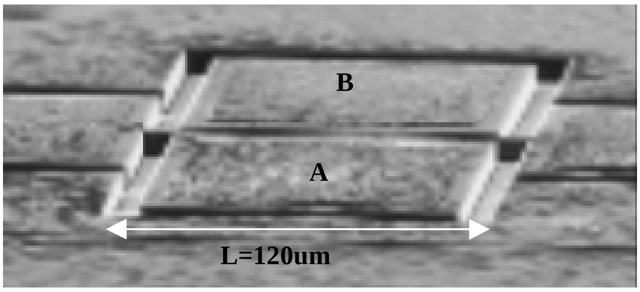


Figure 19. SEM-picture of clamped-clamped beam SOI-resonator.

5.4.2 High-Q micromechanical silicon oscillators

K.Nera, O.Hahtela, M.Kujala, T.Lamminmäki, K.Ruokonen, V.Voipio and I.Tittonen

High-Q oscillators mean mainly structures having a well-defined very narrow mechanical resonance. Such resonances are very sensitive to various kinds of changes in the physical environment. Combined with very low-noise detection system these micromechanical devices enable novel physical phenomena to be observed especially at low temperatures. One such effect could be the mechanical quantum squeezing [1].

The main idea in designing high-Q oscillators is to construct structures with low mechanical energy flow from the active resonating part of the system. Single crystal silicon has very low intrinsic losses which makes it excellent material for this kind of resonators. Favourable structures in oscillator designs are narrow bridges, torsional modes and double sided symmetry.

The most widely used method in micromechanical manufacturing is anisotropic wet etching. This is a simple and suitable method for manufacturing of silicon bulk micromechanical devices. The research group has its own reaction chamber which enables better and more reproducible control over the reaction parameters. Due to anisotropic etching, edges of manufactured components are parallel to silicon crystal planes, therefore a need for double-sided symmetry in oscillator structures requires also double-sided etching. A new two-sided mask aligner in HUT Microelectronics centre has made this possible.

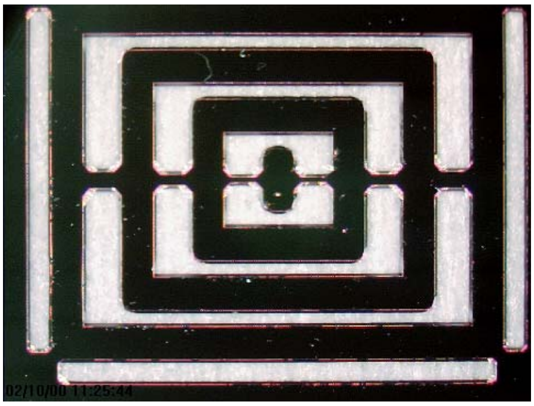


Figure 20. An example of a torsional, high-Q oscillator structure made with double-sided etching.

Properly designed and processed silicon structures may have very accurate resonance frequency and mechanical quality factors of several millions at low cryogenic temperatures. The group has purchased a liquid helium bath cryostat which provides a cryogenic temperature environment especially for optical measurements. The current equipment enables optical and capacitive measurements for resonance frequencies and Q-values of resonators as a function of temperature and pressure. The cryostat provides excellent control and stability of the sample temperature from 300 K down to 4,2 K (option to 1,5 K).

This is quite essential property because it is known that the Q-value oscillates as a function of temperature and, in addition, temperature and pressure have a remarkable effect to the characteristic frequency of the resonator. Because of the microscaled size of resonator structures, the various noise sources become very important and they must be eliminated carefully. Thermal motion is a major noise source for silicon resonators. Thus low temperature and low pressure environments are interesting because harmful effects due to thermal motion and gas damping can be minimized.

[1] M.P. Blencowe and M.N. Wybourne, "Quantum squeezing of mechanical motion for micron-sized cantilevers".

5.4.3 Gas sensors

M. Kujala, K. Ruokonen, K. Nera, O. Hahtela and I. Tittonen

During the last year the microtechnologies group at MRI has made large advances in developing a comprehensive expertise with microtechnology design and manufacturing processes.

The core idea is to create a micromechanical silicon resonator of which characteristics change in a detectable manner, when external mass is absorbed on the resonator surface from the surrounding gas mixture. To make the sensor selective to only certain gases, a special coating has to be applied to the resonator surface. This coating can e.g. consist of long-chained organic polymers. The sensor can be made selective to different gases by varying the composition of the coating.

The absorbed mass can be measured in multiple ways. First, the resonance frequency of the oscillator changes with an amount depending on the amount of absorbed mass. The oscillating frequency can be read for example capacitively. Second, the dielectric constant of the coating changes, when gas is absorbed. This can be easily detected. By combining these methods it is possible to create a multiparametric sensor for selective detection of the concentration of several gases in air or other gas mixture. Applications exist especially in enviromental monitoring.

So far the project has launched with the design of several possible geometries for the micromechanical resonator. These designs are now entering manufacturing and characterisation phase. After the first prototypes have been created with two-sided wet etching, they will be measured in the optical cryostat to determine their mechanical properties. The results obtained from this will be used to refine the design and process parameters. The target is a resonator with extremely high Q-value to achieve a maximally high mass resolution.

To create the selective coating, collaboration with VTT Chemical Technology at Tampere is the next step after the resonator properties have been deemed good enough. Their expertise in the field of selectively absorbing materials is essential. The whole project is a collaboration between HUT/MRI, VTT Chemical Technology, and Vaisala Oyj.

5.4.4 Finite element modeling of microsystems

K. Ruokonen, T. Lamminmäki and I. Tittonen

Various microsystems utilise capacitive read-out and actuation. Here we present some examples of calculating capacitance $C(x)$ as a function of the displacement. Moreover, we can directly take into account the physical cause of this displacement, for example an external pressure or an applied actuating electric field leading to the non-linear voltage-displacement dependence:

$$x = \frac{F_e(x)}{k_m} = \frac{d}{dx}\frac{C(x)U^2}{2k_m}$$

This external actuation is rather non-trivial and thus simulations with detailed structural information are necessary in the design and optimisation of capacitive systems.

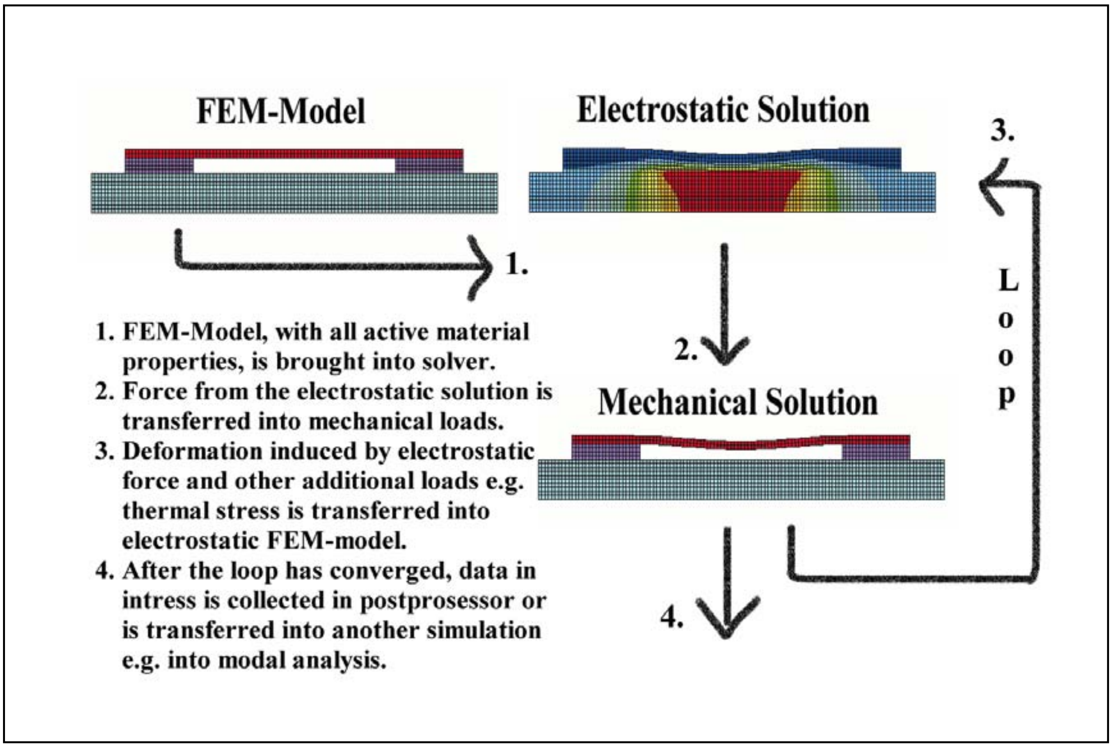


Figure 21. Iterative calculation of electromechanical problem.

The FEM simulations were performed with ANSYS/Multiphysics® program package. The capacitance simulations were done by coupling mechanical and electrostatic simulations and the displacement-voltage dependence was obtained by iterative calculations (Figure 21). We also included additional loads to this iterative calculation. For example, the stresses, caused by the change of temperature affecting the $\frac{dx(U)}{dU}(T)$-behaviour due to the mismatch of the thermal expansion coefficients of the used materials, were taken into account.

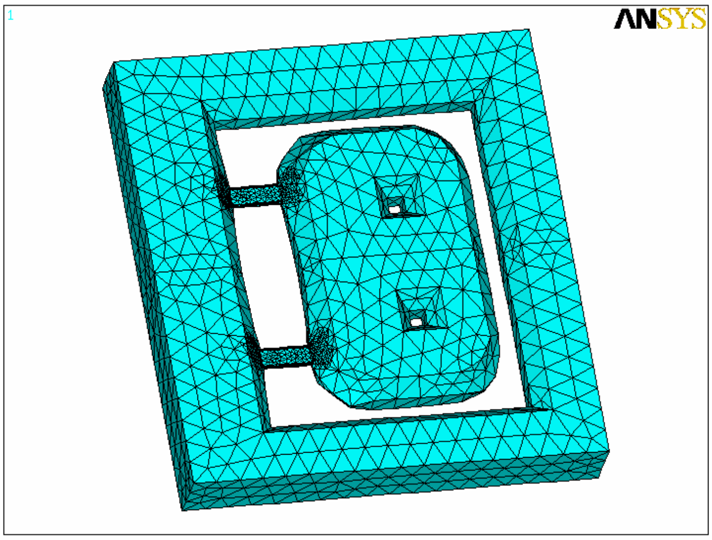


Figure 22. Finite element mesh model of the accelerometer manufactured by VTI Hamlin.

Figure 22 shows a 3D finite element mesh model of the accelerometer manufactured by VTI Hamlin. The sensor consists of an electroelastic mass supported by two cantilever beams. This structure is placed between two electrodes, which form a dual capacitor. The changes of the two capacitances are opposite and were simulated as a function of the vertical displacement (Figure 23).

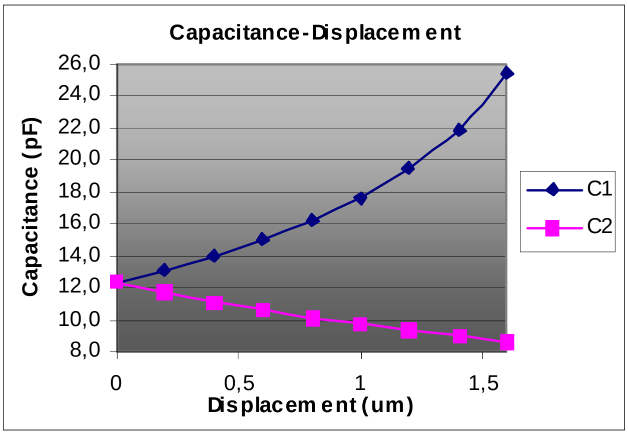


Figure 23. Capacitance as a function of displacement.

Another typical capacitively read mechanical sensor is a pressure sensor based on a silicon diaphragm. An external pressure change deforms the diaphragm and causes a change in the capacitance. This simulated capacitance-pressure dependence C(p) could also be experimentally verified. The non-linearity in the mechanical structures was taken into account and the agreement with measured data was excellent without any fit parameters as can be seen in Fig. 24.

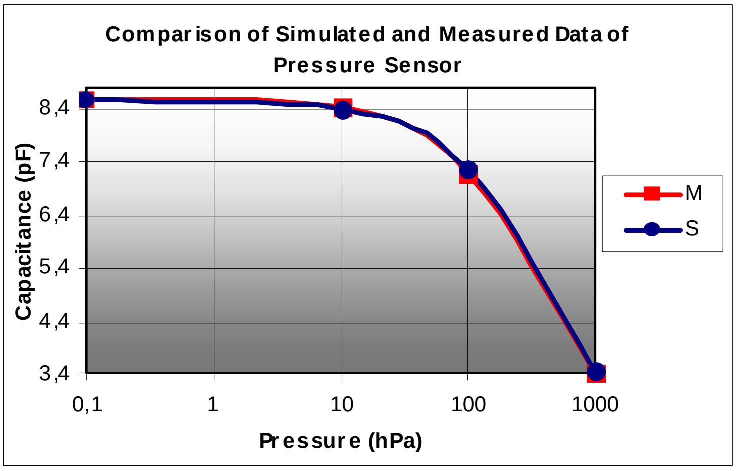


Figure 24. Simulated and measured capacitances as a function of pressure.

An applied voltage is used for actuation in numerous applications (e.g. micro switches and resonators). Fig. 25 shows the induced displacement as a function of an applied voltage. A result that directly follows is the pull-in voltage. For the two parallel electrode plates, it is the voltage, which causes a displacement of one third of the electrode gap. A use of higher voltage would pull the electrodes into a contact. One interesting result is that the maximum dynamic vibration amplitude equals to the displacement from the electrostatic analysis times the mechanical quality factor:

$$A_{\max} = Q\frac{F_e(U)}{m\omega_0^{\ 2}} = Qx(U)$$

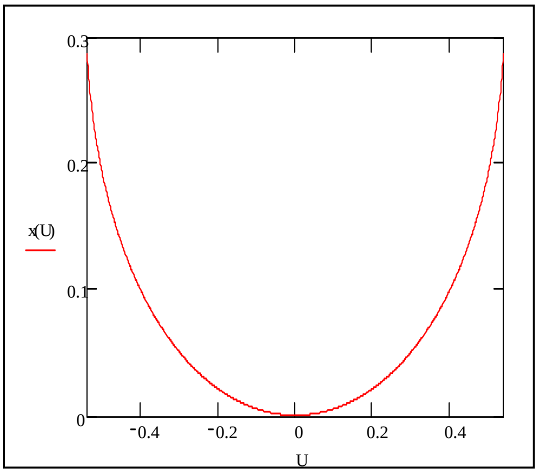


Figure 25. Displacement as a function of DC-biasvoltage.

5.5 APPLIED QUANTUM OPTICS

5.5.1 Laser cooling of neutral atoms

T. Lindvall, M. Hirvonen and I. Tittonen

A magneto-optical trap (MOT), where neutral atoms are cooled and trapped by laser beams and a magnetic field, creates rather ideal conditions for atom spectroscopy, since the Doppler broadening is significantly reduced. The cooling laser affects, however, the energy levels of the trapped atoms. This interaction between light and atoms can be analyzed if the spectrum of these so-called dressed atoms is compared to the pure atomic spectrum.

We have measured the transmission of a weak probe laser beam through the cloud of cold rubidium atoms. The effect of the cooling laser is eliminated by cutting the cooling beams off for periods short enough for the atom cloud not to disappear. If the transmission is measured alternately with the beams on and off, while sweeping the frequency of the probe laser, the two desired spectra are obtained.

Figure 26 shows the energy levels and dressed state transitions of ^{85}Rb. The strong cooling laser has a frequency slightly below the frequency of the transition $5S_{1/2}$, F=3 $\rightarrow$ $5P_{3/2}$, F'=4. Thus it splits both these states into two dressed states, which are superpositions of the uncoupled states of the atom-laser system and separated by the generalized Rabi frequency $\Omega = \sqrt{\Omega_0^2 + \delta_L^2}$, where Ω_0 is the Rabi frequency and δ_L is the cooling laser detuning. The Rabi frequency is for zero detuning the frequency at which the probability of finding a two-level atom in the ground state oscillates (Rabi flipping). It is proportional to the square root of the cooling laser intensity and characterises the strength of the coupling between the field and the atom. Because of the splitting there will be two transitions, an Autler-Townes doublet, for each of the excited states F'=2,3. For F'=4 there are four different transitions, of which only two (L4- and L4+) can be observed in transmission spectroscopy, since the last two occur between equally populated levels. Expressions for the positions and strengths of the different lines can be derived. From these the Rabi frequency and detuning can be solved. These quantities can thus be calculated from the measured spectra and compared to known values.

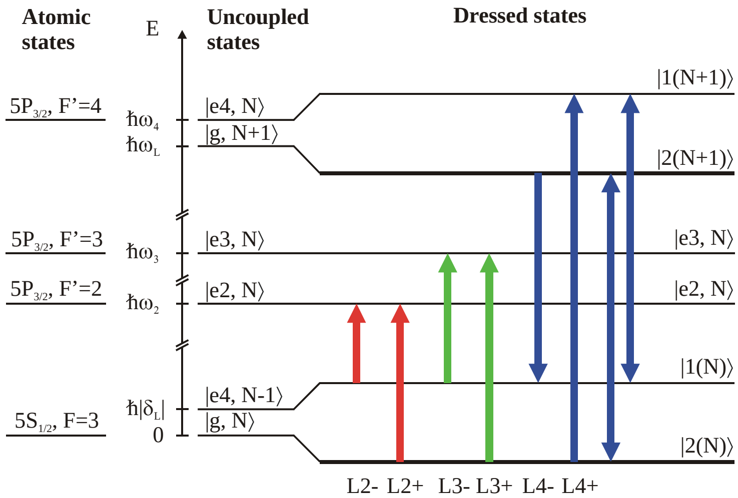


Figure 26. Dressed state levels and transitions of ^{85}Rb.

In addition to the dressed state lines, the measured spectrum contains three additional lines close to the atomic resonance frequencies of the transitions $5S_{1/2}$, F=3 $\rightarrow$ $5P_{3/2}$, F'=2,3,4. This could indicate that part of the trapped atoms are unaffected by the cooling laser. However, further measurements are needed to find the origin of this effect.

5.5.2 Digital Laser Frequency Stabilization

K. Lahti, E. Vahala, M. Heiliö, A. Kasvi and I. Tittonen

Frequency stable coherent light sources have a great significance in areas of optical spectroscopy, metrology and communications. Very high stabilities have been achieved using the Pound-Drever-Hall method [1], where the laser frequency is locked to a high-Q optical resonator using a phase modulation scheme. We use this technique to lock a Nd:YAG laser to an optical resonator with finesse more than 14 000. [2]. One of the crucial elements of the stabilisation system is the laser servo control which tunes the laser frequency electromechanically and electrothermally based on the frequency fluctuation information given by the resonator (Fig. 27). The servo control must be able to operate at a frequency bandwidth covering totally the laser technical frequency noise. The frequency noise of our laser becomes quantum-limited approximately at frequencies higher than 100 kHz. Servo controls operating at this high frequencies have traditionally been constructed using analog electronics. We use state-of the-art digital signal processors and special locking algorithms to obtain a digital servo operating effectively at the whole technical noise bandwidth. The locking algorithm is the core of the digital loop. It is based on a dynamic vector, which contains output values for each discrete error signal input. Dynamic aspect of the vector leads to a converging learning process, where the algorithm itself finds the optimum output values for each error signal inputs.

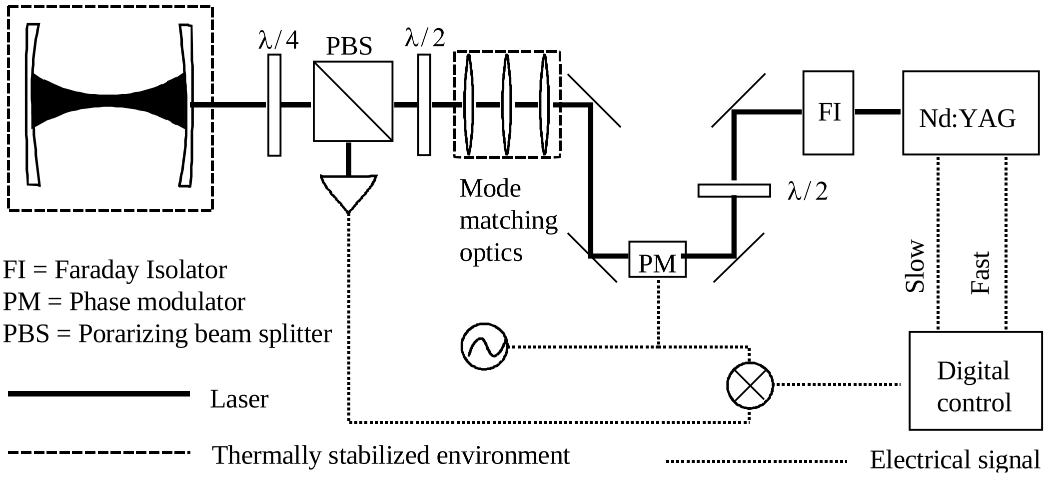


Figure 27. Nd:YAG laser is locked to a high-Q optical resonator using a phase modulation scheme.

[1] R. W. P. Drever *et al*, Appl. Phys. B. **31**, 97-105 (1983).

[2] T. J. Kane *et al*, Appl. Opt. **10**, 65-67 (1985).

5.5.3 Determination of Gaussian Beam Parameters

K. Lahti, E. Vahala, A. Kasvi, M. Heiliö and I. Tittonen

The determination of laser beam parameters is essential in designing of optical systems [1]. Known such techniques are the slit [2], knife-edge [3] and the CCD-camera methods [4] in various modifications. Usually only the beam sizes smaller than the detector sensing area can be measured. For large laser beams, a major uncertainty would be associated with the required focussing elements. We have developed a method that overcomes this restriction. The technique gives out the total beam profile as in the CCD-camera method, but with a resolution that can go well below the CCD pixel area.

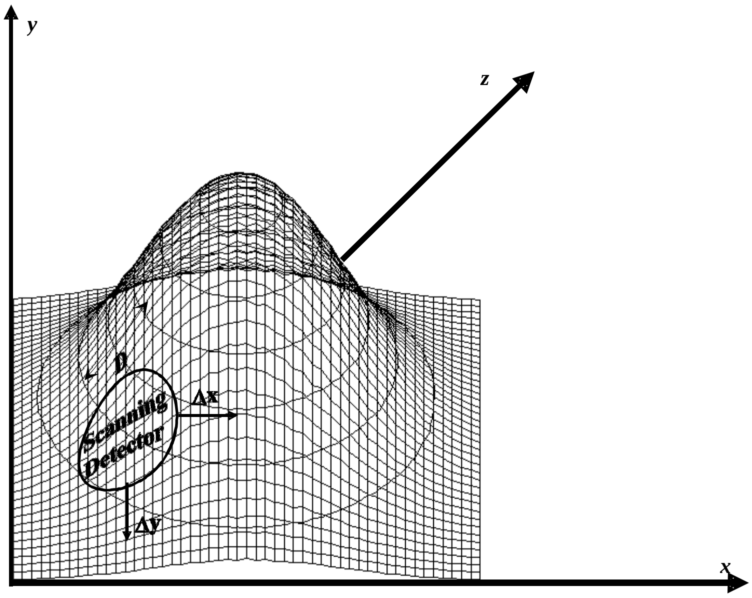


Figure 28. Measurement scheme of the intensity profile of an optical beam. The grid represents the scanning resolution set by Δx and Δy. Grid nodal points are the detector centre positions in individual measurements.

In this method [5], the beam intensity distribution is scanned by moving a photodetector on the *xy*-plane orthogonal to the direction of propagation. The measurement procedure is presented in Fig. 28, where the scanning detector has the diameter of *D*. The measurement results form a matrix *M*, in which a single entry is the result of integration

$$M_{i,j} = \eta \int_{i\Delta x - D/2}^{i\Delta x + D/2} \int_{j\Delta y - \sqrt{D^2/4 - (x - i\Delta x)^2}}^{j\Delta y + \sqrt{D^2/4 - (x - i\Delta x)^2}} I(x, y)\, dy dx \, ,$$

where each center position of the detector is given by the coordinates $i\Delta x$ and $j\Delta y$. This integration is performed over the detector active area, which is required to have a uniform quantum efficiency η.

The obtained matrix *M* can directly be used to determine the beam parameters if the detector area is small compared with the spatial variations in the intensity distribution. This, however, is not usually the case. When reconstructing an original distribution from the sampled data, each sample point naturally represents the value of the distribution at a given position. The averaged values describe correctly the real distribution if on the whole integration area

$$d^2 I(x,y)/dr^2 \approx 0\,,$$

where r is the direction of maximum spatial variation.

If the above equation is not satisfied, the effect of averaging has to be taken into account in calculating the beam parameters. This is done by simulating the measurement procedure and computationally iterating the beam parameters that produce a matrix *M*' that is usually close to *M*. Individual measurements are simulated by integrating the corresponding fractions of the intensity distribution over the known detector area. The analytical form of the intensity distribution has to be defined for the calculations. If this form is not known, which is not usually the case, the previously defined matrix *M* can be used to obtain the form of the distribution.

The iteration process is based on matrix calculus describing the difference between the computed and measured values. Explicitly this is

$$M''_{i,j} = M'_{i,j} - M_{i,j}\,,$$

which vanishes for the correct beam parameters. The entries of the matrix $M'_{i,j}$ are numerically calculated as a sum of the intensity distribution points lying on the detector integration area. The step size used in the summation is a crucial parameter in the method. If the step is large compared to the spatial variations of the distribution, the measurement is not properly simulated. A converging loop is performed as many times as needed to obtain the required iteration uncertainty. It should be pointed out that the iteration uncertainty gives directly the accuracy of the obtained beam parameters. The ultimate limit for the accuracy of the indirect determination is set by the step size in summation.

[1] H. Kogelnik, Appl. Opt. **5**, 1550-1567 (1966).

[2] J. Soto, M. Rendón and M. Martín, Appl. Opt. **36**, 7450-7454 (1997).

[3] J. M. Khosrosian and B. A. Garetz, Appl. Opt. **22**, 3406 (1983).

[4] G. P. Karman *et al*, Appl. Opt. **36**, 8091-8095 (1997).

[5] K. Lahti, E. Vahala, A. Kasvi, M. Heiliö, I. Tittonen (submitted).

6 INTERNATIONAL CO-OPERATION

6.1 INTERNATIONAL COMPARISON MEASUREMENTS

CCPR-K2.a International comparison of spectral responsivity in the NIR region

The measurements for this intercomparison were carried out by HUT in 1999.

CCPR-K3.b International comparison of luminous responsivity

Draft B of the final report has been published [R. Köhler, M. Stock, and C. Garreau, *An international comparison of luminous responsivity*, **Draft B**, BIPM, March 19, 1999]. The final result (-0,33 % deviation from the reference value with an uncertainty of 0,18 %) agrees well with the measurement uncertainty 0,6 % of HUT. (All measurement uncertainties are given at 95 % confidence level).

CCPR-S3 International comparison of cryogenic radiometers

Draft B of the final report has been published [R. Goebel, M. Stock, and R. Köhler, *Report on the international comparison of cryogenic radiometers based on transfer detectors*, **Draft B**, BIPM, 1999]. HUT made their measurements in 1996. The final results (-0,008…+0,016 % deviation from the reference value with an uncertainty of 0,027 %) agree well with the measurement uncertainty 0,05 % of HUT.

EUROMET 475 Intercomparison of spectral irradiance with PTB, Germany

The final report has been accepted for publication [K.D. Stock, K.-H. Raatz, P. Sperfeld, J. Metzdorf, T. Kübarsepp, P. Kärhä, E. Ikonen and L. Liedquist, "Detector-stabilized FEL lamps as transfer standards in an international comparison of spectral irradiance," *Metrologia* (in press)]. In this intercomparison, the spectral irradiance scale of HUT was compared with the spectral irradiance scale of PTB in the wavelength region 290 - 900 nm. The measurements of HUT were made in February 1999. The deviation of the scales (<2,5 % throughout the wavelength region) is well within the uncertainty of the intercomparison.

Bilateral intercomparison of luminous intensity units with NPL, UK

The final report has been published [T.M. Goodman, P. Toivanen, H. Nyberg, and E. Ikonen, “International comparison of luminous intensity units between the NPL (UK) and the HUT (Finland),” *Metrologia* 36, 15-18 (1999)]. The two units agree within 0,27 % with an uncertainty of 0,56 %.

Improving the accuracy of ultraviolet radiation measurement

In this project funded by the SMT-programme of the EU, novel filter radiometer techniques developed by HUT are used to compare various ultraviolet calibration facilities in France (BNM), Finland and UK (NPL). HUT acts as the pilot laboratory in the intercomparison and measures all filter radiometers used twice, before and after the measurements by other participants. During 1999, HUT designed and built 9 of the 18 filter radiometers used, characterised 9 filter radiometers, and sent them further to NPL to be measured.

International comparison of iodine-stabilised diode-lasers

HUT participated in an intercomparison of I_2-stabilised diode lasers in collaboration with MIKES. In this comparison 8 different laser systems were compared. The laser used by MIKES has been constructed at HUT in a collaboration project. During 1999, the measurements were carried out, and the final report [A. Zarka *et al*, “International comparison of eight semiconductor lasers stabilized on $^{127}I_2$ at $\lambda \approx 633$ nm,” (submitted)] was written.

International comparison of green He-Ne lasers

MIKES participated in the second international comparison between He-Ne lasers at 543 nm. The comparison was carried out in December 1999 at the Danish Institute of Fundamental Metrology (DFM). One laser from DFM (DFM1) and one from MIKES (MGI2) were involved. The laser used by MIKES is constructed in collaboration with the Metrology Research Institute of HUT. A final report was written: H. Simonsen, J. Hu, and K. Nyholm “International comparison of He-Ne lasers stabilized with I_2 at $\lambda = 543$ nm (December 1999): Northern European lasers”, *Metrologia* (submitted).

6.2 THEMATIC NETWORKS

6.2.1 Thematic network for ultraviolet measurements

The Thematic Network for Ultraviolet Measurements is a three-year project (SMT4-CT97-7510) funded by the Standards, Measurements and Testing (SMT) programme of the European Union (EU). The network is co-ordinated by the Helsinki University of Technology (HUT). It started its operation on November 15, 1997.

The Thematic Network is aimed to enhance exchange of results and ideas between research laboratories and industry and also to obtain a better understanding of the problems associated with the calibration and testing work. The network has 51 participants from 13 European countries. In addition, there are numerous additional members also outside the Europe. The participants include e.g. small industrial companies, national standards laboratories, and research organisations working with ozone research and measurements related with occupational health.

During its three years of operation, the network arranges a series of four workshops. During 1999, the third workshop was arranged at the National Physical Laboratory (NPL) in United Kingdom. In association with the workshop, a two-day training course was arranged. This training course contained twelve lectures on the basics of UV measurements. It was aimed for young scientists and technicians who are just entering the field of UV measurements.

The network publishes a newsletter, *UVNEWS*, which is edited by the HUT. The editor in chief is currently Petri Kärhä. *UVNEWS* contains mainly information about the past and forthcoming events of the network. During 1999, two issues were printed in March and July.

6.2.2 Fibre optics technology network

HUT is also a member in the *Fibre Optics Technology Network* -(FOToN)-(SMT4-CT98-7523) co-ordinated by the National Physical Laboratory (NPL) in United Kingdom. FOToN is an interactive information network for the optical fibre users community. It is sponsored by the European Commission under the Standards Measurement and Testing Programme. This three-year project was launched in November 1998 and comprises of thirteen Regional Groups. Hanne Ludvigsen acts as the regional co-ordinator of Finnish participants in the network. The Regional Groups hold two meetings a year for members of the network.

The main objective of the network is to bring together a broad spectrum of European industry and other organisations with an interest in the application of fibre optics. It has the aim of facilitating the practical and economic exploitation of fibre optic technology. World wide web pages are being developed for the promotion of regional groups activities and to provide an interactive source of information on all things fibre optic.

6.3 CONFERENCES AND MEETINGS

The personnel participated in the following conferences and meetings:

NRC Expert Seminar “Laser diodes in optical communications: state of the art and future trends”, Helsinki, Finland, January 12, 1999; *Hanne Ludvigsen and Goëry Genty*

Laser Comparison Meeting, Paris, France, January 17-24, 1999; *Mikko Merimaa*

Key Comparison Meeting, Paris, France, January 18-20, 1999; *Erkki Ikonen*

Conference on Microsystems Modeling, Espoo, Finland, January 28, 1999; *Ilkka Tittonen, Ville Voipio, Markku Kujala, Tuomas Lamminmäki and Kaius Ruokonen*

Creativity Forum 1999, Espoo, Finland, January 28, 1999; *Ilkka Tittonen*

Euromet Rapporteurs Meeting, Delft, The Netherlands, February 4, 1999; *Erkki Ikonen* (gave a talk on the Key Comparison meeting)

2nd UICEE Annual Conference on Engineering Education, Auckland, New Zealand, February 10-13, 1999; *Pekka Wallin*

Steering Group Meeting of the Fibre Optic Technology Network at NPL, London, UK, February 15, 1999; *Hanne Ludvigsen*

OFC’99 Conference, San Diego, California, USA, February 19-27, 1999; *Hanne Ludvigsen*

XXXIII Annual Conference of the Finnish Physical Society, Turku, Finland, March 4-6, 1999; *Goëry Genty* (gave a talk), *Miika Heiliö, Toomas Kübarsepp* (presented a poster), *Kristian Lahti*, *Thomas Lindvall*, *Tapio Niemi* (presented a poster), *Kaius Ruokonen* (presented a poster), *Ilkka Tittonen* (gave a talk), *Pasi Toivanen* (gave a talk), *Eero Vahala and Pekka Wallin*

Optical Fibre Measurement Course, NPL, London, England, March 8-10, 1999; *Hanne Ludvigsen*

Meeting of CCPR, Paris, France, March 23-28, 1999; *Erkki Ikonen*

3rd Hermann von Helmholtz Symposium, "Precision Measurement of Electromagnetic Radiation", PTB, Berlin-Charlottenburg, Germany, March 30, 1999; *Petri Kärhä*

Inauguration of the PTB Synchrotron Radiation Laboratory at BESSY II, PTB, Berlin-Adlershof, Germany, March 29, 1999; *Petri Kärhä*

Euromet Contact Persons Meeting, Delft, The Netherlands, April 11-13, 1999; *Erkki Ikonen* (chairman)

Optics Day 1999, Joensuu, Finland, April 23-24, 1999; *Goëry Genty* (gave a talk), *Jari Hovila* (presented a poster), *Erkki Ikonen* (gave an invited talk), *Kristian Lahti*, *Thomas Lindvall* (gave a talk), *Mikko Merimaa* (gave a talk), *Tapio Niemi* (gave a talk*) and Ilkka Tittonen*

Kick-off meeting of EUROMET project 515, Copenhagen, Denmark, May 10, 1999; *Erkki Ikonen*

Work Package Manager Meeting of the EU-project "Improving the Accuracy of Ultraviolet Radiation Measurement", London, UK, May 17-18, 1999; *Petri Kärhä*

Euromet Committee Meeting 13, Prague, Checz Republic, May 19-21, 1999; *Erkki Ikonen* (gave a talk on the activities of the EUROMET photometry and radiometry group)

Minisymposium on Cold Atoms and Bose-Einstein Condensation, Stockholm, Sweden, June 2, 1999; *Ilkka Tittonen and Thomas Lindvall*

Seminar of Fibre optic Communication Technology, Tampere, Finland, June 8, 1999; *Hanne Ludvigsen* (gave a talk)

CIE Division 2 TC2-47 meeting, Warsaw, Poland, June 28-30, 1999; *Petri Kärhä*

TMR School on “Quantum Computation and Quantum Information Theory”, Torino, Italy, July 12-23, 1999; *Thomas Lindvall*

Advanced Semiconductor Lasers and Applications, Santa Barbara, USA, July 18-23, 1999; *Mikko Merimaa* (gave a talk)

22nd International Conference on Low Temperature Physics, Helsinki, Finland, August 4-11, 1999; *Thomas Lindvall* (presented a poster), *Kaisa Nera* (presented a poster), *Kaius Ruokonen and Ilkka Tittonen*

Meeting on Optical Fibre Systems based on RCLED's and VCEL's, Tampere, Finland, August 17, 1999; *Hanne Ludvigsen*

Training Course of the Thematic Network for UV-Measurements, NPL, Teddington, UK, September 6-8, 1999; *Petri Kärhä*

Third Workshop of the Thematic Network for UV-Measurements, NPL, Teddington, UK, September 9-10, 1999; *Erkki Ikonen* (chairman of one session) *and Petri Kärhä* (chairman of one session)

Eurosensors XIII, The Hague, Netherlands, September 12-15,1999; *Ilkka Tittonen, Markku Kujala and Ville Voipio* (gave a talk)

Optical Fibre Measurement Conference, Nantes, France, September 22-24, 1999; *Hanne Ludvigsen, Goëry Genty and Tapio Niemi* (gave two talks)

COST 265 meeting, Nantes, France, September 25-26, 1999; *Hanne Ludvigsen*

OSA Annual Meeting/ILS-XV, Santa Clara, CA, USA, September 26-30,1999; *Goëry Genty* (gave a talk)

European Union Conference on Quantum Optics, Mallorca, Spain, October 2-7, 1999; *Ilkka Tittonen*

7th International Conference on New Developments and Applications in Optical Radiometry NEWRAD99, Madrid, Spain, October 25-27, 1999; *Erkki Ikonen, Petri Kärhä* (gave a talk), *Farshid Manoocheri* (presented a poster), *Pasi Toivanen* (gave a talk and presented two posters) *and Toomas Kübarsepp* (gave a talk)

Second International Workshop on Detector-Based UV Radiometry, Madrid, Spain, October 28, 1999; *Erkki Ikonen* (gave an invited talk on the Thematic

Network for UV measurement), *Petri Kärhä, Farshid Manoocheri, Pasi Toivanen and Toomas Kübarsepp*

Meeting of the Air-UV Working Group of the CCPR, Madrid, Spain, October 29; *Erkki Ikonen*

Winter Graduate School on Atom Traps, Ion Traps and Optical Tweezers, Solbacka, Stjärnhov, Sweden, November 2-5, 1999; *Thomas Lindvall*

ANSYS Heat Transfer Course, Helsinki, Finland, November 16-17, 1999; *Tuomas Lamminmäki and Kaius Ruokonen*

Work Package Manager Meeting of the EU-project "Improving the Accuracy of Ultraviolet Radiation Measurement", Paris, France, November 16-17, 1999; *Petri Kärhä*

21st Nordic Conference on Measurements and Calibration, Oslo, Norway, November 22-23, 1999; *Erkki Ikonen* (gave an invited talk)

Euromet contact persons meeting, Braunschweig, Germany, December 12-14, 1999; *Erkki Ikonen* (chairman) *and Petri Kärhä*

6.4 VISITS BY THE LABORATORY PERSONNEL

Jari Hovila to Elektronik/EP'99 Trade, Stockholm, Sweden, January 19-22, 1999

Tomi Blomqvist to SP Swedish National Testing and Research Institute, Borås, Sweden, March 5-6, 1999

Petri Kärhä to PTB-Berlin and OMTEC GmbH, Berlin, Germany, March 27-28, 1999; LNE, Paris, France, November 17, 1999

Erkki Ikonen to NMi-VSL, Delft, The Netherlands, April 13, 1999; DFM Optics Laboratory, Copenhagen, Denmark, May 10, 1999; CMI, Prague, Czech Republic, May 20, 1999; JV, Oslo, Norway, November 23, 1999

Toomas Kübarsepp to the Observatory of Tarto, Estonia, October 6-7, 1999

Kaj Nyholm to Danish Institute of Fundamental Metrology DFM, Denmark, December 9-10, 1999

6.5 RESEARCH WORK ABROAD

Maria Uusimaa, Institut National de Sciences Appliquées de Lyon, Lyon, France, January 1 - March 31, 1999

Markku Vainio, Lund University of Technology, Lund, Sweden, September 1 - December 31, 1999

6.6 GUEST RESEARCHERS

José Ramón Casado Dominguez, Centro Politécnico Superior, University of Zaragoza, Spain, January 1- March 31, 1999

Saulius Nevas, University of Kaunas, Kaunas, Lithuania, January 1 - May 31, 1999

Masaki Takada, Kyoto University, Kyoto, Japan, June 10 - August 8, 1999

Anne-Claire Dupart, Institut National Des Telecommunications, Paris, France, June 28 - August 31, 1999

6.7 VISITS TO THE LABORATORY

Dr. Volker Bentlage, OMtec GmbH, Germany, January 11, 1999

Mr. Leif Liedquist, SP Swedish National Testing and Research Institute, Borås, Sweden, April 8, 1999

Prof. Åsa Lindberg and Pawel Kluczynski, University of Umeå, Sweden, June 4, 1999

Dr. J. F. Clare, Measurement Standards Laboratory, Industrial Research Limited, New Zealand, June 21, 1999

Dr. Jian Guo Zhang, Asian Institute of Technology, School of Advanced Technologies, Thailand, June 30, 1999

Dr. George Eppeldauer, National Institute of Standards and Technology, USA, October 30 - November 3, 1999

Dr. Peter Huang, Nartional Institute of Standards and Technology, USA, December 2-6, 1999

Prof. Mart Min, Tallinn Technical University, Estonia, December 9-11, 1999

Dr. Uno Veismann, Department of Physics, Tartu University, Tartu, Estonia, December 10-11, 1999

Prof. Wolfgang Heering, University of Karlsruhe, Karlsruhe, Germany, December 9-12, 1999

Dr. Magnus Ljungström, Gamma Optronik AB, Uppsala, Sweden, December 14, 1999

Dr. Mackillo Kira, KTH Stockholm, Sweden, December 22, 1999

7 PUBLICATIONS

7.1 ARTICLES IN INTERNATIONAL JOURNALS

P. Toivanen, F. Manoocheri, P. Kärhä, E. Ikonen and A. Lassila, "Method for characterization of filter radiometers," *Appl. Opt.*, **38** (1999), pp. 1709-1713.

Niemi, S. Tammela, T Kajava, M. Kaivola and H. Ludvigsen, "Temperature-tunable silicon-wafer etalon for frequency chirp measurements", *Microwave and Optical Technol. Lett.*, **20** (1999), pp. 190-193.

M. Merimaa, H. Talvitie, J. Hu, and E. Ikonen, "Iodine-stabilized diode laser at 633 nm: Effects of optical feedback", *IEEE Trans. Instrum. Meas.*, **48** (1999), pp. 587-591.

F. Manoocheri, L. Palva, E. Garam and E. Ikonen, "Characterization of a multipoint measuring system of photosynthetically active radiation", *Instrum. Sci. Technol.*, **27** (1999), pp. 45-58.

A. Haapalinna, F. Manoocheri and E. Ikonen, "High-accuracy measurement of specular spectral reflectance and transmittance", *Analytica Chimica Acta,* **380** (1999), pp. 317-325.

A. Haapalinna, T. Kübarsepp, P. Kärhä and E. Ikonen, "Measurement of the absolute linearity of photodetectors with a diode laser", *Meas. Sci. Technol.,* **10** (1999), p. 1075-1078.

F. Manoocheri, P. Kärhä, L. Palva, P. Toivanen, A. Haapalinna and E. Ikonen, "Characterization of optical detectors using high-accuracy instruments", *Analytica Chimica Acta*, **380** (1999), pp. 327-337.

T. M. Goodmann, P. Toivanen, H. Nyberg and E. Ikonen, "An intercomparison of luminous intensity units between the NPL, (UK) and the HUT, (Finland)", *Metrologia,* **36** (1999), pp. 15-18.

K. Jacobs, I. Tittonen, H. M. Wiseman and S. Schiller, "Quantum noise in the position measurement of a cavity mirror undergoing Brownian motion", *Phys. Rev. A,* **60** (1999), pp. 538-548.

I. Tittonen, G. Breitenbach, T. Kalkbrenner, T. Müller, R. Conradt, S. Schiller, E. Steinsland, N. Blanc and N. F. de Rooij, "Interferometric measurements of the position of a macroscopic body: towards observation of quantum limits", *Phys. Rev.*, **A 59** (1999), pp. 1038-1044.

P. Kärhä, T. Kübarsepp, F. Manoocheri, P. Toivanen, E. Ikonen, R. Visuri, L. Ylianttila and K. Jokela, "Portable detector-based primary scale of spectral irradiance", *J. Geophysical Research* (in press).

K. Jokela, L. Ylianttila, R. Visuri, P. Kärhä and E. Ikonen, "Intercomparison of lamp and detector-based UV-irradiance scales for solar UV radiometry", *J. Geophysical Research* (in press)

T. Kübarsepp, P. Kärhä and E. Ikonen, "Interpolation of the spectral responsivity of silicon photodetectors in the near ultraviolet", *Appl. Opt.* (in press).

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