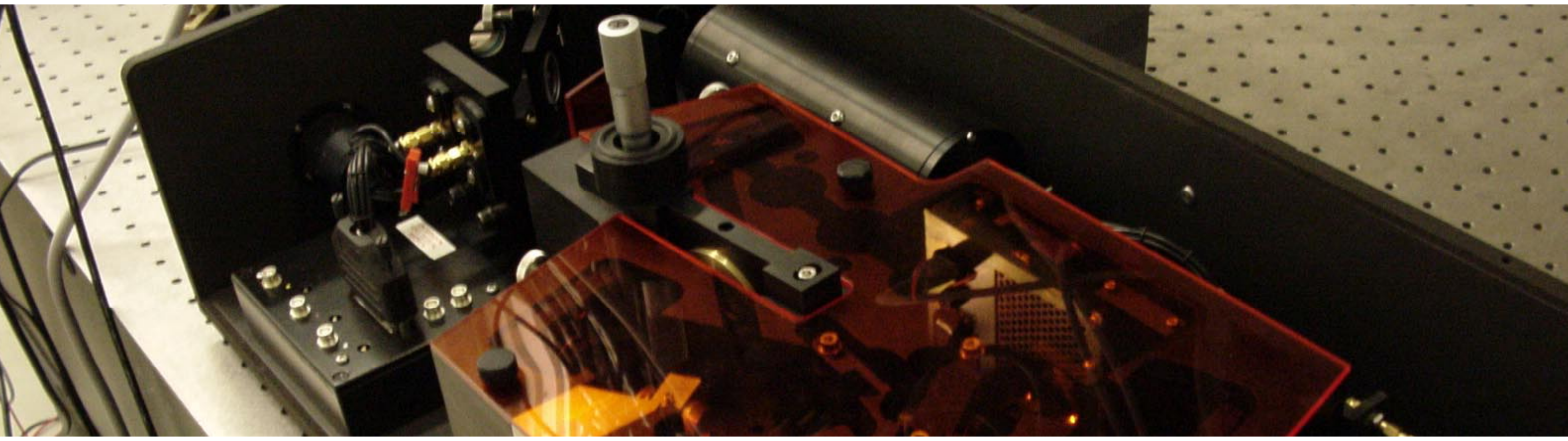
Helsinki University of Technology Department of Electrical and Communications Engineering

Metrology Research Institute Report 18/2001

Espoo 2001

ANNUAL REPORT 2000



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HELSINKI UNIVERSITY OF TECHNOLOGY
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Helsinki University of Technology
Metrology Research Institute Report 18/2001
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ANNUAL REPORT 2000

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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1 INTRODUCTION

The research activities in the Metrology Research Institute cover a broad range from microsystems to fibre optics or from quantum optics to applied metrology. Year 2000 was very successful for the Institute and the number of personnel increased rapidly. Two major scientific positions were established in the Institute: Hanne Ludvigsen received the position of the Academy Research Fellow in August 2000 and Ilkka Tittonen was appointed as Professor in December 2000.

A considerable teaching task of the Metrology Research Institute is involved in the course Fundamentals of Measurements, which is offered to all second year students of the Department. The Institute is active also in post-graduate education and is partner in several National Graduate Schools. Eight master's degrees and one doctoral degree were completed in 2000.

An exceptionally large number of international comparison measurements, altogether eleven, were carried out last year by the Metrology Research Institute. One of the main research efforts of the Institute during the recent years has been development of characterised filter radiometers for absolute measurement of optical radiation quantities. The comparison measurements have clearly indicated that the developed methods are very competitive and meet the high demands for the measurement uncertainty of spectral irradiance in the visible and ultraviolet wavelength region.

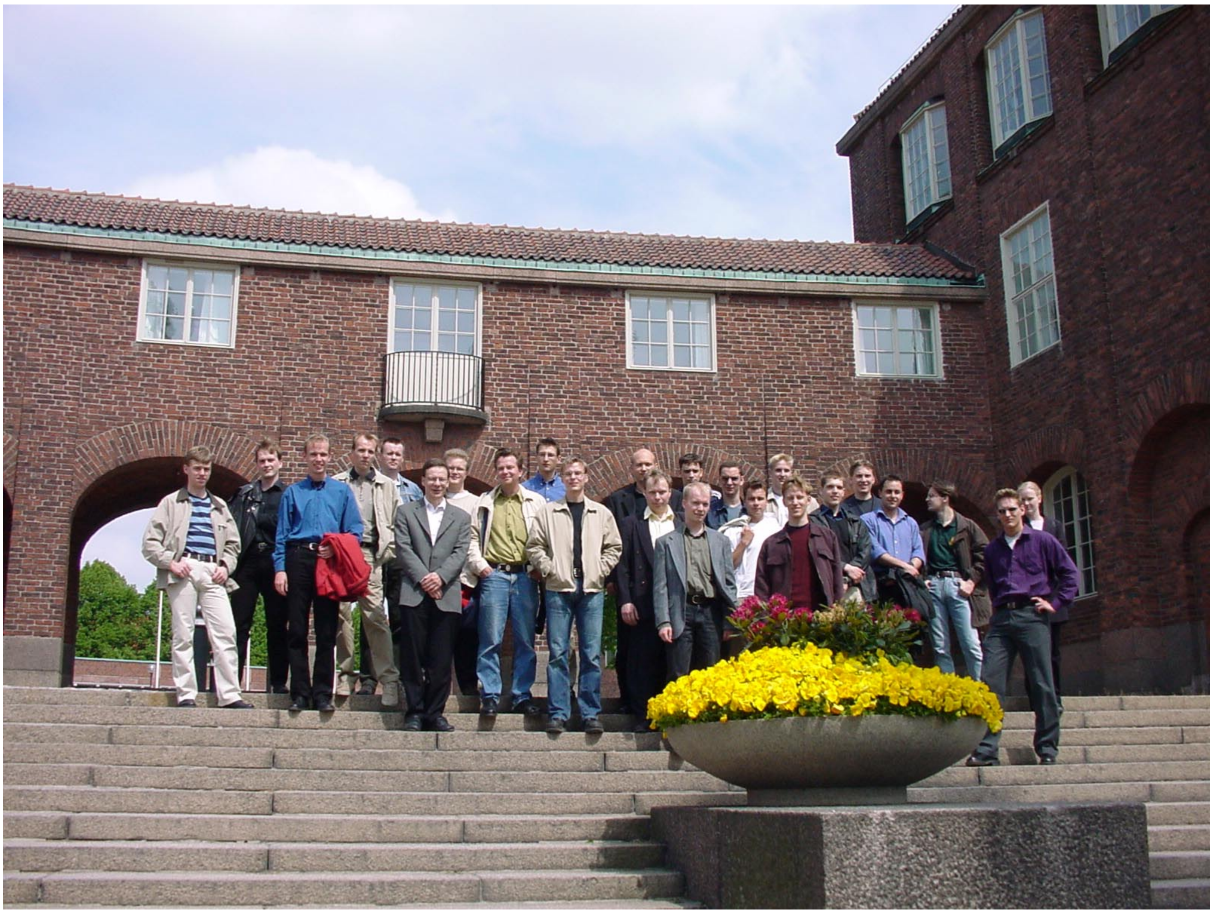
For optical communication systems, a tunable micro-filter was developed to improve and monitor the transmitter performance. This work was presented in the Optical Fiber Communications Conference (OFC 2000). It is remarkable that the presentation is the first Finnish oral contribution in this demanding series of conferences.

A new Ti:Sapphire laser system was installed in 2000. With its high output power and wavelength tunability, this laser facility will offer the possibility for exciting applications in quantum optics and basic metrology.

The Metrology Research Institute is an active participant within EU Research Programmes. We co-ordinate the Thematic Network for Ultraviolet Measurements with about fifty participants from all over the Europe. The EU funded part of this project was successfully completed in November 2000. Other EU projects where the Institute plays a significant role are Fibre Optic Thematic

Network (FOToN) and an R&D project on ultraviolet radiation measurements. We take part in international activities within the framework of EUROMET, CCPR and COST. It should be noted that during the past year collaboration with National Metrology Institutes outside Europe has also developed considerably.

Erkki Ikonen



Personnel of the Institute visiting Kungliga Tekniska Högskolan in Sweden.

2 PERSONNEL

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3 TEACHING

3.1 Courses

The following courses were offered by the Metrology Research Institute (Mittaustekniikan laboratorio) in 2000. 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	Microsystems technology 4 credits (Ilkka Tittonen and Sami Franssila)
S-108.184	Computer-based Measurements 2 credits (Kristian Lahti)
S-108.189	Project Work in Measurement Technology 2-5 credits (Pekka Wallin)
S-108.191	Fundamentals of Measurements Y 2 credits (Mikko Merimaa)
S-108.194	Electronic Instrumentation 3 credits (Pekka Wallin)
S-108.195	Fundamentals of Measurements A 2.5 credits (Mikko Merimaa)
S-108.198	Biological Effects and Measurements of Electromagnetic Fields and Optical Radiation 2 credits (Kari Jokela)
S-108.199	Optical Communications and Optical Instruments 5 credits (Erkki Ikonen)
S-108.901	Electrical Engineering Project 1-5 credits (Pekka Wallin)

S-108.903	Fourier Transforms in Measurements* 4 credits (Jyrki Kauppinen)
S-108.911	Postgraduate Course in Measurement Technology 7.5 credits (Ilkka Tittonen)
S-108.913	Postgraduate Course in Physics of Measurement* 3 credits (Birger Ståhlberg)
S-108.914	Research Seminar on Measurement Science 1 credit (Erkki Ikonen)

3.2 Degrees

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

Pasi Toivanen: Detector based realisation of units of photometric and radiometric quantities. Opponent: Dr. Yoshi Ohno, National Institute of Standards and Technology (NIST)

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

Ari Karjalainen: Micro-pattern detectors and readout electronics

Tiina-Liisa Forssell: Mode field diameter and cut-off wavelength in optical fibers with OTDR measurements

Maria Uusimaa: Temperature-tunable micro-filter for improving and monitoring transmitter performance in optical communications systems

Saulius Nevas: Facility for measurements of spectral diffuse reflectance

Thomas Lindvall: All-optical 3-GHz frequency standard based on rubidium transitions

Kaisa Nera: Fabrication and characterisation of a high-Q micromechanical silicon oscillator

Tuukka Hytönen: Challenges in the implementation of the long haul wavelength division multiplexing network

Tommi Laukkanen: Erbium-doped fiber-ring laser for telecommunication research

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 the optical quantities listed in the following tables. During 2000, 41 calibration certificates were issued. The calibration services are mainly used by the Finnish industry and various research organisations. 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 organisations ensure that the laboratory can also influence e.g. international standardisation 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 standards EN45001 and ISO Guide 25. Work is underway to update the system to meet new requirements of ISO/IEC 17025.

4.1 Radiometry

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

Quantity	Range	Wavelength range	Uncertainty (*k*=2)
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 %

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

Quantity	Range	Wavelength range	Uncertainty (*k* = 2)
Spectral irradiance	10 pW mm^{-2} nm^{-1} – 500 µW mm^{-2} nm^{-1}	290 – 380 nm	1,1 % – 2,8 %
		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 %
Colour co-ordinates (x, y)	0 – 1	–	0,1 %
Colour temperature	1 000 – 3 500 K	–	0,15 %

4.2 Photometry

Photometric calibrations are based on a reference photometer, the calibration of which is traceable to the cryogenic radiometer. Using the reference photometer, units for illuminance, luminous intensity, luminance and luminous flux may be realised. Most photometric calibrations are performed on a 4,5-m long optical bench enclosed in a light-tight enclosure. Stable photometric lamps and an integrating sphere source are used as light sources. Luminous flux measurements are done with a 1,65-m integrating sphere.

Quantity	Range	Uncertainty (k = 2)
Luminous intensity	10 – 10 000 cd	0,3 %
Illuminance	10 – 200 lx	0,2 %
	200 – 2 000 lx	0,3 % – 0,5 %
Luminance	5 – 40 000 cd m^{-2}	0,8 %
Luminous flux	10 – 10 000 lm	1,0 %

4.3 Spectrophotometry

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

A commercial spectrophotometer (Perkin Elmer Lambda 900) is also being used as a transfer standard instrument for the measurements of regular spectral transmittance. The instrument provides transmittance calibrations of a range of optical components traceable to the reference spectrometer. The performance of the instrument has been tested by internal quality control and comparison measurements for the visible spectral range.

Quantity	Range	Wavelength range	Uncertainty (k = 2)
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	> 0,01 A/W	250 – 380 nm	1 %
		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	0,05 – 1	360 – 830 nm	0,4 % – 1 %

4.4 Wavelength

Optical wavelength calibrations are carried out with a commercial spectrum analyser. The analyser is calibrated using the known wavelengths of gas lasers stabilised to transitions in iodine and acetylene.

Quantity	Range	Uncertainty (k = 2)
Optical wavelength	400 nm – 1,55 µm	0,01 nm

5 RESEARCH PROJECTS

5.1 Optical Radiation Measurements

5.1.1 Improving the accuracy of UV radiation measurement

Petri Kärhä, Neil Harrison, Saulius Nevas, Bill Hartree*, Issam Abu-Kassem†, and Toomas Kübarsepp‡*

** National Physical Laboratory (NPL), UK*
† Bureau National de Métrologie (BNM), France
‡ HUT, now with Tartu Observatory, Estonia

One of the main objectives of the European Commission funded project '*Improving the Accuracy of Ultraviolet Radiation Measurement'* was to develop filter radiometers to measure the radiation emitted from UV sources in the spectral range from 248 nm up to 365 nm with a target accuracy between 0,1 % and 1 %. Two types of filter radiometers were developed for the purpose. The first type built by NPL was based on wide band-gap solar blind photodiodes. The second type of filter radiometer built by HUT utilised trap detectors based on silicon photodiodes.

All filter radiometers were characterised by three institutes; HUT, NPL and BNM. The only exception was the 248 nm filter radiometers that were measured by NPL and BNM only. The measurement results provide intercomparisons between the spectral responsivity scales, spectral irradiance scales, wavelength scales, and facilities for filter radiometer characterisation between the three institutes. HUT and BNM characterised the radiometers using conventional monochromator-based spectrophotometers whereas NPL utilised their laser-based characterisation facilities.

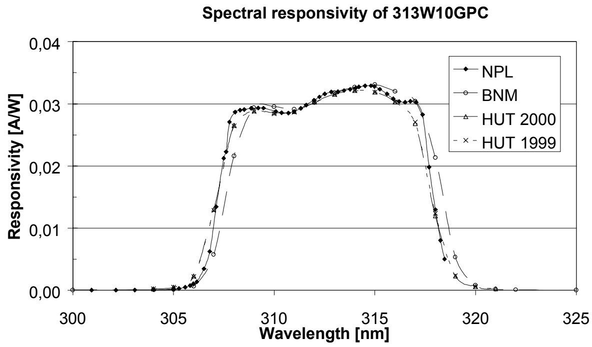

Figure 5.1.1-1. Typical UV filter radiometer calibrations by HUT, NPL and BNM-INM.

This part of the project ended in year 2000, and the final report has been written. Figure 5.1.1-1 shows an example of the results.

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 2 %.

The study pointed out various things to improve. The wavelength scales of the participating laboratories differ more than the stated uncertainties would imply. This appears to be a point that has not earlier been properly tested, as intercomparisons are usually performed using spectrally flat artefacts.

The study did not show that one of the filter radiometer types would be better than the other. The angular properties of trap detectors are complicated, but solar blind photodiodes have higher non-uniformity. These things may explain some of the discrepancies, because the beam geometries of the participating laboratories were not common.

The stability of the interference filters used was worse than anticipated. Changes up to 1,7 % in the transmittance within one year were noticed.

The work has been financially supported by the Standards, Measurements and Testing programme of the European Union and TEKES.

5.1.2 A portable field calibrator for solar UV measurements

Petri Kärhä, Lasse Ylianttila[*]*, and Toomas Kübarsepp*[†]

[*] *STUK, Radiation and Nuclear Safety Authority*
[†] *HUT, now with Tartu Observatory, Estonia*

Work package 4 of the European Commission funded project '*Improving the Accuracy of Ultraviolet Radiation Measurement'* develops a portable detector-stabilised calibration system for solar UV spectroradiometers. This work is collaboration between STUK, HUT, and NPL.

Calibration of e.g. Brewer spectroradiometers is problematic, because their transportation to calibration laboratories may affect their calibration, and calibration outside in the measurement sites is influenced by environmental conditions.

During year 2000, the first prototype of the calibrator was finished just before summer. The construction of the first prototype calibrator can be seen in Figure 5.1.2-1. The calibrator utilises 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 measurement distance of 50 cm can easily be adjusted by using unique interchangeable adapter plates for each spectroradiometer to be calibrated.

Figure 5.1.2-1. A photograph of the first prototype calibrator with the associated electronics for lamp control and the monitoring filter radiometers.

A significant part of the work has been assigned for measuring the ageing properties of DXW and FEL lamps. 12 specimens of each type where burned for 80 hours and monitored for various parameters. Based on the measurement results, DXW lamps where chosen. The lamp is operated in current-stabilised mode. When the ageing 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.

The preliminary measurements are encouraging. The device works satisfactorily in both laboratory and in field. Based on the experience gained, a second improved prototype calibrator will be built by summer 2001.

The work has been financially supported by the Standards Measurements and Testing programme of the European Union and TEKES.

5.1.3 Comparison measurements of spectral irradiance

T. Kübarsepp[*], H. Yoon[†], S. Nevas, P. Kärhä, and E. Ikonen

[*] *HUT, now with Tartu Observatory, Estonia*
[†] *National Institute of Standards and Technology (NIST), USA*

Comparison measurements of spectral irradiance between NIST and HUT were conducted in June 2000. The purpose of the measurements was to directly compare the spectral irradiance scales in the wavelength range from 290 nm to 900 nm.

In the comparison two sets of three FEL-type 1 kW lamps were measured at HUT. One set had the calibration from NIST source-based facility and the other from HUT detector-based realisation of the scale.

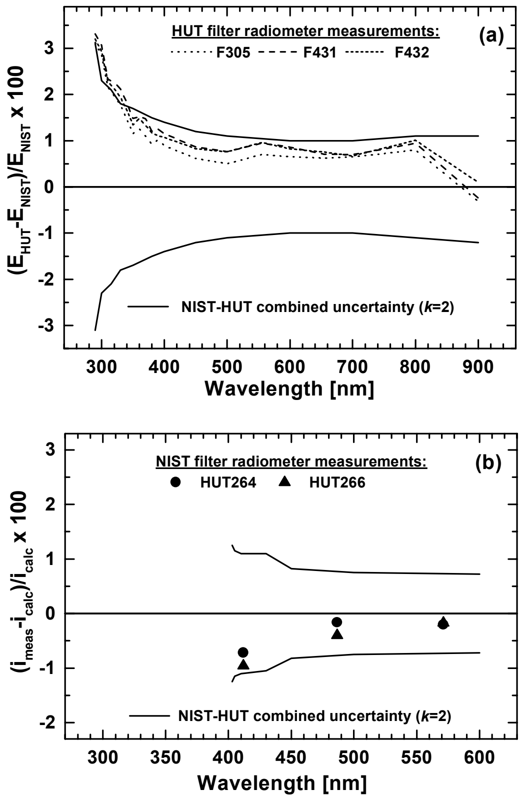

Figure 5.1.3-1. Comparison of the measurement results obtained with a) NIST calibrated lamps F305, F431, and F432, and b) HUT calibrated lamps HUT264 and HUT266.

The NIST-calibrated lamps were measured against the primary standard for spectral irradiance of HUT. Based on the measurement results of HUT, the spectral irradiance values of NIST lamps were derived and compared to those given by NIST. The results of the comparison are depicted in Figure 5.1.3-1 a).

The HUT-calibrated lamps were measured with three NIST filter radiometers. Based on the spectral irradiance values of HUT lamps and the spectral irradiance responsivity values of NIST filter radiometers, the expected photocurrent values were calculated. The calculated photocurrent values were compared to those obtained in the measurements by NIST. The comparison results are shown in Figure 5.1.3-1 b).

The combined uncertainty of NIST-HUT comparison measurements varies between 3,1 % and 1,1 % ($k = 2$) in the wavelength range from 290 nm to 900 nm.

The results of the comparison measurements between NIST and HUT show that the spectral irradiance scales are in good agreement down to the wavelength of 350 nm.

The work has been financially supported by the Centre for Metrology and Accreditation and the Academy of Finland.

5.1.4 Absolute measurement method for luminous flux

J. Hovila, P. Toivanen, K. Lahti, I. Tittonen, and E. Ikonen

Luminous flux (unit lm) is a photometric quantity, which describes the total power of a light source as seen by a human eye (lighting ability). For this reason, high accuracy calibrations of luminous flux standard lamps are widely needed in the lighting industry. So far these standard lamps have been calibrated elsewhere, leading to longer traceability chain and higher uncertainties.

The HUT luminous flux measurement set-up using the absolute integrating sphere method [1] was completed in 2000 after a three-year project (see Figure 5.1.4-1). The luminous flux of the external source (1000 W Osram FEL T6) is obtained by measuring the illuminance within the calibrated precision aperture by illuminance standard photometer. This ensures the traceability to the HUT illuminance unit. The signal of the sphere photometer is measured for both the external and the internal source. The luminous flux of the internal source is calculated from the signal ratio. The result is fine-tuned by using a correction factor obtained from the system characterisation. The correction factor of the HUT set-up is 1,0032.

Some modifications were made during the year 2000 to improve the set-up and the characterisation procedures. For example, the aperture array (made of black-anodised aluminium) was completely re-designed and its inner walls are now coated with a high-absorbance material to reduce the stray light in the illuminance measurement. Also the LED scanner used for measuring the reflectance non-uniformity of the sphere coating was modified to improve the LED mounting and beam collimation.

The luminous flux standard lamp calibration range is 10 – 10 000 lm. The relative expanded uncertainty of the realisation of the HUT luminous flux unit is 0,72 % ($k = 2$). The uncertainty may still decrease after a better lamp holder for the internal source is installed.

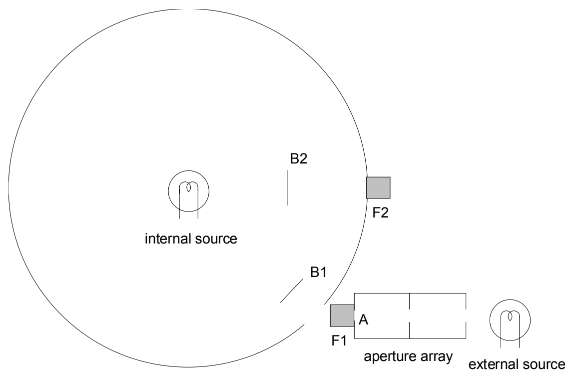

Figure 5.1.4-1. The luminous flux measurement set-up consisting of light sources, baffles B1 and B2, precision aperture A, illuminance standard photometer F1 and sphere photometer F2.

The accuracy of the HUT luminous flux unit was tested in summer 2000 by international comparison. Four NIST (National Institute of Standards and Technology, USA) luminous flux standard lamps (180 W Osram Wi41/GLOBE) were measured using the HUT sphere set-up. On the average, the measured values deviated less than 0,1 % from the values measured at NIST. This deviation is much smaller than the standard uncertainty of the measurements.

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

[1] K. Lahti, J. Hovila, P. Toivanen, E. Vahala, I. Tittonen, and E. Ikonen, "Realisation of the luminous flux unit using a LED scanner for the absolute integrating sphere method," *Metrologia* **37**, 595-598 (2000).

5.1.5 Relative scale of spectral diffuse reflectance

S. Nevas and F. Manoocheri

Spectral diffuse reflectance measurements are widely used for determination of optical properties of materials such as the colour and appearance. Paper industry needs calibration of diffuse reflectance standards, mainly used as reference in measurements of whiteness of paper. To meet such needs, a facility for the measurements of spectral diffuse reflectance has been established at the Metrology Research Institute of Helsinki University of Technology.

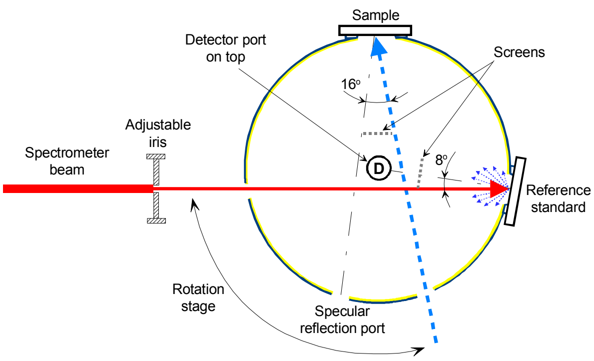

Figure 5.1.5-1. Schematic view of the integrating sphere in the setup for the measurements of spectral diffuse reflectance.

The facility is based on a high-accuracy spectrometer and an integrating sphere detection system. Schematic view of the measurement setup is shown in Figure 5.1.5-1. The single grating monochromator-based spectrometer provides a well-collimated beam. The 150-mm-diameter integrating sphere is positioned on a high-accuracy rotary stage. The sphere features five 25-mm diameter ports designed for 8° geometry. The 0°/d geometry can be obtained by using 8° sample and reference holders. Two internal screens prevent the first reflection components from the sample and the standard from reaching the detector. A computer controls the spectrometer, the rotary stage, and reads the signal from the detector via a digital voltmeter.

The measurements are made relative to reference standards traceable to an absolute scale. At present, the relative scale at HUT takes its traceability from the absolute scales of PTB (Physikalisch-Technische Bundesanstalt, Germany) and NRC (National Research Council, Canada). Spectralon and white opal glass samples are used as reference materials. The diffuse reflectance of a sample is determined by the ratio of the detector signals obtained during the irradiation of the sample and the standard. This is achieved by rotating the sphere to irradiate the reference and the sample alternately. The measurement geometry of irradiation/view of the facility can be either 8°/diffuse (with specular component included and excluded) or 0°/diffuse.

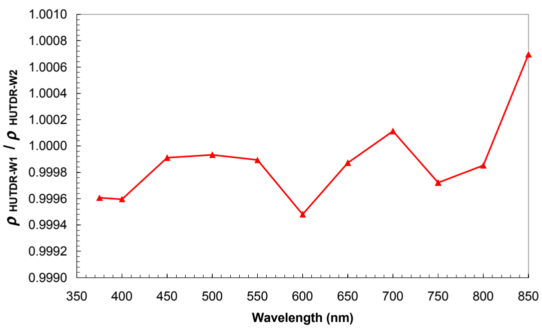

Figure 5.1.5-2. Spectral diffuse reflectance ratio measured for two identical samples.

With our facility we can measure optical quality samples for spectral diffuse reflectance in the range of 0,05 – 1,00 and within 360 – 830-nm wavelengths. The measurements can be performed with an expanded uncertainty of 0,4 % – 1,0 %. The uncertainty analysis includes components related to the reference standards, beam parameters, and detection system.

Accuracy of the measurements has been verified by a series of test measurements on a set of diffuse reflectance standards. Results of the comparison measurements are in agreement well within the uncertainty of the measurements. Figure 5.1.5-2 shows test measurement results for two identical samples, HUTDR-W1 and HUTDR-W2.

As an extension of the project, the development of the absolute scale of spectral diffuse reflectance was started in the year 2000. The facility under development will provide spectral diffuse reflectance, transmittance and bidirectional radiance and transmittance factors of a range of standards in absolute units.

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

5.1.6 Development of a national standard for fibre optic power

J. Envall and P. Kärhä

Fibre optic power measurement is one of the fundamental measurements in telecommunications. These measurements are needed for example to determine the losses in telecommunication cables, in the maintenance of telecommunication networks and in the development of several fibre optic devices. Our goal is to achieve an uncertainty of 1,5 % ($k = 2$) or less for the calibrations, which are traceable to our cryogenic radiometer.

Our calibration equipment consists of three photodiodes. Two of these photodiodes are mounted into black anodised aluminium cases. Adapters with standard FC connectors are fitted into the cases to allow an easy connection for optical fibre. The third photodiode is fitted into an 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. This structure makes it possible to measure the response of the sphere by either connecting the fibre straight to the sphere or by aligning a collimated beam into the sphere. Using the integrating sphere makes it possible to measure the power from the optical fibre over the whole solid angle. This is a convenient feature because typically the optical power spreads to a wide solid angle from the end of the fibre. On the other hand, the response of the plain photodiode is greater than that of the integrating sphere by at least a factor of five. This means that by using the plain diodes it is possible to do the calibrations with lower power levels.

The equipment is to be calibrated using the existing standards for optical power. The calibrations are done for the two most common wavelengths used in telecommunications, that is 1550 nm and 1310 nm, and probably for 850 nm in the future. The calibration of the integrating sphere is yet to be done, but the characterisation of the two plain diodes has been completed. The following characteristics were measured: response for optical power, linearity of the response, angular response and spatial response.

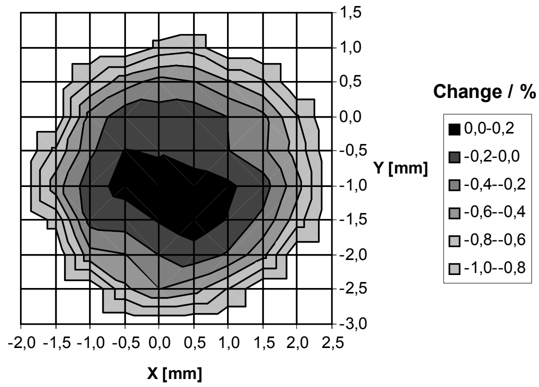

Figure 5.1.6-1. The spatial response of one of the two plain photodiodes at 1310 nm wavelength given as relative change from the average response at the centre.

Figure 5.1.6-1 shows the spatial response of one of the photodiodes. Although we have the option of using the integrating sphere to improve uniformity, it was very encouraging to notice that both the angular response and the spatial response of the diodes were considerably flat. This increases the accuracy of the measurements in which the plain diodes are used, and no correction factors are needed. In fact, a flat spatial response was one of the key issues in choosing the photodiodes for this project.

The work has been financially supported by the Centre for Metrology and Accreditation and the Academy of Finland.

5.1.7 UV-laser for radiometric characterisations of detectors

M. Vainio, M. Merimaa, T. Kübarsepp, and E. Ikonen

Compact and reliable continuous-wave ultraviolet (UV) lasers are needed for radiometric characterisation of detectors in the biologically interesting solar UV band around 320 nm. Also, UV lasers are needed in spectroscopic applications, where wavelength tunability is required. Diode lasers would be almost ideal for these applications, but so far their available wavelength range covers only the red and infrared section of the spectrum. However, shorter wavelengths can be obtained by second harmonic generation (SHG) in a nonlinear crystal. We have developed a continuous-wave UV laser at 317 nm based on diode laser and SHG.

Spectral properties of solitary diode lasers are not sufficient for efficient SHG, but these properties can be improved by operating diode laser in an external cavity. To improve the spectrum a compact transmission-grating laser is used in this work. In addition to forcing the laser to operate in a single mode, the external-cavity configuration improves the wavelength tunability. The transmission geometry is used to remove the problem of directional variation of the output beam while tuning the laser. The external-cavity laser is based on a commercial, AR-coated 30-mW diode laser operating at 635-nm band.

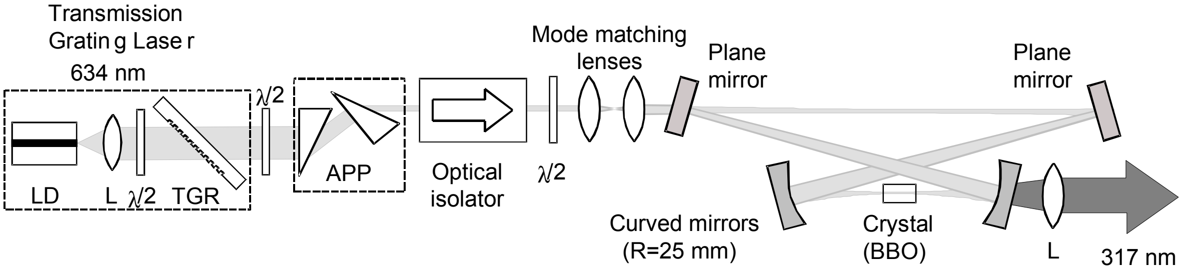

Figure 5.1.7-1. Experimental setup of UV-laser realised with optical second harmonic generation.

The experimental setup is schematically shown in Figure 5.1.7-1. UV light is generated from red 634-nm laser radiation using a nonlinear BBO (β-Barium-Borate) –crystal. To increase SHG efficiency, the crystal is placed inside a resonator that builds up the incoming red power with a factor of approximately 49. The resonator is formed by four mirrors in a bow-tie ring configuration, which has unidirectional operation. Mode-matching lenses are used to couple a maximum amount of the fundamental power into the resonator and to optimise the beam focusing inside the crystal. Electronic feedback, based on lock-in technique, is used to lock the laser frequency to a cavity resonance. The maximum UV power measured so far is 36 μW.

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

5.2 Length Metrology

5.2.1 Iodine-stabilised He-Ne lasers

K. Nyholm

Three iodine-stabilised red He-Ne lasers and two multi-colour 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. Measurements on the frequency stability and repeatability of the two multi-colour He-Ne lasers (MGI1 and MGI2) were carried out at the metrologically important wavelength of 543 nm. The dependence of the laser frequency on such parameters as pressure of the iodine cell and modulation amplitude was studied, also. The results of these experiments together with the results of a bilateral comparison with DFM (Danish Institute of Fundamental Metrology) showed that the MGI1 and MGI2 lasers are reliable enough to enable the start of calibration services in MIKES at the wavelength 543 nm.

5.2.2 Iodine-stabilised diode lasers

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

Frequency-stabilised He-Ne gas lasers at 633 nm form the current basis for accurate length measurements and are generally used for the realisation of the definition of the metre. However, there has been growing interest in frequency stabilisation of diode lasers at 633 nm during last few years since the output power of a He-Ne laser is small and He-Ne lasers are large in size and mechanically vulnerable.

We have constructed a portable (32 cm × 13 cm × 6 cm) laser frequency standard by frequency stabilising an external-cavity diode laser to the Doppler-free spectrum of iodine. Compact structure is achieved using a novel transmission grating in a miniaturised external-cavity laser. The laser has excellent noise properties, which leads to high S/N-ratio of detection and allows direct observation of the inverse Lamb-dips as shown in Figure 5.2.2-1.

The optical set-up of the iodine-stabilised external-cavity laser is schematically shown in Figure 5.2.2-2. Frequency stabilisation of the laser is based on Doppler-free saturation spectroscopy using collinear geometry in an external iodine cell.

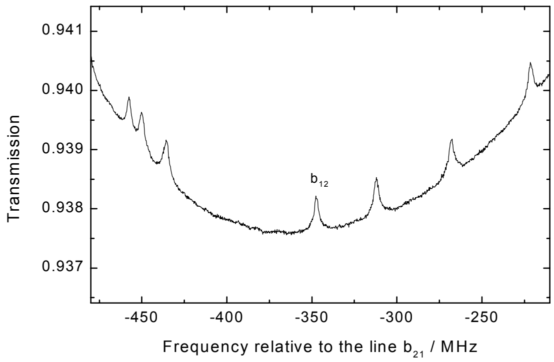

Figure 5.2.2-1. The high S/N-ratio allows detection of inverse Lamb-dips even without a lock-in-amplifier.

The valuation of the performance of the laser system as an optical frequency standard proves that an iodine-stabilised external-cavity diode laser can reach similar or better stability than typically achieved with iodine-stabilised He-Ne-lasers. The relative frequency stability (square root of the Allan variance) follows a slope of $7{,}9 \times 10^{-12}\ \tau^{-1/2}$ (10 s < τ < 4000 s) and the best stability of 1×10^{-13} (47 Hz) is reached at an integration time of $\tau =$ 4000 s. A good (4×10^{-12}) day-to-day repeatability (1 σ) and good agreement with the CIPM values was also reached.

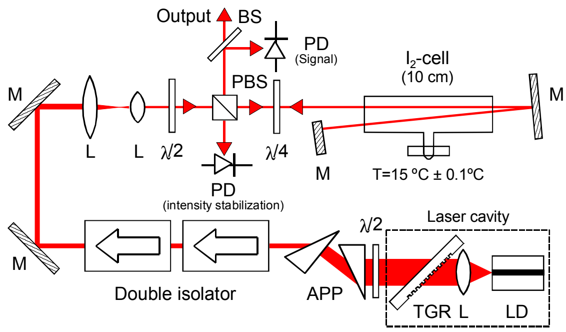

Figure 5.2.2-2. Experimental set-up.

The work is a collaboration project between HUT and the Centre for Metrology and Accreditation.

5.2.3 Iodine-stabilised Nd:YAG lasers

T. Ahola, K. Nyholm, M. Merimaa, and E. Ikonen

High-precision spectroscopy, optical communications, and modern length metrology rely on reference wavelengths generated by lasers frequency-stabilised to atomic or molecular transitions. Currently, practical length metrology is mainly carried out using iodine-stabilised He-Ne lasers at the wavelength 633 nm. Also, among the twelve reference wavelengths (frequencies) recommended by the Comité Internationales des Poids et Mesures for the practical realisation of the definition of the metre is the wavelength 532 nm realised by an iodine-stabilised Nd:YAG laser.

Recently, diode-pumped iodine-stabilised Nd:YAG lasers at 532 nm have demonstrated better stability than He-Ne lasers. These lasers have many attractive metrological features, e.g., they are compact in size, have low intrinsic frequency and intensity noise, and they offer high power levels, simultaneous output of two wavelengths, and long lifetime. Moreover, the absorption lines of iodine are very strong and narrow near 532 nm and, therefore, form an almost ideal frequency reference. Hence, the interest on Nd:YAG lasers is steadily increasing within metrology community.

A commercial diode-pumped Nd:YAG laser was frequency-stabilised to Doppler-free spectrum of iodine at 532 nm. The resonator of the laser is a monolithic non-planar ring. Because of this non-reciprocal ring, the cavity eliminates spatial hole-burning, operates in a single longitudinal mode, and is insensitive to optical feedback. Moreover, the monolithic cavity construction offers excellent passive frequency and intensity stability. The second harmonic output at 532 nm is generated in a periodically poled KTP crystal. The power of the laser is 1,1 W at 1064 nm and 20 mW at 532 nm. In order to use third-harmonic locking technique for the stabilisation, two piezo-crystals were attached at the laser crystal. One of the piezos is used for the frequency modulation and the other for frequency tuning. Coarse tuning is realised by temperature control of the laser crystal.

In preliminary measurements, several absorption lines of iodine were detected and identified and the frequency of the laser was successfully locked on the hyperfine components. The short-term relative frequency stability of the laser was estimated to be $1{,}7\times10^{-12}\ \tau^{-½}$ from the signal-to-noise ratio of the measured hyperfine structure spectra.

The work is a collaboration project between HUT and the Centre for Metrology and Accreditation.

5.3 Fibre-Optic Measurements

5.3.1 Characterisation of group-delay ripple in chirped fibre Bragg gratings

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

Characterisation 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 measurements. 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.

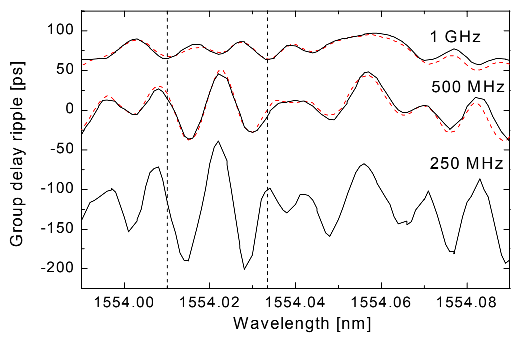

Figure 5.3.1-1. Measured (solid lines) and simulated (dashed lines) group delay for three different modulation frequencies.

We have built an experimental setup based on the phase-shift method for characterisation of various filters such as fibre Bragg gratings (FBG) and multiplexers/demultiplexers. In particular, we have studied the accuracy of the method in resolving dense group-delay ripple that is present in chirped FBGs [1].

An example of the measured group delay for different modulation frequencies of a 20-cm long chirped FBG with a bandwidth of 2 nm and a nominal dispersion –660 ps/nm is given in Figure 5.3.1-1. To confirm the measured group-delay values at 500 MHz and 1 GHz we used the 250 MHz group delay curve for simulation of the operation of the measurement system at higher frequencies. The agreement between the simulated and measured group delays is good.

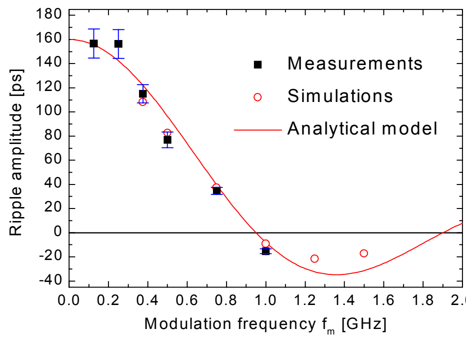

Figure 5.3.1-2. Comparison of the measured ripple amplitude with the analytical model.

A comparison between the measured amplitude of the ripple and the amplitude calculated using an analytical model with sinusoidal variation of the ripple amplitude is given in Figure 5.3.1-2. According to the model the measured amplitude of sinusoidal ripple follows a sinc-function. It is clearly seen from both of the figures that the ripple is effectively averaged out when the modulation frequency approaches a multiple of half a period of the ripple. The model gives a means for estimating the accuracy of the group-delay ripple measurements for the selected modulation frequency. It finds applications in the development of standardised measurement procedures of fibre Bragg gratings.

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

[1] T. Niemi, M. Uusimaa, and H. Ludvigsen, "Measurements of dense group delay ripple using the phase shift method: Effect of modulation frequency," in *Proceedings of Symposium on Optical Fiber Measurements*, September 26-28, 2000, pp. 165-167.

5.3.2 Fibre laser

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

Current optical communication systems make use of the dense wavelength division multiplexing (DWDM) technique in the wavelength window of 1530 – 1565 nm (C-band). To increase the transmission capacity of optical fibres in the future, the wavelength window will be extended to the wavelength range from 1565 nm to 1625 nm (L-band). Erbium-doped fibre lasers have the potential to be used in the L-band as optical transmitters and in the characterisation of various types of fibre-optic components.

We have constructed an Erbium-doped fibre-ring laser, which operates in the C-band in both continuous wave and pulsed mode. It will in the near future be redesigned to operate in the L-band. An outline of the laser setup for pulsed operation is presented in Figure 5.3.2-1. The laser design is based on a fibre-ring cavity where the Erbium-doped fibre (EDF) is pumped by a diode laser at 980 nm. The pump light is coupled into the cavity by a wavelength division multiplexer. An optical isolator (I) determines the propagation direction of the laser field. The birefringence of the fibre is compensated for with a polarisation controller (PC). Pulsed operation is achieved by introducing a Mach-Zehnder modulator (MZ) into the cavity. The MZ is driven with a wide bandwidth signal generator (S.G.). Ten percent of the optical field power is coupled to the laser output with a fibre coupler (FC).

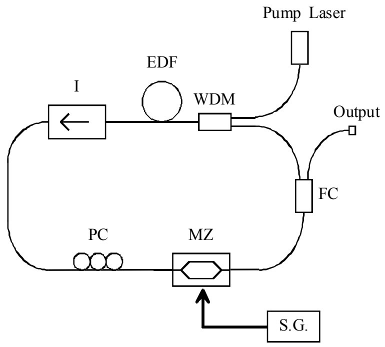

Figure 5.3.2-1. Setup of the fibre laser for mode-locked operation.

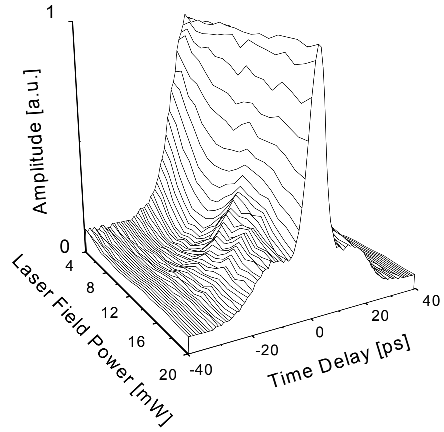

Figure 5.3.2-2. Autocorrelation traces of the optical pulse train for different intra-cavity powers.

We have obtained repetition rates of 3 – 18 GHz and pulse widths down to 5 ps for laser operation in the C-band. Autocorrelation traces of the optical pulses for different average powers are shown in Figure 5.3.2-2.

The work has been financially supported by the Academy of Finland

5.3.3 Effect of optical filtering on pulses generated with a gain-switched DFB-laser

T. Niemi, J.-G. Zhang, and H. Ludvigsen*

** HUT, Communications Laboratory*

Short optical pulses have found many applications in optical fibre measurements, optical soliton transmission, and high-speed optical time-division multiplexing (OTDM) communication systems. Several techniques to generate short optical pulses have been proposed.

One commonly used method to produce short pulses is gain switching of a semiconductor laser. To achieve gain switching, the laser is biased below its threshold current and, subsequently, modulated with a reasonably high-voltage signal. By appropriately selecting the magnitudes of the DC-bias and the RF-signal, the laser can generate optical pulses with the duration of a few tens of picoseconds.

Usually, the gain-switched pulses are strongly chirped, indicating that the frequency of the light varies over the duration of the pulse. This feature can be used for pulse compression by using either a normally dispersive fibre or an optical filter. In general, an optical filter can be applied to remove the highly chirped pulse components, which leads to the generation of nearly transform-limited pulses. The use of optical filtering permits compact optical transmitter implementation.

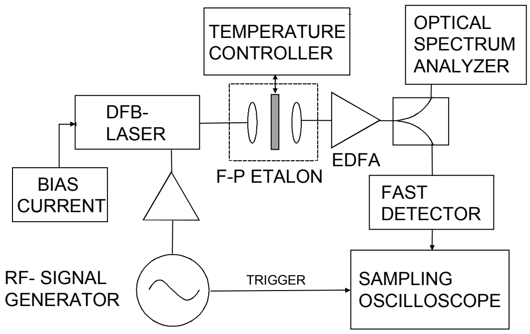

Figure 5.3.3-1. Experimental setup for generating gain-switched pulses with a DFB laser and for detecting these pulses.

We have studied the effects of optical filtering on the shape of short optical pulses generated with a gain-switched distributed feedback (DFB) laser diode applying the setup depicted in Figure 5.3.3-1. We found that tuning of an optical bandpass filter over the optical spectrum of such a laser exhibits a strong effect on the temporal shape of the resulting gain-switched pulses (see Figure 5.3.3-2).

We observed the generation of a series of secondary oscillations when the centre frequency of the optical filter was tuned to the short-wavelength side of the spectrum. An investigation of this phenomenon was carried out by means of experimental observations. Furthermore, an analytical model based on filtering of linearly chirped Gaussian pulses with a Fabry-Perot filter was developed to reveal the origin of the generation of the secondary oscillations.

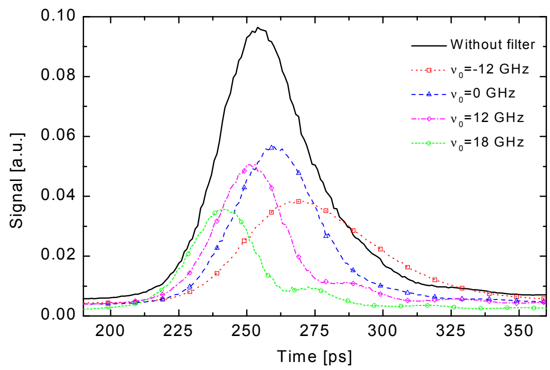

Figure 5.3.3-2. Measured pulse waveforms of the gain-switched laser for several positions of the centre frequency of an optical passband filter.

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

5.3.4 Nonlinear crosstalk in a WDM network transmitting digital television channels

T. Niemi and H. Ludvigsen

Broadband distribution, such as CATV, can conveniently be carried out by using fibre-optic links. CATV networks currently offer broadcast services indicating that each customer, such as a single household, receives the same information. In the near future, the information carried in a CATV network is directed to narrowcast services, which offer a means to deliver customised services to a selected group of customers. The services provided in these networks may include e.g. digital television, fast internet and video-on-demand. One way to upgrade the fibre-optic CATV-network is to make use of the wavelength-division multiplexing (WDM) technique in which each wavelength can be used to allocate a selected service. The implementation of WDM in CATV transmission systems, however, requires a deeper understanding of the interplay of the nonlinearities of the optical fibre.

We have constructed a test bed in collaboration with Teleste Ltd. for measuring the effect of nonlinear crosstalk in a digital television WDM application having eight wavelengths. The modulation format used in digital television transmission is QAM (Quadrature Amplitude Modulation), which is less sensitive to distortion and noise compared to the purely analogue modulation format. The goal of the study was to determine the practical limits for the optical power that can be launched into the fibre without degradation of the signal quality due to nonlinear crosstalk.

At high level of optical power nonlinear crosstalk is mainly induced by stimulated Raman scattering (SRS) and cross-phase modulation (XPM). These effects cause interference between the electrical subcarriers that are modulated at different wavelengths. The contribution of SRS dominates for low subcarrier frequencies and XPM increases for high subcarrier frequencies. We have built a model for estimating nonlinear crosstalk in a multi-wavelength CATV-links.

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

5.3.5 Wavelength monitoring of DWDM systems using a temperature-controlled Fabry-Perot filter

T. Niemi, T. Laukkanen, J. Tuominen, S. Tammela, and H. Ludvigsen*

** VTT, Microelectronics*

As the channel spacing is decreasing in optical DWDM-systems the need for accurate wavelength monitoring of laser transmitters and the calibration of DWDM measurement equipment increases. We have developed a device concept for monitoring and calibration purposes of a multi-channel DWDM-system.

The device makes use of a single temperature-tunable Fabry-Perot etalon filter. The filter has been fabricated by depositing two dielectric mirrors on both sides of a double-side polished silicon wafer. The transmission of the filter can be tuned by controlling the temperature of the chip. The filter can be used as a calibrated wavelength reference by locking one of its fringes to a stable reference, such as a molecular absorption line. When the filter transmission as a function of wavelength is known, the close-by-lying transmission fringes can be applied for monitoring and referencing with an accuracy adequate for practical applications.

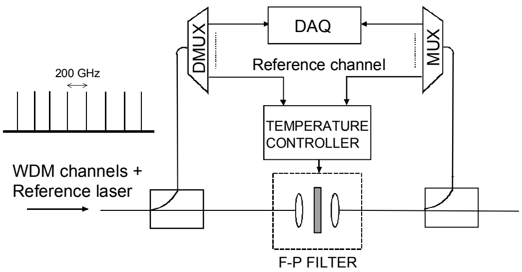

Figure 5.3.5-1. Setup for wavelength monitoring of WDM channels using a temperature-stabilised Fabry-Perot filter.

To demonstrate the concept we have locked a transmission fringe of the filter to a laser stabilised in frequency to an absorption line of acetylene ($^{13}C_2H_2$, Line P(22) at 1546,174 nm). The setup for applying the filter to monitor the wavelengths of a WDM system is shown in Figure 5.3.5-1 [1].

When the wavelength of the laser in the monitored channel shifts the changes in its transmission can be directly used to estimate the shift by comparing it to the transmission spectrum of the filter. The transmission spectrum of the filter while it is locked to the reference laser was measured by using a broadband source and an optical spectrum analyser (see Figure 5.3.5-2). To improve the accuracy of the device concept both the wavelength and temperature dependence of the refractive index of silicon will be modelled.

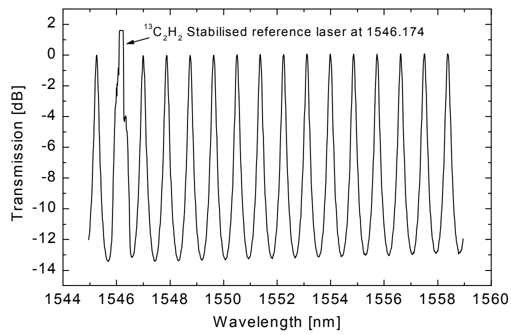

Figure 5.3.5-2. Measured transmission spectrum of the filter which is referenced to an acetylene stabilised laser line.

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

[1] T. Niemi, T. Laukkanen, S. Tammela, and H. Ludvigsen, "Wavelength monitoring of multi-channel DWDM-systems using a single temperature-tunable Fabry-Perot filter," in *Proceedings of Conference on Lasers and Electro-Optics Europe*, September 10-15, 2000, CTuP4, p. 164.

5.4 Microtechnologies

5.4.1 Micromechanical resonators for RF-applications

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

Bulk silicon offers both unique electrical and mechanical properties. Mechanical silicon resonators have intrinsically very low-loss resonances, which can be even further improved by appropriate design. By using the state-of-the-art SOI (silicon-on-insulator) processing technology also small enough constructions can be obtained that can possess mechanical resonances that are capacitively read-out and excited even in the MHz range.

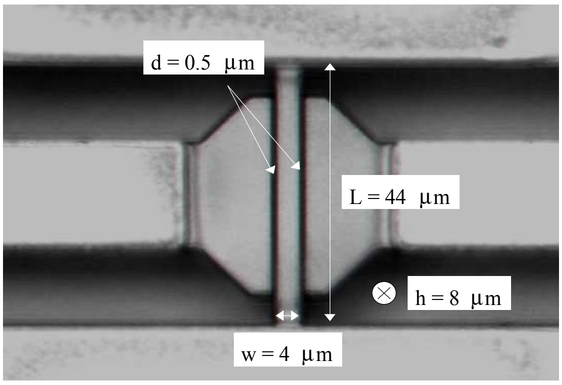

Figure 5.4.1-1. 14 MHz micromechanical bridge resonator.

Detailed analysis and understanding of miniature size oscillators requires numerical methods. Capacitively actuated mechanical systems can successfully be analysed 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 then later fed into the circuit-simulation program revealing how the mechanical design in effect works as a part of an RF electronics circuit.

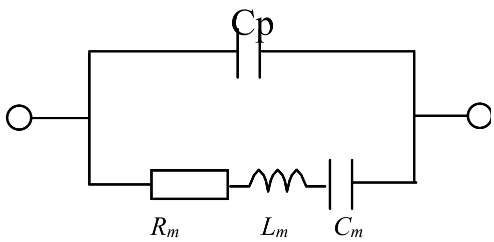

Figure 5.4.1-2. An RLC equivalent circuit of a micromechanical resonator.

The processed constructions were measured using the network analyser in transmission (Figure 5.4.1-1). The component is coupled to electronics via capacitance trying to minimise parasitic contributions. Vacuum encapsulation was required to enhance signal levels and to avoid air- damping effects. From the measured data a detailed transfer function was deduced. This data was even further processed and also fitted using the APLAC circuit simulator and equivalent RLC circuit parameter values were obtained (Figure 5.4.1-2). At this point, we have also obtained information about the damping values (∝ 1/Q) which cannot be obtained as an output from the FEM analysis. We also added various nonidealities (e.g. parasitic capacitances) to optimise and evaluate the over-all performance of the novel RF circuit.

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

5.4.2 Finite element modelling of microsystems

K. Ruokonen, O. Väänänen, M. Ylönen, T. Lamminmäki, and I. Tittonen

Accurate modelling of the resonator structures is required to allow the design of components with the desired properties. Analytic modelling of micromechanical capacitively actuated resonators is complex, since the resonators are described by dynamic, nonlinear equations coupling electric and mechanical energy domains.

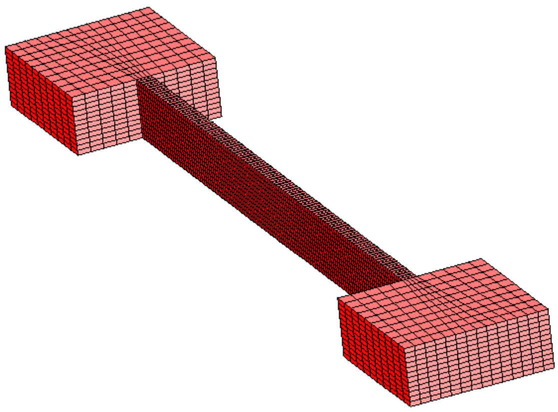

Figure 5.4.2-1 Finite element model of a clamped-clamped beam resonator.

Finite element method (FEM) simulations are first used to calculate the mechanical properties of the resonator structures. Scaling behaviour of the relevant physical parameters (f, Q) are derived by calculating modal frequencies and estimating mechanical radiated losses. Using a static displacement analysis the effective spring constant k^* is calculated, and the effective mass m^* is obtained from the equation

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k^*}{m^*}}\,.$$

Nonlinear behaviour of effective spring constant is analysed and used in optimisation of the resonator design. Several resonator geometric shapes are investigated in order to obtain a design fulfilling the RF and high-Q requirements.

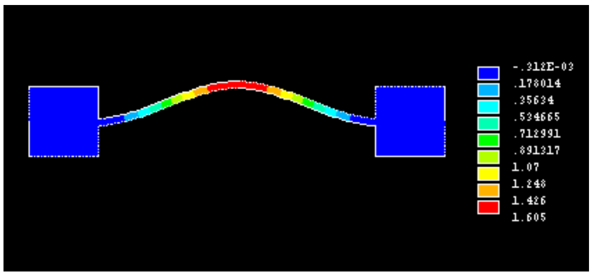

Figure 5.4.2-2 Simulated displacement of the beam under the action of an external force.

Next an electrical equivalent circuit model is introduced for the resonator to allow simulation of its electromechanical behaviour. The FEM-calculated mechanical parameters are incorporated into the model by using a series RLC-circuit with frequency response equal to the mechanical resonator. We use a standard circuit simulation software (APLAC) for numerical calculations. The effect of non-idealities (e.g. parasitic capacitances) is carefully analysed.

Finally the FEM and circuit analysis results are used to explain the measurement data on resonator structures fabricated using silicon-on-insulator (SOI) technique. As an example the detailed analysis of simple clamped-clamped beam lateral resonators operating at a few MHz frequencies is shown in Figure 5.4.2-3. Q-values of the order of 10^4 are obtained.

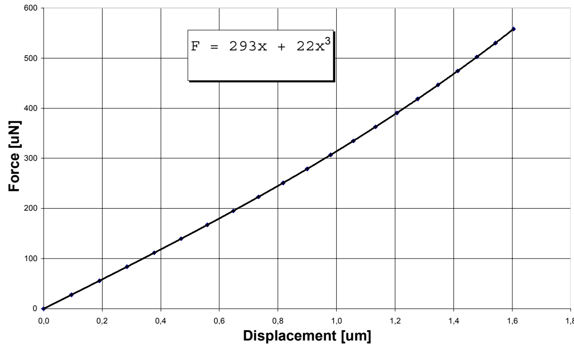

Figure 5.4.2-3 Nonlinear effective spring constant calculated by the finite element method (FEM).

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

5.4.3 High-Q micromechanical silicon oscillators

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

In sensor technology, high-Q silicon micro-oscillators can elegantly be used in measurements of very small changes for instance in temperature and pressure. It is evident that the response of a resonant system is proportional to inverse of the resonance linewidth, thus motivating the pursuit for very narrow resonances.

Some typical results of the processed silicon oscillators have shown Q-values exceeding even one million (Figure 5.4.3-1 and Figure 5.4.3-2).

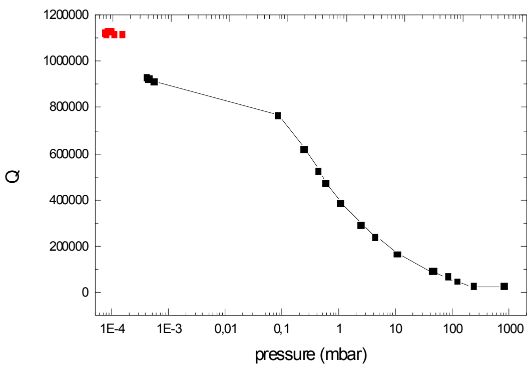

Figure 5.4.3-1. Micromechanical resonator Q-value as a function of pressure, measured using the quadrature detection method.

Mechanical susceptibility can usually be measured either capacitively or optically. The standard optical techniques used are based on quadrature- and Doppler- detection schemes. More sensitive methods are needed for example, in the detailed analysis of the oscillator phase noise.

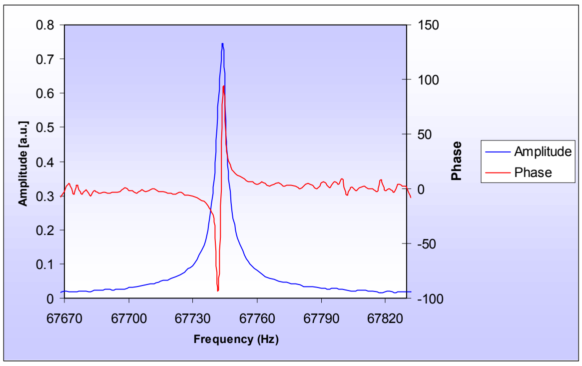

Figure 5.4.3-2. Typical amplitude and phase response of a resonator as a function of frequency.

In our configuration, the resonator surface is high-reflection coated and used as a planar mirror in a Fabry-Pérot interferometer (Figure 5.4.3-3). The essence of the method lies in monitoring the changes in the interferometer response driven by the physical oscillations of the mechanical oscillator. From the changes of the response the mechanical susceptibility of the oscillator can be determined. At very low temperatures we expect to observe even quantum effects in optomechanics.

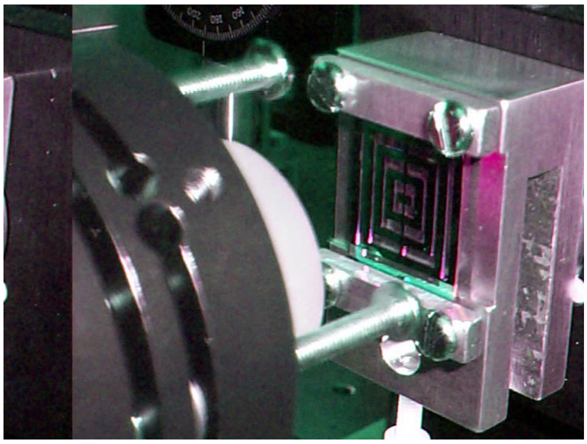

Figure 5.4.3-3. Micromechanical oscillator is used as a planar mirror in a Fabry-Perot interferometer. An optical measurement should also reveal interesting phase changes caused by thermal and other noise sources.

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

5.5 Applied Quantum Optics

5.5.1 Installation of the Ti:Sapphire laser system

K. Lahti and I. Tittonen

During the year 2000 a new state-of-the-art laser system was acquired and installed. The idea was to create possibilities for various kinds of forthcoming research projects by having single frequency laser light with rather high output power in a broad tuning range.

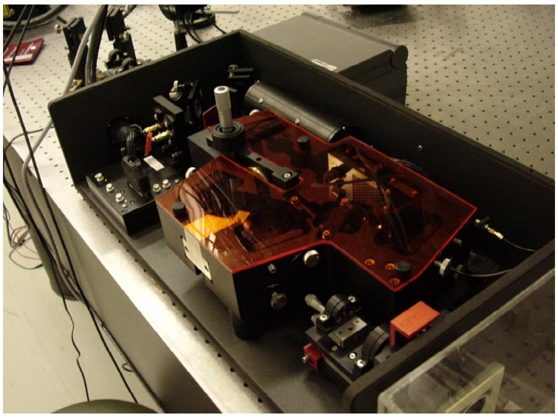

Figure 5.5.1-1. Ti:Sapphire laser with the cover opened.

Lasers having high tunability are usually dye lasers or solid state Ti:Sapphire lasers. The laser system that was bought contained a diode pumped frequency doubled Nd:YVO_4 Verdi™ pump laser producing 10 W at 532 nm and a monolithic block resonator (MBR-110™) Ti:Sapphire laser. The average output power is 2W in the range of approximately 700 – 1000 nm. This range can be covered with three separate optics sets that need to be changed manually.

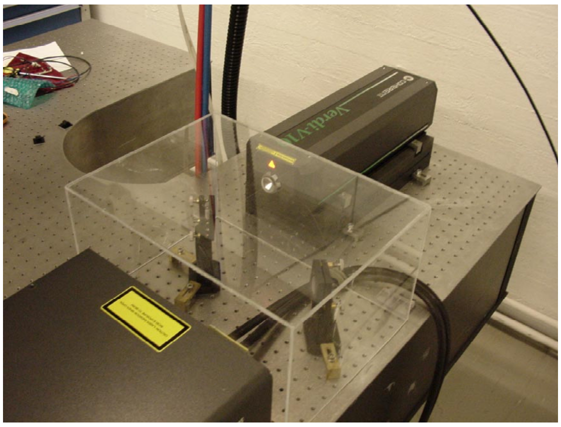

Figure 5.5.1-2. 10.5W 532 nm Verdi pump and the Ti:Sapphire laser.

The system contains also a thin etalon and a servo-locking system for eliminating mode hops. Locking to the built-in reference cavity should give the linewidth of 10 kHz. An automatic scanning range is approximately 40 GHz based on the two Brewster plates. In addition an external frequency doubling unit (MBD-200™) was bought with what one can reach even upper UV range. So the overall system can create simultaneously green, red and even blue laser light.

The system, when ready, will have various applications. In radiometry, it will be used to characterise spectral irradiance responsivities of filter radiometers. These filter radiometers will then be used for high-accuracy measurements of spectral irradiance and radiation temperature.

5.5.2 Microtrap for neutral atoms

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

** Microelectronics Centre, HUT*
† Laboratory of Computational Engineering, HUT
‡ Optics and Molecular Materials, HUT

A new 3-year project for trapping and guiding of neutral atoms and even molecules was initiated as a collaboration between three HUT laboratories. 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 vapours and to control the translational motion of atoms. 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. The miniaturisation can also make it possible to construct atom traps with only a few populated energy levels, if the physical dimensions of the trap are of the same order of magnitude as the de Broglie wavelength of the atoms.

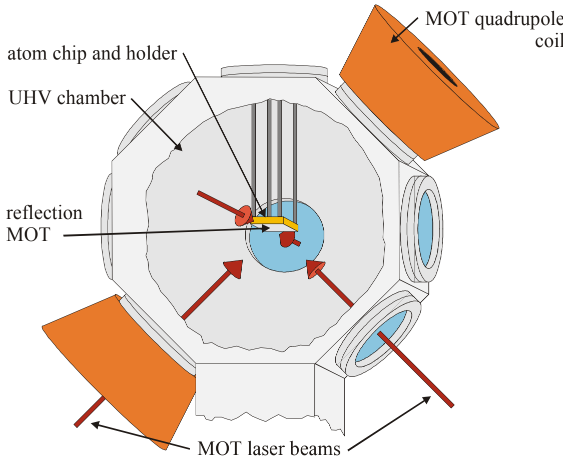

Figure 5.4.2-1: Schematic picture of the atom chip inside the UHV chamber. The atoms are first trapped in a magneto-optical trap, then transferred to the magnetic traps on the chip.

The goal of the project is to develop new chip fabrication techniques and to construct an ultrahigh-vacuum (UHV) setup, where the chips can be tested and used for experiments, as well as to theoretically study these concepts, in particular the influence of heating and noise on the trapped atoms. The atom chips will be fabricated at the HUT Microelectronics Centre.

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

5.5.3 Coupling of coherent fields in second harmonic generation

K. Lahti and I. Tittonen

Nonlinear properties of a medium act as the basis for evaluation of the potentiality of the medium for second harmonic generation (SHG) purposes. The next step is the maximum exploitation of the nonlinear properties, i.e. coupling of the coherent fields participating in the process. There are two major phase matching schemes used to ensure the maximal coupling, that is birefringent- and quasi-phase-matching schemes.

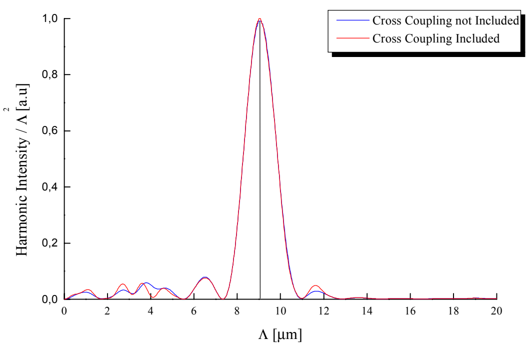

Figure 5.5.3-1: Generated second harmonic intensity as a function of poling period in type II quasi-phase-matching for KTP. The effect of cross coupling away from the major coherence length peak is clearly seen.

The strongest coupling scheme is the direct coupling, where the oscillating dipole moments pumped by a certain polarisation interfere. However, also the dipoles pumped by different polarisations are able to interfere leading to cross coupling of the fields. Due to the weakness of this effect, the reported experimental results are generally in good accordance with numerical calculations where the cross coupling is neglected.

We have numerically analysed the effect of cross coupling in two of the currently most common SHG processes, that is the lithium triborate (KTP) and potassium titanyl phosphate (LBO) pumped with a Nd:YAG laser. The maximal effect of cross coupling was calculated to exists with type II quasi-phase-matched KTP crystal. There the maximum poling period was shifted by tens of nanometers (See Figure 5.5.3-1). Additionally, when considering the regions away from the major coherence length peak, the response and hence the possible other local optimisations are stronger affected (See Figure 5.5.3-1). In future, the theoretical and numerical coupling analysis should be extended to the optical parametric oscillator (OPO) systems, since the optimisation of operation at multiple wavelengths is a more complex task than that of a single frequency process.

5.5.4 Digital laser frequency stabilisation

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 14 000 [2].

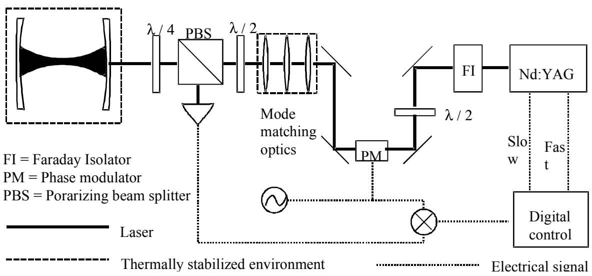

Figure 5.5.4-1. Nd:YAG laser is locked to a high-Q optical resonator using a phase modulation scheme.

One of the crucial elements of the stabilisation system is the laser servo control which tunes the laser frequency electromechanically and electrothermally based on the frequency fluctuation information given by the resonator (Figure 5.5.4-1). The servo control must be able to operate at a frequency bandwidth covering totally the laser technical frequency noise. The frequency noise of our laser becomes quantum-limited approximately at frequencies higher than 100 kHz. Servo controls operating at this high frequencies have traditionally been constructed using analogue 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 far beyond lasers technical noise bandwidth and enables the use of a rather complex algorithm combining the advantages of traditional fringe side locking and PDH method. Locking methods based on transmission suffer from delay induced by cavity response time. However, transmission provides the locking algorithm with explicit information concerning triggering and achieving the lock in general.

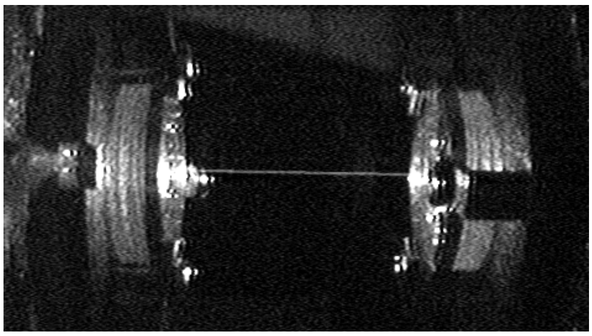

Figure 5.5.4-2. The standing optical mode inside the interferometer captured on CCD.

[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).

5.5.5 Coherent population trapping in ^{85}Rb

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

Coherent population trapping (CPT) [1] was first discovered by studying the fluorescence of sodium (Na) atoms pumped by a multimode laser [2]. In combination with an excited level the two hyperfine ground levels of Na form a three-level system (Λ configuration, Figure 5.5.5-1 a). A reduction in fluorescence was detected when one laser mode $\omega_{L1,2}$ was resonant with each of the Λ transitions. This *dark resonance*, a two-photon Raman resonance, could classically be explained by saying that each absorption of a photon from one laser mode is followed by a stimulated emission of a photon into the other mode. Thus the excited state remains practically unpopulated and no fluorescence can be observed.

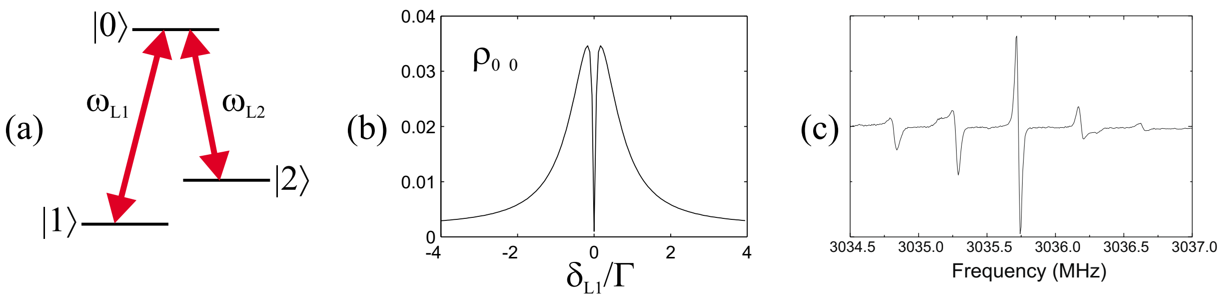

Figure 5.5.5-1. (a) Λ configuration, (b) excited state population ρ_{00} as a function of detuning δ_{L1}, and (c) spectrum measured using ^{85}Rb (1st derivative) with five Zeeman resonances.

CPT can be analysed semiclassically by solving the optical Bloch equations including relaxation mechanisms. This shows how the atomic populations and coherences depend on the laser detunings and intensities (Figure 5.5.5-1 b), but does not explain why. One can, however, introduce a new basis consisting of the excited state and two orthogonal superpositions of the two ground states. These superposition states are excited by both fields and the corresponding transition amplitudes are correlated by the ground state coherence. The transition probabilities will add up destructively for the *uncoupled* superposition state and constructively for the *coupled* state. Thus the atoms are optically pumped into the non-absorbing uncoupled state. Practical implementation of this theory includes taking into account the atomic velocity distribution, collisions, and other broadening mechanisms.

CPT has several applications. The linewidth of the resonance is determined by the ground state coherence and can therefore be very narrow, which makes it suitable as a frequency standard. One can also use it as a magnetometer by measuring the frequency difference between resonances corresponding to different Zeeman sublevels (Figure 5.5.5-1 c).

[1] E. Arimondo, *Prog. Opt.* **35**, 257 (1996).

[2] G. Alzetta, A. Gozzini, L. Moi, and G. Orriols, *Nuovo Cimento* **36 B**, 5 (1976).

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

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

Atomic clocks form the basis for accurate time and frequency measurements. Cesium atomic clocks, having a relative frequency reproducibility of approximately 1×10^{-13}, are generally used for the realisation of the definition of the second. However, the cesium atomic clock is a complex device with limited lifetime and thus crystal oscillators are used in practical applications.

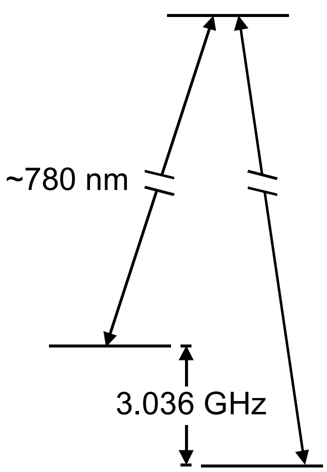

Figure 5.5.6-1. The Λ-system of ^{85}Rb.

The frequency of crystal oscillators is determined by mechanical properties of the crystal and regular calibrations are needed to maintain their accuracy. To provide an intermediate step between the cesium atomic clock and a crystal oscillator in the calibration chain, a secondary frequency standard with better stability than what can be obtained with a crystal oscillator is needed.

A relatively simple way to realise an all-optical secondary atomic clock is coherent population trapping (CPT). In CPT, two laser fields interacting with an atomic three-level Λ-system (see Figure 5.5.6-1) are coupled by the ground state coherence and interfere destructively at two-photon resonance. The classical explanation to this so-called dark resonance is that each absorption of a photon from one laser field is followed by a simultaneous emission to the other, if the fields are in phase and the frequency difference is exactly the same as the ground-level splitting. Since the transition connecting the ground states has a long lifetime, $>10^{10}$ s, the natural linewidth of this resonance is very small and it forms an almost ideal frequency reference.

In practice, the experimental parameters determine the linewidth, which is widened due to pressure, power, transit-time and wall collision broadening. The frequency noise of the RF-oscillator and lock-in detection further increase the observed linewidth. The absolute frequency of the transition is also slightly affected by pressure, light and Zeeman-shifts.

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 level splitting.

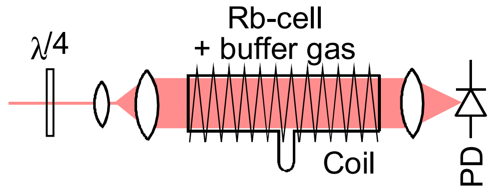

Figure 5.5.6-2. Experimental setup.

The principle of the experimental set-up is shown in Figure 5.5.6-2. In practice, it is, however, necessary to lock the laser frequency to the hyperfine structure of rubidium. An expanded beam and buffer gas are used in the set-up to reduce transit-time and wall-collision broadening and a current coil is applied to lift the Zeeman-degeneracy. The RF-oscillator frequency has been successfully locked to a 6 kHz wide CPT resonance using the magnetic sublevels $m_F = 0$. Evaluation of the frequency stability of the system is being carried out.

6 INTERNATIONAL CO-OPERATION

6.1 International Comparison Measurements

CCPR-K1.a International comparison of spectral irradiance

The 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. The first part of the measurements for this comparison were carried out by HUT in 2000.

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

The 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.

CCPR-K6 International comparison of regular spectral transmittance

The 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.

CCPR-S2 International comparison of aperture area measurements

The measurements for this comparison were carried out by HUT in 2000.

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 within the uncertainties of about 1 %, except below 350 nm wavelength, where the discrepancies (3 – 2 %) are slightly higher than the uncertainty of the comparison.

Bilateral comparison of illuminance responsivity with NIST, USA

The illuminance scales of NIST and HUT were compared. The comparison indicates an excellent agreement [0,08 % ± 0,5 % (k = 2)] within the uncertainty of the realisations of the units.

Bilateral comparison of luminous flux with NIST, USA

The new luminous flux scale of HUT was compared with the scale of NIST. The comparison indicates an excellent agreement [0,06 % ± 0,9 % ($k = 2$)] within the uncertainty of the realisations of the units.

Bilateral comparison of spectral responsivity with IFA-CSIC, Spain

The spectral responsivity scales of IFA-CSIC and HUT were compared in the wavelength region from 260 nm to 400 nm. The comparison indicates an agreement within the uncertainty of the comparison.

Bilateral comparison of optical frequencies of diode lasers with ISI Brno, Czech Republic

Optical frequencies of diode lasers were compared at the HUT in 2000. Due to instability of one of the lasers, the results were inconclusive.

Improving the accuracy of ultraviolet radiation measurement

In this project funded by the SMT-programme of the EU, novel filter radiometer techniques developed by HUT are used to compare various ultraviolet calibration facilities in France (BNM), Finland and UK (NPL). HUT acts as the pilot laboratory in the comparison and measured during 1999 – 2000 all filter radiometers twice, before and after the measurements by other participants. According to the preliminary results, measurements of HUT are in agreement with NPL and BNM.

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

A comparison was carried out for measurements of group delay, bandwidth and relative transmittance for a fibre Bragg grating with several European participants. The results are not yet available.

6.2 Thematic Networks

6.2.1 Thematic network for ultraviolet measurements

The Thematic Network for Ultraviolet Measurements is a three-year project (SMT4-CT97-7510) funded by the Standards, Measurements and Testing

(SMT) programme of the European Union (EU). The network is co-ordinated by the Helsinki University of Technology (HUT). It started its operation on November 15, 1997, and the official Commission-funded part ended on November 14, 2000.

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

During its three years of operation, the network arranged a series of four workshops. In year 2000, the fourth workshop was arranged at the Swedish National Testing and Research Institute (SP) in Sweden, and the second training course was arranged in Austria.

The network publishes a newsletter, *UVNews*, which is edited by the HUT. *UVNews* contains mainly information about the past and forthcoming events of the network. In year 2000, three issues were printed in March, October and November. The extra issue of November contains final reports of the working groups within the network. All issues of *UVNews* and reports to Commission are available in the web-pages (http://metrology.hut.fi/uvnet/) of the Network.

6.2.2 Fibre Optics Technology Network

HUT is a member in the *Fibre Optics Technology Network* -(FOToN)- (SMT4-CT98-7523) co-ordinated by the National Physical Laboratory (NPL) in United Kingdom. FOToN is an interactive information network for the optical fibre users community. It is sponsored by the European Commission under the Standards Measurement and Testing Programme.

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 fibre industry and for co-ordinating collaborative research. They also provide a national forum for the transfer of technology relating to standardisation issues.

The FOToN network is preparing web pages for the promotion of regional group activities and to provide an interactive source of information on fibre optics.

In year 2000, two regional FOToN meetings were arranged in Finland. The first meeting was held in the spring at HUT and the second meeting in the autumn at NK Cables in Vantaa. The 4th regional meeting will be held in connection with the Optics Days 2001 in Tampere. On national level the activity has been organised within an Optical Fibre Measurement Club (OFMeC) which currently has 39 members.

6.3 Conferences and Meetings

The personnel participated in the following conferences and meetings:

Euromet Consultative Committee/Rapporteur Meeting, Bern, Switzerland, January 12 – 13, 2000; *Erkki Ikonen*

Optical Fiber Communication Conference (OFC'2000), Baltimore, Maryland, USA, March 5 – 10, 2000; *Tapio Niemi*

XXXIIII Annual Conference of the Finnish Physical Society, Espoo, Finland, March 9 – 11, 2000; *Miika Heiliö, Erkki Ikonen, Aki Kasvi, Petri Kärhä, Kristian Lahti, Thomas Lindvall, Ilkka Tittonen, Maria Uusimaa, Eero Vahala, and Pekka Wallin*

FOToN – 2nd Regional Meeting, Otaniemi, Finland, March 22, 2000; *Hanne Ludvigsen and Tapio Niemi*

Third International Conference on Modeling and Simulation of Microsystems, San Diego, USA, March 27 – 29, 2000; *Tuomas Lamminmäki and Kaius Ruokonen*

POLAR kick off meeting, Tampere, Finland, March 30, 2000; *Hanne Ludvigsen*

EUROMET Contact Persons Meeting, Istanbul, Turkey, April 1 – 5, 2000; *Erkki Ikonen and Petri Kärhä*

Optics Expert Seminar, Helsinki, Finland, April 28, 2000; *Hanne Ludvigsen*

The Second Training Course on Ultraviolet Measurement, Innsbruck, Austria, May 4 – 5, 2000; *Saulius Nevas*

COST Action 265 – 3rd MC meeting, Gothenburg, Sweden, May 8 – 9, 2000; *Hanne Ludvigsen*

FOToN – 2nd MC meeting, Gothenburg, Sweden, May 10, 2000; *Hanne Ludvigsen*

EU-project working group meeting, Berlin, Germany, May 13 – 17, 2000; *Toomas Kübarsepp and Petri Kärhä*

Conference on Precision Electromagnetic Measurements CPEM'00, Sydney, Australia, May 14 – 19, 2000; *Mikko Merimaa and Goëry Genty*

CCPR KC WG/RMO Meeting, London, United Kingdom, June 4 – 6, 2000; *Erkki Ikonen*

Northern Optics 2000, Uppsala, Sweden, June 6 – 8, 2000; *Ilkka Tittonen, Miika Heiliö, Jari Hovila, Aki Kasvi, Ossi Kimmelma, Kristian Lahti, Mikko Merimaa, Saulius Nevas, Tapio Niemi, Eero Vahala, and Maria Uusimaa*

POLAR meeting, Tampere, Finland, June 12, 2000; *Hanne Ludvigsen*

EUROMET Committee Meeting, Istanbul, Turkey, June 13 – 16, 2000; *Erkki Ikonen*

Tag der Physik und Zehn Jahre Quantenoptik an der Universität Konstanz, July 6 – 12, 2000; *Ilkka Tittonen*

EU-project working group meeting, Borås, Sweden, September 5, 2000; *Toomas Kübarsepp and Petri Kärhä*

3rd international workshop on detector-based UV radiometry (EUROMET project 437), Borås, Sweden, September 6, 2000; *Erkki Ikonen, Toomas Kübarsepp, and Petri Kärhä*

Fourth Workshop of the Thematic Network for UV Measurements, Borås, Sweden, September 6 – 8, 2000; *Erkki Ikonen, Toomas Kübarsepp, and Petri Kärhä*

2000 Conference on Lasers and Electro-optics Europe, CLEO, Nice, France, September 10 – 15, 2000; *Tapio Niemi, Thomas Lindvall, and Ilkka Tittonen*

Symposium of Fiber Optic Measurements (SFOM'2000), Boulder, Colorado, USA, September 26 – 29, 2000; *Tapio Niemi*

Second Annual Seminar on Finnish Silicon Sampo, Helsinki, Finland, October 2 – 3, 2000; *Kaisa Nera and Ilkka Tittonen*

FOToN – 3rd Regional Meeting, Vantaa, Finland, October 4, 2000; *Hanne Ludvigsen, Tapio Niemi, Goëry Genty, Petri Kärhä, and Erkki Ikonen*

Baltic Electronics Conference BEC 2000, Tallinn, Estonia, October 8 – 11, 2000; *Toomas Kübarsepp*

Conference on Quantum Optics, Mallorca, Spain, October 14 – 19, 2000; *Ilkka Tittonen*

POLAR meeting, Tampere, Finland, October 20, 2000; *Tapio Niemi*

COST Action 265 - 4th MC Meeting, Bratislava, Slovac, October 23 – 24, 2000; *Hanne Ludvigsen*

6.4 Visits by the Laboratory Personnel

Kaisa Nera to CNET, France Telecom, Paris, France, February 18, 2000

Personnel of the laboratory to Tallinn Technical University and Kuberneetika AS Ltd, Tallinn, Estonia, June 19 – 20, 2000

Petri Kärhä to NPL, London, United Kingdom, August 15, 2000

Toomas Kübarsepp to Nederlands Meetinsituut, Delft, The Netherlands, November 20 – 22, 2000

Hanne Ludvigsen to COM, Lyngby, Denmark, November 20 – 22, 2000

6.5 Research Work Abroad

Farshid Manoocheri, National Institute of Standards and Technology (NIST), USA, August 1 – December 31, 2000

Goëry Genty, COM/Technical University of Denmark, Lyngby, Denmark, October 24 – December 31, 2000

6.6 Guest Researchers

Sandrine Sigonneau, Ecole Supérieure d'Optique, Paris, France, June 1 – August 31, 2000

Mr. Ondrej Cip and Dr. Josef Lazar, Institute of Scientific Instruments, Brno, Czech, September 25 – October 7, 2000

6.7 Visits to the Laboratory

Mr. Malcolm White, National Physical Laboratory NPL, London, United Kingdom, January 29 – February 1, 2000

Dr. Ulf Leonhardt, KTH Stockholm, Sweden, March 20 – 21, 2000

Mr. Otto Glatz, Coherent, Germany, May 2 – 5, 2000

Mr. Lars Holm, Gamma Optronik Ab, Uppsala, Sweden, May 2 – 5, 2000

Prof. David J. Richardson, Optoelectronics Research Centre, University of Southampton, United Kingdom, June 14, 2000

Dr. Peter Blattner, EAM, Switzerland, June 14 – 16, 2000

Dr. Howard Yoon, National Institute of Standards and Technology (NIST), Gaithersburg, USA, June 25 – July 1, 2000

Dr. Yoshi Ohno, National Institute of Standards and Technology (NIST), Optical Technology Division, Gaithersburg, USA, June 29 – July 5, 2000

Dr. Angus Bell, (MicroLase) Coherent, Scotland, July 24 – 28, 2000 and September 14 – 17, 2000

Mr. Mart Noorma, University of Tartu, Department of Physics, August 17, 2000

Dr. Olev Saks, Dr. Ivo Leito, and M.Sc. Viljar Pihl, University of Tartu, Department of Physics and Chemistry, August 24, 2000

Dr. Xu Gan, Singapore Productivity and Standards Board, Singapore, September 8 – 11, 2000

7 PUBLICATIONS

7.1 Articles in International Journals

P. Kärhä, T. Kübarsepp, F. Manoocheri, P. Toivanen, E. Ikonen, R. Visuri, L. Ylianttila, and K. Jokela, "Portable detector-based primary scale of spectral irradiance," *J. Geophys. Res.* **105**, 4803-4807 (2000).

K. Jokela, L. Ylianttila, R. Visuri, P. Kärhä, and E. Ikonen, "Intercomparison of lamp and detector-based UV-irradiance scales for solar UV radiometry," *J. Geophys. Res.* **105**, 4821-4827 (2000).

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