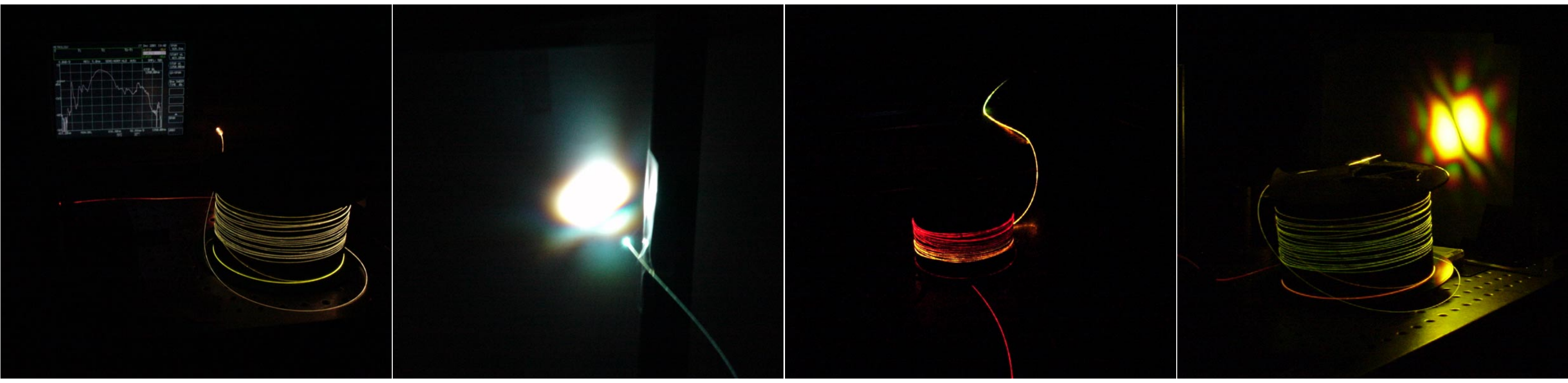
Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute Report 20/2002
Espoo 2002

ANNUAL REPORT 2001



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TEKNISKA HÖGSKOLAN
HELSINKI UNIVERSITY OF TECHNOLOGY
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Editor Petri Kärhä

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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ISSN 1237-3281

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Helsinki 2002

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1 INTRODUCTION

Expansion of the research activities of the Metrology Research Institute continued in 2001. In the University's present financial situation, new activities can only be based on acquired funding which covers already almost two thirds of the total budget of the Institute. It should be noted that the fastest growing section of the budget is the direct funding from companies.

The research fields of the Institute include optical radiation measurements, microtechnologies, applied quantum optics, and fiber optics where several significant developments were carried out in 2001. New equipment was constructed for characterization of filter radiometers with a wavelength tunable Ti:Sapphire laser. Such characterizations can be made only in a couple of other National Metrology Institutes. An all-optical 3-GHz frequency standard was developed using coherent population trapping in rubidium vapor. The measured linewidth of this system is one of the narrowest ever reported. Collaboration with Crystal Fiber A/S in Denmark was initiated to study novel optical properties of photonic crystal fibers and supercontinuum generation in these fibers.

The Metrology Research Institute offers several courses where the practical laboratory exercises are emphasized. For example, Fundamentals of Measurements is offered to all second year students of the Department. A new laboratory course on microsystems was implemented in 2001. The Institute is active also in post-graduate education and is partner in several National Graduate Schools. Seven master's degrees and two doctoral degrees were completed in 2001.

The Metrology Research Institute is an active participant within international research programs. European Union funded projects Improving the Accuracy of Ultraviolet Radiation Measurements and Fiber Optic Thematic Network (FOToN) were successfully completed in 2001. A project on Optical Communication Wavelength References was initiated with the support of Nordic Industrial Fund. We take part in international activities within the framework of EUROMET, CCPR and COST. The personnel of the Institute are chairing several international committees including the CCPR Ultraviolet Working Group, the Scientific Committee for the 5th Workshop on Ultraviolet Radiation Measurements and COST Action 265 Working Group on Photonic Crystal Fibers.

Erkki Ikonen

2 PERSONNEL

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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute (Mittaustekniikan laboratorio) in 2001. Those marked by * are given biennially.

S-108.180	Electronic Measurements and Electromagnetic Compatibility 2 credits (Petri Kärhä, Esa Häkkinen, Kristian Lahti)
S-108.181	Optics 2 credits (Erkki Ikonen)
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-108.184	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 and Matti Kaivola)
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.)

Mikko Merimaa: Frequency Standards based on Diode Lasers.

Opponent: Dr. Lennart Robertsson, BIPM, France.

Ville Voipio: Instrument for Measuring pH with Optical Indicator Thin Film.

Opponents: Professor Vahid Sandoghdar, ETH Zurich, Switzerland and Dr. Juha Rantala, Guideoptics, 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.

Kristian Lahti: Phase-Matching in the Optical Nonlinear Process of Second Harmonic Generation.

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

Mari Ylönen: Glass as pressure sensor material.

Markku Vainio: Optical nonlinear frequency doubling with a transmission grating laser.

Tero Ahola: Frequency-stabilized Nd:YAG laser at 532 nm.

Miika Heiliö: Digital laser frequency stabilization using a high finesse interferometer as a reference.

Pekka Hilke: Transmission of digital television channels in wavelength division multiplexed fiber optic networks.

Jari Hovila: Characterization of the national standard of the unit of luminous flux.

Ossi Hahtela: Optical Interferometry on a mechanical silicon oscillator.

3.2.4 Awards

Thomas Lindvall: Award for the Master’s Thesis in 2000, issued by Helsinki University of Technology.

4 NATIONAL STANDARDS LABORATORY

Metrology Research Institute is the Finnish national standards laboratory for the measurements of optical quantities, appointed by the Center for Metrology and Accreditation (MIKES). The institute gives official calibration certificates on the optical quantities listed in Table 4.1. Recent changes include calibration services on new quantities - luminous flux, diffuse reflectance factor, and fiber optic power.

During 2001, 46 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 standard ISO/IEC 17025.

Further information for the calibration services may obtained from Farshid Manoocheri (Head of the calibration services) or Petri Kärhä (Quality manager).

Table 4.1. Calibration services offered by the Metrology Research Institute of HUT.

Quantity	***Range***	***Wavelength range***	***Uncertainty*** **(*k*=2)**
Luminous intensity	10 – 10 000 cd	–	0.3 %
Illuminance	10 – 200 lx	–	0.2 %
	200 – 5 000 lx		0.3 % – 0.5 %
Luminance	5 – 40 000 cd m^{-2}	–	0.8 %
Luminous flux	10 – 10 000 lm	–	1.0 %
Spectral irradiance	10 pW mm^{-2} nm^{-1} –	290 – 380 nm	1.1 % – 2.8 %
	500 μW mm^{-2} nm^{-1}	380 – 900 nm	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 %
Color coordinates (x, y)	0 – 1	–	0.1 %
Color temperature	1 000 – 3 500 K	–	0.15 %
Optical power	0.1 – 0.5 mW	458.1, 465.9, 472.8, 476.6, 488.1, 496.6, 501.9, 514.7, 543.5, 633.0 nm	0.05 %
	10 nW – 1 mW	250 – 380 nm	0.3 % – 0.8 %
	10 nW – 1 mW	380 – 920 nm	0.1 % – 0.3 %
	10 μW – 10 W	250 nm – 16 μm	2 % – 10 %
Transmittance	0.0005 – 1	250 – 380 nm	0.1 % – 1 %
	0.0001 – 1	380 – 920 nm	0.05 % – 0.5 %
	0.0005 – 1	920 – 1700 nm	0.1 % – 1 %
Spectral responsivity		250 – 380 nm	1 %
	> 0.01 A/W	380 – 920 nm	0.5 %
		920 – 1700 nm	4 %
Reflectance (5°–85°)	0.05 – 1	250 – 380 nm	0.5 % – 5 %
	0.01 – 1	380 – 1000 nm	0.3 % – 3 %
Diffuse reflectance factor	0.05 – 1	360 – 830 nm	0.4 % – 1 %
Optical wavelength	400 nm – 1.55 μm	–	0.01 nm
Fiber optic power	1 nW – 7 mW (-60 dBm – +8 dBm)	1310 nm, 1550 nm	1.5 %

5 RESEARCH PROJECTS

5.1 Optical Radiation Measurements

5.1.1 Intercomparison of characterization techniques of filter radiometers in the ultraviolet region

P. Kärhä, N. J. Harrison[*]*, S. Nevas,*
W. S. Hartree[*]*, and I. Abu-Kassem*[†]

[*] *National Physical Laboratory (NPL), UK*
[†] *Bureau National de Métrologie (BNM), France*

Narrow-band filter radiometers are in wide use in radiometry in such areas as the realization of spectral irradiance scales or the measurement of radiation temperature. Very low calibration uncertainties are often reported but the comparability of the characterization techniques used has rarely been verified in intercomparisons.

We developed two types of filter radiometers to measure the radiation emitted from UV sources at the wavelengths of 248, 313, 330 and 368 nm [1]. The first type was based on single, wide band-gap solar blind photodiodes. The second type utilized trap detectors based on silicon photodiodes. Interference filters with a nominal 10-nm bandwidth were used for the spectral selection with both types of radiometers.

HUT and BNM characterized the radiometers for spectral responsivity using conventional monochromator-based spectrophotometers. NPL utilized their laser radiometry facility for similar characterization.

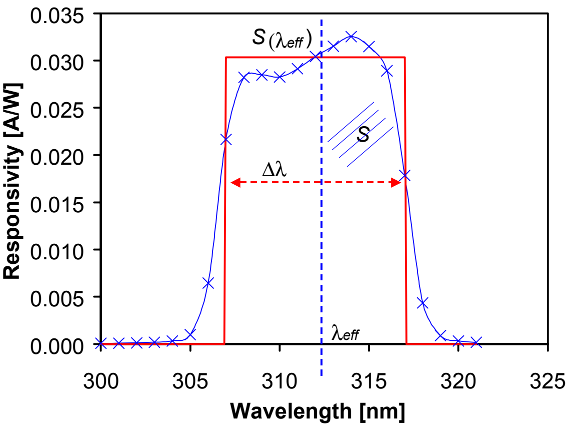

Figure 5.1.1-1. Analysis of filter radiometer data. λ_{eff} describes the agreement of the wavelength scales. Integrated response S can be used to compare spectral responsivity measurements.

New methods suitable for narrow-band radiometers were developed for analyzing the spectral responsivity measurements. The effects of wavelength shifts were separated from the data. (Figure 5.1.1-1). Spectral irradiance values that institutes would measure on black body radiators were also compared.

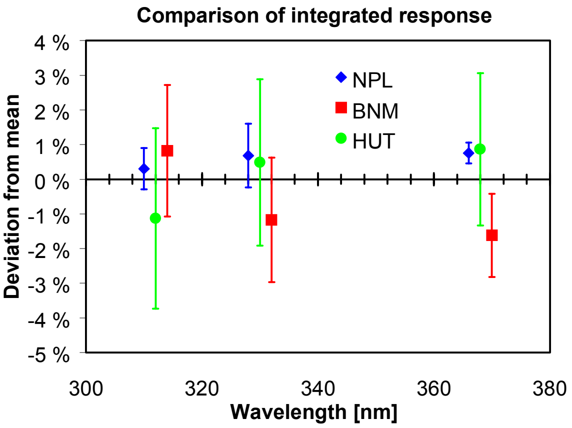

Figure 5.1.1-2. Comparison of spectral responsivity measurements on wide band-gap filter radiometers.

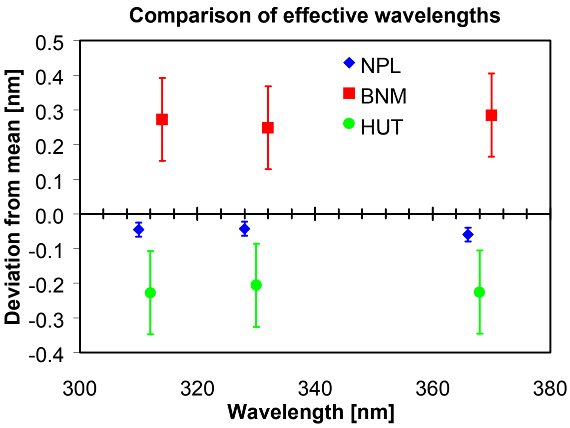

Figure 5.1.1-3. Comparison of wavelength scales.

Most of the results were in agreement within their uncertainties. The agreement between the participating laboratories in the spectral irradiance and spectral responsivity measurements was roughly on the level of 0.1 – 2 % (Figure 5.1.1-2).

The study identified various aspects of the measurement facilities that required improvement. The wavelength scales of the participating laboratories differ more than the stated uncertainties would imply (Figure 5.1.1-3). This appears to be a point that has not earlier been properly tested, as intercomparisons are usually performed using spectrally flat artifacts.

The study did not demonstrate that one of the filter radiometer types was superior to the other. The angular properties of trap detectors are complicated, but solar blind photodiodes have higher nonuniformity. These two characteristics may explain some of the discrepancies that arose during the intercomparison, as the beam geometries used for the filter radiometer calibration were not common.

The work has been carried out within project SMT4-CT98-2242 "Improving the Accuracy of Ultraviolet Radiation Measurement," funded by the Standards, Measurements and Testing program of the European Union.

[1] 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," (submitted).

5.1.2 A portable field calibrator for solar UV measurements

P. Kärhä, L. Ylianttila[*]*, T. Koskela*[†]*,*
K. Jokela[*]*, and E. Ikonen*

[*] *STUK, Radiation and Nuclear Safety Authority*
[†] *Finnish Meteorological Institute (FMI)*

Stationary roof-mounted spectroradiometers are used to monitor the solar UV radiation passing through the atmosphere. Calibration of these spectroradiometers is problematic, because transportation to calibration laboratories may affect their calibration, and calibration outside in the measurement site is influenced by environmental conditions. Another problem faced by field monitoring sites is the length of the traceability chain. Several steps are required to transfer the calibration from the primary standards laboratory to the spectroradiometers, which results in increased uncertainty.

We have developed a portable detector-monitored calibration system for solar UV spectroradiometers [1]. The calibrator utilizes a 1-kW DXW lamp as the light source. The output of the light source is continuously monitored with two temperature-controlled filter radiometers at 313 nm and 368 nm wavelengths. The lamp is operated in current-stabilized mode. When the aging characteristics of the lamp are known, the signals of the monitoring filter radiometers can be used to calculate corrections for the spectrum as the lamp ages.

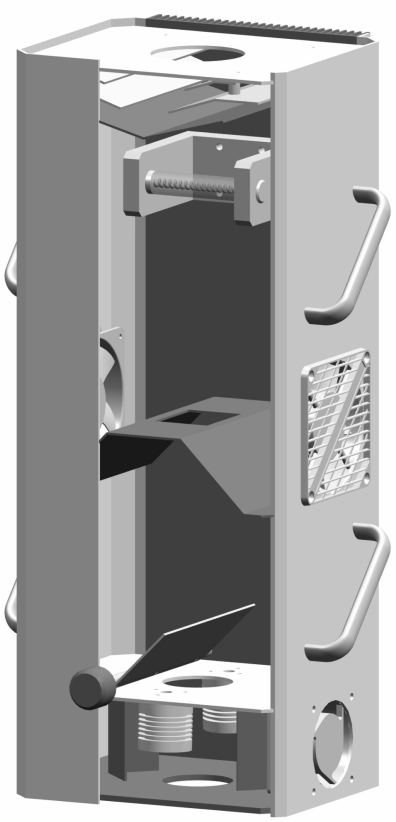

Figure 5.1.2-1. Construction of the improved calibrator.

The spectral irradiance in the output of the calibrator is calibrated either with a spectroradiometer or absolutely characterized filter radiometers. The use of latter provides the shortest possible traceability chain for the calibrations.

Figure 5.1.2-2. Calibrator assembled on top of a Brewer spectroradiometer.

In 2001, a second improved prototype of the calibrator was issued (Figure 5.1.2-1). Modifications include e.g. handles that make alignment more reliable and improved cabling inside the housing.

The calibrator has been thoroughly tested in both laboratory and in field. The results of the field calibrations indicate that the device works satisfactorily under a wide variety of environmental conditions. The device can be used in summer, when temperature can be as high as 30 °C and direct sunshine heats the housing of the calibrator. Successful calibrations have also been carried out in winter, with light snowfall and ambient temperature of –7 °C (Figure 5.1.2-2).

The work has been carried out within project SMT4-CT98-2242 "Improving the Accuracy of Ultraviolet Radiation Measurement," funded by the Standards, Measurements and Testing program of the European Union.

[1] P. Kärhä, L. Ylianttila, T. Koskela, K. Jokela, and E. Ikonen, "A portable field calibrator for solar ultraviolet measurements," *Metrologia* (accepted).

5.1.3 Characterization of filter radiometers with wavelength-tunable laser source

M. Noorma, P. Toivanen, F. Manoocheri, and E. Ikonen

Monochromators are traditionally used for characterization of the spectral irradiance responsivity of filter radiometers. The problems arising from the wide bandwidth of the monochromator and also from the non-uniformities of the filter radiometer can be avoided by using a scanning method (Figure 5.1.3-1). The irradiance responsivity is obtained by moving the filter radiometer in relation to a power-stabilized beam of a wavelength-tunable laser. The scanning is repeated at several wavelengths to cover the whole pass-band of the filter radiometer. In addition, online monitoring of the laser wavelength completely removes the problem of wavelength shifts, often present in monochromator measurements.

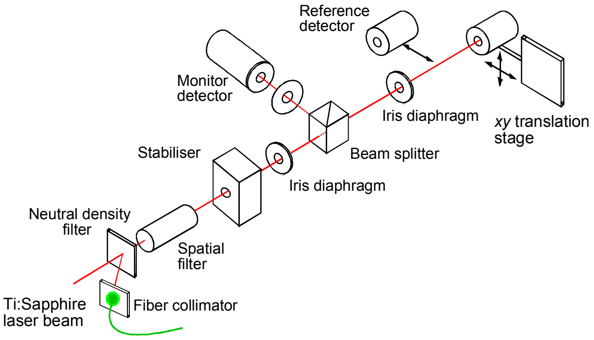

Figure 5.1.3-1. Setup for the filter radiometer characterization.

With coherent laser light, interference between the filter surfaces can cause spurious effects in the measured responsivity. Wedged filters and anti-reflection coatings of air-glass surfaces were used to reduce the effects of interference. Measuring the responsivity as a function of wavelength over a very narrow band normally reveals any remaining interference effects. Ti:Sapphire laser was used in the wavelength band from 800 to 900 nm for the measurements. The results were compared with more conventional monochromator measurements. It appears that filter radiometers can be characterized with an uncertainty lower than 0.1 % using the scanning method.

The work has been financially supported by the Center for Metrology and Accreditation.

5.1.4 Radiometric determination of radiation temperatures

P. Kärhä, M. Noorma, T. Jankowski,
*T. Weckström**, *and E. Ikonen*

* *Center for Metrology and Accreditation (MIKES)*

According to the international temperature scale of 1990 (ITS-90), temperatures above 961.78 °C are defined in terms of a defining fixed point and the Planck radiation law [1]. The defining fixed points include freezing points of silver (961.78 °C), gold (1064.18 °C) and copper (1084.62 °C). A black body radiator operating at a fixed-point temperature is used to calibrate an optical pyrometer that measures radiance at a single wavelength, typically 650 nm. This pyrometer is then used to measure the temperature of a variable temperature black body that operates between and above the defining fixed points.

We have studied an alternative approach to define radiation temperatures in the range from 968 °C to 1450 °C. The spectral irradiance in front of a variable temperature black body is measured by using a high accuracy filter radiometer. The filter radiometer consists of a trap detector, a precision aperture, and a set of temperature stabilized narrow band-pass filters. All components are absolutely characterized.

The geometry of the measurements is

determined by the area of the opening of the black body radiator, the area of the precision aperture of the filter radiometer, and the distance between the radiometer and the black body radiator. Known geometry allows calculation of the spectral radiance, and thus determination of the radiation temperature of the black body radiator.

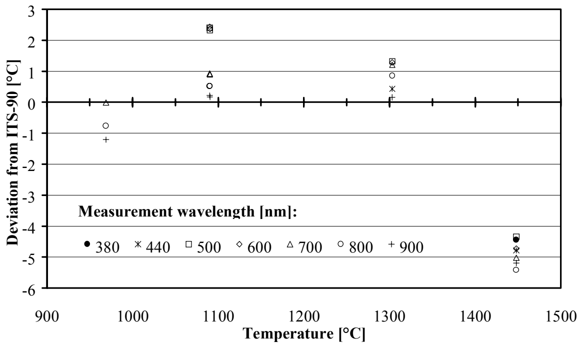

Figure 5.1.4-1. Preliminary results. The graph shows differences of the measured temperatures from the ITS-90. Different symbols indicate measurements at different wavelengths.

Preliminary measurements carried out are presented in Figure 5.1.4-1. A variable temperature black body radiator was measured with four temperature settings using 7 different filters for wavelength selection. The temperatures were also measured using a pyrometer calibrated with a silver point cell of ITS-90. The results are in good agreement at 1090 °C and 1300 °C temperatures. At 900 nm wavelength the deviation is only of the order of +0.2 °C. The deviation increases with decreasing wavelength probably because of weaker signal levels with the filter radiometer. Largest deviation was noted at the temperature of 1450 °C, where the deviation is of the order of -5 °C.

The future work in the project will concentrate in improving the measurement accuracy. A new method will be tested for determining the irradiance responsivities of the filter radiometer [see chapter 5.1.3]. Distance measurements will also be improved, and measurements will be carried out with different black body radiators. The reason for the large discrepancy at 1450 °C will be studied. Linearity measurements of the pyrometer indicate that it is unlikely that the discrepancy would be due to the extrapolation of the ITS-90 based values. Measurements give useful information on the emissivity properties of the black body radiators and offer improvements between and above the fixed-point temperatures.

[1] H. Preston-Thomas, “The International Temperature Scale of 1990 (ITS-90),” *Metrologia* **27**, 3-10 (1990).

5.1.5 Study of fiber optic power measurements using photodiodes with and without integrating sphere

J. Envall, P. Kärhä, and E. Ikonen

Fiber optic power measurement is one of the fundamental measurements in telecommunications. These measurements are needed for example to determine losses in telecommunication cables, in the maintenance of telecommunication networks, and in the development of several fiber optic devices.

We have developed a setup for calibration of fiber optic power meters. The calibration equipment consists of three InGaAs photodiodes (Figure 5.1.5-1). Two of the photodiodes are mounted directly to adapters with standard FC connectors. The third photodiode is fitted into a 5-cm integrating sphere. The sphere has two input ports, one equipped with a similar adapter as the two detectors mentioned earlier, and one with no extra mountings. The second input port can be used for calibrating the sphere detector within a sequence of measurements without removing the adapter.

Detectors, with their FC connectors removed, are calibrated with collimated laser beams against a pyroelectric radiometer traceable to a cryogenic absolute radiometer. In addition, spatial uniformities and angular responsivities have been measured. This data is used to calculate corrections due to the geometry of the beam from the fiber end.

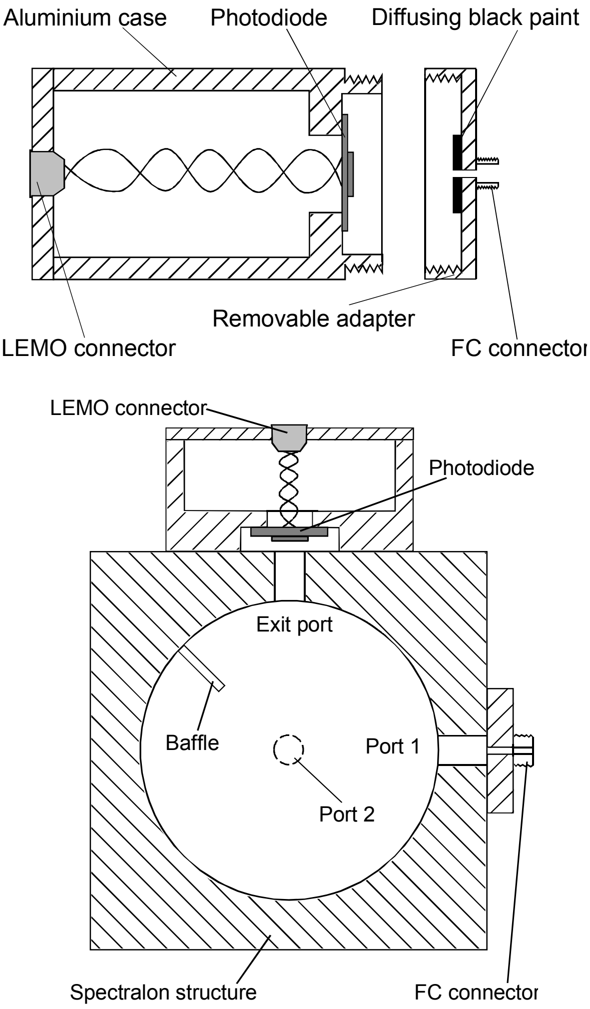

Figure 5.1.5-1. Physical structure of the detectors studied.

Lasers are available for calibrations at the wavelengths of 1310 nm and 1550 nm wavelengths. In future, it is planned to include 850 and 1620 nm lasers. Calibrations can be performed with single-mode fibers.

Characterization measurements carried out so far indicate good results even without using the integrating sphere. The spatial nonuniformities of the plain photodiodes are of the order of 0.3 % throughout the active area of 5 mm in diameter. The angular response varies less than ±0.2 % within the exit angle of ±8°, where the radiation emitted by the fiber end subsists. These extremely good values eliminate the need of integrating sphere in practice. The uncertainty obtainable is presently of the order of 1.5 % ($k = 2$).

The work has been financially supported by the Center for Metrology and Accreditation.

5.1.6 Development of absolute scale of spectral diffuse reflectance

S. Nevas, F. Manoocheri, and E. Ikonen

Measurements of spectral diffuse reflectance play an important role in various fields of industrial and research applications. In most cases, the measurements are made relative to the reference standards. By international agreement, the primary standard for diffuse reflectance is the perfect reflecting diffuser. Since there is no such material that would satisfy the definition of the perfect diffuser, absolute measurement methods are employed that relate the reflectance values of a standard to that of the perfect reflecting diffuser. At present in Europe, there are only a few traceable scales of absolute diffuse reflectance.

The present scale of spectral diffuse reflectance at HUT is based on direct comparison with standards obtained from the absolute scales of PTB (Physikalisch-Technische Bundesanstalt, Germany) and NRC (National Research Council, Canada). In order to overcome the limitations of a relative scale, a facility is under development that will provide spectral diffuse reflectance, transmittance, and bi-directional radiance and transmittance factors of a range of standards in absolute units.

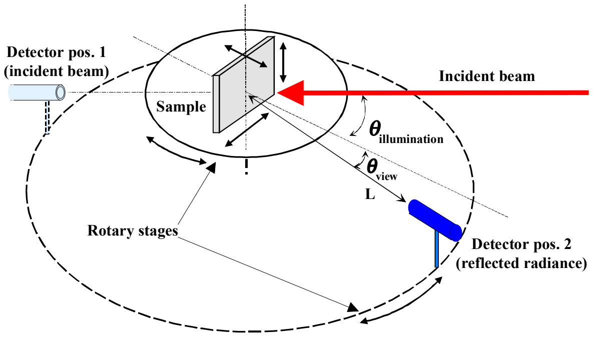

Figure 5.1.6-1. Basic layout of the gonio-spectrometric detection system. The bi-directional radiance factor for certain geometries is determined by comparing two fluxes: the incident and the reflected into the solid angle.

The developed facility will enable measurements of spectral diffuse reflectance and bi-directional radiance factor of samples under the most of the CIE recommended geometries of illumination and view in the wavelength range of 360-830 nm. The instrument will involve the use of goniospectrometric detection system. To provide the facility with a monochromatic source of radiation a state-of-the-art optical source system will be implemented. We aim to reach an uncertainty of less than 0.2 % (1 σ) in the visible spectral range.

The work has been financially supported by the Center for Metrology and Accreditation.

5.1.7 Optical characterization of thin films

S. Nevas, F. Manoocheri, and E. Ikonen

Thin films are one of the building blocks in optical / opto-electronic technology. It is often necessary to measure optical parameters of the deposited layer: the complex index of refraction and the thickness of the film. The most common measurement techniques are based either on ellipsometry or on determining spectrophotometric properties of the layer. We use the latter approach exploiting our high-accuracy reference spectrophotometer for reliable transmittance measurements.

Typically, the coherence length of the spectrophotometer output is considerably smaller than the substrate thickness and much larger than the thickness of the film. As a result, the multiple interreflections in the film layer are coherent while in the substrate slab they are non-coherent. This fact allows describing the spectral transmittance / reflectance of thin film samples by using analytical equations.

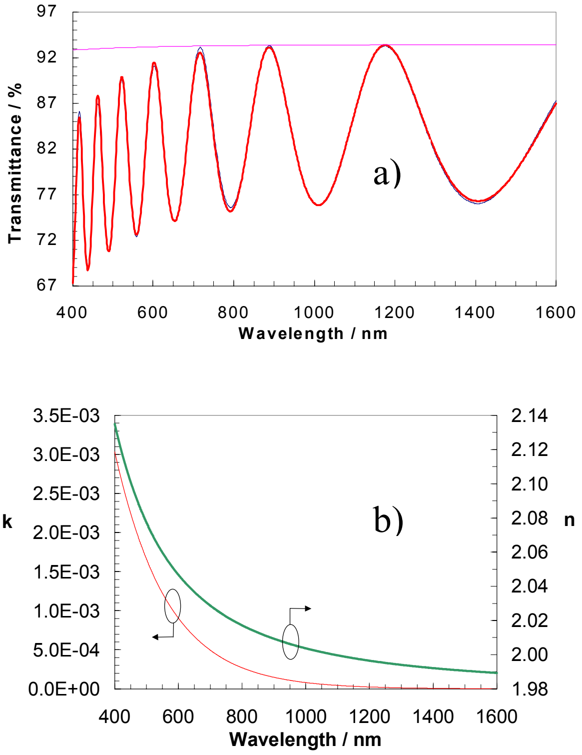

Figure 5.1.7-1. Characterization of a Ta_2O_5 thin film deposited on fused quartz substrate: a) the measured, fitted and bare-substrate transmittances; b) the obtained real, n, and imaginary, k, parts of the refractive index. The determined film thickness is 883 nm.

We determine the complex index of refraction and the thickness of the layer deposited on a known substrate by means of nonlinear least-squares regression. During the fitting procedure, parameters of the dispersion formulas and film thickness are adjusted until the calculated spectrum matches the measured transmittance.

Several samples of dielectric thin films deposited on optical-quality substrates have been investigated. The transmittances were measured in the VIS-NIR region and optical parameters of the layers were extracted from the spectra. Fitted and measured transmittances are in good agreement with each other.

The accuracy with which thin film properties can be determined is highly dependent on the quality of the transmittance measurements. Factors such as the accuracy of the wavelength scale, stability and linearity of the detection system have a profound effect on the reliability of the retrieved parameters. Our reference spectrophotometer has demonstrated excellent continuity of the measurement results over the spectral range of 400-1600 nm. This provided a good starting point for the application of the measurement capability for reliable characterization of thin films.

The work has been financially supported by Planar Systems, Guideoptics, and TEKES.

5.2 Length Metrology

5.2.1 Iodine-stabilized diode lasers

M. Merimaa, M. Vainio, K. Nyholm[*]*, and E. Ikonen*

[*] *Center for Metrology and Accreditation (MIKES)*

Frequency stabilized He-Ne gas lasers at 633 nm are generally used for the realization of the definition of the meter and form the current basis for accurate length measurements. However, there is definite interest in frequency stabilization of diode lasers at 633 nm, as their output power is comparatively high and diode lasers are inherently compact. The invention of the femtosecond frequency comb for direct link between optical and microwave frequencies has recently increased the interest in diode laser frequency stabilization, as diode lasers can easily achieve power levels which are sufficient for beat frequency measurements with the comb.

In 2001 the emphasis of the development of iodine stabilized diode lasers has been on the construction of a more robust and hermetically sealed transmission-grating laser to obtain better passive frequency stability of the laser source. The aim is to develop a compact laser source that can, without adjustments, reproduce desired wavelength at a few GHz accuracy despite changes in ambient temperature or pressure. In addition, the modulation properties of the laser have been improved to shift the measurement to higher frequencies where 1/f-type intensity and frequency noise of diode lasers is lower.

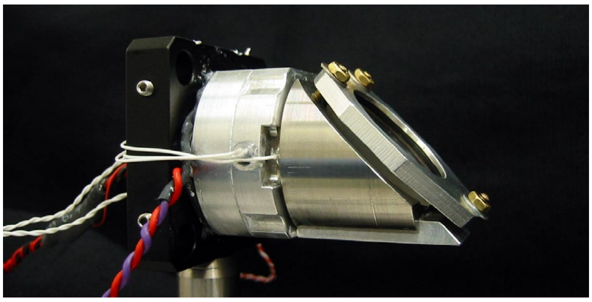

Figure 5.2.1-1. Photograph of the prototype laser.

Figure 5.2.1-1 shows a photograph of the developed prototype laser, which is manufactured from Invar and aluminum. The design has been optimized for small and mode-hop free frequency change, if the temperature of the laser body changes. Preliminary tests of the laser source are being carried out and the laser will be used in the stabilization set-up in 2002.

5.2.2 Iodine-stabilized Nd:YAG lasers

K. Nyholm[*]*, T. E. Ahola, M. Merimaa, and E. Ikonen*

[*] *Center for Metrology and Accreditation (MIKES)*

Traditionally, practical length metrology is carried out using iodine-stabilized He-Ne lasers at 633 nm. In 1997, when Nd:YAG lasers stabilized to iodine at 532 nm had demonstrated stabilities comparable to He-Ne lasers, the wavelength 532 nm realized by Nd:YAG laser was added to the wavelengths recommended for the practical realization of the meter.

Diode-pumped Nd:YAG lasers have many attractive features for length metrology, e.g. low intrinsic frequency and intensity noise, and high output power. Moreover, the iodine absorption lines are strong and narrow near 532 nm forming an almost ideal frequency reference. Excellent frequency stabilities and repeatabilities have been achieved by Nd:YAG lasers stabilized to iodine using FM-sideband techniques. However, similar performance can be reached using standard third-harmonic technique widely used in frequency stabilization, as it provides means to construct compact and relatively inexpensive systems.

In collaboration with the Center for Metrology and Accreditation, a diode-pumped Nd:YAG laser was frequency-stabilized to the Doppler-free spectrum of iodine at 532 nm. The high power of the Nd:YAG laser and the use of a PPKTP-crystal enable frequency doubling without an external cavity and hence the use of third-harmonic technique. In Figure 5.2.2-1 is shown the Nd:YAG laser system.

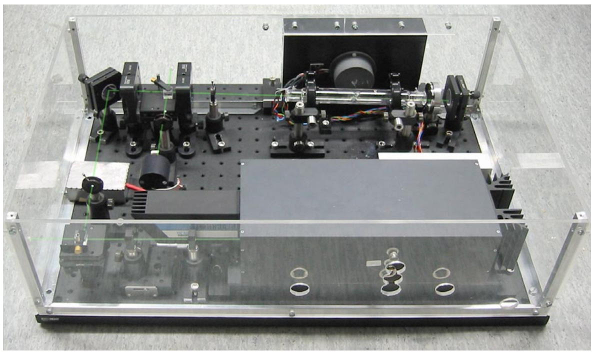

Figure 5.2.2-1. Iodine-stabilized Nd:YAG laser system.

In order to use third-harmonic technique two piezo-crystals were attached on the laser crystal: one for frequency modulation and the other for frequency fine-tuning. Coarse-tuning is realized by temperature control of the laser crystal.

The performance of the system was tested in an international comparison held at the BIPM. The results show that good relative frequency stability (7×10^{-14}, 1 s, 40-cm iodine cell) and excellent repeatability are achievable even by using third-harmonic locking.

5.3 Microtechnologies

5.3.1 Micromechanical resonators for RF-applications

T. Lamminmäki, P. Rantakari, M. Koskenvuori, and I. Tittonen

The general trend towards the use of smaller, better integrable MEMS (Micro ElectroMechanical Systems) RF-components to replace discrete RF-filters, oscillators and switches is shown in Figure 5.3.1-1.

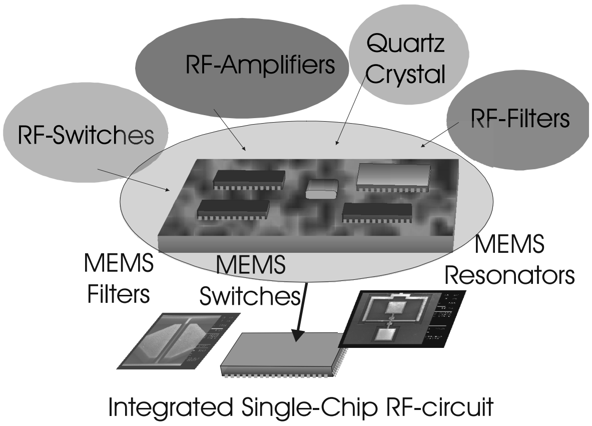

Figure 5.3.1-1. Integrating the discrete RF-components into a single-chip RF-circuit.

Microscale mechanical resonators (Figure 5.3.1-2) fabricated on SOI (Silicon On Insulator) wafers can be used as building blocks for the RF-components. The excellent mechanical properties of single crystal silicon enable low losses even for microscale resonators, but the lack of piezoelectricity in silicon leads to a need for different drive and excitation methods from those used in conventional quartz resonators. Therefore capacitive coupling is used to excite and read the resonance. Capacitively actuated mechanical systems can successfully be analyzed using FEM (Finite Element Method) simulation techniques by simultaneously taking into account mechanical, thermal and electromagnetic dynamic interactions. FEM can also be used to estimate those parameters that are later fed into the circuit-simulation program revealing how the mechanical design in effect works as a part of an RF electronics circuit.

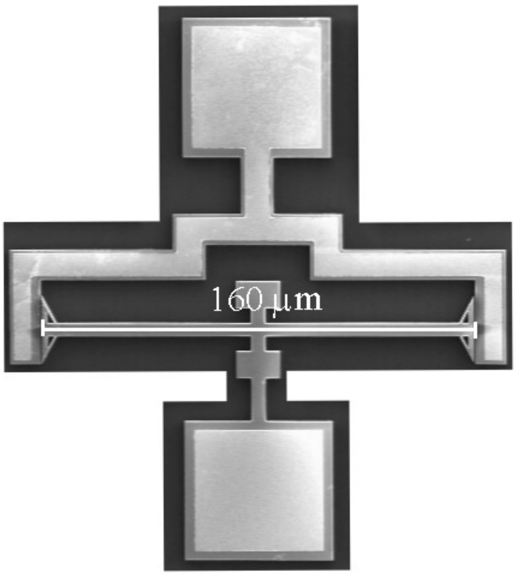

Figure 5.3.1-2. Length extensional mode microresonator for 13 MHz.

The capacitive coupling of microscale structures to surrounding electronics usually leads to non-optimal coupling due to the high impedance levels of the microstructures. This non-optimal coupling in turn causes an increase in short-term noise. Again, FEM-simulations together with state-of-the-art fabrication techniques can be used to decrease the impedance levels and short-term noise.

This collaboration between HUT/MRI, VTT Electronics, and VTT Automation has been financially supported by Nokia Research Center, VTI Hamlin, and TEKES.

5.3.2 Finite element modeling of microsystems

P. Rantakari, N. Tsekurov, and I. Tittonen

The finite element method is very suitable for modeling complex 3D-microsystems, which are usually exposed to many physical effects. In FEM, the complex differential equations of a 3D physical model with multiple variables are transformed into a series of linear equations to be solved numerically. In general, the modeling flow is as follows: *create the model → select a suitable element type → define the material properties → mesh the model → define constrains to subscribe the physical environment → solve problem → analyze the results.*

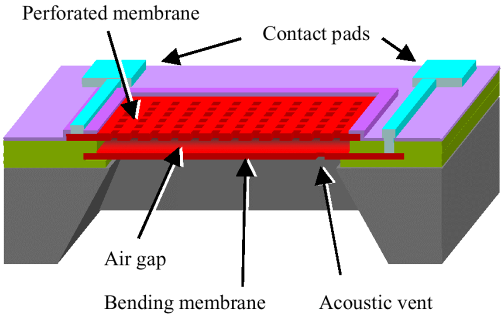

Figure 5.3.2-1. Micromechanical microphone designed at VTT.

Often a micromechanical device needs to be coupled to electronics. The coupling is usually implemented with a capacitive transducer. This kind of coupled-field problem is very suitable to the FEM analysis.

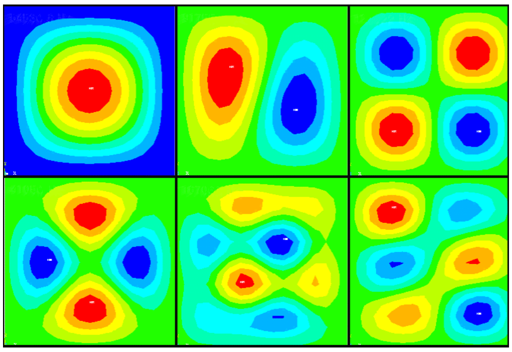

Figure 5.3.2-2. Eigenmodes of the prestressed membrane.

One typical example of a coupled-field microdevice is a micromechanical microphone (see Figure 5.3.2-1). The sensing element of the microphone is a thin prestressed silicon membrane. The response of the membrane to sound waves is detected capacitively via electrodes.

At first, the mechanical properties of the microphone are modeled. The first resonant eigenfrequency should be well above 20 kHz to achieve a maximum flat response (Figure 5.3.2-2).

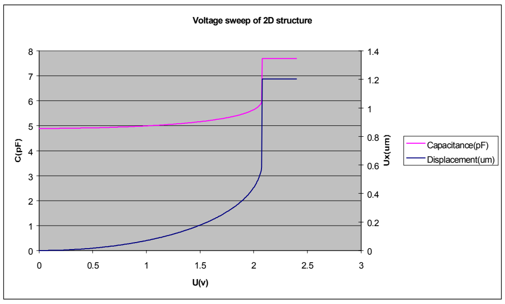

Figure 5.3.2-3. DC-voltage sweep for finding out the pull-in voltage.

Since the capacitive detection needs a DC-voltage difference between the vibrating membrane and the electrode, one needs to solve how the electric field affects the mechanical properties of the microphone. Figure 5.3.2-3 shows results from the pull-in voltage analysis of the microphone.

Finally, the dynamical behavior of the microphone is inspected (Figure 5.3.2-4). The gas damping by the surrounding air is modeled by a spring-damper element to correspond to the analytical result of the gas damping of the membrane.

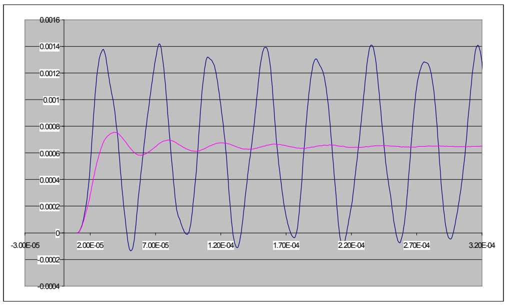

Figure 5.3.2-4. Dynamical behavior of the microphone was inspected by transient analysis.

The work has been financially supported by VTI Hamlin, Vaisala, Aplac Solutions, Nokia Research Center, and TEKES.

5.3.3 Optical interferometry on a mechanical silicon oscillator

O. Hahtela, K. Nera, K. Lahti, and I. Tittonen

A HR-coated high-Q mechanical silicon oscillator was employed as a planar rear mirror in a Fabry-Pérot interferometer (Figure 5.3.3-1). Active stabilization of the interferometer improves the stability of the resonance and makes it possible to perform sensitive interferometric measurements.

The frequency locking of a laser to an optical cavity usually requires the generation of an error signal with a typical slope at the resonance. The Hänsch-Couillaud locking method utilizes polarization spectroscopy by monitoring changes in the polarization of the reflected light. A polarization analyzer detects dispersion shaped resonances, which give the error signal for the electronic servo loop. The error signal contains information about the changes in the cavity length of the optical resonator and thus the motion of the mechanical oscillator can be observed.

The error signal was detected with the use of a spectrum analyzer. The noise floor of the interferometer response indicates that the sensitivity of the interferometer, or the minimum displacement in the oscillator position that can be detected, is $\Delta x_{\mathrm{min}}=1.7\times10^{-14}$ m. This gives the optomechanical sensor a high enough sensitivity to observe for example the Brownian motion ($\Delta x_{\mathrm{the}}=1.9\times10^{-13}$ m) of the mechanical oscillator at room temperature.

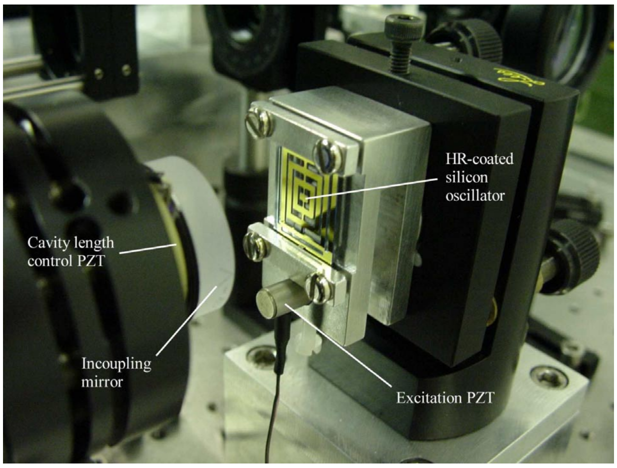

Figure 5.3.3-1. High-Q mechanical silicon oscillator with HR-coating (R=0.98) is employed as a planar rear mirror in a Fabry-Pérot interferometer, which has a finesse of 100, FSR of 6 GHz and an optical passband of 60 MHz.

5.3.4 High-Q micromechanical silicon oscillators

K. Nera, O. Hahtela, T. Lamminmäki, and I. Tittonen

Mechanical oscillators that have a stable resonance with a high quality factor have applications as reference oscillators, sensors and even in very sophisticated high-precision experiments for observing quantum effects.

The main idea in designing a high-Q oscillator is to construct structures with low mechanical energy flow from the active resonating part of the system. Balanced torsionally vibrating structures have proved to be very promising in this respect. At atmospheric pressure the most significant loss mechanism is gas damping. For an oscillator working in vacuum the major part of the mechanical energy losses is caused by the coupling to the support structure and by internal friction which in turn is a result of a variety of physical mechanisms like thermoelastic effects and phonon scattering.

The influence of a dielectric coating layer on the Q-factor and the resonance frequency has been studied since the oscillators need to be coated with high-reflectivity coating in some optomechanical experiments. Since the mass of the oscillator increased due to the coating, the resonance frequency (~68 kHz) decreased by about one percent. The decreasing effect of the coating layer on the Q-factor is shown in Figure 5.3.4-1.

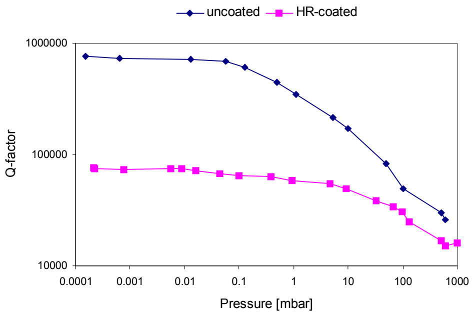

Figure 5.3.4-1. Influence of the high-reflectivity coating layer on the Q-factor of a mechanical silicon oscillator.

We also studied the behavior of the mechanical motion of oscillators as a function of the temperature since the physical effects that restrict the quality factor at low temperatures are rather vaguely known. In Figure 5.3.4-2 the Q-factor and the resonance frequency of an RF-oscillator are presented as a function of temperature. As the temperature was lowered below 50 K, the Q-factor began to increase rapidly. At 4.2 K the Q-factor was roughly three times that of the room temperature value.

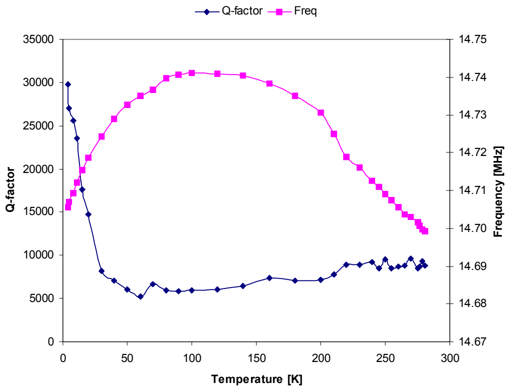

Figure 5.3.4-2. Q-factor and resonance frequency of a mechanical silicon oscillator as a function of temperature.

5.4 Applied Quantum Optics

5.4.1 Integrated atom optics

T. Lindvall, A. Liukko, L. Niinikoski, I. Tittonen, S. Franssila[*], A. Huttunen[†], M. Rodriguez[†], P. Törmä[†], A. Shevchenko[‡], and M. Kaivola[‡]

[*] *Microelectronics Center, HUT*
[†] *Laboratory of Computational Engineering, HUT*
[‡] *Optics and Molecular Materials, HUT*

The progress in laser cooling and trapping of neutral atoms during the past decade has produced a variety of techniques based on the use of light forces and electromagnetic fields to reach extremely low temperatures in atomic vapors and to control the translational motion of atoms. This has led to a field called atom optics, where the goal is to manipulate atomic samples and beams analogously to how light is manipulated in traditional optics.

Using modern microfabrication techniques it is possible to construct micron-sized magnetic microtraps on the surface of a substrate. These traps can be loaded with cold atoms from, for example, magneto-optical traps (MOT). This could allow the integration of several atom traps and other atom-optical components onto a so-called atom chip. Recently also Bose-Einstein condensation has been achieved on an atom chip [1, 2].

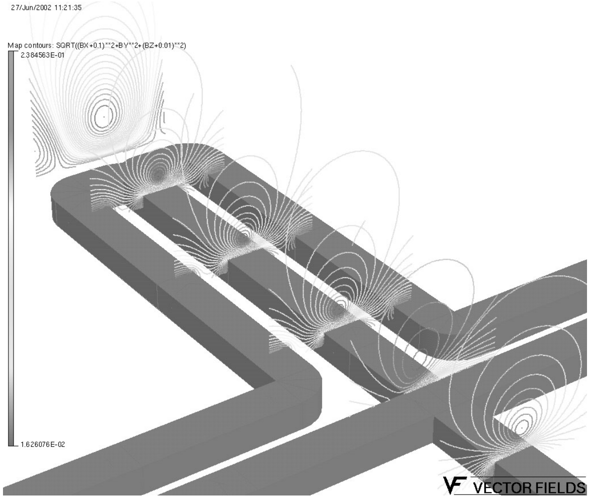

Figure 5.4.1-1. Calculated equipotential lines for a magnetic atom trap created by current-conducting wires.

The goal of the project is to develop new chip fabrication techniques and apply these for different atom-optical components. New components must be modeled before fabrication, see Figure 5.4.1-1. During 2001 the first test chips were designed and then fabricated at the HUT Microelectronics Center, see Figure 5.4.1-2. Some preliminary tests of the current-carrying capabilities of the wires have also been made (Figure 5.4.1-3). The parts for the ultra-high vacuum system, where the chips will be more thoroughly tested, were acquired.

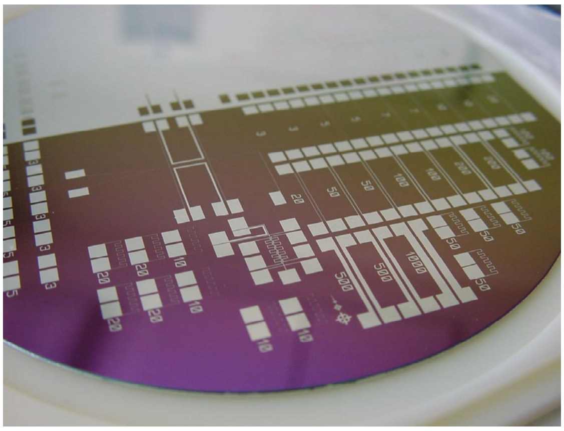

Figure 5.4.1-2. Photograph of one of the test wafers containing atom-chip prototypes.

A suggestion to use a gravito-optical trap for the loading of an atom chip was also developed [3]. The other theoretical studies include investigation of the influence of heating and noise on the trapped atoms.

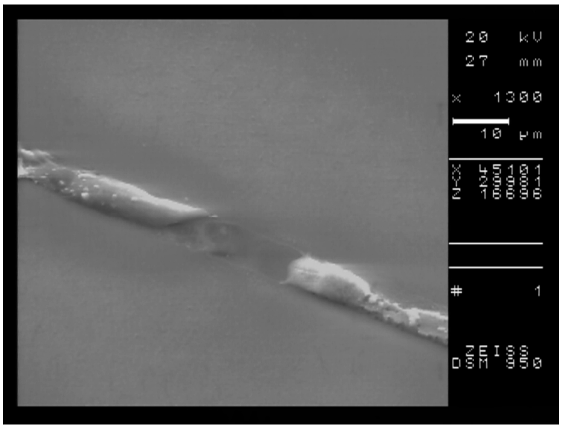

Figure 5.4.1-3. Scanning electron microscope (SEM) picture of a 10-μm wire that has been burned in a maximum-current-density test.

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

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[1] H. Ott, J. Fortagh, G. Schlotterbeck, A. Grossmann, and C. Zimmermann, *Phys. Rev. Lett.* **87**, 230401 (2002).

[2] W. Hänsel, P. Hommelhoff, T.W. Hänsch, and J. Reichel, *Nature* **413**, 498 (2001).

[3] A. Shevchenko, M. Kaivola, T. Lindvall, and I. Tittonen, (submitted).

5.4.2 Digital laser frequency stabilization

M. Heiliö, E. Vahala, O. Kimmelma, K. Lahti, 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 around 4 000 [2].

One of the crucial elements of the stabilization system is the laser servo control, which tunes the laser frequency electromechanically and electrothermally based on the frequency fluctuation information given by the resonator (Figure 5.4.2-1).

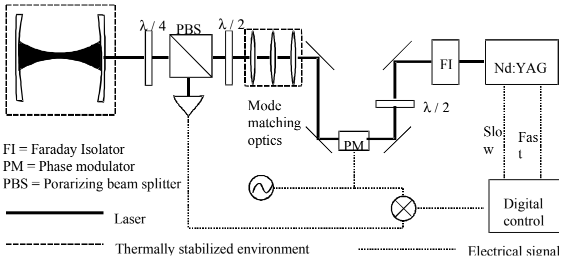

Figure 5.4.2-1. Nd:YAG laser is locked to a high-Q optical resonator using a phase modulation scheme.

The servo control operates at a frequency bandwidth totally covering the technical noise of the laser. The frequency noise of our laser becomes shot noise-limited approximately at frequencies higher than 100 kHz. Servo controls operating at this high frequencies have traditionally been constructed using analog electronics. In our experiment we have been using a high-speed digital signal processor together with high-resolution A/D & D/A converters incorporating efficient digital filtering. The 150 MHz processor clock frequency ensures operation beyond the technical noise bandwidth and enables the use of a rather complex algorithm combining the advantages of a traditional fringe side locking and a PDH method. Locking methods based on transmission measurements suffer from delay induced by cavity response time. However, the transmission intensity provides the locking algorithm with explicit information concerning triggering and achieving the lock in general.

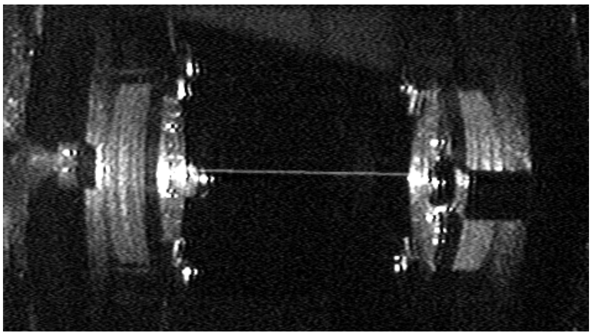

Figure 5.4.2-2. The standing optical mode inside the interferometer captured on a CCD.

[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).

5.4.3 All-optical 3-GHz frequency standard based on dark states of ^{85}Rb

M. Merimaa, T. Lindvall, I. Tittonen, and E. Ikonen

A compact atomic frequency reference has potential applications in areas where an intermediate step between the Cs-atomic clock and a crystal oscillator is desired. A relatively simple way to realize an all-optical atomic frequency reference using coherent population trapping (CPT) was proposed by Cyr et al in 1993. Advances in diode lasers have made such devices feasible and if sufficient stability is achieved these devices could be used for example in telecommunications applications.

In CPT two laser fields interacting with an atomic three-level Λ-system are coupled by the ground state coherence and interfere destructively at two-photon resonance. Since this two-photon Raman resonance takes place between two ground states the linewidth is very narrow and the resonance forms an almost ideal frequency reference. In practice the linewidth and the absolute frequency of the resonance are determined by the experimental parameters.

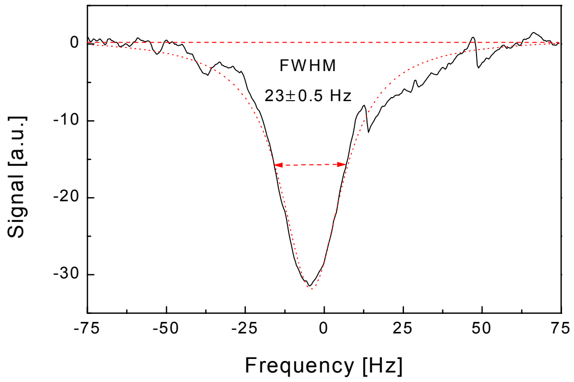

Figure 5.4.3-1. The measured ultra-narrow CPT line.

In this work we use a diode laser equipped with an integrated microlens as a laser source. Optical feedback from the closely mounted microlens can be used to improve the spectrum without hampering the modulation properties of the laser and the second laser field can be generated directly by modulating the laser frequency via injection current. The Λ-system of ^{85}Rb is used in this work because laser diodes operating at the frequency of the Rb $5^2S_{1/2}$-$5^2P_{3/2}$ transition (780.24 nm) are easily available and the modulation bandwidth of an edge-emitting diode laser covers the 3.0357 GHz ground state hyperfine-splitting.

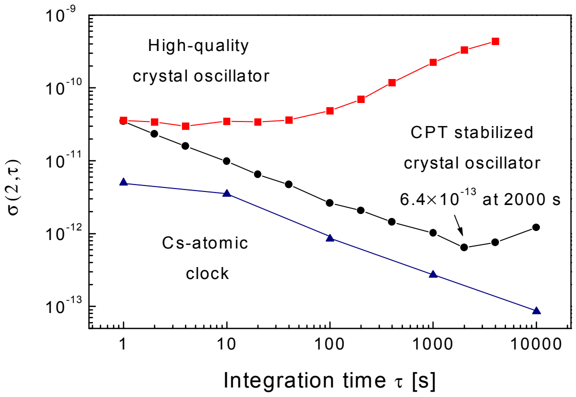

Figure 5.4.3-2. Frequency stability of an oscillator locked to the CPT resonance.

Our system allows detection of ultra-narrow CPT resonance below 25 Hz as shown in Figure 5.4.3-1. An RF-oscillator has been successfully locked to the resonance between the $m_F=0$ magnetic sublevels. Figure 5.4.3-2 shows the measured frequency stability of the system. The frequency stability slope is $3.5\times10^{-11}\ \tau^{-1/2}$ and the best stability of 6.4×10^{-13} is reached at an integration time of 2000 s [1].

[1] M. Merimaa, T. Lindvall, I. Tittonen, and E. Ikonen, *J. Opt. Soc. Am. B* (accepted).

5.4.4 Quasi-phase-matching in nonlinear laser frequency conversion

O. Kimmelma, K. Lahti, and I. Tittonen

Nonlinear crystals are used to convert laser light frequencies. A critical required condition for the constructive interference in a crystal is phase-matching. A special method to perform phase-matching is the use of quasi-phase-matching where the crystal orientation, corresponding to the maximum nonlinearity, changes periodically in alternating layers of different orientation (Figure 5.4.4-1).

A quasi-phase-matched potassium-titanyl-phosphate (KTP) crystal is used to convert the 1064nm laser to the second harmonic at 532nm. The size of the used crystal is 5x2x1 mm^3. The setup adjustments to maximize the output are carried on. The setup has been designed in collaboration with Laboratoire de Photonique et de Nanostructures, CNRS-LPN (Dr. Kamel Bencheikh).

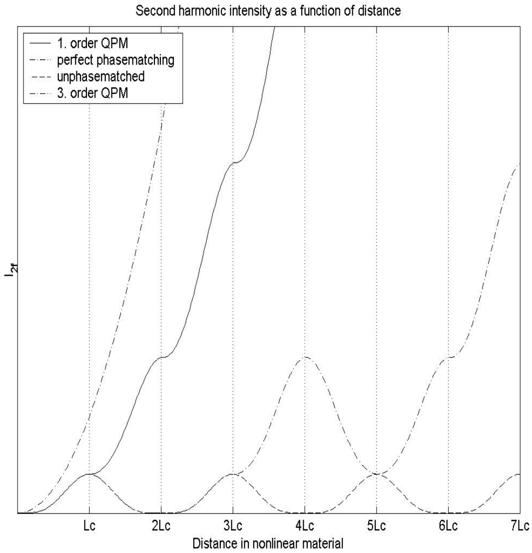

Figure 5.4.4-1. Effect of phase matching type to the second harmonic intensity.

5.5 Characterization of fiber-optic components

5.5.1 Group-delay ripple in chirped fiber Bragg gratings

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

Characterization of group delay and amplitude properties of various components is important in designing advanced optical networks. The phase-shift method is an established technique for performing high-accuracy measurements of these parameters. The accuracy in resolving the fine structure of the group delay, however, depends critically on the modulation frequency used in the measurement [1]. The choice of the modulation frequency is, in general, a trade off between the desired accuracy of the method and the resolution of the electrical phase measurement. We have developed a new method to evaluate the error of the measurement and to improve the accuracy of the phase-shift technique when high modulation frequency is applied to achieve a high resolution.

The new method is based on the instrument function for a group-delay measurement with the phase-shift technique. The measured group delay can be written as

$$\tau_{meas} = \int_{-\infty}^{\infty} \tilde{\tau}_{comp}(u).\frac{\sin(\omega_m u)}{\omega_m u}.e^{j\omega u}du = \tau_{comp}(\omega) * rect(\omega/2\omega_m)\text{'}$$

where τ_{comp} is the actual group delay of the component and τ_{meas} is the measured group delay. *rect* and * denote the rectangular instrument function and the convolution operation. This formula can conveniently be used to investigate the effects of the modulation frequency on the measured group delay ripple of FBGs and estimate the error induced by the technique [2]. The method allows the actual group delay of the component to be accurately reconstructed and it is applicable to any arbitrary group delay profile.

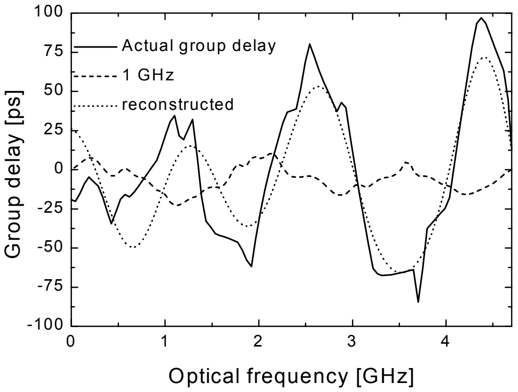

Figure 5.5.1-1. Reconstruction of the actual group delay of a fiber Bragg grating using the data measured at 1 GHz. The measured data and the actual profile are also plotted.

We have applied the method to reconstruct the actual profile of the group delay of the FBG presented earlier. The measurement data obtained for modulation frequency of 1 GHz is presented in Figure 5.5.1-1. It can be observed that the amplitude of the group delay is decreased from the actual value measured with low modulation frequency. However, after reconstruction the actual group delay profile is almost completely restored. This new method permits an improvement of the accuracy of the conventional phase-shift technique without any modifications to the measurement setup. The reconstruction is done by post-processing of the measured group delay

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

[1] T. Niemi, M. Uusimaa, and H. Ludvigsen, *Photon. Technol. Lett.* **13**, 1334-1336 (2001).

[2] G. Genty, T. Niemi, and H. Ludvigsen, *Opt. Commun.* **204**, 119-126 (2002).

5.5.2 Photonic crystal fibers

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

Photonic crystal fibers (PCFs) exhibit novel and interesting optical properties. To explore existing measurement techniques to acquire these properties an extensive characterization of PCFs has been conducted in co-operation between several European laboratories. The novel features of these fibers include anomalous dispersion in the visible wavelengths, single-mode operation over all wavelengths and high optical nonlinearity. Example of a large-mode area PCF is displayed in Figure 5.6.2-1.

The parameters of main interest include polarization-related properties and chromatic dispersion. Chromatic dispersion of a 19 m long highly nonlinear PCF with a core diameter of 1.7 μm is displayed in Figure 5.5.2-2. The dispersion is anomalous at this wavelength range.

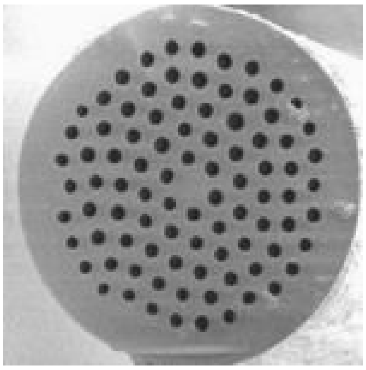

Figure 5.5.2-1. Cross section of large-mode area PCF (Crystal Fiber A/S).

Various techniques to characterize polarization-mode dispersion (PMD), polarization dependent loss (PDL), polarization beatlength along the fiber and chromatic dispersion have been studied. Standard measurement methods work reasonably well for the most of the parameters [1]. However, some so far unexplained features related to measurement of PMD at different wavelengths make it clear that more investigations will be necessary. High-resolution (OFDR) measurement methods proved to be invaluable for the characterization of the beatlength and loss profiles of the short fiber samples at hand. The measurements performed so far indicate that the homogeneity of the fiber is a source for large polarization dependence and excess loss.

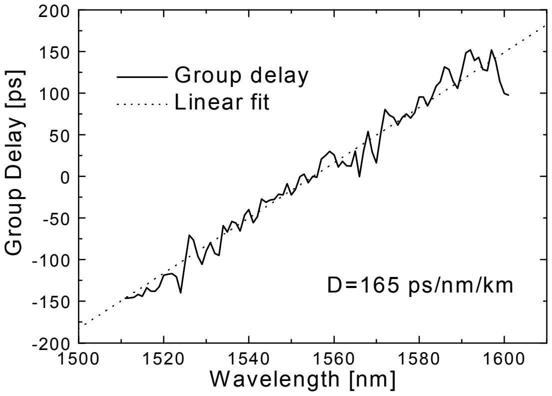

Figure 5.5.2-2. Group delay of the highly nonlinear PCF around 1550 nm.

This work which was lead by H. Ludvigsen has been conducted in collaboration with the Group of Applied Physics/ University of Geneva, National Physical Laboratory and Service d'Electromagnétisme et de Télécommunications/Faculté Polytechnique de Mons within the COST Action 265.

Crystal Fiber A/S in Denmark kindly lent the fibers to the COST group.

[1] M. Wegmuller, F. Scholder, A. Fougères, N. Gisin, T. Niemi, G. Genty, H. Ludvigsen, O. Deparis, and M. Wicks, “Evaluation of measurement techniques for characterization of photonic crystal fibers,” *CLEO/QELS′02*, Long Beach, CA, 2002, paper JThA4.

5.5.3 Intercomparison of measurement techniques to characterize fiber Bragg gratings

T. Niemi and H. Ludvigsen

Fiber Bragg gratings (FBGs) are being increasingly used in WDM systems for wavelength selection and dispersion compensation. A European intercomparison has been conducted build on work carried out primarily in North America to determine the industrial metrology capability for spectral and group delay measurements of FBGs, which was co-ordinated by NIST [1].

Two chirped gratings were circulated amongst several laboratories. The first was a commercial chirped grating (Bragg Photonics Inc.) mounted in an athermal package without any additional temperature stabilization. The second was a chirped broadband grating which was also athermally packaged. Furthermore, its temperature was controlled to better than 0.1

°C using a thermo-electric cooler. This grating was used in the North American round robin.

An example of the measured group delay of the broadband chirped grating is displayed in Figure 5.5.3-1. It shows that the group delay measured with the phase-shift method agrees well. The group delay measured with photon counting deviates from the measurement conducted with the phase-shift method.

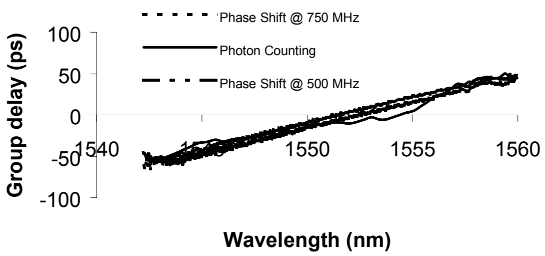

Figure 5.5.3-1. Group delay of chirped grating.

The dispersion of the broadband grating with different measurement methods from both ends of the grating is given in Table 5.5.3-1.

Table 5.5.3-1. Summary of average dispersion, D, of broadband grating.

Method	*D* (ps/nm) Port A	*D* (ps/nm) Port B
Photon counting	5.71	-7.54
Phase shift @ 500 MHz	6.09	-7.23
Phase shift @ 750 MHz	6.24	-7.16

The European intercomparison was co-ordinated by National Physical Laboratory. Preliminary results have been presented in a conference report [2] and further analysis is to be conducted.

This work has been conducted within the COST Action 265.

[1] A. H. Rose, C.-M. Wang, and S. D. Dyer, “Round robin for optical fiber Bragg gratings metrology,” *J. Res. Nat. Inst. Stand. Technol.* **105**, 839-866 (2000).

[2] M. Wicks, T. Niemi, H. Ludvigsen, M. Wegmuller, H. de Riedmatten, and N. Gisin, “Preliminary results of a European intercomparison of group delay measurements of fiber Bragg gratings,” in *OFMC’01,* Conference Digest 2001, pp. 241-244.

5.6 Novel components for optical telecommunications

5.6.1 Supercontinuum generation in photonic crystal fibers

G. Genty, M. Lehtonen, M. Kaivola‡, J. R. Jensen, and H. Ludvigsen*

‡ Optics and Molecular Materials, HUT
** Crystal Fiber A/S, Denmark*

Photonic crystal fibers (PCFs) consist of a periodic array of air holes running alongside the core of a silica fiber. This new type of optical waveguide structure has proven to be particularly efficient for supercontinuum light generation due to the unique dispersion properties and enhanced optical nonlinearities. Such a continuum source has led to numerous novel applications in the field of optical metrology and telecommunications.

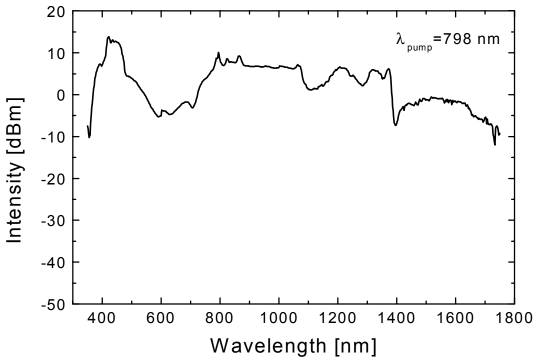

Figure 5.6.1-1. Ultra-broad supercontinuum.

We have generated supercontinua by launching femtosecond pulses from a mode-locked Ti:Sapphire laser into various crystal fibers [1]. The linearly polarized pulses from the pump laser can be tuned in wavelength from 715 to 830 nm. The maximum peak power of the 100 fs FWHM pulses is 170 kW.

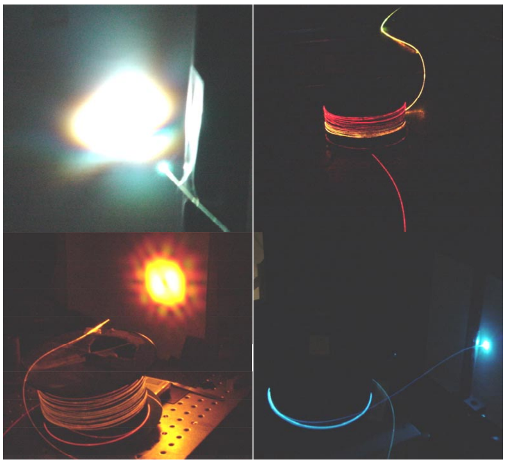

Figure 5.6.1-2. Pictures of the generated supercontinua.

The evolution of the input pulse spectrum into a supercontinuum was studied by gradually increasing the power of the pump laser. The influence of the polarization and wavelength of the pump pulses on the generated continuum was also investigated. Various nonlinear phenomena were found to contribute to the formation of the continuum, such as self-phase modulation, Raman scattering, four-wave mixing, and soliton decay, depending on the type of fiber used to generate the continuum. Different spectral features of the supercontinuum can be controlled by adjusting the parameters of the pump pulses. By optimizing the parameter of the input pulses, we are able to generate an ultra broad supercontinuum that extends from 400 to 1700 nm, as is shown in Figure 5.6.1-1.

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

[1] G. Genty, M. Lehtonen, J. R. Jensen, M. Kaivola, and H. Ludvigsen, "Route to supercontinuum in photonic crystal fibers," in *Conference on Lasers and Electro-Optics and Laser Science Conference (CLEO/QELS´02)*, Long Beach, CA, 2002, paper CTuU1.

5.6.2 Fiber laser for L-band

G. Genty, T. Laukkanen, and H. Ludvigsen

Wavelength division multiplexing (DWDM) technique in the wavelength window of 1535-1565 nm (C-band). To increase the transmission capacity of optical fibers in the future, the wavelength window will be extended to the wavelength range from 1565 nm to 1625 nm (L-band). Erbium-doped fiber lasers have the potential to be used in the L-band as optical transmitters and in the characterization of various types of fiber-optic components.

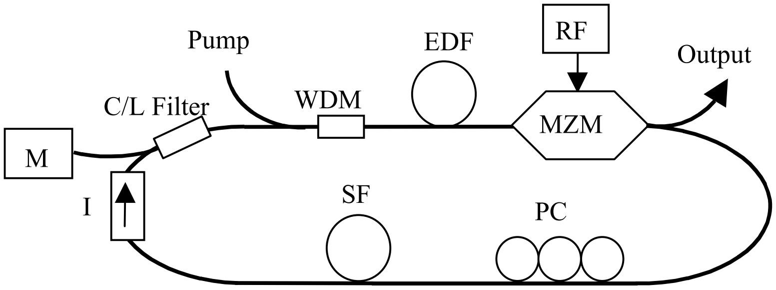

Figure 5.6.2-1. Setup of the fiber laser for mode-locked operation.

We have constructed an Erbium-doped fiber-ring laser, which operates in both continuous wave and pulsed mode. An outline of the laser setup for pulsed operation is presented in Figure 5.6.2-1. The laser design is based on a fiber-ring cavity where the erbium-doped fiber (EDF) is pumped by a diode laser at 980 nm. The pump light is coupled into the cavity by a wavelength division multiplexer (WDM). An optical isolator (I) determines the propagation direction of the laser field. The birefringence of the fiber is compensated for with a polarization controller (PC). Pulsed operation is achieved by introducing a Mach-Zehnder modulator (MZ) into the cavity. The modulator is driven with a wide-bandwidth signal generator (RF) which set the repetition rate of the pulse train. Ten percent of the optical field power is coupled to the laser output with a fiber coupler (FC). A C/L band reflecting filter and a mirror (M) allows the C-band ASE noise to be re-utilized as pump.

The laser is temperature-stabilized and delivers 1 mW output power. We have obtained repetition rates of up to 6 GHz and pulse widths of few ps [1].

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

[1] G. Genty, T. Laukkanen, and H. Ludvigsen, “Characterization of a harmonically mode-locked fiber ring laser: modeling and experiments,” in 6th *Optical Fiber Measurement Conference (OFMC’01),* Conference Digest 2001, pp. 259-262.

5.6.3 Wavelength reference

J. Tuominen, T. Niemi, P. Heimala[*]*, and H. Ludvigsen*

[*] *VTT, Information Technology*

Modern WDM systems working over a broad wavelength range require means to monitor and calibrate the channel wavelengths with high accuracy. Silicon Fabry-Perot etalon provides a compact and flexible wavelength reference for these purposes. These references also find use in calibration of measurement devices and frequency stabilization of lasers.

We have developed a wavelength reference based on a tunable silicon etalon. The refractive index of silicon has a temperature dependence that can be utilized to tune the transmission spectrum of the etalon as shown in Figure 5.6.3-1. By knowing the parameters of the etalon, the positions of the transmission fringes can be determined. Subsequently, a fringe can be tuned to any desired wavelength in the operating range of the device with a change of the temperature of the etalon. A computer program has been written to automate the calculations and the tuning procedure.

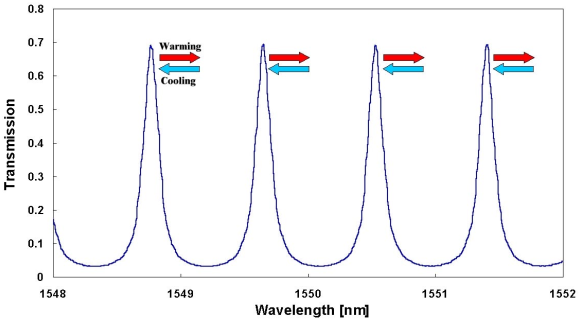

Figure 5.6.3-1. Tunable transmission spectrum of the etalon.

The wavelength accuracy of the device was determined at the 1.55-µm region by measuring the beat frequency of two lasers. One laser was locked to the center of a transmission fringe of the etalon and another laser was locked to an acetylene absorption line for an accurate reference. The accuracy was measured against over 50 absorption lines. The measurement points indicate accuracy better than 125 MHz.

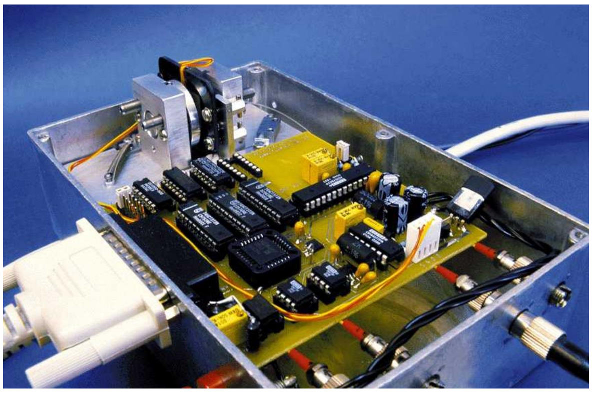

Figure 5.6.3-2. Realized wavelength reference.

The wavelength reference developed is found to be compact, robust, and cost-effective. Its operating range (1300-1700 nm) is superior compared to molecular or atomic references, covering the whole wavelength range of interest for fiber-optic telecommunications. The accuracy is measured to be ~1 pm. The realized device is presented in Figure 5.6.3-2.

The work has been financially supported by the Nordic Industrial Fund and the Center for Metrology and Accreditation.

5.6.4 Measurements of thermally poled waveguides with Bragg gratings

G. Genty, C. J. Marckmann, Y. Ren*, J. Arentoft*, and M. Kristensen**

**Research Center COM, Technical University of Denmark*

Due to its centrosymmetric nature, silica does not exhibit second-order nonlinear optical properties. This has prevented fabrication of silica-based electro-optic devices such as switches, modulators or wavelength converters. By poling silica-based optical waveguides it is possible to induce second-order nonlinear optical properties in silica. Electric field poling is performed by applying a large electric field across the sample while exciting it by either heat or radiation.

We have performed measurements on thermally poled UV-written waveguides with Bragg gratings. Using the charge separation model and fitting the shift of the wavelength of the reflection peaks as function of an externally applied field to a parabolic profile, we were able to extract the induced second and third-order nonlinearities as well as the poling induced dc electric field. The linear electro-optic coefficient, the quadratic coefficient and the poling induced internal dc electric field were deduced from the shift of the reflection peak of the gratings when increasing the voltage [1].

These values are consistent with the results obtained by other groups that have performed interferometric measurements on samples similar to the sample used in this work and are well explained by the charge separation model.

This research has been conducted at Research Center COM and it has been funded by the Nordic Academy for Advanced study (NorFA) and the GETA Graduate School.

[1] C. J. Marckmann, G. Genty, Y. Ren, J. Arentoft, and M. Kristensen, “Bragg gratings as probes to determine nonlinearities induced by thermal poling,” in *Bragg Gratings, Photosensitivity, and Poling in Glass Waveguides*, Stresa, Italy, July 4-6, 2001, paper BFC3.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

Bilateral comparison of spectral irradiance with NIST, USA

The spectral irradiance scales of NIST and HUT were compared in the 290 – 900 nm region. The comparison indicates an agreement except in the UVB region, where the discrepancies are slightly higher than the uncertainty of the comparison. During 2001, the comparison report has been prepared to be submitted to Metrologia.

Bilateral comparison of illuminance with NIST, USA

The illuminance scales of NIST and HUT were compared in summer 2000. The comparison indicates an excellent agreement within the uncertainty of the comparison. The results have been accepted to be published in Metrologia.

Bilateral comparison of luminous flux with NIST, USA

The new luminous flux scale of HUT was compared with the scale of NIST in summer 2000. The comparison indicates an excellent agreement within the uncertainty of the comparison. The results have been accepted to be published in Metrologia.

Improving the accuracy of ultraviolet radiation measurement

In this project funded by the SMT-program of the EU, novel filter radiometer techniques developed by HUT were used to compare various ultraviolet calibration facilities in France (BNM), Finland and UK (NPL). In 2001, HUT prepared the final report on the measurements [Petri Kärhä, Neil Harrison, Saulius Nevas and Issam Abu-Kassem, *Improving the Accuracy of Ultraviolet Radiation Measurement, Report on the filter radiometer measurements in Work Package 1*, February 2001]. The results indicate an agreement between the spectral responsivity and spectral irradiance scales of NPL and HUT in the UVA region within the uncertainties of the comparison.

International comparison of fiber Bragg grating group delay (COST-project)

A comparison was carried out for measurements of group delay, bandwidth and relative transmittance for a fiber Bragg grating with several European participants in 2000. The results showing excellent agreement between HUT, NPL and University of Geneva were published in OFMC'01.

Bilateral comparison of spectral diffuse reflectance with MSL, New Zealand

The new diffuse reflectance scale of HUT was compared with the scale of MSL. In 2001, HUT conducted their part of the measurements. The results are not yet available.

6.2 Thematic Networks

6.2.1 Thematic network for ultraviolet measurements

HUT is the co-ordinator of the Thematic Network for Ultraviolet Measurements, which has continued its activities after the EU-funded period. During 2001, preparations for the 5th workshop were carried out.

6.2.2 Fiber Optics Technology Network

HUT is a member in the *Fiber 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 fiber user community. It is sponsored by the European Commission under the Standards Measurement and Testing Program.

The three-year project was launched in November 1998 and it co-ordinates the work of thirteen Regional Groups. Hanne Ludvigsen acts as the regional co-ordinator of the Finnish participants in the network. The Regional Groups are responsible for identifying common issues and concerns relating to fiber industry and for co-ordinating collaborative research. They also provide a national forum for the transfer of technology relating to standardization issues.

The FOToN network has prepared web pages for the promotion of regional group activities and to provide an interactive source of information on fiber optics.

In year 2001, the 4th regional FOToN meeting was held in connection with *Optics Days 2001* in Tampere. Furthermore, the 3rd steering group meeting was arranged on 16 May 2001 in connection with the *COST Action 265* meeting in Helsinki. On national level the activity has been organized within an Optical Fiber Measurement Club (OFMeC) which currently has 46 members. OFMeC has been established as a sub-activity within the Finnish Optical Society (FOS).

A link to the Finnish OFMeC and the FOToN network can be found from the Fiber-Optics Group's web pages: metrology.hut.fi/fiberopticsgroup.

This project ended on November 31, 2001.

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

CIE Uncertainty Workshop, Vienna, Austria, January 22 – 24, 2001; *Petri Kärhä*

EUROMET CC/Rapporteur meeting, Vienna, Austria, January 23 – 24, 2001; *Erkki Ikonen*

EUROMET Contact persons meeting, Vienna, Austria, January 24 – 25, 2001; *Erkki Ikonen and Petri Kärhä*

Optical Communication Wavelength References – 1st steering group meeting, Helsinki, Finland, February 9, 2001, *Hanne Ludvigsen*

Fourth International Conference on Modeling and Simulation of Microsystems (MSM'2001), Hilton Head, USA, March 19 – 21, 2001; *Tuomas Lamminmäki and Pekka Rantakari*

OFC 2001 Conference, Anaheim, California, USA, March 17 – 23, 2001; *Hanne Ludvigsen*

XXXV Annual Conference of the Finnish Physical Society, Jyväskylä, Finland, March 22 – 24, 2001; *Tero Ahola, Miika Heiliö, Ossi Kimmelma, Mika Koskenvuori, Kristian Lahti, Thomas Lindvall, Mikko Merimaa, Kaisa Nera, Laura Niinikoski, Kaj Nyholm, Ilkka Tittonen, Eero Vahala, and Markku Vainio*

FOToN - 4th Regional Meeting, Tampere, Finland, April 19, 2001; *Hanne Ludvigsen, Goëry Genty, Tommi Laukkanen, and Petri Kärhä*

Optics Days 2001, Tampere, Finland, April 20 – 21, 2001; *Tero Ahola, Jouni Envall, Goëry Genty, Ossi Hahtela, Jari Hovila, Erkki Ikonen, Kristian Lahti, Tommi Laukkanen, Mikko Merimaa, Ilkka Tittonen, Pasi Toivanen, Jesse Tuominen, and Markku Vainio*

Work Package Manager Meeting for the EU-project "Improving the Accuracy of Ultraviolet Radiation Measurement," Espoo, Finland, April 23, 2001; *Petri Kärhä*

CCPR Key Comparison Working Group Meeting, Paris, France, April 23, 2001; *Erkki Ikonen*

CCPR meeting, Paris, France, April 23 – 26, 2001; *Erkki Ikonen*

2nd CIE LED Symposium 2001 and CIE LED Tutorial Workshop 2001, Gaithersburg, MD, USA, May 10 – 12, 2001; *Pasi Toivanen*

CORM 2001, Gaithersburg, MD, USA, May 13 – 16, 2001; *Pasi Toivanen*

COST Action 265 – 5th meeting, Helsinki, Finland, May 14 – 15, 2001; *Hanne Ludvigsen, Goëry Genty, and Tapio Niemi*

COST Action 265 – 5th MC Meeting Helsinki, Finland, May 14 – 15, 2001; *Hanne Ludvigsen*

FOToN – 3rd Steering Group meeting, Espoo, Finland, May 16, 2001; *Hanne Ludvigsen*

EUROMET General Assembly, Bern, Switzerland, May 14 – 17, 2001; *Erkki Ikonen*

Nordic School on Atomic Quantum Gases and Matter Wave Optics, Turku, Finland, May 22 – 31, 2001; *Thomas Lindvall*

11th International Conference on Solid-State Sensors and Actuators, Munich, Germany, June 10 – 14, 2001; *Tuomas Lamminmäki, Pekka Rantakari, and Mika Koskenvuori*

Summer School on Advanced Photonics, Copenhagen, Denmark, August 17 – 25, 2001; *Hanne Ludvigsen, Goëry Genty, and Tommi Laukkanen*

International Summer School on Advanced Topics on Fiber Optic Communications, Tampere, Finland, August 20 – 24, 2001; *Tapio Niemi*

6th Symposium of Frequency Standards and Metrology, University of St. Andrews, Scotland, September 9 – 15, 2001; *Thomas Lindvall and Mikko Merimaa*

6th Optical Fibre Measurement Conference OFMC 2001, Girton College Cambridge, United Kingdom, September 26 – 28, 2001; *Hanne Ludvigsen and Goëry Genty*

COST Action 265 - 6th MC Meeting, Girton College Cambridge, Cambridge, United Kingdom, September 28, 2001; *Hanne Ludvigsen*

Optical Communication Wavelength References – 2nd Steering Group meeting, Girton College Cambridge, Cambridge, United Kingdom, September 28, 2001; *Hanne Ludvigsen*

27th European Conference on Optical Communication ECOC'01, Amsterdam, The Netherlands, September 30 – October 4, 2001; *Hanne Ludvigsen and Tapio Niemi*

Quantum Optics Euroconference 2001, San Feliu de Guixols, Spain, October 6 – 11, 2001; *Ilkka Tittonen and Thomas Lindvall*

6.4 Visits by the Laboratory Personnel

Ilkka Tittonen and Thomas Lindvall, University of Heidelberg, Germany, January 30 – February 2, 2001

The personnel of the laboratory, The Royal Institute of Technology and University of Stockholm, Sweden, June 7, 2001

6.5 Research Work Abroad

Farshid Manoocheri, National Institute of Standards and Technology (NIST), USA, January 1 – April 30, 2001

Goëry Genty, Technical University of Denmark, Lyngby, Denmark, January 1 – 31, 2001

Mikko Merimaa, Kaj Nyholm, and Tero Ahola, Bureau International des Poids et Mesures (BIPM), Paris, France, May 7 – 23, 2001

Petri Kärhä, Ulusal Metroloji Enstitüsü (UME), Turkey, August 26 – September 3, 2001

Markku Vainio, HELP Institute, Kuala Lumpur, Malesia, September 1 – December 31, 2001

6.6 Guest Researchers

Benoit Sabys, SupOptique, Paris, France, June 1 – August 31, 2001

Diego Beltrami, Politecnico di Milano, Milan, Italy, June 1 – August 31, 2001

Toomas Kübarsepp, Metrosert Ltd., Tartu, Estonia, August 15 – 31, 2001 and October 1 – 5, 2001

Robert Mosig, University of Chemnitz, Chemnitz, Germany, August 1 – September 30, 2001

Kamel Bencheikh, Laboratoire de Photonique et de Nanostructures (LPN), Paris, France, August 16 – 26, 2001

6.7 Visits to the Laboratory

Anne Andersson-Fäldt, SP Swedish National Testing and Research Institute, Sweden, February 8 – 9, 2001

Jan C. Petersen, DFM, Denmark, *Per Anell, Frederik Brandt*, *Adel Asseh,* Proximion, Sweden, *Hasse Ekengren,* Nordisk Industrifond, Norway, February 9, 2001

Toomas Kübarsepp, Metrosert Ltd., Tartu, Estonia, March 20, 2001

Jeevek M. Parpia, Cornell University, Ithaca, NY, USA, April 5, 2001

Hans Rabus, PTB, Germany*,* April 23, 2001

Neil Harrison and Hannah Oliver, NPL, United Kingdom*,* April 23 – 25, 2001

Tibor Berceli, Technical University of Budapest, Hungary, May 4, 2001

Anne Andersson-Fäldt, SP, Sweden, *Jan C. Petersen,* DFM, Denmark, *Ottokar Leminger and Werner Weierhausen,* T Nova, Germany, May 15, 2001

Hadi Damirji, Optitune PLC, London, United Kingdom, August 13, 2001

Masami Kihara, NTT Network Innovation Laboratories, Kanagawa, Japan, August 17, 2001

Chris Chunnilall, NPL, United Kingdom, August 29, 2001

Toomas Kübarsepp and Juhan Tuppits, Metrosert Ltd., Tartu, Estonia, September 18, 2001

Daniel Bos, NMi-VSL, The Netherlands, November 19, 2001

Mackillo Kira, KTH Stockholm, Sweden, November 29 – 30, 2001

Vahid Sandoghdar, ETH Zurich, Switzerland, December 6 – 8, 2001

Lennart Robertsson, BIPM, Paris, France, December 9 – 11, 2001

7 PUBLICATIONS

7.1 Articles in International Journals

T. Niemi, M. Uusimaa, S. Tammela, P. Heimala, T. Kajava, M. Kaivola, and H. Ludvigsen, "Tunable silicon etalon for simultaneous spectral filtering and wavelength monitoring of a DWDM transmitter," *Photon. Technol. Lett.* **13**, 58-60 (2001).

M. Merimaa, P. Kokkonen, K. Nyholm, and E. Ikonen, "A portable laser frequency standard at 633 nm with a compact external-cavity diode laser," *Metrologia* **38**, 311-318 (2001).

T. Niemi, J-G. Zhang, and H. Ludvigsen, "Effect of optical filtering on pulses generated with a gain-switched DFB laser," *Opt. Commun.* **192**, 339-345 (2001).

K. Ylä-Jarkko, S. Tammela, T. Niemi, A. Tervonen, and M. Leppihalme, "Scalability of a metropolitan bidirectional multifiber WDM-ring network," *Photonics Network Communications* **3**, 349-362 (2001).

T. Niemi, M. Uusimaa, and H. Ludvigsen, "Limitations of phase-shift method in measuring dense group delay ripple of fiber Bragg gratings," *IEEE Photonics Technol. Lett.* **13**, 1334-1336 (2001).

T. Niemi, S. Tammela, and H. Ludvigsen, "Device for frequency chirp measurements of optical transmitters in real time," *Rev. Sci. Instrum.* (in press).

G. Genty, M. Kaivola, and H. Ludvigsen "Linewidth variations of a grating-cavity laser measured within one external cavity mode," (accepted).

P. Helistö and I. Tittonen, "Experiments with Coherent Fields: Gamma Echo and Related Phenomena," *Hyperfine Interactions* (in press).

T. Mattila, O. Jaakkola, J. Kiihamäki, J. Karttunen, T. Lamminmäki, P. Rantakari, A. Oja, H. Seppä, H. Kattelus, and I. Tittonen, "14 MHz micromechanical oscillator," *Sensors and Actuators* (in press).

J. Hovila, P. Toivanen, E. Ikonen, and Y. Ohno, "Intercomparison of the illuminance responsivity and luminous flux units between HUT (Finland) and NIST (USA)," *Metrologia* (in press).

T. Kübarsepp, H. W. Yoon, S. Nevas, P. Kärhä, and E. Ikonen, "Comparison of spectral irradiance scales between NIST and HUT," *Metrologia* (in press).

7.2 International Conference Presentations

P. Kärhä, "Uncertainties for measurements on sources using broad band detectors," *Abstracts of the CIE Expert Symposium on Uncertainty Evaluation*, Vienna, Austria, January 22-24 (invited talk).

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T. Lindvall, M. Merimaa, and I. Tittonen, "Coherent population trapping in rubidium vapor," Quantum Optics Euroconference 2001, San Feliu de Guixols, Spain, October 6 – 11, 2001 (poster).

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K. Lahti and I. Tittonen, "Coupling of coherent optical fields in the process of second harmonic generation," in *Proceedings of the XXXV Annual Conference of the Finnish Physical Society*, Research Report No. 5/2001, University of Jyväskylä, 2001, p. 51 (talk).

M. Merimaa, P. Kokkonen, K. Nyholm, and E. Ikonen, "A portable laser frequency standard at 633 nm with a compact external-cavity diode laser," in *Proceedings of the XXXV Annual Conference of the Finnish Physical Society*, Research Report No. 5/2001, University of Jyväskylä, 2001, p. 55 (talk).

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ISSN 1237-3281
Picaset Oy, Helsinki 2002