Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute Report 21/2003
Espoo 2003

ANNUAL REPORT 2002

TEKNILLINEN KORKEAKOULU
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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Cover: Coupling supercontinuum radiation generated in a photonic crystal fiber (fabricated by Crystal Fibre A/S, Denmark) into a multimode fiber

CONTENTS

1 INTRODUCTION

The Metrology Research Institute is one of the units at the Department of Electrical and Communications Engineering of HUT. The research work of the Institute consists of optical radiation measurements, laser applications, fiber optics and microtechnologies. In 2002, significant achievements were made in supercontinuum generation in photonic crystal fibers and tapered fibers. The supercontinuum can be applied to construct an optical frequency comb generator on which subject an extensive new project was started. The comb generator will eventually allow direct absolute measurement of the optical frequencies of laser lines.

One interesting application of optical radiation measurements is spectrophotometric determination of the parameters of thin-film optical coatings which are important for various optical components. Our spectrophotometric equipment has significant advantages in reliable determination of the thin-film parameters. In microtechnologies, silicon-based oscillators have been developed which have a short-term stability comparable with quartz oscillators. The micromechanical oscillators would have important advantages in applications when integrating the components with other circuit elements.

Much of our research work is highly dependent on collaboration with other organizations. For the work briefly described in above paragraphs, important research partners are Crystal Fiber A/S (Denmark), Center for Metrology and Accreditation, Moscow State University (Russia), Laser Zentrum Hannover (Germany), VTT, and Nokia Research Centre, just to mention a few.

The Metrology Research Institute provides calibration services for external customers resulting in 50 certificates in 2002. During the year a considerable effort was devoted to the quality system of these services, which was completed by the end of the year. The quality system relies on international comparison measurements participated on a regular basis. Favorable results were received from these comparison measurements in 2002.

Considering the teaching activities of the Institute, one doctoral degree and fourteen Master's degrees were completed in 2002. The latter number is a new record of the Institute.

Erkki Ikonen

2 PERSONNEL

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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute (Mittaustekniikan laboratorio) in 2002. 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-108.189	Project Work in Measurement Technology 2-5 credits (Pekka Wallin)
S-108.191	Fundamentals of Measurements Y 2 credits (Tapio Niemi, Mikko Lehtonen, Pekka Wallin)
S-108.194	Electronic Instrumentation 3 credits (Pekka Wallin)
S-108.195	Fundamentals of Measurements A 2.5 credits (Tapio Niemi, Mikko Lehtonen, Pekka Wallin)
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, Edward Mutafungwa)
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 (Technology), D.Sc. (Tech.)

Tapio Niemi: Dispersion measurements of fiber-optic components and applications of a novel tunable filter for optical communications

Opponent: Prof. Kristian Stubkjær, Technical University of Denmark/COM

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

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

Tuomas Lamminmäki: Coupled micromechanical silicon resonators for high frequency

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

Mikko Luusalo: Valokuitutukan etäisyys- ja vaimennusmittauksen kalibrointi aktiivisen viiveen avulla

Mika Koskenvuori: Mekaanisen resonaattorin toteuttaminen MHz-alueella SOL-teknologialla

Samuli Laukkanen: Laser-based Photoacoustic Gas Measurement

Mikko Lehtonen: Supercontinuum generation in photonic crystal fiber

Mikael Sokolnicki: WDM-kaupunkiverkon teknistaloudellinen analyysi

Mart Noorma: Characterisation of filter radiometers with wavelength – tunable laser source

Antti Reijonen: Base transceiver station integration and verification

Marko Karhiniemi: Modern optical access networks and services

Jesse Tuominen: Wavelength reference for optical telecommunication

Gibson Mwakipesile: Characterization of temperature effects in thin-film filters for optical communications

Reijo Kärkäs: Kiihtyvyysanturituotteen visuaalisen tarkastuksen automatisointi

Ossi Kimmelma: Laser frequency doubling using a periodically poled nonlinear crystal

Tuomo Ritari: Measurement of polarization-mode dispersion of novel optical fibers

Miikka Jalanka: UMTS terrestrial radio access network protocols and transmission testing environment for the third generation base station

4 NATIONAL STANDARDS LABORATORY

Metrology Research Institute is the Finnish national standards laboratory for the measurements of optical quantities. The institute was appointed by the Centre for Metrology and Accreditation (MIKES) in April 1996.

The institute gives official calibration certificates on various optical quantities in the fields of Photometry, Radiometry, Spectrophotometry and Fiber Optics. During 2002, 50 calibration certificates were issued. The calibration services are mainly used by the Finnish industry and various research organizations. There are three accredited calibration laboratories in the field of optical quantities.

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

The Metrology Research Institute performs its calibration measurements under a quality system approved by MIKES. The quality system is based on ISO/IEC 17025.

Further information on the offered calibration services can be obtained from the web-pages of the laboratory (http://metrology.hut.fi/). Especially the following sub-pages might be useful:

Maintained quantities: http://metrology.hut.fi/cgi-bin/index.cgi?calibration

Price list for regular services: http://metrology.hut.fi/files/pricelist.pdf

Quality system: http://metrology.hut.fi/quality/

Additional information may also be asked from Farshid Manoocheri (Head of Calibration Services) or Petri Kärhä (Quality Manager):

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5 RESEARCH PROJECTS

5.1 Optical Radiation Measurements

5.1.1 Absolute scale of spectral diffuse reflectance

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

Measurements of spectral diffuse reflectance provide valuable information in various fields of industrial and research applications. They are usually performed relative to a reference standard traceable to an absolute scale. 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 gonioreflectometer has been developed that will provide spectral diffuse reflectance and bi-directional radiance factors of a range of standards in absolute units.

The instrument consists of a light source and a goniometric detection system. The source system includes xenon-arc and quartz-tungsten-halogen lamps and a double monochromator with input and output optics. The layout of the detection system is shown in Figure 5.1.1-1. The detector consists of a precision aperture followed by a lens, several baffles, and a silicon photodiode with high-gain preamplifier. The aperture defines the solid angle for the reflected radiant flux. The lens focuses the beam such that the detector is underfilled. It also images the plane of sample surface onto the detector, giving a well-defined collection field of view.

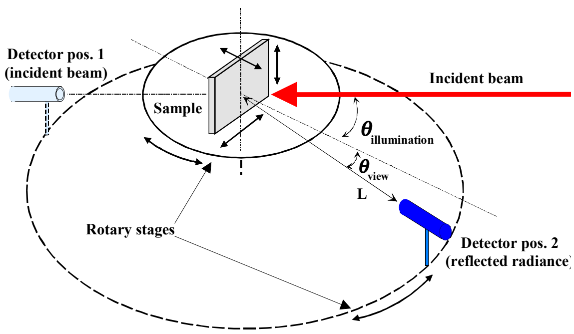

Figure 5.1.1-1. The layout of the goniometric detection system.

The spectral radiance factor is measured at a particular illumination and viewing angle. This is realized by measuring ratio of the reflected and the incident fluxes. The diffuse reflectance is obtained by numerical integration of the radiance factors over the whole hemisphere including as many combinations of incidence and reflection angles as possible in the measurement plane.

The measurement facility has been carefully characterized by identifying all possible sources of systematic errors and by establishing uncertainty budget of the measurements. The developed instrument is going to be used to establish an absolute scale of spectral diffuse reflectance at HUT.

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

5.1.2 Optical metrology of thin films with oblique-incidence spectrophotometric measurements

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

Dielectric thin films find variety of applications in optical technology. It is often necessary to determine optical parameters of the deposited layer: the complex index of refraction and the thickness of the film. Optical characterization techniques such as least-squares fitting of spectrophotometric transmittance and reflectance data are widely used for this purpose. Usually, normal incidence transmittance measurements are exploited. However, to compare reflectance and transmittance measurement data, also oblique angle-of-incidence transmittance results should be available. Furthermore, oblique-incidence data may provide additional information, such as transmittance at Brewster angle with p-polarized light, which would give directly the absorption of the sample.

An important precondition for the analysis procedures to yield reliable results is accuracy of the spectrophotometric measurements with well-collimated beams. We are able to carry out high-accuracy measurements of spectral regular transmittance and reflectance in such conditions. This is a good starting point for studying characterization of thin films by using normal and oblique angles of incidence.

By employing a thin-film mathematical model we have analyzed the effect of systematic errors onto the derived optical parameters of thin films. The studied systematic effects include the angle of incidence, the distribution in the angle of incidence due to beam collimation, and the angle between the plane of polarization and the plane of incidence.

We have also measured and characterized several thin-film samples. The results of optical parameters are consistent over the incidence angles between 0 and 60 degrees, within the present angle-determination uncertainties. It is especially important to determine correctly the angle of incidence and the polarization angle when measuring close to the Brewster angle.

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

5.1.3 Characterization of temperature dependence of thin-film filters for optical communications

G. Mwakipesile, T. Niemi, and E. Ikonen

Wavelength division multiplexing (WDM) in optical-fiber transmission systems are very attractive due to their many advantages, i.e., increased transmission capacity, applicability to two-way transmission and simultaneous transmission of digital and analog signals. Consequently, WDM is used in almost all types of optical-fiber transmission systems, such as long and short-haul transmission systems.

One of the key elements in the WDM optical communication systems is the optical filter which is used as a multiplexer and demultiplexer. Narrow-band interference filters have been commercially in use for some decades, they permit isolation of wavelength intervals down to a few nanometers or less. In using these filters it is often desirable to know how the angle of incidence, temperature variations and possible imperfections affect their performance. Usually, only the center wavelength, bandwidth and loss are specified. Among the important properties with respect to their application is the wavelength shift with temperature changes which causes a drift of the central wavelength and thus degraded performance.

In this work, the temperature effects of two kind of thin-film filters, gain flattening filter and dense wavelength division multiplexing filter, are investigated. For making these measurements a special holder for the filters was designed. The filter was inserted in this holder which included a thermo-electric cooler. The holder was inserted in the air-gap of two collimators.

A wavelength-tunable laser was used as the light source and a wavemeter was used to measure the optical power and wavelength. Control and data acquisition program (LabView) was used to monitor and record the measurements while the temperature of the filter was manually tuned and controlled by a temperature controller.

It was found out that changes in the temperature resulted in a shift of the center wavelength of the passband and had relatively little effect on its shape. The measured wavelength shift for these filters was ~1pm/ºC at a temperature range of 27ºC – 72 ºC.

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

5.1.4 Applications of laser scanning method

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

Laser scanning method is a method to simulate spatially uniform light by superposition of laser beams. The first application of the resulting known spectral irradiance is the measurement of the spectral irradiance responsivity of filter radiometers with standard uncertainty less than 1×10^{-3}.

In 2002, we studied the method for characterization of 900-nm narrow-band filter radiometers, using a wavelength-tunable Ti:Sapphire laser as the light source. The effect of interference between the reflections from filter surfaces in the case of coherent laser light was studied and reduced with special filter design with anti-reflection coatings. Measuring the responsivity as a function of wavelength over a very narrow band was used to reveal remaining interference effects. Uncertainty analysis and test results indicate that filter radiometers can be characterized with a relative standard uncertainty of 9×10^{-4} using the scanning method. The results were compared with more conventional monochromator-based measurements. As can be seen in Figure 5.1.4-1, the results agree well, which illustrates improved credibility of both methods.

Another application of the scanning method is the aperture area measurements. During the year 2002 we revealed an interesting effect in the stability of the areas of precision apertures made of black anodized aluminum.

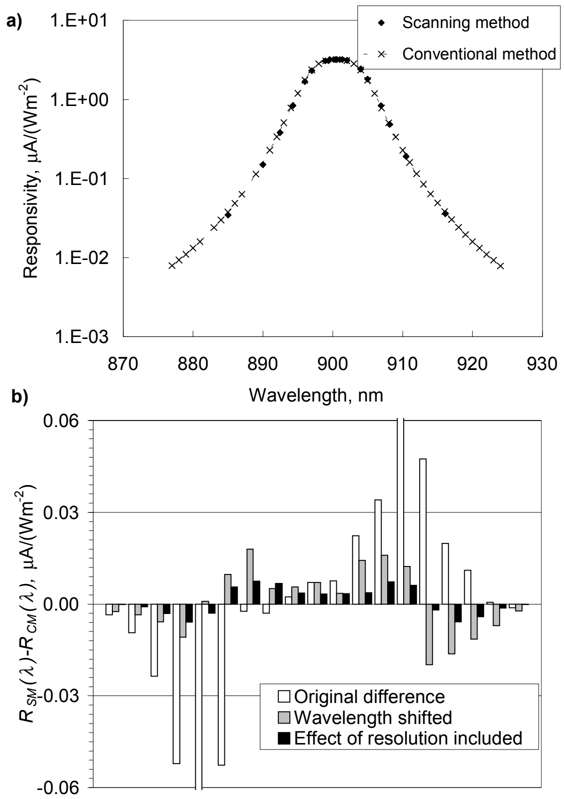

Figure 5.1.4-1. Spectral irradiance responsivities measured with the scanning method, $R_{SM}(\lambda)$*, and with the conventional method,* $R_{CM}(\lambda)$*. Absolute differences at measured points are shown in figure b).*

We have measured the areas of a set of apertures during a period of five years. The aperture area has traditionally been considered to be stable with time. However, our measurement results indicate a systematic decrease in the area, which significantly exceeds the uncertainty of calibrations. We have calibrated a set of apertures with 3 mm, 4 mm and 8 mm diameters during 1997-2002. The laser scanning method with a 633-nm HeNe laser is used for the high-precision area measurements. The relative standard uncertainty of the calibrations is in the order of 4×10^{-4}.

The calibration results indicate a continuous decrease in the areas of all measured apertures. The relative decrease is on the average 6×10^{-4} per year, which corresponds to a decrease in radii by 0.5 µm/year. The behavior does not seem to depend on the use of the apertures.

Figure 5.1.4-2. Edge of a precision aperture. The height of the photo corresponds to approximately 40 µm.

The actual shape of the aperture edge is shown in Figure 5.1.4-2. The decrease could be explained by a continuous growth of the aluminum oxide layer. However this effect should be theoretically much slower. Other possible causes include diffusion of the black dye to the surface of the oxide layer, mechanical stresses in the bulk, and contamination.

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

5.1.5 Development of spectral comparator facility to calibrate ultraviolet detectors with low sensitivity

J. Envall and P. Kärhä

The result of calibration of a broadband ultraviolet detector, using conventional methods, usually depends on the light source. This is due to the non-ideal spectral responsivity function of the detector, which may differ considerably from the desired box shape. Systematic measurement errors as high as 50 % are possible if the detector is used to measure light sources with different spectral shapes [1].

If the spectral responsivity function of the detector is known, correction factors can be calculated to transfer the calibration between different light sources. However, measurement of the spectral irradiance responsivity of UV meters is often complicated because of the low sensitivity of the meters. Detectors have attenuators to allow measurements of high-intensity sources without saturating the photodiodes used as sensitive elements.

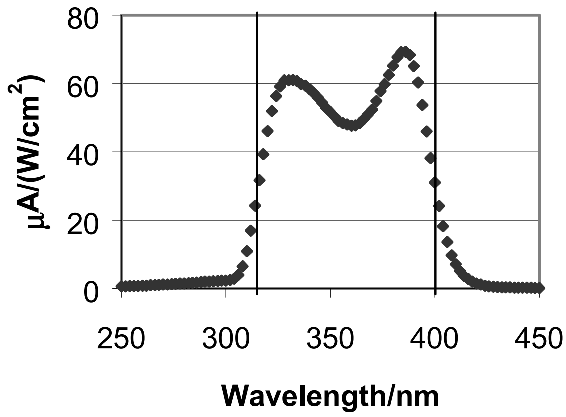

Figure 5.1.5-1. Measured spectral irradiance responsivity of a commercial UVA detector.

We have developed a high-intensity spectral comparator facility. The equipment consists of a single grating monochromator and a light source. 450-W Xe lamp has been used as light source because of its smooth and continuous spectrum over the UV region. In the future, a high-intensity Hg lamp will be acquired to produce narrow, intense spectral lines.

Detectors are calibrated in overfilled mode in the diverging output beam of the monochromator. A linear translator is used to switch the calibrated meter with the reference detector. As the reference, UV-enhanced, large area silicon photodiodes with precision apertures are used. For the characterization of the photodiodes, a pyroelectric radiometer with flat spectral responsivity is used.

Figure 5.1.5-1 shows an example of a measured spectral irradiance responsivity of a UVA detector. The irradiance levels within the calibrations are between 1.5 and 4 $\mu W \cdot cm^{-2} \cdot nm^{-1}$ throughout the UVA and UVB regions. The uncertainty of the calibrations is estimated to be less than 2 %.

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

[1] G. Xu and X. Huang, "Characterization and calibration of broadband ultraviolet radiometers", Metrologia, **37**, 235-242 (2000).

5.1.6 Characterization of a photometer measuring LED sources

J. Hovila, P. Kärhä, and L. Mansner[*]

[*] *Sabik Oy, Porvoo, Finland*

The technology to produce LEDs has improved rapidly and this has quickly brought them to wide use in the lighting industry. The robust structure and long lifetime of LEDs make them superior to incandescent lamps in certain applications. However, characterization, colorimetry and photometry of LED light sources are complicated because of the sharp spectral features. Measurement errors up to several percents may occur unless these spectral features are accounted for in the calibration.

In this work we studied different approaches to calibrate a photometer used to measure the luminous intensities of LED buoy lanterns (Figure 5.1.6-1) used in maritime applications. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) recommends two alternative methods for photometer characterization when measuring LED sources [1].

Figure 5.1.6-1. Sabik LED 155 buoy lantern (height 140 mm, diameter 170 mm).

The first method is more traditional photometry, where SCFs are calculated from relative spectral responsivity of the photometer and the relative spectra of the lanterns. Final correction factors are obtained by multiplying the SCFs with a correction factor obtained from CIE standard illuminant A calibration.

The second method is quite different, since the LED lanterns are used as standard light sources during calibration where the photometer is calibrated absolutely against the reference photometer. The relative spectra of the lanterns are also measured, but only to calculate the color correction factors for the reference photometer.

Measurements were done with both methods for red, green, yellow and white lanterns. The results agree well within their uncertainties (~1 %). However, our experiences indicate that the first method, despite being laborious, is more practical and applicable way to calibrate a photometer for measuring LED sources. Geometrical properties of LED sources are complicated, thus adding uncertainty to measurements, if lanterns are used as standard light sources. Corrections based on relative spectra can be calculated more accurately. Also introducing new LED-types to production line is more straightforward, when only the relative spectra of the new LEDs have to be known.

[1] International Association of Marine Aids to Navigation and Lighthouse Authorities, “Recommendation on the Photometry of Marine Aids to Navigation Signal Lights,” *IALA Recommendation E-122* (IALA, 2001).

5.1.7 Improved calibration facilities for UV-meters and UV standard lamps

P. Kärhä

During 2002, HUT presented two new UV calibration facilities - Spectroradiometric calibration setup for broadband UV meters and a vertical calibration setup for DXW lamps.

The vertical setup for calibrating DXW lamps is presented in Figure 5.1.7-1. The lamp is aligned on top of a 1-m optical rail. The reference filter radiometer for HUT realization of spectral irradiance is assembled on the bottom at 0.5-m distance from the reference surface of the lamp. Between the lamp and the filter radiometer one can either install a dual-beam alignment laser or a baffle. Behind the lamp there is a radiation shield directing the back reflection of the lamp away. The calibration service is mainly used by institutes measuring solar UV, because their standard lamps have to be calibrated with the same orientation that is used in the spectroradiometer calibration.

The calibration facility for broad band UV meters is based on a calibrated spectroradiometer (wavelength region 250 – 845 nm) and a collection of 18-W UV fluorescent tubes. The meters are calibrated with the same type of lamps that the customers plan to measure with their calibrated meter. Also the measurement distance is unified if practical.

The lamp is first calibrated at the specified location using the spectroradiometer. The measured spectrum is used to calculate the desired measurement quantity that can be for example UVA, UVB, Erythema or V(λ). Measurement of the same source with the customer meter in the same location yields an accurate calibration factor for the specified measurement situation.

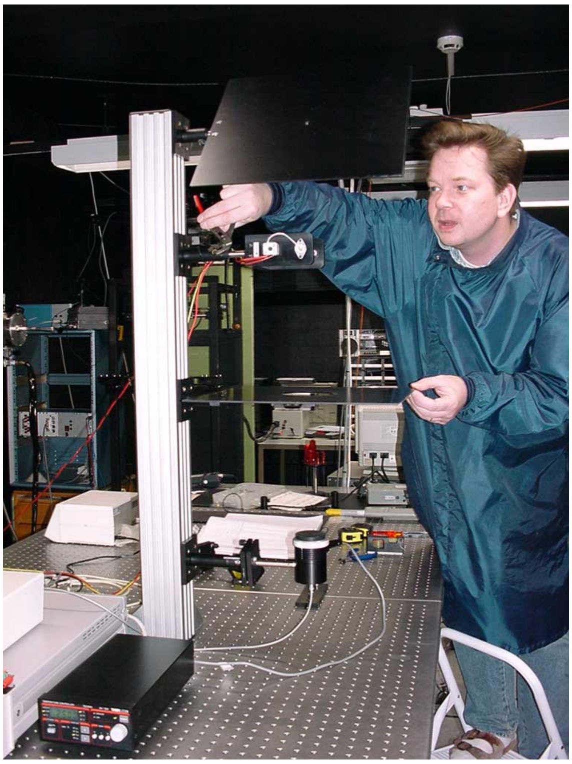

Figure 5.1.7-1. Vertical setup for calibrating DXW-lamps.

Calibration of the UV-meters depends strongly on the source used. If the light source needed can not be found in the HUT lamp collection, the customers may submit their own lamps to be used with the calibration.

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

5.1.8 Extension of spectral irradiance scales

P. Kärhä and F. Manoocheri

In 2002, HUT started a new project that aims to extend the spectral region of the spectral irradiance calibrations. Measurements can presently be done in the wavelength region 290 – 900 nm. The plan is to extend this region to cover 250 nm – 2.5 µm that would better fulfil the requirements of customers.

Two new filters at wavelengths of 220 and 256 nm were purchased to be used with a trap detector. Characterization of the filters indicated that the out-of-band transmittances of the filters are too high. Furthermore, the leakage can not be reduced by additional glass filters because this would reduce the peak transmittances too much. Preliminary measurements with lamps verified these findings. The signals obtained in lamp measurements were too high. To overcome the problem, solar-blind photodiodes will be studied.

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

5.1.9 Radiation temperature measurement

T. Jankowski, M. Noorma, P. Kärhä, T. Weckström[*],
L. Uusipaikka[*], *and E. Ikonen*

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

In 2002, HUT continued in a cooperation with the Centre for Metrology and Accreditation (MIKES) the development of the radiation temperature measurement project as an alternative to the already existing standards of ITS-90 temperature scale.

During this year, three measurement sessions were performed to identify, and eliminate various sources of errors, such as misalignment of the filter radiometer, temperature fluctuations of the cavity of the radiator and possible contribution of the background. Additionally, various numerical simulations were performed in order to estimate the influence of the leakages of the filers used in filter radiometer.

Misalignment studies led to obtaining various angular characteristics of both the filter radiometer, and the radiator revealing a small misalignment of the cavity of the radiator.

Performed intercomparisons between the filter radiometer (500 – 900 nm) and the pyrometer (650 nm) of

MIKES revealed varying differences of the order of 5 – 0.5 K between temperature values measured with ITS-90 and the filter radiometer equipped with different filters. The observed temperature dependence of the signal lead to discovery of the thermal expansion of insufficiently cooled aperture plate of the black body. Analysis of this effect reduced the discrepancies. The error between the reference pyrometer and the 800-nm filter was brought down to 0.73 ºC in the measurement of 1500 ºC temperature.

The work was summarized in the master thesis titled "Measurement of Radiation Temperatures with the Filter Radiometers" containing all the obtained data together with their interpretation.

5.2 Length Metrology

The lasers used for the basic realization of the meter are located in the laboratories of the Metrology Research Institute. The devices are property of the Centre for Metrology and Accreditation (MIKES).

5.2.1 Iodine-stabilized Nd:YAG laser

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

** Centre for Metrology and Accreditation (MIKES)*

The frequency stabilization of a frequency-doubled Nd:YAG laser is based on observing saturated absorption of iodine at 532 nm in an external iodine cell. The Nd:YAG-laser is directly modulated and the standard third-harmonic technique is used for frequency locking.

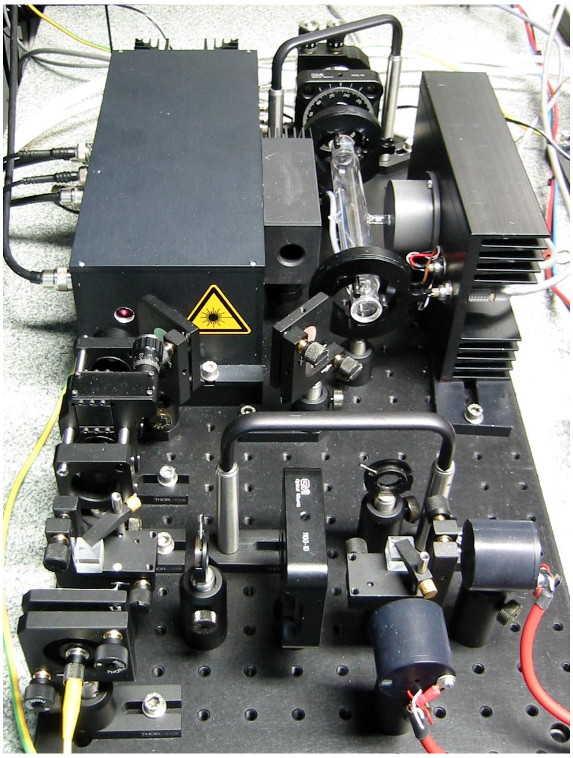

Figure 5.2.1-1. A photograph of the frequency stabilization set-up.

The laser system was characterized in 2001 in an international comparison of Nd:YAG lasers (BIPM, May 2001). Since then the frequency stabilization set-up has been further improved (Figure 5.2.1-1). The size of the laser set-up has been reduced by one-third and the set-up can now be accommodated with longer iodine cells. An attenuated infrared output is also added for e.g. frequency comb applications.

5.2.2 Iodine-stabilized He-Ne lasers

K. Nyholm and M. Merimaa*

** Centre for Metrology and Accreditation (MIKES)*

Three iodine-stabilized red He-Ne lasers and two multi-color He-Ne lasers constructed jointly by MIKES (Centre for Metrology and Accreditation) and HUT (Helsinki University of Technology) have been maintained in the qualified conditions. The multi-color MGI2 laser participated in an international comparison of 543 nm iodine-stabilized He-Ne lasers held at BIPM, France, in February 2002. Absolute frequency measurement of the R(12)26-0 and R(106)28-0 transitions in $^{127}I_2$ at 543 nm were carried out during the comparison.

5.2.3 Optical frequency comb generator

M. Merimaa, K. Nyholm, V. Ahtee, and E. Ikonen*

* *Centre for Metrology and Accreditation (MIKES)*

A new research project was started to construct an optical frequency comb for direct frequency measurements at the optical range. A commercial femtosecond Ti:Sapphire laser (Gigaoptics GigaJet 20) and photonic crystal fiber (PCF) are used to generate a frequency comb extending over a full optical octave (Figure 5.2.3-1).

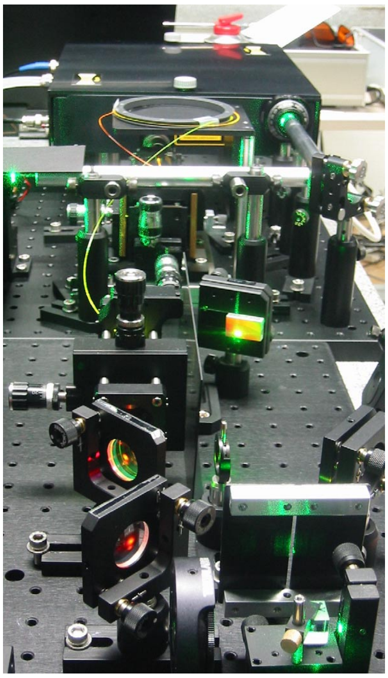

Figure 5.2.3-1. Optical setup of the frequency comb.

The PCF-expanded frequency comb is collimated into free space and particular frequency ranges are separated for frequency measurements. The frequency comb repetition rate will be locked to a frequency stabilized Nd:YAG-laser ($\sigma(2,\tau) \approx 1\times10^{-13}$ at τ =1 s), which serves as a low-noise oscillator. The repetition rate and frequency comb offset frequency are then determined and referenced to a Cs-atomic clock, which provides link to the primary frequency standard.

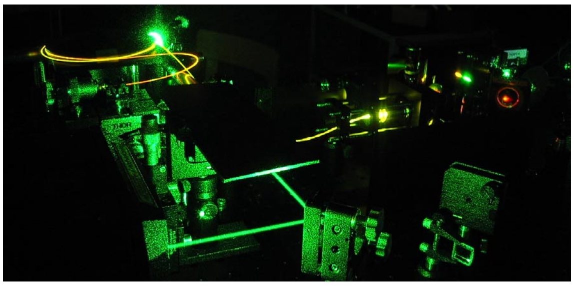

Figure 5.2.3-2. Frequency comb in operation.

Presently, most of the components have been purchased or constructed and generation of the frequency comb has been demonstrated (Figure 5.2.3-2). First absolute frequency measurements will be carried out in 2003.

5.2.4 Transmission grating based diode lasers

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

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

External-cavity diode lasers are widely used e.g. in optical and atom physics experiments, mainly due to their good wavelength tunability and improved spectral properties compared to the solitary diode lasers. External-cavity diode lasers have been used also in frequency stabilized lasers, e.g. at 633 nm, which is an interesting wavelength from the metrology point of view. This interest to frequency stabilized diode lasers has been recently increased as a result of the invention of the femtosecond frequency comb, and consequently arisen demand for relatively high power laser sources with high spectral purity.

Using a transmission grating as the frequency selective component of an external-cavity diode laser allows compact and stable mechanical design. Motivated by the need for optical beat frequency measurements with the frequency comb, improved iodine stabilized diode laser has been under development in 2002. An essential part of the implementation has been to construct a more robust and stable transmission-grating laser, operating at 633-nm wavelength. Cavity of the new laser is hermetically sealed and it is manufactured from Invar in order to give protection against environmental disturbances. Tests and measurements performed with the first prototype of the laser demonstrate good spectral purity and enhanced passive frequency stability.

In 2002, the concept of transmission grating based external-cavity diode laser has also been extended to the telecommunication wavelengths around 1.55 μm. In addition to the high output power and good spectral purity, the laser wavelength is widely tunable. These favorable properties make the laser suitable for the purposes of optical telecommunications, metrology and spectroscopy. The overall tuning range of the constructed 1.55-μm transmission-grating laser is 128 nm, covering the entire S- and C- bands of optical communications.

The coarse wavelength tuning is obtained by mechanically adjusting the grating angle, while the fine-tuning of approximately 30 GHz is provided by piezoelectric transducers. Due to the transmission grating geometry, the problem of the beam direction variation while tuning the wavelength is avoided.

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

5.3 Fiber-Optics

5.3.1 Supercontinuum generation in photonic crystal fibers

G. Genty, M. Lehtonen M. Kaivola, J. Broeng†, and H. Ludvigsen*

* *Department of Engineering Physics and Mathematics, HUT*
† *Crystal Fibre A/S, Denmark*

Photonic crystal fibers (PCFs), also known as microstructured fibers, consist of a periodic array of air holes running along the core of a silica fiber. This new type of optical waveguide structure has proven to be particularly efficient for supercontinuum generation due to the unique dispersion properties and enhanced optical nonlinearities.

We have generated supercontinuum by launching femtosecond pulses from a mode-locked Ti:Sapphire laser into a highly birefringent PCF [1]. The fiber has core dimensions of 1.5×2.4 μm^2, and a mode-field area of 2.3 μm^2. Evolution of the input pulse spectrum into a supercontinuum was studied by gradually increasing the power of input pulses. Figure 5.3.1-1 shows the output spectra recorded for the PCF at different average pump powers with the wavelength lying on the anomalous side of the dispersion profile.

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. This kind of a continuum source has numerous novel applications in the fields of optical metrology and telecommunications.

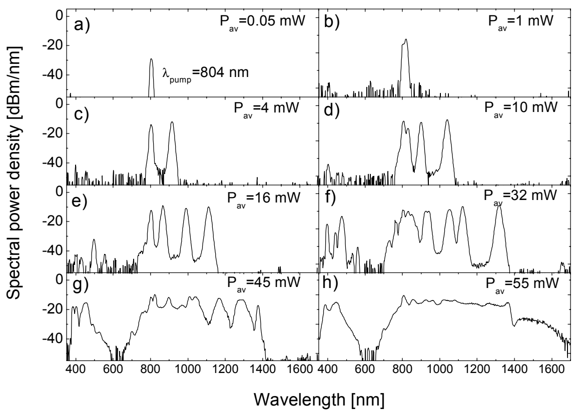

Figure 5.3.1-1. Evolution of the supercontinuum spectrum with increasing pump power.

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

[1] G. Genty, M. Lehtonen, J. Broeng, M. Kaivola, and H. Ludvigsen, *Opt. Express* **10**, 1083 (2002).

5.3.2 Supercontinuum in tapered fibers

T. Niemi, J. Tuominen, M. Lehtonen, G. Genty, and H. Ludvigsen

Tapering of optical fibers refers to a process where the diameter of the fiber is reduced by heating and stretching [1]. In practice, the diameter of the fiber can be reduced from a standard size of 125 µm down to 1-2 µm. A small diameter of the taper results in high intensity of the light. High power laser pulses combined with nonlinearity of the fiber can be applied in, for example, generation of an ultra-broad band coherent light source referred to as a supercontinuum [2].

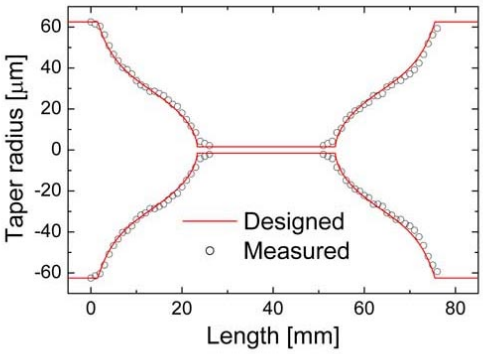

Figure 5.3.2-1. Shape of a fabricated fiber taper.

We have built an apparatus for fabricating tapers having various profiles. To couple light efficiently from the core of a standard single-mode fiber to the tapered waist requires the transition region to be smooth. An example of a tapered fiber fabricated with our device is displayed in Figure 5.3.2-1. Lengths of he transition regions are 20 mm, the waist is 25 mm long and it is designed to be 3 μm thick. The diameter of the taper is measured with a microscope. However, a reliable measurement of the waist diameter was not possible due to insufficient magnification of the microscope.

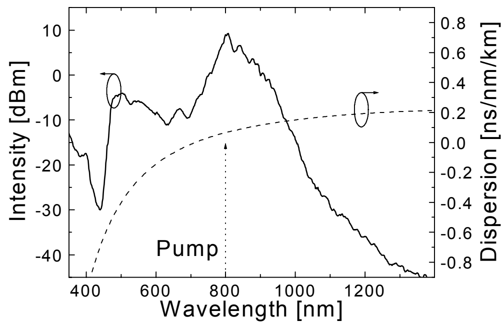

Figure 5.3.2-2. Supercontinuum from tapered fiber (solid line). Dispersion of tapered fiber (dotted line).

Generation of a supercontinuum is possible in tapered fibers with a small waist. An example of such a continuum is shown in Figure 5.3.2-2. It was generated by launching ~200 fs pulses from a femtosecond Ti:Sapphire (Tsunami/Spectra-Physics) laser with a repetition rate of 80 MHz and a pump power of ~100 mW into a ~30 mm long tapered fiber with a waist thickness of ~2 μm. The transition regions connecting the taper to the standard single-mode fiber are 25 mm long. The spectrum of the laser broadens to cover wavelengths from the blue to near infrared. This kind of a broadband supercontinuum source finds applications in, e.g., frequency metrology, spectroscopy and tomography.

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

[1] T. A. Birks et al., *J. Lightwave Technol.* **10**, 432 (1992).

[2] W. J. Wadsworth et al., *JOSA B* **19**, 2148 (2002).

5.3.3 Spectral modulation in photonic crystal fibers

*G. Genty, M. Lehtonen, M. Kaivola**, *and H. Ludvigsen*

* *Department of Engineering Physics and Mathematics, HUT*

Microstructured photonic crystal fibers (PCFs) exhibit some unique optical properties compared to standard optical fibers. For instance, their dispersion characteristics can be quite unusual as the zero-dispersion wavelength of these fibers can be pushed far into the visible. Also, the possibility to control the mode area in broad ranges allows various nonlinear optical processes to be greatly enhanced in PCFs. These characteristics make such fibers interesting objects for study of some fundamental features of pulse propagation; conveniently in the near infrared using short lengths of fiber. We report here on experimental observations on strong modulation in the spectrum of short optical pulses propagating in a PCF [1].

To observe the phenomenon, an 80-MHz pulse train from a Ti:Sapphire laser operating at 785 nm was coupled into a few meter-long highly birefringent PCF (Crystal Fibre A/S). The Ti:Sapphire laser produces linearly polarized Gaussian pulses with a FWHM of 200 fs. The spectrum of the output pulses after propagation through the PCF was recorded using an optical spectrum analyzer. Spectra of the pulses for different input powers are shown in Figure 5.3.3-1.

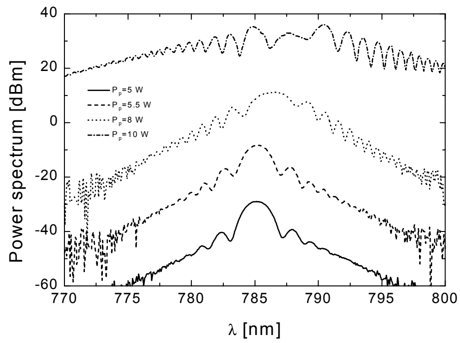

Figure 5.3.3-1. Optical spectra of initially Gaussian pulses after propagation through a PCF. P_p *represents the input peak power. An arbitrary vertical shift for the spectra has been added for clarity.*

For increasing input power, the amplitude of the oscillations on the wings of the spectra is seen to increase and their period to decrease. In addition, at high power levels the shape of the central part of the spectrum is altered and the whole spectrum becomes asymmetrical. We attribute the higher amplitude of the red spectral components and the shift of the central peak to arise from Raman scattering.

The observations we have made for pulse propagation in the photonic crystal fiber are in qualitative agreement with the earlier results obtained with the standard fiber. The oscillations are, however, more pronounced and extend over a much wider wavelength range.

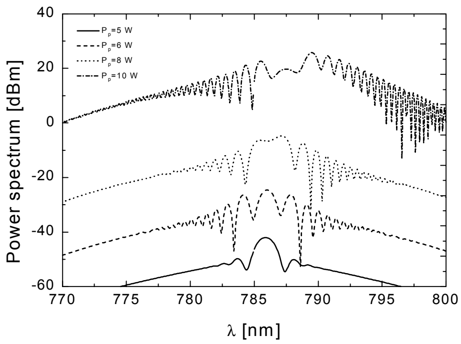

Figure 5.3.3-2. Simulation of optical spectrum of a pulse after propagation through a PCF using NLS.

To confirm the observed phenomena, we have numerically solved the nonlinear Schrödinger (NLS) using the split-step Fourier algorithm. Employing the parameter values of our particular fiber (α= 0.15 dB/m, β_2= 178 ps^2/km, γ= 110 /W/km and T_R= 15 fs), we have simulated the spectrum of the pulses after propagation through the fiber.

The results are presented in Figure 5.3.3-2. Good agreement is found between the experimental observations and the theoretical predictions. The modulation is explained to result from interference between the soliton and the radiation field, which is created when the Gaussian input pulse evolves into an asymptotic soliton [1].

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

[1] G. Genty et al., CLEO/QELS´02, paper CTuU5.

5.3.4 Polarization properties of photonic crystal fibers

T. Ritari, T. Niemi, H. Ludvigsen, F. Scholder, M. Legré*, M. Wegmuller*, N. Gisin*, J. R. Folkenberg†, A. Petersson†, and P.M.W. Skovgaard†*

** Group of Applied Physics, University of Geneva, Switzerland*
† Crystal Fibre A/S, Denmark

Photonic crystal fibers (PCFs) are a new class of optical fibers having a silica core surrounded by air holes running along the length of the fiber in the cladding area. We have investigated polarization-mode dispersion (PMD) of PCFs having a large mode-area. PMD is a pulse broadening mechanism limiting high-speed data transmission in future optical networks. The three fiber samples studied are made of pure silica with a hexagonal arrangement of air holes around the core. They are labeled PCF10, PCF15, and PCF20, according to their core sizes of 10.8, 14.8, and 19.4 μm (mean distance between opposite hole edges of the core). The cross-section of PCF20 is shown in Figure 5.3.4-1. The ratio of the hole diameter, *d*, to the pitch of the structure, Λ, is around 0.45.

The PMD of the fiber samples was measured utilizing three conventional measurement techniques. At HUT the Jones Matrix Eigenanalysis (JME) and fixed analyzer methods were used employing a commercially available device (Profile PAT9000). The measurement techniques used in the Group of Applied Physics, Geneva (GAP) were JME and the interferometric method. The light source for JME was a tunable laser with a tuning range of 1455-1612 nm (GAP) and 1510-1650 nm (HUT). The source for the interferometric method was a polarized LED with a spectrum of 1517-1565 nm (FWHM). At Crystal Fibre A/S (CF), the PMD was investigated by utilizing the FA method.

The measurement results of HUT and GAP agree within the inherent PMD measurement limit [1]. The values obtained at HUT are in excellent agreement and the same holds for the values measured at GAP. The PMD results of Crystal Fibre A/S are closer to the values obtained in GAP in the case of PCF10 and HUT in the case of PCF20.

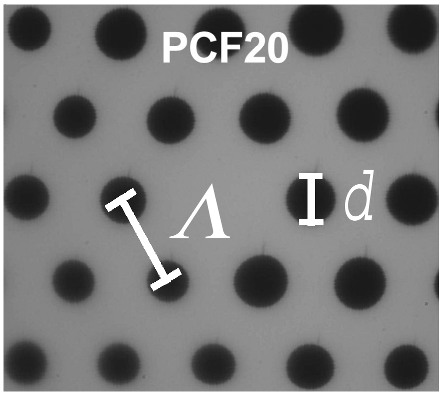

Figure 5.3.4-1. Cross-section of PCF20.

An extremely low PMD value of PCF15 indicates that it has an excellent symmetry in the hole structure. This proves that it is possible to manufacture long fibers with a high symmetry and an even stress distribution. To our knowledge, this is the first observation of such a low PMD value indicating high quality of the fiber. This could lead to a major breakthrough in the production of long PCF structures.

This work was conducted within the COST Action 265. The work has been financially supported by the Academy of Finland.

[1] T. Niemi *et al.*, ECOC'02, paper M.S1.09.

5.3.5 Compact wavelength reference for optical communications

J. Tuominen, T. Niemi, and H. Ludvigsen

Modern WDM systems working over a broad wavelength range require means to monitor and calibrate the channel wavelengths with high accuracy. A silicon Fabry-Perot etalon provides a compact and flexible wavelength reference for these purposes [1]. 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 index of refraction of silicon has a temperature dependence that can be utilized to tune the transmission spectrum of the etalon as shown in Figure 5.3.5-1. Increasing the temperature of the etalon moves the periodic fringes to higher wavelengths and vice versa. The sensitivity of the tuning is ~65 pm/K. By knowing the parameters of the etalon, the positions of the transmission fringes can be accurately 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 with LabView to automate the calculations and the tuning procedure. Operating the device includes only typing the required wavelength to the user interface. Another program was developed to turn the device into a wavelength meter. The operation is based on a fringe scanning a wavelength range smaller than the *FSR*. The transmission is measured at intervals throughout the scan and the wavelength is determined from the data.

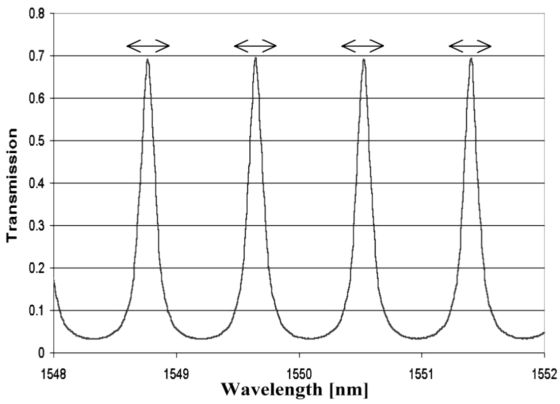

Figure 5.3.5-1. Tunable spectrum of the etalon.

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 an accuracy better than 125 MHz (~1 pm). At a broader wavelength range, form 1.3 µm to

1.6 µm, a proper operation has been confirmed with a wavelength meter, which limits the accuracy to ±3 pm. The stability of the device was evaluated by measuring the wavelength for a period of more than 100 h. The wavelength remained inside ±0.5 pm for the duration of the measurement.

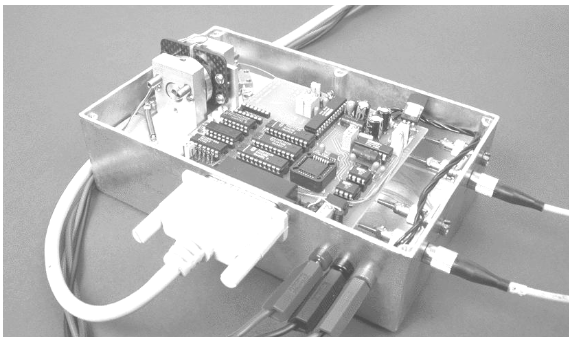

Figure 5.3.5-2. The wavelength reference.

The reference was also tested in a WDM testbed at the Technical Research Centre of Finland (VTT). ~50 kHz pilot tones with 2 kHz spacing were used to identify the channels. At the receiver end, the reference was scanned across the channels measuring the amplitude of the pilot tones from the –30 dBm signal. The scanning takes 3 s of time per channel and the accuracy of the derived channel wavelength was about 3 pm.

The wavelength reference developed is found to be compact, robust, and cost-effective. Its continuous 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 work has been financially supported by Nordic Industrial Fund and MIKES.

[1] J. Tuominen, T. Niemi, P. Heimala, and H. Ludvigsen, URSI GA..´02, p1512.

5.4 Microtechnologies

5.4.1 High-Q micromechanical silicon oscillators

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

High-Q oscillators are mechanical structures with stable and spectrally very narrow resonance. Such oscillators have applications as reference oscillators, sensors and even in very sophisticated high-precision experiments for observing quantum effects.

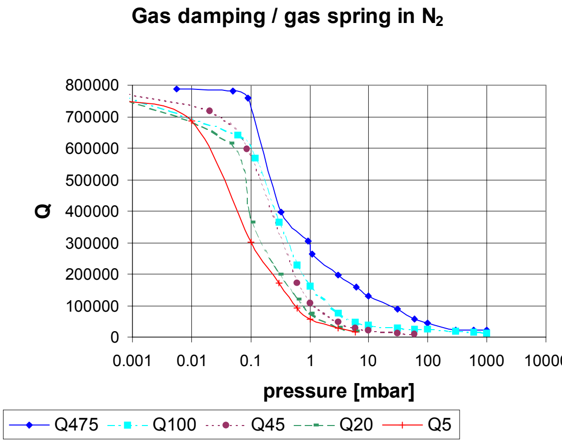

Figure 5.4.1-1. Q-factor measured in vacuum chamber with different gap sizes (Q475,…,Q5 are gap sizes of 475,…,5 µm respectively).

The dynamics of a high-Q mechanical silicon oscillator was studied in nitrogen gas the planar silicon surface being placed close to the torsionally vibrating oscillator (Figure 5.4.1-1 and Figure 5.4.1-2).

Squeezed film damping is due to the viscous losses of gas flowing in a narrow gap and it has effects both on the resonance frequency and Q-factor. Besides dissipative damping effect, the squeezed film damping force introduces also a gas spring effect. At large squeeze number (high frequency, small gap) gas is essentially trapped in the gap and behaves as an additional spring which can shift the resonance (Figure 5.4.1-2).

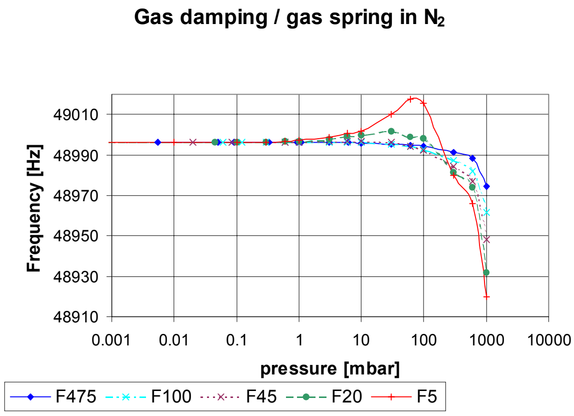

Figure 5.4.1-2. Gas spring effect caused clear shift in resonance when gap size was decreased (F475,…,F5 are gap sizes of 475,…,5 µm respectively).

Typically MEMS devices are characterized by very small air gaps between the moving and fixed parts. Thus squeezed film damping effects must carefully be taken into account when designing and operating MEMS and they cannot be ignored until at very low pressures.

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

5.4.2 Micromechanical resonators for RF-applications

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

Microelectromechanical (MEM) resonators are electrically excited and read mechanical resonators that are usually fabricated on a silicon wafer (Figure 5.4.2-1 and Figure 5.4.2-2).

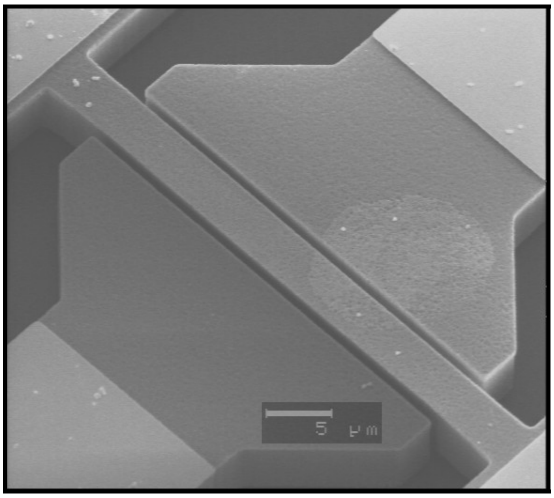

Figure 5.4.2-1. Micromechanical beam resonator.

These resonators can be a significant parts in the Radio Frequency (RF) – circuits in the future, because many of the building blocks of a RF-circuit can be realized using micromechanical resonators as a replacement for large and expensive discrete components (Figure 5.4.2-3). For example RF-filters and RF-switches can be fabricated using micromechanical components. The greatest expectations are, however, placed on a reference oscillator realized with the aid of micromechanical resonators. The annual sales of these oscillators could reach up to hundreds of millions.

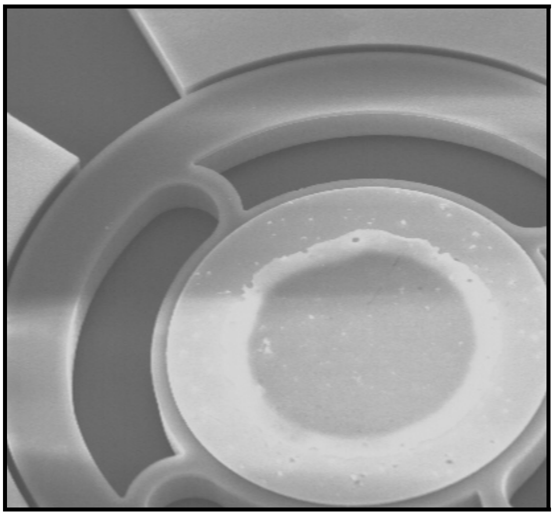

Figure 5.4.2-2. Micromechanical ring resonator.

Micromechanical resonators have already shown the ability to compete with the quartz crystals in short term stability. In practice this means that we have been able to fabricate resonators with such a high quality factor (Q), that it is possible to realize oscillators that are comparable with the quartz oscillators in terms of short-term stability. A length-extensional mode resonator that has been used to realize the aforementioned demonstration oscillator is presented in Figure 5.4.2-4.

So far the oscillator circuits have been fabricated using the discrete components, but with micromechanical resonator. This means that one of the key areas in research will be integrating the oscillator electronics with the resonator on a single chip. The other key areas will include increasing the long term and temperature stability of the oscillator.

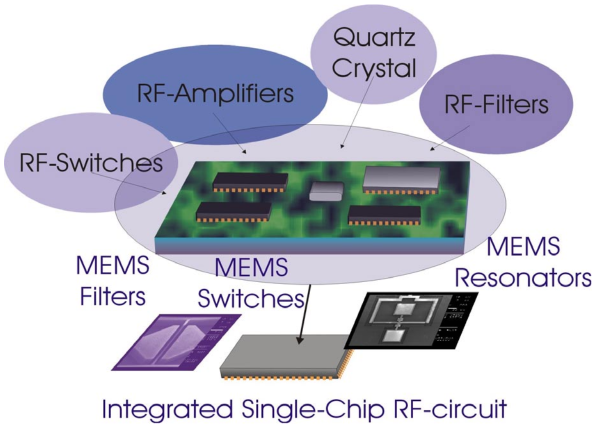

Figure 5.4.2-3. Schematic view of the RF-circuit of the future.

The effect of external factors on stability can be minimized by packaging the resonators hermetically. This minimizes the damping effect of ambient air and also excludes the effect of humidity and the contaminating particles in the surrounding atmosphere. The effect of temperature variations, however, cannot be excluded by packaging technology. Also the familiar method to cut the quartz crystal in a direction that minimizes the temperature dependency doesn't work with silicon. This leads to a need to design and develop a temperature compensation method for oscillator to maintain the reference frequency despite the changes in temperature.

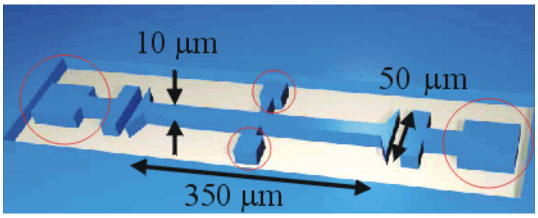

Figure 5.4.2-4. Length-extensional microelectromechanical resonator on SOI (Silicon On Insulator). The resonance frequency in the longitudinal direction of the beam is 13 MHz. The areas surrounded by red are attached to the structural layer.

The work has been financially supported by TEKES, Nokia Research Centre and VTI Technologies.

5.4.3 Finite element modeling of microsystems

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

Present-day 'state-of-the-art' sensor technology is quite often based on measuring very small and complicated physical effects. To analyze and optimize these devices properly, a finite element method (FEM) based software is usually required. Here we give an example of analysis of thermal anemometer utilizing ANSYS multiphysics software package.

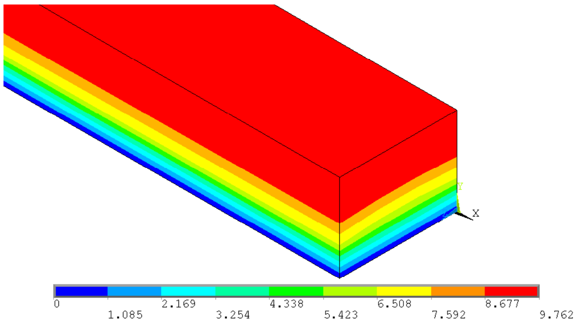

Figure 5.4.3-2. Speed profile of the flow above the deflector.

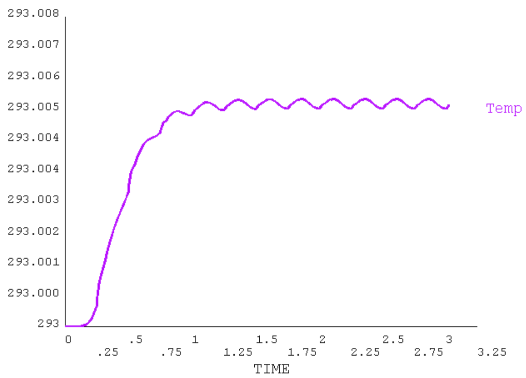

Figure 5.4.3-1. Dynamical behavior of the microphone was inspected by transient analysis.

A thermal anemometer measures a velocity of airflow by measuring a traveling time of a heat pulse from a heater to a detector. A 3-ms long heat pulse was generated every 250 ms. The dynamics of the electrical temperature measurement signals were then used to determine the speed of the wind. Thus, the time-dependent heat transfer was needed to be simulated both in the solid detector and in the fluid (air).

The measured data was averaged over 100 pulses. No random fluctuations were included in the simulation. The simulation was performed as long as it was required for that the initial transient oscillations to disappear and the signal level to stabilize. The example of this phenomenon is shown in Figure 5.4.3-1.

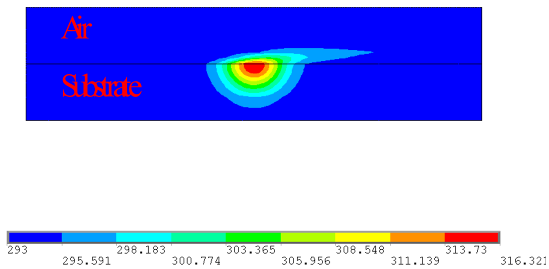

Figure 5.4.3-3. The Heat distribution of sensor: heat is transported to the probe lines much faster by flowing air than by the solid substrate.

Before the actual anemometer design was modeled, the speed profile of the moving air above the sensor had to be calculated (see Figure 5.4.3-2). The deflector was assumed to be a thin circular plate in order to avoid any turbulent effects also the no slip condition was assumed at the fluid-structural interface.

Next the speed profile result was added as a constraint to the fluid domain and the transient analysis for the heat pulses was performed. During the transient analysis the heat distribution was observed in the substrate and in the air region as a function of time (Figure 5.4.3-3).

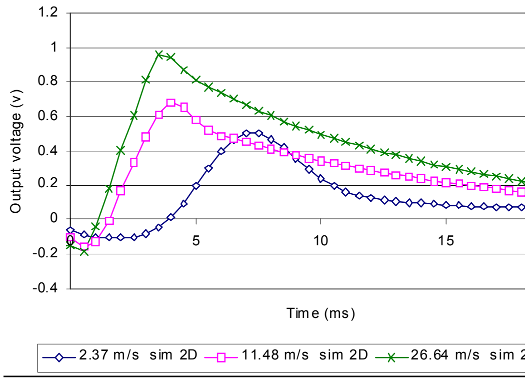

Figure 5.4.3-4. Delay times of heat pulses with various flow speeds.

From the time depended heat distribution the flow velocity can be resolved as a function of time (Figure 5.4.3-4).

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

5.5 Applied Quantum Optics

5.5.1 Trapping of neutral atoms

T. Lindvall, M. Heiliö, L. Niinikoski, M. Auromaa, E. Herola, M. Merimaa, I. Tittonen, A. Shevchenko[*], *M. Hautakorpi*[*], *and M. Kaivola*[*]

[*] *Optics and Molecular Materials, HUT*

Recently there has been a lot of progress in the field of integrated atom optics. The research has mainly concentrated on the use of magnetic confinement of atoms in the so-called low-field seeking states, using the magnetic field created by current-carrying wires. We have proposed an alternative technique, where the atoms are transferred from a gravito-optical trap (GOT) consisting of an evanescent-wave (EW) atom mirror on a prism and a vertical repulsive hollow beam (HB) into transparent microtraps fabricated onto the surface of the prism, see Figure 5.5.1-1. The microtraps can be electro-optical, using transparent indium tin oxide (ITO) conductors, or magneto-optical, using a transparent magnetic yttrium iron garnet (YIG) film. The ITO traps are spin-independent, whereas YIG traps can be made for atoms in either low- or high-field seeking states.

The operation procedure is the following: First, rubidium atoms are cooled in a magneto-optical trap (MOT) located some millimeters above the prism surface. The MOT can be loaded with atoms using a closely mounted alkali metal dispenser as a pulsed source. After cooling in the MOT, the atoms are transferred downwards to the GOT inside the hollow beam by simply letting them fall or by shifting the zero of the magnetic field of the MOT. In the GOT the atoms are further cooled to a temperature of the order of a few μK. Finally, the microscopic surface trap is turned on.

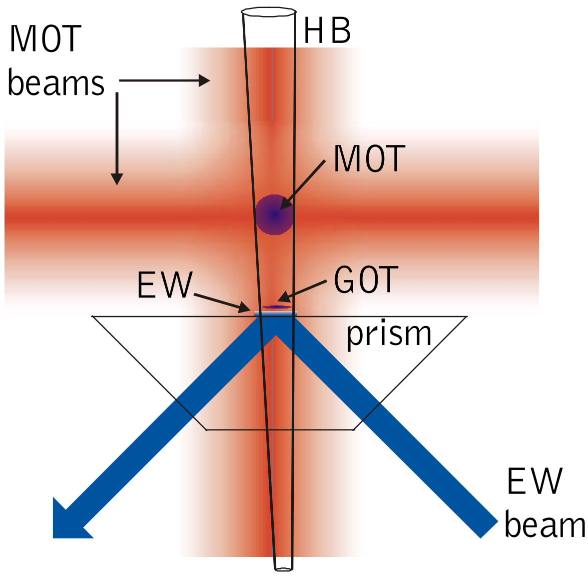

Figure 5.5.1-1. The MOT and the GOT. For abbreviations see text.

The ultra-high vacuum system and the lasers are included in the experimental realization of the MOT. We use a master-slave configuration, where three diode lasers, capable of delivering up to ~50 mW each, are injection-locked to a transmission grating-based external-cavity diode laser stabilized to the hyperfine spectrum of rubidium. The vacuum system and the Rubidium dispensers have been tested and the realization of the MOT is the next step.

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

5.5.2 Laser frequency doubling using a periodically poled nonlinear KTP crystal

O. Kimmelma, S. Buchter, and I. Tittonen*

** Department of Engineering Physics and Mathematics, HUT*

Converting the laser light to new optical frequencies can be done by means of nonlinear optics. In a nonlinear material the polarization of the material is not only directly proportional to the electric field. The nonlinear effects can be observed when the electric field is strong and the generated field interferes constructively when it is propagating in the crystal.

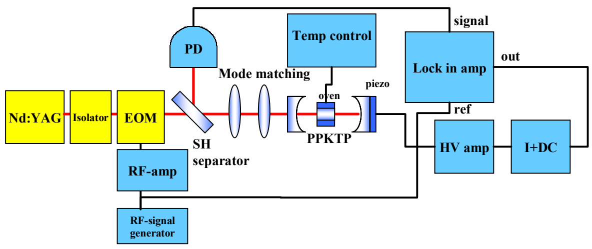

Figure 5.5.2-1. Setup.

In this work a crystal with periodically changed nonlinear coefficient is used. The poling is done by exceeding the coercive field of the ferroelectric crystal with an external field. The technique is called periodic poling and the phase matching using a periodic structure is called quasi-phase-matching. The used nonlinear material is potassium titanyl phosphate ($KTiOPO_4$) or KTP and it has very good mechanical and optical properties for nonlinear optics.

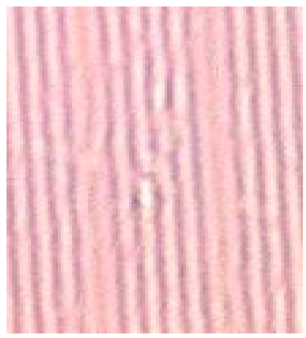

Figure 5.5.2-2. A microscope picture of the poled KTP crystal.

The crystal has been poled with a period of 9 µm. A Fabry-Perot resonator is used to amplify the interaction between the laser light and the crystal in order to convert the fundamental IR-frequency at 1064 nm effectively to the second harmonic at 532 nm. This wavelength is in the region of green. A second harmonic power of 111 mW is created with a fundamental input power of 290 mW.

For practical applications it is useful to stabilize the output power. The resonator is locked to the laser using a Pound-Drewer-Hall locking scheme. A 2σ stability of 2.5% is achieved in the period of 8 minutes.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

CCPR-K1.a International comparison of spectral irradiance

The key comparison is on spectral irradiance measurements of tungsten lamps in the wavelength region from 250 nm to 2500 nm. HUT participates in the wavelength region 290 – 900 nm. HUT conducted their second round of measurements in September 2002. The lamps have been returned to NPL for final measurements. Draft A is expected in spring 2003.

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

The measurements for this key comparison were carried out by HUT in 1999. No progress in 2002.

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

The key comparison is on spectral responsivity measurements of trap detectors and photodiodes in the wavelength region from 300 nm to 1000 nm. The measurements for this comparison were carried out by HUT in 2000. Draft A-1 was circulated to participants in 2002. The results indicate a good agreement for HUT within uncertainties.

CCPR-K6 International comparison of regular spectral transmittance

The key comparison is on spectral regular transmittance measurements in the wavelength region from 380 nm to 1000 nm. The measurements for this comparison were carried out by HUT in 2000. No progress in 2002.

CCPR-S2 International comparison of aperture area measurements

The measurements for this supplementary comparison were carried out by HUT in 2000. No progress in 2002.

Bilateral comparison of spectral irradiance with NIST, USA

The spectral irradiance scales of HUT and NIST (1992 scale) 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 2002, the comparison report has published in Metrologia [T. Kübarsepp, H.W. Yoon, S. Nevas, P. Kärhä and E. Ikonen, "Comparison of spectral irradiance scales between the NIST and the HUT", *Metrologia* **39**, 399-402 (2002)].

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 published in Metrologia [J. Hovila, P. Toivanen, E. Ikonen, and Y. Ohno, "International comparison of the illuminance responsivity scales and units of luminous flux maintained at the HUT (Finland) and the NIST (USA)," *Metrologia* **39**, 219-223 (2002)].

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 published in Metrologia [J. Hovila, P. Toivanen, E. Ikonen, and Y. Ohno, "International comparison of the illuminance responsivity scales and units of luminous flux maintained at the HUT (Finland) and the NIST (USA)," *Metrologia* 39, 219-223 (2002)].

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 were used to compare various ultraviolet calibration facilities in Finland (HUT), France (BNM), and UK (NPL). The results have been accepted to be published in Metrologia.

Bilateral comparison of spectral diffuse reflectance with MSL, New Zealand

The diffuse reflectance scale of HUT was compared with the scale of MSL. HUT conducted their part of the measurements in 2001. The results received in 2002 indicate good agreement with the white samples. The deviations noted with gray samples are still under investigation.

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 2002, the Thematic Network arranged its fifth Workshop in Kassandra, Greece and published one Newsletter. The Workshop took place on October 6-8. It was hosted by the Aristotle University of Thessaloniki. The number of participants was 51. Ten oral and nine poster presentations were given to introduce latest innovations in the field of UV measurements. The outcome of the Workshop was summarized in the extended abstracts published in *UVNews* **7** in December 2002. This Newsletter and further information on the Workshop can be found in the web-pages of the Network (http://metrology.hut.fi/uvnet/).

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

SPIE's Photonics West Meeting BiOS 2002, Optoelectronics 2002, LASE 2002, San Jose, California USA, January 19 – 25, 2002; *Mikko Merimaa*

Meetings with Crystal Fibre A/S and NKT Innovations, Copenhagen, Denmark, February 8 – 10, 2002; *Hanne Ludvigsen*

Estonian Physics Days, Tartu; Estonia, February 14 – 17, 2002; *Mart Noorma*

XXXVI Annual Conference of the Finnish Physical Society, Joensuu, Finland, March 14 – 16, 2002; *Ilkka Tittonen, Kaj Nyholm, Mika Koskenvuori, Pekka Rantakari, Jouni Envall, Jesse Tuominen and Mikko Lehtonen*

Micro Structure Workshop 2002, Aronsborg, Sweden, March 19 – 21, 2002; *Mika Koskenvuori and Pekka Rantakari*

EUROMET Photometry and Radiometry TC meeting, Bern, Switzerland, April 7 – 9, 2002; *Erkki Ikonen*

Finnish Optics Days, Kajaani, Finland, April 24 – 26, 2002; *Tomasz Jankowski and Mart Noorma*

DTIP 2002 of MEMS and MOEMS, Mandelieu, France, May 5 – 8, 2002; *Kaisa Nera and Ossi Hahtela*

CLEO 2002, Long Beach, California, USA, May 19 – 24, 2002; *Goëry Genty*

NEWRAD 2002, 8th International Conference on New Developments and Applications in Optical Radiometry, Gaithersburg, USA, May 19 - 23, 2002; *Erkki Ikonen, Farshid Manoocheri, Petri Kärhä, Jari Hovila, Saulius Nevas and Mart Noorma*

UV Workshop, NIST, Gaithersburg, USA, May 24, 2002; *Erkki Ikonen, Petri Kärhä*

Final meeting of the EU-project "Improving the Accuracy of Ultraviolet Radiation Measurement," NMi-VSL, Delft, Netherlands, June 7, 2002; *Petri Kärhä*

Cooling 2002, Visby, Sweden, June 9 – 12, 2002; *Thomas Lindvall*

The 4th International Conference on Materials for Microelectronics and Nanoengineering, Espoo, Finland, June 10 – 12, 2002; *Saulius Nevas, Mika Koskenvuori*

CPEM 2002, Ottawa, Canada, June 16 – 21, 2002; *Mikko Lehtonen, Mikko Merimaa*

XXVII General Assembly URSI 2002, Maastricht, the Netherlands, August 17 – 24, 2002; *Jesse Tuominen*

ECOC 2002, Copenhagen, Denmark, September 8-12, 2002; *Hanne Ludvigsen and Tapio Niemi*

Eurosensors XVI, Praha, Czech Republic, September 15 – 18, 2002; *Mika Koskenvuori and Pekka Rantakari*

Quantum Optics Euroconference 2002, San Feliu de Guixols, Spain, September 21 – 26, 2002; *Thomas Lindvall and Ilkka Tittonen*

Thematic Network for Ultraviolet Measurements, 5th Workshop on Ultraviolet Radiation Measurements, Kassandra, Halkidiki, Greece, October 6 – 8, 2002; *Petri Kärhä and Erkki Ikonen*

NOT kick-off meeting at NKT Research, Copenhagen, Denmark, October 25, 2002; *Hanne Ludvigsen and Tapio Niemi*

Metrology in European Research Area (MERA) Workshop, Rotterdam, the Netherlands, December 16 – 17, 2002; *Erkki Ikonen*

6.4 Visits by the Laboratory Personnel

Ilkka Tittonen, University of Konstanz and ETH Zürich, December 29, 2001 – January 4, 2002

Mikko Merimaa, NIST National Institute of Standards and Technology, Boulder, USA, January 26, 2002 and JILA Joint Institute of Laboratory Astrophysics, University of Colorado, Boulder, USA, January 27, 2002

Ilkka Tittonen, Markku Vainio and Ossi Kimmelma, KTH, Stockholm, Sweden, February 4 – 6, 2002

Erkki Ikonen, ETH Zurich, Switzerland, April 10, 2002

Saulius Nevas, National Physical Laboratory (NPL), Teddington, UK, August 19, 2002

Erkki Ikonen, Farshid Manoocheri, Petri Kärhä, Jari Hovila, Saulius Nevas and Mart Noorma, National Institute of Standards and Technology (NIST, USA) May 23, 2002.

Petri Kärhä, NMi-VSL, Delft, Netherlands, September 1 – 2, 2002

Petri Kärhä and Erkki Ikonen, Aristotle University of Thessaloniki, Laboratory of Atmospheric Physics, Greece, October 8, 2002

Goëry Genty and Mikko Lehtonen, Optoelectronics Research Centre, Tampere University of Technology, Finland, November 4, 2002

6.5 Research Work Abroad

Dr. Kaj Nyholm, Bureau International des Poids et Mesures (BIPM), Paris France, February 4 – 10, 2002

6.6 Guest Researchers

6.7 Visits to the Laboratory

Dr. Toomas Kübarsepp, Metrosert Ltd., Tartu, Estonia, January 14, 2002

Dr. Yakov Sidorin, Optitune PLC, London, United Kingdom, February 4, May 30, June 5, 2002

Prof. Alexander Tikhonravov, Moscow State University, Research Computing Center, Moscow, Russia, March 2 – 6, 2002

Dr. Toomas Kübarsepp and Toomas Kolk, Metrosert Ltd., Tartu, Estonia, June 12, 2002

Prof. Kristian Stubkjær, Technical University of Denmark/COM, Denmark, June 13 – 15, 2002

Dr. M. Kokarev, Moscow State University, Research Computing Center, Moscow, Russia, August 8, 2002

Prof. J. Javanainen, University of Connecticut, Storrs, USA, September 17, 2002

Mr. Pan Biqing, Mr. Zhang Yue, Mr. Wu Jian, Mrs. Wang Lanxiang, Mr. Liang Jin, and Mrs. Guo Xiaolin, NIM, China, October 4, 2002

7 PUBLICATIONS

7.1 Articles in International Journals

G. Genty, M. Kaivola, and H. Ludvigsen, "Measurements of linewidth variations within external cavity modes of a grating-cavity laser," *Opt. Commun.* **203,** 295-300 (2002).

G. Genty, T. Niemi, and H. Ludvigsen "New method to improve the accuracy of group-delay measurements using the phase-shift technique," *Opt. Commun.* **204**, 119-126 (2002).

T. Niemi, S. Tammela, and H. Ludvigsen, "Device for frequency chirp measurements of optical transmitters in real time," *Rev. Sci. Instrum*. **73**, 1103-1107 (2002).

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A. Haapalinna, S. Nevas, F. Manoocheri, and E. Ikonen, "Precision spectrometer for measurement of specular reflectance," *Rev. Sci. Instrum.* **73**, 2237-2241 (2002).

C. J. Marckmann, Y. Ren, G. Genty, and M. Kristensen, "Strength and symmetry of the third-order nonlinearity during poling of glass waveguides," *IEEE Photonics Technol. Lett.* **14**, 1294-1296 (2002).

J. Hovila, P. Toivanen, E. Ikonen, and Y. Ohno, "International comparison of the illuminance responsivity scales and units of luminous flux maintained at the HUT (Finland) and the NIST (USA)," *Metrologia* **39**, 219-223 (2002).

T. Kübarsepp, H. W. Yoon, S. Nevas, P. Kärhä, and E. Ikonen, "Comparison of spectral irradiance scales between the NIST and the HUT," *Metrologia* **39**, 399-402 (2002).

E. Ikonen, "Applications related to maximum intensity correlation of hard x rays," *Phys. Rev. A* **66**, 065802 (2002).

T. Mattila, J. Kiihamäki, T. Lamminmäki, O. Jaakkola, P. Rantakari, A. Oja, H. Seppä, H. Kattelus, and I. Tittonen, "12 MHz Micromechanical Bulk Acoustic Mode Oscillator," *Sensors and Actuators A* **101**, 1-9 (2002).

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S. Picard, L. Robertsson, L.-S. Ma, K. Nyholm, M. Merimaa, T. E. Ahola, P. Balling, P. Kren, and J.-P. Wallerand, "A comparison of $^{127}I_2$-stabilized frequency-doubled Nd:YAG lasers at the BIPM," *Appl. Opt.* (in press).

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

S. Picard, L. Robertsson, L.-S. Ma, Y. Millerioux, P. Juncar, J.-P. Wallerand, P. Balling, P. Kren, K. Nyholm, M. Merimaa, T. E. Ahola, and F.-L. Hong, "Results from international comparisons at the BIPM providing a world-wide reference network of $^{127}I_2$ stabilized frequency-doubled Nd:YAG lasers," *IEEE Trans. Instrum. Meas.* (in press).

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

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

L. Ylianttila, K. Jokela, and P. Kärhä, "Ageing of DXW-lamps," *Metrologia* (in press).

S. Nevas, F. Manoocheri, and E. Ikonen, "Determination of Thin-Film Parameters from High Accuracy Measurements of Spectral Regular Transmittance," *Metrologia* (in press).

M. Noorma, P. Toivanen, F. Manoocheri, and E. Ikonen, "Characterisation of filter radiometers with wavelength-tunable laser source," *Metrologia* (in press).

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M. Merimaa, “Compact frequency stabilized diode lasers,” in *Technical Summary Digest of SPIE’s Optoelectronics 2002*, January 20 – 25, 2002, p. 71 (invited talk).

T. Lindvall, M. Merimaa, I. Tittonen, and E. Ikonen, “An all-optical atomic clock based on dark states of ^{85}Rb,” in *Proceedings of the Sixth Symposium on Frequency Standards and Metrology*, Ed. P. Gill, World Scientific, New Jersey, 2002, pp. 183-190.

M. Noorma, P. Toivanen, F. Manoocheri, and E. Ikonen, “Characterisation of filter radiometers with wavelength-tunable laser source,” Estonian Physics Day, Tartu, Estonia, February 14 – 17, 2002 (poster).

P. Rantakari, M. Koskenvuori, T. Lamminmäki, and I. Tittonen, “High-Q micromechanical length extensional mode resonator,” Micro Structure Workshop 2002, Aronsborg, Sweden, March 19 – 21, 2002 (poster).

P. Rantakari, J. Kiihamäki, M. Koskenvuori, T. Lamminmäki, and I. Tittonen, “Reducing the effect of parasitic capacitance on MEMS measurements,” Micro Structure Workshop 2002, Aronsborg, Sweden, March 19 – 21, 2002 (poster).

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G. Genty, M. Lehtonen, J. R. Jensen, M. Kaivola, and H. Ludvigsen, “Route to supercontinuum in photonic crystal fibers,” *Proceedings of CLEO/QELS 2002*, Long Beach, California, USA, May 19 – 24, 2002, paper CtuU1 (talk).

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T. Kübarsepp, H. Rabus, and C. A. Schrama, "Comparison of methods to derive the quantum yield of silicon in the near UV," *in Abstracts of NEWRAD2002*, 8th International Conference on New Developments and Applications in Optical Radiometry, Gaithersburg, USA, May 20 – 24, 2002, p. 97 (poster).

T. Kübarsepp, H. W. Yoon, S. Nevas, P. Kärhä, and E. Ikonen, "Comparison measurements of spectral irradiance between NIST and HUT," *in Abstracts of NEWRAD2002*, 8th International Conference on New Developments and Applications in Optical Radiometry, Gaithersburg, USA, May 20 – 24, 2002, p. 102 (poster).

F. Manoocheri, S. W. Brown, and Y. Ohno, "Uncertainty of colorimetric calibration of displays at NIST," *in Abstracts of NEWRAD2002*, 8th International Conference on New Developments and Applications in Optical Radiometry, Gaithersburg, USA, May 20 – 24, 2002, p. 114 (poster).

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P. Kärhä, J. Envall, and E. Ikonen, "Study of fiber optic power measurements using photodiodes with and without integrating sphere," *in Abstracts of*

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M. Noorma, P. Toivanen, F. Manoocheri, and E. Ikonen, "Characterization of filter radiometers with wavelength-tunable laser source," *in Abstracts of NEWRAD2002*, 8^{th} International Conference on New Developments and Applications in Optical Radiometry, Gaithersburg, USA, May 20 – 24, 2002, p. 155 (poster).

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