Helsinki University of Technology
Department of Electrical and Communications Engineering
Metrology Research Institute Report 25/2005
Espoo 2005

DEVELOPMENT OF DETECTORS AND CALIBRATION METHODS FOR SPECTRAL IRRADIANCE AND RADIOMETRIC TEMPERATURE MEASUREMENTS

Mart Noorma

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Electrical and Communications Engineering, Helsinki University of Technology, for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 6th of July, 2005, at 12 o'clock noon.

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

Teknillinen korkeakoulu
Sähkö- ja tietoliikennetekniikan osasto
MIKES TKK Mittaustekniikka

Distribution:
Helsinki University of Technology
Metrology Research Institute
P.O. Box 3000
FIN-02015 HUT
Finland
Tel. +358-9-4511
Fax. +358-9-451 2222
E-mail: mart.noorma@tkk.fi

ISBN 951-22-7748-4

Picaset Oy
Helsinki 2005

Abstract

The research work, described in this thesis, has been carried out at the Metrology Research Institute of Helsinki University of Technology between 2000 and 2005. The research focused on the development of new detectors, calibration methods and their applications in optical radiometry.

A new photodetector, which is based on three GaAsP Schottky-barrier photodiodes, has been introduced. The spectral properties of the GaAsP trap detector have been studied in the wavelength range between 200 nm and 600 nm. Spectral reflectance of a single windowless GaAsP photodiode, measured with high-accuracy gonioreflectometer, has been presented. Based on these measurements, the internal quantum efficiencies for both the single photodiode and the trap detector have been calculated.

A novel scanning method for characterization of filter radiometers, which uses a wavelength tuneable Ti:Sapphire laser source, has been described. High accuracy calibration of filter radiometers at 900 nm has been conducted. The results have been compared to the spectral irradiance responsivities measured with the more conventional monochromator-based method.

Both the laser-based method and the monochromator-based method have been used for characterization of the detectors for radiometric measurements of the thermodynamic temperatures of several blackbodies in irradiance mode. Four filter radiometers with central wavelengths between 600 nm and 900 nm have been used. The measured temperatures include the freezing temperature of silver and copper, which are defined by the International Temperature Scale of 1990.

Preface

The research work resulting in this thesis has been carried out at the Metrology Research Institute, Department of Electrical and Communications Engineering of the Helsinki University of Technology, during a time period from 2000 to 2005. I would like to thank the Head of the department and laboratory, Professor Pekka Wallin for providing me the opportunity to do this interesting research.

I am deeply grateful to my supervisor Professor Erkki Ikonen for his guidance and help during this work. I would like to thank all my co-workers at the Metrology Research Institute, especially Saulius Nevas, Antti Lamminpää, Ville Ahtee, Jouni Envall, Jari Hovila, Markku Vainio, Farshid Manoocheri, and Petri Kärhä for all the help and fun. I would not have been able even to start the post-graduate studies without the support of my former instructor Olev Saks at the Tartu University and my friends Toomas Kolk and Toomas Kübarsepp at Metrosert AS.

I express my gratitude to the Centre for Metrology and Accreditation of Finland, MIKES, which financed most of the research described in this work. Thank you, Thua Weckström, for introducing me to the exciting world of thermometry!

I would like to thank my wife Friderika and children Timo, Kris and Karolina for being so patient during the evenings and weekends I spent at work. Dear parents, I apologize for being abroad for such a long time!

Gaithersburg, June 2005.

Mart Noorma

List of Publications

This thesis consists of an overview and the following selection of the author's publications.

I. M. Noorma, P. Kärhä, A. Lamminpää, S. Nevas, and E. Ikonen, "Characterization of GaAsP trap detector for radiometric measurements in ultraviolet wavelength range," *Rev. Sci. Instrum.* **76,** 033110 (2005) (5 pages).

II. M. Noorma, P. Toivanen, F. Manoocheri, and E. Ikonen, "Characterisation of filter radiometers with wavelength tuneable laser source,“ *Metrologia* **40**, S220-223 (2003).

III. M. Noorma, P. Kärhä, T. Jankowski, F. Manoocheri, T. Weckström, L. Uusipaikka, and E. Ikonen, "Absolute detector-based radiometric temperature scale,“ *Accepted for publication in Proceedings of TEMPMEKO 2004.*

IV. M. Noorma, V. Ahtee, A. Lamminpää, P. Kärhä, F. Manoocheri, T. Weckström, and E. Ikonen, "Radiometric temperature measurements with absolutely characterized filter radiometers in irradiance mode," *Metrology Research Institute Report* **24/2005.**

Author's contribution

The research work presented in this thesis has been carried out at the Metrology Research Institute of Helsinki University of Technology (TKK). All publications included are the results of a team work.

The author has prepared the manuscripts of all publications included in this thesis. He has been actively involved in the planning phase of all the projects resulting in the presented publications and acted as the project manager for the radiometric temperature measurements, presented in Publications III and IV.

The author has constructed the GaAsP trap detector described in Publication I. He has carried out the spectral responsivity and reflectance measurements with the laser sources. Furthermore, he has analysed all the measurement results and carried out the theoretical simulations, reported in this publication.

The author has designed the measurement setup and carried out all the measurements with Ti:Sapphire laser in Publication II. He has also analysed all the results in this publication.

In Publications III and IV, the author has carried out most of the radiometric temperature measurements and analysed the results. He has conducted the calibration of the optical power responsivity of trap detectors with cryogenic radiometer and numerically extrapolated the spectral responsivity to near infrared wavelengths. He has also calibrated the areas of the apertures used for the temperature measurements.

List of abbreviations

FWHM	full-width at half-maximum
FPC	fixed point cell
HeCd	helium-cadmium
HeNe	helium-neon
TKK	Helsinki University of Technology, Finland
IQE	internal quantum efficiency
IR	infrared
ITS-90	International Temperature Scale of 1990
NIR	near infrared wavelength region
NIST	National Institute of Standard and Technology
PRT	platinum resistance thermometer
Ti:Sapphire	titanium-sapphire
UV	ultraviolet wavelength region
VIS	visible wavelength region
VTBB	variable temperature blackbody

List of symbols

A	area of an aperture
c	speed of light (=2.99792458×10^8 m s^{-1})
c_1	first radiation constant in Planck's law (≈3.7418 10^{-16} W m^2)
c_2	second radiation constant in Planck's law (≈1.4388 10^{-2} m K)
$E(\lambda)$	spectral irradiance
i	photocurrent
k	coverage factor
$R(\lambda)$	spectral power responsivity
$S(\lambda)$	spectral irradiance responsivity
T	absolute temperature
$\alpha(\lambda)$	spectral absorption coefficient
$\varepsilon(\lambda,T)$	emissivity of blackbody cavity
$\eta(\lambda)$	internal quantum efficiency
λ	wavelength of radiation
$\rho(\lambda)$	spectral reflectance
$\tau(\lambda)$	spectral transmittance
Ag	silver
Au	gold
Cu	copper
GaAsP	gallium arsenide phosphide
Ge	germanium
PtSi	platinum silicide
Si	silicon
w	half of the waist size of a laser beam (the radius at the irradiance level of $1/e^2$ of maximum)

Contents

1. Introduction

1.1. Background

Historically, the realization of the units of optical quantities has been based on blackbody radiation, first described by Kirchhoff in 1860 [1]. From the known thermodynamic temperature of a blackbody radiator it is possible to derive the spectrum of the output radiation by Planck's radiation law if the emissivity of the source is known [2]. Thus the Planck's law establishes a link between the temperature and spectral radiance scales [3]. The accurate temperature determination of the blackbody sources can be used for the realizations of the spectral radiance and irradiance scales [4, 5, 6, 7].

During the last decades, detector-based realization of units of optical quantities has undergone significant development. The first major landmark in the reduction of the uncertainty of the optical power realization was the development of an electrical substitution radiometer operated at liquid helium temperature, introduced by Martin et al. [8] in the middle of the eighties. The method is based on comparison of the optical-radiation-induced temperature rise of an absorbing cavity with the corresponding temperature rise that is due to electrical heating. Since then, the cryogenic radiometer has been accepted by many national standard laboratories as a device to establish the primary standards for absolute spectral responsivity [9, 10, 11, 12, 13].

The second major landmark of the detector based realizations was the introduction of a specific configuration of photodiodes, called trap detectors [14, 15, 16, 17]. Today, these detectors are widely used as reference standards of optical power responsivity in ultraviolet, visible and near-infrared wavelength regions. Originally, only silicon photodiodes were used in the trap detectors. The spectral properties of silicon trap detectors can be modelled with low uncertainty within the VIS-NIR wavelength range, which allows the measurements of absolute responsivity and reflectance to be made only at a few visible wavelengths [11]. However, the responsivity of a silicon detector is limited towards infrared wavelengths, and while very stable in VIS wavelength range [18], it becomes unstable under extensive ultraviolet radiation below 250 nm [19, 20, 21, 22]. Alternative photodiodes, like GaAsP, PtSi, Ge and InGaAs, which possess higher stability or extended range of responsivity, have been tested in trap detector configuration for UV and IR applications [Publ. I, 23, 24, 25].

Filter radiometers, which incorporate a trap detector, are used for the detector-based realizations of the unit of the spectral irradiance [26, 27, 28]. High accuracy calibration of the filter radiometers can be based on the separate measurements of the properties of the components of the device [26, 27, 29, 30]. Alternative characterization methods are based on the direct calibration of the spectral irradiance responsivity of a filter radiometer as a whole [23, 31, 32 33, 34, 35, Publ. II]. The high accuracy of the wavelength scale of the methods, which take advantage of wavelength tuneable laser sources [33, 34, Publ. II], is especially advantageous if the calibrated filter radiometer is to be used for radiometric temperature determination [36, Publ. IV].

Due to the improvements in the accuracy of the detector-based spectral irradiance and radiance scales, described earlier, the uncertainty of the radiometric determination of the thermodynamic temperature of a blackbody source from the measured spectral radiance or irradiance has reduced significantly [36, 37, 38, 39, 40, 41]. Thus it becomes more attractive to realize the scale of radiometric temperature via optical units. In such a way, the measured temperatures are traceable to the electrical and dimensional quantities instead of the defined temperatures of the freezing temperatures of some metals [3, Publ. III, Publ. IV].

1.2. Progress in this work

We have studied the properties of GaAsP Schottky barrier photodetectors in order to extend the scales of spectral responsivity and spectral irradiance down to 200 nm. We have constructed and characterized a trap detector, which utilizes GaAsP photodiodes [Publ. I]. The spectral reflectance of the trap detector was calculated from a theoretical model using the measured reflectances of single photodiodes and compared to the measured reflectances of the trap detector. Based on the measurements of the spectral responsivity and reflectance of the trap detector and of a single photodiode, we have demonstrated an apparent decrease in the internal quantum efficiency of GaAsP trap detector relative to a single photodiode. In addition, we tested the ageing of the GaAsP photodiodes under modest UV radiation. As a result, we have demonstrated that GaAsP trap detector can be used as a reliable reference standard detector in ultraviolet wavelength range with some restrictions on the level of irradiance of the incident radiation [Publ. I].

A novel characterization technique, which is based on Ti:Sapphire wavelength-tunable laser source, has been used to calibrate the spectral irradiance responsivity of filter radiometers in the wavelength range between 750 nm and 950 nm [Publ. II]. We have studied the effect of interference, present in the laser-based calibration of filter radiometers. The amplitude of the interference fluctuations in the measured spectral irradiance responsivity has been reduced by antireflection coatings on both surfaces of the band-pass filter of the filter radiometer. This special design has led to a significant increase of the accuracy of this calibration method.

The Ti:Sapphire laser, which has been used as the radiation source in this method, has bandwidth as narrow as 3 pm. The wavelength of the laser has been measured on-line during the calibration. Thus the uncertainty component, arising from the wavelength scale, is of an order of magnitude lower than in the case of monochromator-based calibrations [Publ. II]. As a result, we have reduced the uncertainty of the radiometric determination of blackbody temperatures at TKK [Publ. IV].

We have demonstrated the radiometric temperature measurements of several blackbody sources in a straightforward irradiance mode, where the measurement geometry is defined by two apertures [Publ. III, Publ. IV]. The freezing temperatures of copper [Publ. III] and silver [Publ. III, Publ. IV] have been measured and compared to the defined values of the ITS-90 [3], 1084.62 °C and 961.78 °C, respectively. We have shown that the straightforward irradiance mode of the measurements can be applied on the measurements of the thermodynamic temperatures of the fixed point cells, which traditionally have small output apertures. Furthermore, the thermodynamic temperatures of a variable temperature blackbody have been measured in the temperature range between 1200 °C and 1500 °C [Publ. IV]. The measurement results with different filter radiometers, which have effective wavelengths between 600 nm and 900 nm, have demonstrated good agreement between different characterization techniques of the filter radiometers [Publ. IV].

2. GaAsP photodetectors

Gallium arsenide phosphide Schottky-barrier photodiodes, which have cut-off wavelength around 610 nm, are used as working standard detectors in the UV wavelength region [42, 43] and their properties have been studied by several research groups [44, 45, 46, 47, 48, 49, 50]. The photodiodes are commercially available with large area, $10\times10\ mm^2$, and with satisfactory spatial uniformity [42, 51]. While the responsivity of GaAsP photodiodes is typically 2–3 times lower as compared to silicon photodiodes, its spectral shape is smoother in the range of 250 nm to 350 nm [42] and it does not degrade under UV radiation so rapidly [52].

The trap detector is a configuration of three or more photodiodes in such a way that the reflected light from one diode hits the next, and so on (Fig. 1) [14, 16, 15]. After several reflections, most of the incident light has contributed to generation of the photocurrent, in contrast to a typical single photodiode detector, where more than 50 % of the incident light is reflected. As a result, the responsivity of a trap detector can be approximately two times higher as compared to a single photodiode (Fig. 2). At the same time, the total reflectance of a trap detector is an order of magnitude lower as compared to the reflectance of a single photodiode at normal incidence.

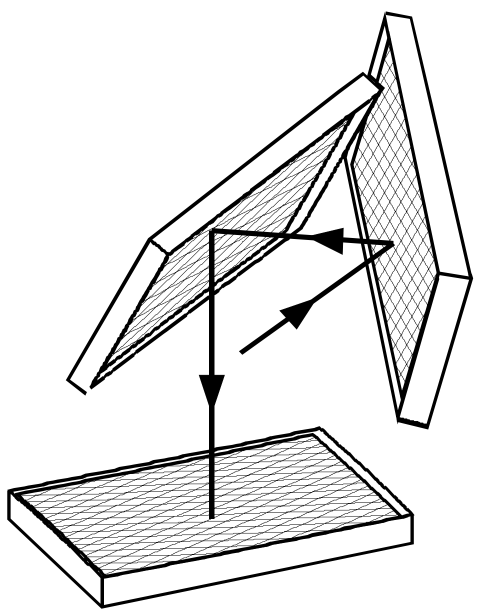

Figure 1. The lay-out of the photodiodes in a three-element trap detector. The hatched areas indicate the active surfaces of the photodiodes [53].

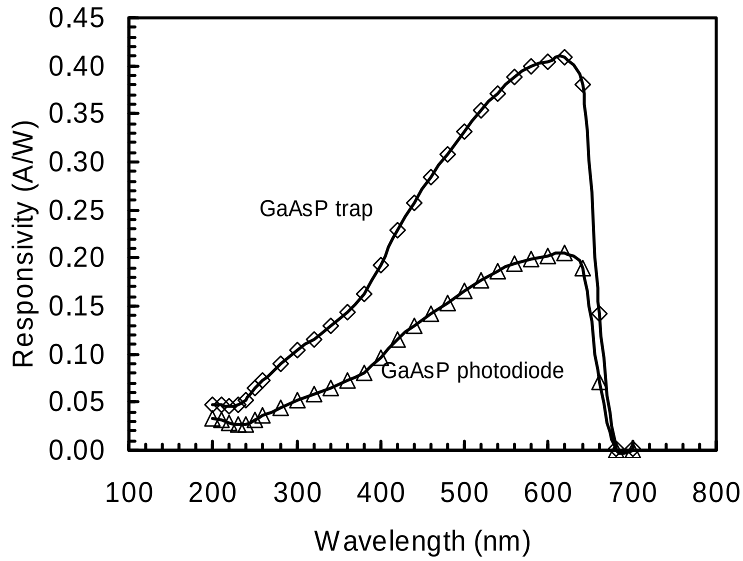

Figure 2. Measured responsivities of GaAsP trap detector and of a windowless GaAsP photodiode at normal incidence.

2.1. Spectral reflectance

The spectral reflectances of GaAsP photodiodes have been studied with synchrotron radiation sources in UV and VUV wavelength ranges [45, 47]. The results however have been published only for a few selected angles of incidence and polarization planes of the incident light [45, 47]. The spectral reflectance of a windowless GaAsP photodiode has also been measured with a high-accuracy gonioreflectometer [54] in the wavelength range between 240 nm and 600 nm [Publ. I]. The measurements have been conducted at the angles of incidence of 45°, 30° and 10° with monochromatic light polarized linearly sequentially in s- and p-planes (Fig. 3).

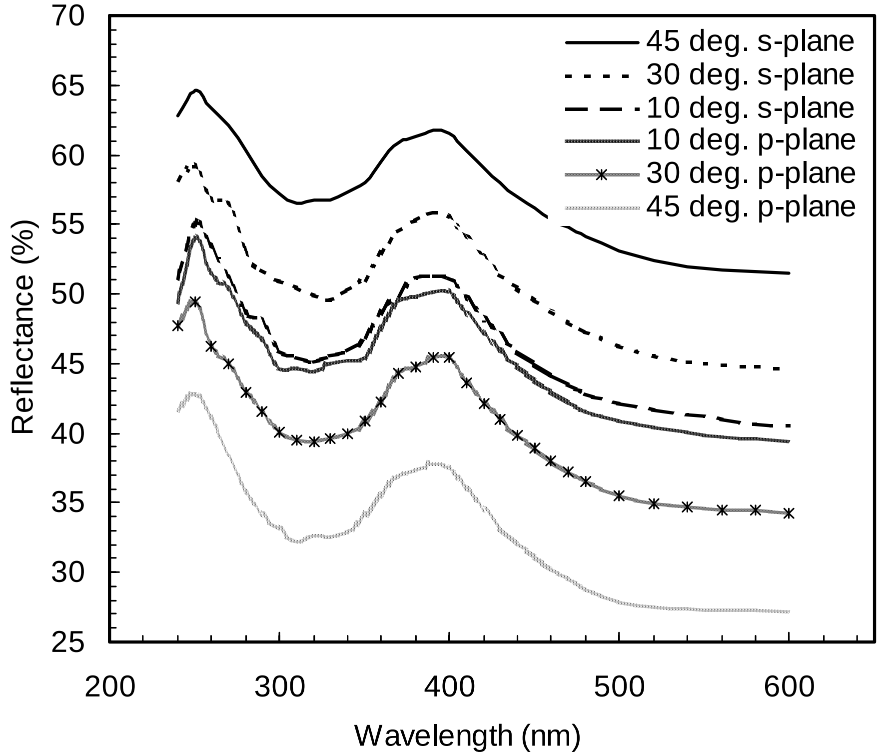

Figure 3. Measured reflectances of GaAsP single photodiode at different angles of incidence with light polarization in both s- and p-planes.

The reflectance of a trap detector, ρ_{trap}, can be calculated from the known reflectances of the single photodiodes used in the trap detector. The calculation takes into account the configuration of the trap detector and the reflectances of the photodiodes at the angles of 0° and 45° for both polarization planes, $\rho(0°)$, $\rho_s(45°)$ and $\rho_p(45°)$, respectively. The reflectance can be calculated as

$$\rho_{trap} = \rho(0°) \cdot \rho_s^2(45°) \cdot \rho_p^2(45°). \quad (1)$$

The reflectance of GaAsP trap detector has been calculated from the data using Eq. 1 (Fig. 3) and compared to the measured reflectances at three laser wavelengths, 325 nm, 442 nm, and 457 nm (Fig. 4). The reflectance at the normal incidence $\rho(0°)$, which has not been directly measured, has been calculated by extrapolation of the measured reflectances at 45°, 30° and 10°.

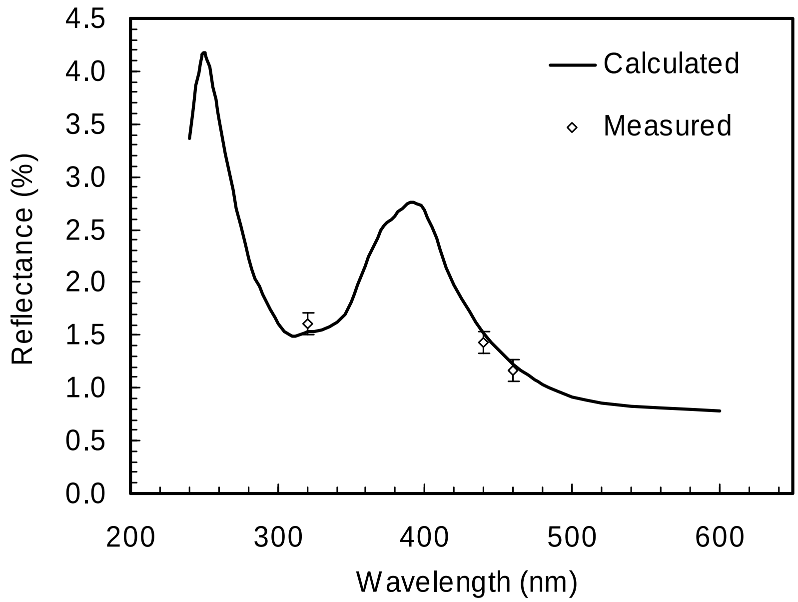

Figure 4. Reflectance of GaAsP trap detector. Measured trap reflectances with uncertainty bars are compared to the values calculated from the measured reflectances of a single photodiode.

2.2. Spectral responsivity and IQE

The spectral responsivity of a semiconductor photodetector $R(\lambda)$ can be calculated by equation

$$R(\lambda) = [1 - \rho(\lambda)]\eta(\lambda)\frac{\lambda}{K}, \tag{2}$$

where λ is the vacuum wavelength of incident light, $\rho(\lambda)$ is the spectral reflectance of the detector, η (λ) is the spectral internal quantum efficiency of the photodetector, and $K \equiv hc/e$ = 1239.84 nm W A^{-1} is determined in terms of fundamental constants.

The absolute spectral responsivity of GaAsP Schottky-barrier photodiodes has been measured with different methods [43, 44, 45, 47, Publ. I]. At TKK, the absolute spectral responsivity of GaAsP trap detector has been measured with a monochromator-based spectrophotometer [55] using a spectrally flat pyroelectric detector as a reference (Fig. 2) [Publ. I].

The internal quantum efficiencies $\eta(\lambda)$ of GaAsP trap detector and of a single GaAsP photodiode under normal incidence have been calculated from the measured spectral responsivities and reflectances using Eq. 2 (Fig. 5) [Publ I]. The comparison reveals a modest reduction of the IQE for the trap detector. This systematic difference varies between 3 % at 400 nm and 14 % at 250 nm (Fig. 5). The probable reason for this effect is the increased absorption in the Schottky contact layer of the photodiodes in the trap detector configuration, where two of the photodiodes are at 45° with respect to the incident light and thus the path length of the light through the contact layer is longer.

The spectral responsivity of GaAsP trap detector is a smooth function of wavelength in the range between 250 nm and 370 nm. On the contrary, the spectral responsivity of a typical silicon detector has a complicated structure around 275 nm, which makes its responsivity difficult to interpolate in this wavelength range. The physical explanation is that while silicon has the peaks of its dielectric functions, corresponding to the direct electron transitions in the energy-band structure, at around 275 nm and 370 nm, the corresponding peaks for the GaAsP compound used appear around 250 nm and 390 nm. Reduced reflectance of the trap detector also contributes to the spectral smoothness, as the peaks, appearing in the spectral reflectance at the same wavelengths, are around one decade lower.

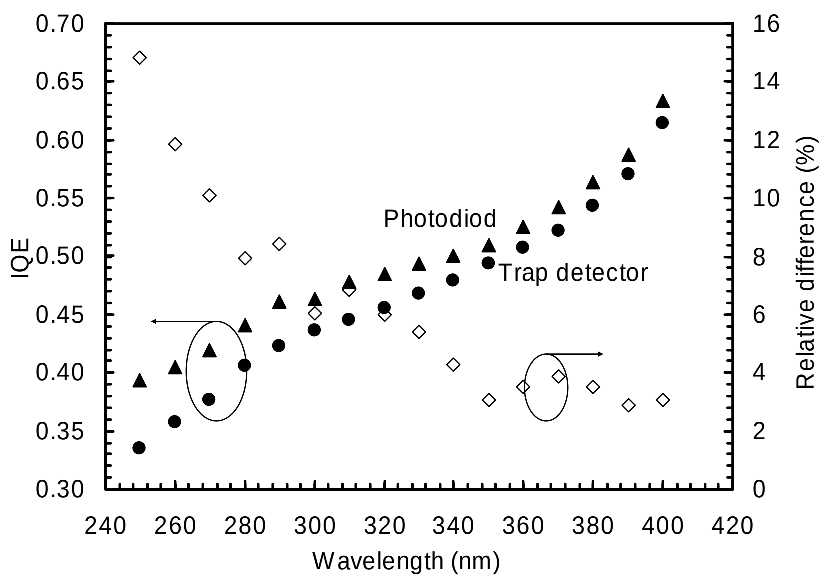

Figure 5. Relative difference in IQE between GaAsP trap detector and a single windowless GaAsP photodiode.

In practice, the spectral density of the calibration points, and thus the required number of the calibrations at different wavelengths, depends on the accuracy of the interpolation between the measured values. Accordingly the smoothness of the responsivity reduces the effort needed, especially if the calibration is performed with a cryogenic radiometer.

2.3. Spatial uniformity of GaAsP detectors

Spatial uniformity of GaAsP photodiodes is modest as compared to high-quality silicon photodiodes [42] (Fig. 6). However, as the total uncertainty of spectral responsivity in the UV wavelength range is significantly higher as compared to VIS wavelength range [56], the uncertainty component arising from the spatial uniformity is not a limiting one [Publ I].

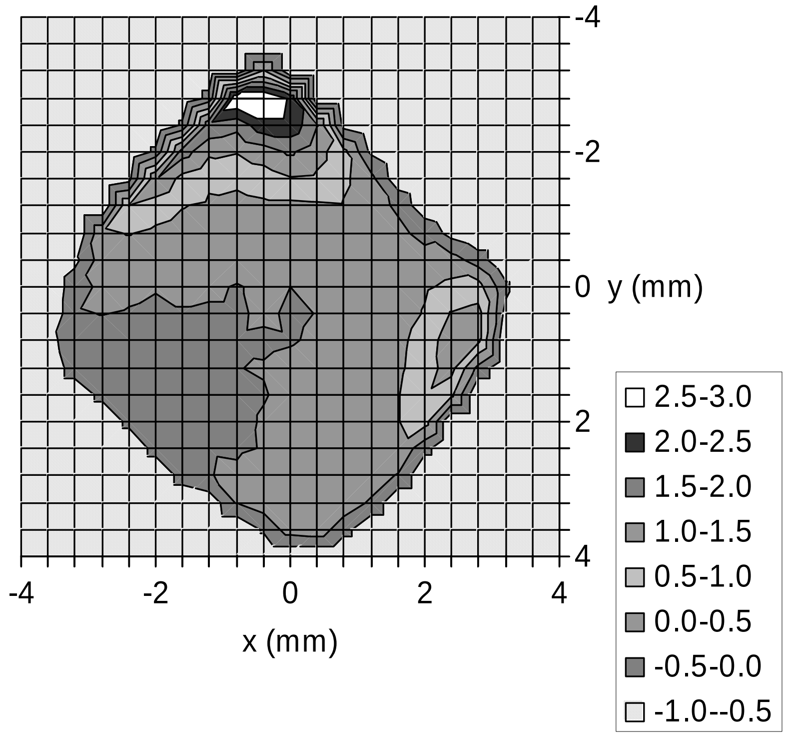

Figure 6. Spatial uniformity of GaAsP trap detector, measured with HeCd laser at 325 nm using a 2 mm beam. The values in percents are given relative to the central measurement point.

3. Characterization of filter radiometers

3.1. Characterization of filter radiometer components

Spectral irradiance of a radiation source can be measured with a spectrally filtered detector. Typically, a filter radiometer consists of a detector with spectral responsivity $R(\lambda)$, a band-pass filter with spectral transmittance $\tau(\lambda)$, and an aperture with area A. The spectral irradiance responsivity of such a detector, $S(\lambda)$, can be calculated from the equation:

$$S(\lambda) = A \cdot R(\lambda) \cdot \tau(\lambda) \tag{3}$$

Thus the spectral irradiance responsivity of the filter radiometer can be calculated as a product of separately measured parameters A, $R(\lambda)$, and $\tau(\lambda)$. In addition, corrections arising from the interreflections between the filter, detector, and aperture have to be applied. Furthermore, the diffraction from the edges of the aperture has to be taken into account.

Typically, diamond-turned circular apertures, made of brass or black anodized aluminium, are used in the filter radiometers [26, 27]. The area of the aperture, A, can be calculated from the diameters measured with contact methods [57] or with non-contact methods [58, 59, 60]. An advantage of a non-contact method is that the risk of damaging of the sharp edges of the aperture is reduced. The area can also be measured directly with optical non-contact methods [61, 30, 62].

A common detector, used in the filter radiometers for measurements in VIS wavelength range, is silicon photodiode. As discussed in the previous chapters, the responsivity of silicon photodiode can be calibrated at a few wavelengths for example with an absolute cryogenic radiometer, and be extrapolated numerically using physical models over all VIS wavelength range with high accuracy [63, 64, 65]. There are also improved models for UV and NIR spectral ranges, but the uncertainty of these extrapolations increases significantly. On the other hand, a single Si photodiode has high reflectance, which is complicated to account for in the filter radiometer configuration if the components of the filter radiometer are characterized separately. In such a case, a trap detector, whose reflectance is much lower as compared to a single photodiode, is more suitable [26, 27].

The filters used in filter radiometers are normally narrow-band interference filters. The spectral transmittance of such a bandpass filter, $\tau(\lambda)$, can be measured with spectrophotometers, which use monochromatic tuneable light sources [29]. In the transmittance measurements, it is important to use beam geometries, which are close to the actual measurement configurations where the calibrated filter radiometer is to be used as the transmittance of the interference filters is sensitive to the angle of incidence. The transmittance of the interference filters is also a function of temperature [66] and the central wavelengths of the interference filters may shift due to temperature variations [67]. For high-accuracy measurements, the filters have to be temperature-controlled.

3.2. Characterization of filter radiometer as a unit

A stable light source consisting of a lamp and a monochromator is traditionally used to calibrate the spectral responsivity of a filter radiometer. During the calibration the filter radiometer and a reference detector with known spectral responsivity are illuminated alternately by radiation from the monochromator. Usually the aperture of the filter radiometer is removed which permits the use of different sizes and positions of the beam. In this approach, additional uncertainty arises from the spatial nonuniformity of the filter radiometer. The spectral resolution of the calibration is also limited by the bandwidth of the monochromator.

A wavelength-tuneable laser can be used instead of the monochromator. The laser beam directed to an integrating sphere can be used as a uniform monochromatic source [33, 34]. The laser-based methods have excellent wavelength resolution and repeatability as compared to the monochromator-based methods. However, the wavelength ranges, which can be covered with wavelength-tuneable lasers, are limited. Furthermore, a significant uncertainty component arising from the interference of the monochromatic laser light inside the bandpass filter of the filter radiometer has to be taken into account [Publ. II].

3.3. The scanning method

The scanning method is based on a known, uniform irradiance produced by combining several identical laser beams [30, 35]. In practice, only one laser beam is used and the position of the filter radiometer is moved by small steps in relation to the laser beam. To produce a uniform irradiance distribution, the beam profile does not need to be either Gaussian or symmetric.

There is a group of identical beams forming a rectangular grid. The beams are placed regularly with spacings between each other Δx and Δy in x and y directions, respectively (Fig. 7). The number of columns is denoted by n_x and number of rows by n_y. Each beam on the grid can be identified by the number of it's column and row (*j,k*).

The irradiance related to the beam can be described by a general distribution

$$\Phi_L G(x - j\Delta x, y - k\Delta y)\,, \tag{4}$$

where Φ_L is the radiant flux of the beam and G is the shape function. The shape function is normalised in such a way that

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} G(x - j\Delta x, y - k\Delta y)\,dx\,dy = 1\,. \tag{5}$$

It is assumed that the spacings Δx and Δy are much smaller than the distances over which there occur significant changes in the shape function G. When $n_x\Delta x$ and $n_y\Delta y$ are much larger than the beam widths in the x and y directions, the irradiance at a point $x = x_0$ and $y = y_0$, close to the centre of the grid, is given by

$$\begin{aligned} E &= \sum_{j=-n_x}^{n_x} \sum_{k=-n_y}^{n_y} \Phi_L G(x - j\Delta x, y - k\Delta y) = \\ &= \frac{\Phi_L}{\Delta x \Delta y} \sum_{j'=-n_x}^{n_x} \sum_{k'=-n_y}^{n_y} G(j'\Delta x + x_0, k'\Delta y + y_0)\Delta x \Delta y \approx \frac{\Phi_L}{\Delta x \Delta y} \end{aligned} \tag{6}$$

where $j' = -j$, $k' = -k$, and Eq. 5 has been used to approximate the double summation in the second row of Eq. 6 to be 1. Equation 6 shows that the generated irradiance close to the centre of the grid depends only on the radiant flux of the beam and distance between beams.

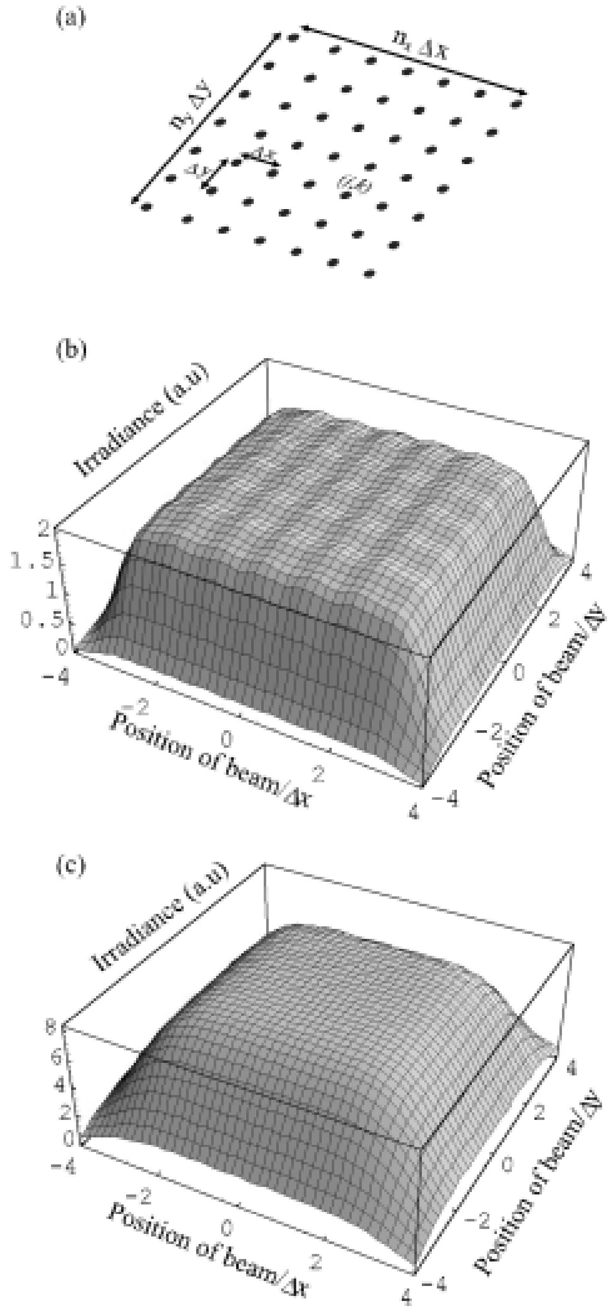

Figure 7. Uniform effective irradiance generated by the sum of identical beams. Figure (a) shows the number and location of the beams. Calculated irradiance profile as a function of ratio between the beam diameter and distance between the beams: (a) Δx=Δy=w and (b) Δx=Δy= 0.63w where w is equal to the radius of the beam at $1/e^2$ irradiance level from maximum [35].

If a filter radiometer is exposed to the monochromatic uniform irradiance E and the output photocurrent I is measured, the spectral irradiance responsivity $S(\lambda)$ can be calculated from the equation

$$S(\lambda) = \frac{I}{E}. \tag{7}$$

By measuring the photocurrent of the filter radiometer, $I_{j,k}$, at each beam position (j,k), one can calculate the total photocurrent which corresponds to E

$$I = \sum_{j=-n_x}^{n_x} \sum_{k=-n_y}^{n_y} I_{j,k} . \tag{8}$$

The spectral irradiance responsivity of the filter radiometer is obtained by combining Equations (6) – (8) as

$$S(\lambda) = \frac{\sum_{j=-n_x}^{n_x} \sum_{k=-n_y}^{n_y} I_{j,k} \Delta x \Delta y}{\Phi_L} . \tag{9}$$

3.4. Comparison of calibration methods

The measurements of spectral irradiance responsivities of filter radiometers using laser- and monochromator-based sources have shown some significant differences. First, the narrow bandwidth of the laser allows achievement of high wavelength resolution in the measured irradiance responsivities. However, this is not always the case, as the interreflections occur between different surfaces of the bandpass filters causing unwanted interference of the monochromatic coherent light. As a result, wavelength-dependent semi-periodic fluctuations in the transmittance of the filter occur. The period of these fluctuations has been measured to be from 0.05 nm to 0.5 nm [Publ. II]. In order to correctly estimate the irradiance responsivity of filter radiometers incorporating such filters, an average over at least one full period of these fluctuations has to be calculated. Thus the spectral resolution of laser-based methods is mainly determined by the properties of the calibrated artifact. Nevertheless, with suitable selection of bandpass filters, spectral resolution as high as 0.05 nm can be achieved with the laser-based method [Publ. II].

Laser sources have typically much higher output power as compared to a monochromator with a lamp source. In addition, the out-of-band radiation of a laser can be extremely low. These properties give the laser-based method a significant advantage for out-of-band spectral irradiance measurements of filter radiometers.

4. Radiometric temperature measurements

4.1. Relative temperature scale

In 1989, the International Temperature Scale of 1990 (ITS-90) was adopted by the International Committee of Weights and Measures [3]. The ITS-90 extends upwards from 0.65 K to the highest temperature practicably measurable. Above the freezing temperature of silver, 961.780 ºC, the temperature is defined in terms of the Planck radiation law using monochromatic radiation by the equation:

$$\frac{L_\lambda(T_{90})}{L_\lambda\left[T_{90}(X)\right]} = \frac{\exp(c_2\left[\lambda T_{90}(X)\right]^{-1}) - 1}{\exp(c_2\left[\lambda T_{90}\right]^{-1}) - 1}, \tag{10}$$

where $T_{90}(X)$ refers to any one of the silver {$T_{90}(Ag)$ = 1234.93 K}, the gold {$T_{90}(Au)$ = 1337.33 K} or the copper {$T_{90}(Cu)$ = 1357.77 K} freezing points and in which $L_\lambda(T_{90})$ and $L_\lambda[T_{90}(X)]$ are the spectral concentrations of the radiance of a blackbody at the wavelength (in vacuum) λ at T_{90} and at T_{90}(X) respectively, and c_2 = 0.014388 m·K [3]. In this approach, the T_{90} values of the freezing points of silver, gold and copper are believed to be self consistent to such a degree that the substitution of any one of them in place of one of the other two as reference temperature T_{90}(X) would not result in significant differences in the measured values of T_{90} [68]. However, later measurements have revealed possible discrepancies between the ratios of the fixed point temperatures of the ITS-90 [36].

Measurements of higher or lower temperatures relative to a fixed point suffer from the possible errors related to the extrapolation, as the defined temperatures of the ITS-90 are limited [69, 70]. During the last decade, intensive research has been carried out to develop new high-temperature fixed points at several national metrology institutes [71, 72, 73, 74, 75, 76]. These blackbodies are based on metal-carbon eutectics. Some of them, namely Ir-C, Re-C, TiC, Os-C, ZrC-C, and HfC-C, have melting temperatures higher than 2500 K [71], and M-C and MC-C even above 2700 K [76]. The uncertainty, related to the extrapolation, can be significantly reduced if fixed points close to the measured temperature are used as the reference. However, the reproducibility of the new metal-carbon eutectics needs further improvement [77].

4.2. Radiometric temperature measurements below 961.780 °C

Radiometric measurements of temperatures below the freezing temperature of silver are very important for different industrial and military applications. According to the ITS-90, the temperature scale between the triple point of equilibrium hydrogen (13.8033 K) and the freezing point of silver (961.78 °C) is defined by means of a platinum resistance thermometer calibrated at specified sets of defining fixed points, and using specified reference and deviation functions for interpolation at intervening temperatures [3]. For radiometric temperature measurements, blackbodies equipped with a calibrated PRT, and with known emissivity can be used as reference standards. However, the spectral emissivities of blackbodies are complicated to estimate and therefore can introduce significant errors for radiometric calibrations [78].

Another approach is to extend the extrapolation methods described in the ITS-90 for the temperature above 961.780 °C also below the freezing temperature of silver. For the temperature range between 200 °C and 961.780 °C, the set of available fixed points includes the freezing temperatures of tin (231.928 °C), zinc (419.527 °C), and aluminum (660.323 °C). At lower temperatures, the measurement wavelength of the pyrometers used has to increase. Pyrometers with silicon detectors and bandpass filters close to 900 nm can typically be used down to 600 °C. Alternative detectors like indium gallium arsenide, germanium, indium antimonide, or thermal detectors have to be used for measurements at lower temperatures.

4.3. Absolute radiometric temperature measurements

Absolute radiometric measurements of blackbody temperature, traceable to electrical and dimensional units, are free of extrapolation errors, and there is no need for the realization of any fixed points. Thermodynamic temperature of a blackbody cavity, T, can be calculated from the measured spectral radiance $L(\lambda,T)$ using Planck's radiation law [2]:

$$L\left(\lambda, T\right) = \frac{c_1}{\lambda^5\left[\exp\left(c_2/\lambda T\right)-1\right]} \tag{11}$$

where λ is the wavelength in vacuum, c_1=3,741 774 9 · 10^{-16} W·m^2 and c_2=1,438 8 · 10^{-2} m·K are the first and second radiation constants defined by the CIE [79].

Filter radiometers equipped with bandpass filters and a lens system can be used for the direct measurement of the spectral radiance in so called radiance mode of measurements [36, 40, 42]. An alternative method uses two apertures in the irradiance mode of measurements, where the radiance of the source is calculated from the measured irradiance at known distance [40, 42, Publ. III, Publ. IV].

If the spectral irradiance responsivity of a filter radiometer, $S(\lambda)$, is known, the thermodynamic temperature of a blackbody can be determined from the measured spectral irradiance at a distance d from the blackbody by equation:

$$i = \frac{A_{BB}(1+\frac{r_{BB}^2 r_{FR}^2}{D^4})}{D^2}\varepsilon(\lambda,T)\int S(\lambda)L(\lambda,T)d\lambda\,, \tag{12}$$

which relates the photocurrent i and the radiance of a blackbody $L(,T)$, given by the Planck's radiation law (Eq. 11). The temperature of the blackbody is found by matching the calculated photocurrent with the measured one. In equation 12, the parameter A_{BB} is the area of the blackbody aperture, $\varepsilon(\lambda,T)$ is the emissivity of the blackbody cavity, r_{FR} is the radius of the filter radiometer aperture, and r_{BB} is the radius of the blackbody aperture. The geometric factor D^2 is calculated as:

$$D^2 = d^2 + r_{BB}^2 + r_{FR}^2\,. \tag{13}$$

The emissivity of a blackbody cavity, $\varepsilon(\lambda,T)$, depends on the material properties and dimensions of the cavity. Furthermore, it is a function of wavelength and temperature of the cavity [80]. For the radiometric measurements of thermodynamic temperature of a blackbody, the emissivity of the cavity is typically calculated using measured emissivities of the material samples and Monte Carlo analysis [81]. According to the Kirchhoff's law, the emissivity equals the absorbance. Thus the emissivity can be estimated also by the measurements of spectral diffuse reflectance of the cavity [82, 80].

Measurements of the spectral irradiance of a blackbody with small cavity diameter are demanding due to multiple factors [Publ. III, Publ IV]. First, the effect of diffraction from the aperture of the cavity is more significant for smaller cavity diameters. The calculations of the diffraction corrections typically use Fresnel integrals [83] or simplified Lommel functions [84]. Different methods for the calculation have been proposed [85, 86, 87, 88, 89]. Next, the level of irradiance from a source with small area at the temperatures close to the fixed point temperatures of the ITS-90 can be very low [Publ. III, Publ IV]. However, the linearity of silicon photodiodes, which are typically used in filter radiometers, is good [90, 91] and the measurement of optical power at the level of 50 pW with high accuracy is possible [Publ. III, Publ IV].

4.4. Measurements at multiple wavelengths

While radiance temperature of a high-emissivity blackbody source can be calculated from the measured radiance at a single wavelength, it can be advantageous to conduct the measurements at multiple wavelengths. The possible discrepancies between the results obtained at different wavelengths may reveal possible systematic errors arising for example from the out-of-band leakages, diffraction, and size-of-source effects. The best estimate for the radiance temperature in the case of measurements at multiple wavelengths is the weighted average $\overline{T}$ of the temperatures obtained at different wavelengths using weighting factors c_j calculated from the standard uncertainties of the measurements at different wavelengths $u(T_j)$. However, the total uncertainty of such an estimate depends on the correlation coefficients $r(T_j, T_k)$ between the measurement results T_j and T_k at different wavelengths as:

$$u^2(\overline{T}) = \sum_{ji=1}^{n} c_j^2 u^2(T_j) + 2\sum_{j=1}^{n-1} \sum_{k=j+1}^{n} c_j c_k u(T_j) u(T_k) r(T_j, T_k)\,, \qquad (14)$$

where $u(\overline{T})$ is the standard uncertainty of $\overline{T}$ and n is the number of wavelengths used [92]. During recent years, the effects of correlations in spectral measurements have been actively studied [93, 94, 95].

Another motivation for temperature measurements at multiple wavelengths is to optimally cover wider temperature range. From the Planck's radiation law, the radiance measurements at lower wavelengths will result in higher accuracy of temperature determination. However, measurements at lower wavelengths are limited by low radiance levels. While bandpass filters at 650 nm are typically used for high temperature measurements, higher measurement wavelengths can be preferable below the freezing temperature of silver. In this temperature range, the improvements achieved in filter radiometer calibration with the laser-based calibration method at 900 nm, are especially useful.

5. Conclusions

In this thesis, properties of radiometric detectors and their calibration have been studied. The GaAsP photodetectors have been characterized in the wavelength range between 200 nm and 600 nm. Spectral reflectances of a single windowless GaAsP photodiode, measured with high-accuracy gonioreflectometer, have been presented. A GaAsP trap detector which is suitable to be used as a working standard detector for the optical power measurements in the ultraviolet wavelength range has been constructed and characterized. The reduction of the internal quantum efficiency of the trap detector as compared to a single photodiode at normal incidence has been shown. This effect arises probably from the increased absorption in the Schottky contact layer, made of gold, on the top of the photodiodes. Nevertheless, the constructed GaAsP trap detector seems to be a suitable detector for spectral responsivity scale realization in the UV wavelength range.

While ideal trap detectors are polarization independent, small errors in alignment or the presence of absorbing metal layer on GaAsP photodiodes can cause polarization dependence of the responsivity [96]. The effect still needs further investigation.

The GaAsP trap detector has been preliminarily tested also in the filter radiometer configuration for spectral irradiance measurements. In the future, the spectral irradiance scale realization at TKK in the UV wavelength range between 200 and 290 nm could be based on the filter radiometers utilizing GaAsP trap detectors. However, the long-term stability of the detector has to be further investigated.

A novel method for characterization of filter radiometers, which uses a wavelength tuneable Ti:Sapphire laser source, has been described. The scanning method has lower uncertainty as well as higher wavelength accuracy as compared to more conventional monochromator-based methods. The tuning range of the Ti:Sapphire laser is suitable for characterization of filter radiometers around 800 nm and 900 nm, which are comfortable wavelengths for radiometric measurements of blackbody temperatures 1000 °C and below. With a doubled frequency of the laser, the method can be used in future for accurate calibrations in the UV wavelength range.

Radiometric measurements of the thermodynamic temperatures of several blackbodies in the irradiance mode have been described. The measured temperatures include the freezing temperature of silver and copper, which are defined by the ITS-90. While we show that the irradiance mode can be used for measurements of small sources, the uncertainty achieved is still somewhat higher as compared to the measurements of the other groups in radiance mode [36]. However, the uncertainty can be further reduced by improving the spectral responsivity calibration of the reference detectors in the NIR wavelength range. Furthermore, the effect of diffraction could be measured directly instead of calculation by a specially designed measurement system, currently under development at NIST.

Comparison measurements with different filter radiometers, characterized with both monochromator-based and laser based methods, have demonstrated good agreement between the methods. In the future, the filter radiometers at 800 nm and 900 nm, calibrated with the laser-based method, can be used to extend the TKK measurement capabilities to lower temperatures. Furthermore, filter radiometers utilizing germanium detectors, are currently studied at the TKK for radiometric measurement of temperatures below 1000 °C [97].

References

1. G. Kirchhoff, “Ueber das Verhältniß zwischen dem Emissionvermögen und dem Absorptionsvermögen der Körper für Wärme und Licht,” *Ann. Phys.* **19**, 275-301 (1860).
2. M. Planck, “Ueber das gesetz der energieverteilung im normalspectrum,” Ann. D. Phys. **4**, 553-563 (1901).
3. H. Preston-Thomas, “The ITS-90,” Metrologia **27**, 3-10 (1990).
4. J. Metzdorf, ”Network and traceability of the radiometric and photometric standards at the PTB,” Metrologia **30**, 403-408 (1993).
5. P. Sperfeld, J. Metzdorf, S. G. Yousef, K. D. Stock, and W. Moller, “Improvement and extension of the black-body-based spectral irradiance scale,” Metrologia **35**, 267-271 (1998).
6. B. Chu, H. C. McEvoy, and J. W. Andrews, “The NPL reference sources of blackbody radiation,” Meas. Sci. and Tech. **5**, 12-19 (1994).
7. V. I. Sapritski, ”Black-body radiometry,” Metrologia **32**, 411-417 (1996).
8. J. E. Martin, N. P. Fox, and P. J. Key, “A cryogenic radiometer for absolute radiometric measurements,” Metrologia **21**, 147-155 (1985).
9. T. Varpula, H. Seppä, and J.-M. Saari, “Optical power calibrator based on a stabilized green He-Ne laser and a cryogenic radiometer,” IEEE Trans. Instrum Meas. **28**, 558-564 (1989).
10. O. Touayar, H. Reyn, J. Bastie, and T. Varpula, “Indirect comparison of cryogenic radiometers from the INM (France) and the VTT (Finland) with a QED-200 from VSL (Netherland),” Metrologia **32**, 561-564 (1995/96).
11. T. R. Gentile, J. M. Houston, and C. L. Cromer, “Realization of a scale of absolute spectral response using the National Institute of Standards and Technology high-accuracy cryogenic radiometer,” Appl. Opt. **35**, 4392-4403 (1996).
12. A. Lassila, H. Hofer, E. Ikonen, L. Liedquist, K. D. Stock, and T. Varpula, “Intercomparison of Cryogenic radiometers using silicon trap detectors,” Meas. Sci. Instrum. Technol. **8**, 123-127 (1997).
13. J. E. Martin and P. R. Haycocks, “Design considerations for the construction of an absolute radiation detector at the NPL,” Metrologia **35**, 229-233 (1998).
14. E. F. Zalewski and C. R. Duda, “Silicon photodiode device with 100 % external quantum efficiency,” Appl. Opt. **22**, 2867-2873 (1983).
15. N. P. Fox, “Trap detectors and their properties,” Metrologia **28**, 197-202 (1991).
16. J. L. Gardner, “Transmission trap detectors,” Appl. Opt. **33**, 5914-5918 (1994).

17. T. Kübarsepp, P. Kärhä, and E. Ikonen, "Characterization of polarization independent transmission trap detector, " Appl. Opt. **36**, 2807-2812 (1997).

18. R. Köhler, R. Goebel, and R. Pello, "Results of an international comparison of spectral responsivity of silicon photodetectors," Metrologia **32**, 463-468 (1995/96).

19. R. Goebel, R. Köhler, and R. Pello, "Some effects of low-power ultraviolet radiation on silicon photodiodes," Metrologia **32**, 515-518 (1995/96).

20. R. Korde and J. Geist, "Quantum efficiency stability of silicon photodiodes," Appl. Opt. **26**, 5284-5290 (1987).

21. L. Werner, "Ultraviolet stability of silicon photodiodes," Metrologia **35**, 407-411 (1998).

22. P. Kuchnerus, H. Rabus, M. Richter, F. Scholze, L. Werner, and G. Ulm, "Characterization of photodiodes as transfer detector standards in the 120 nm to 600 nm spectral range," Metrologia **35**, 355-362, (1998).

23. M. Richter, U. Johannsen, P. Kuchnerus, U. Kroth, H. Rabus, G. Ulm, and L. Werner, "The PTB high-accuracy spectral responsivity scale in the ultraviolet," Metrologia **37**, 515 (2000).

24. K. D. Stock, R. Heine, and H. Hofer, "Spectral characterization of Ge trap detectors and photodiodes used as transfer standards," Metrologia **40**, S163 (2003).

25. K. D. Stock and R. Heine, "Spectral characterization of InGaAs trap detectors and photodiodes used as transfer standards," Metrologia **37**, 449 (2000).

26. P. Kärhä, P. Toivanen, F. Manoochehri, and E. Ikonen, "Development of a detector-based absolute spectral irradiance scale in the 380-900-nm spectral range," Appl. Opt. **36**, 8909-8918 (1997).

27. P. Kärhä, A. Haapalinna, P. Toivanen, F. Manoocheri, and E. Ikonen, "Filter radiometry based on direct utilization of trap detectors," Metrologia **35**, 255-259 (1998).

28. T. Kübarsepp, P. Kärhä, F. Manoocheri, S. Nevas, L. Ylianttila, and E. Ikonen, "Absolute spectral irradiance measurements of quartz-halogen tungsten lamps in the spectral range of 290-900 nm," Metrologia **37**, 305-312 (2000).

29. F. Manoocheri and E. Ikonen, "High-accuracy spectrometer for measurement of regular spectral transmittance," Appl. Opt. **34**, 3686-3692 (1995).

30. A. Lassila, P. Toivanen, and E. Ikonen, "An optical method for direct determination of the radiometric aperture area at high accuracy," Meas. Sci. Technol., **8**,. 973-977 (1997).

31. C. A. Schrama and H. Reijn, "A novel calibration method for filter radiometers," Metrologia **36**, 179-182 (1999).

32. C. A. Schrama and E. W. van der Ham, "Sampling period criterion in a scanning beam technique," Appl. Opt. **39**, 1500-1504 (2000).

33. M. White, N. P. Fox, V. E. Ralph, and N. J. Harrison, ”The characterization of a high-temperature black body as the basis for the NPL spectral-irradiance scale,” Metrologia **32**, 431-434 (1995/96).

34. S. W. Brown, G. P. Eppeldauer, and K. R. Lykke, ”NIST facility for spectral irradiance and radiance responsivity calibrations with uniform sources,” Metrologia **37**, 579-582 (2000).

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

36. N. P. Fox, J. E. Martin, and D. H. Nettleton, “Absolute spectral radiometric determination of the thermodynamic temperatures of the melting/freezing points of gold, silver and aluminium,” Metrologia **28**, 357-374 (1991).

37. M. Stock, J. Fischer, R. Friedrich, H. J. Jung, R. Thornagel, G. Ulm, and B. Wende, “Present state of the comparison between radiometric scales based on three primary standards,” Metrologia **30**, 439-449 (1993).

38. H. W. Yoon, C. E. Gibson, and P. Y. Barnes, “Realization of the National Institute of Standards and Technology detector-based spectral irradiance scale,” Appl. Opt. **41**, 5879-5890 (2002).

39. N. J. Harrison, N. P. Fox, P. Sperfeld, J. Metzdorf, B. B. Khlevnoy, R. I. Stolyarevskaya, V. B. Khromchenko, S. N. Mekhontsev, V. I. Shapoval, M. F. Zelener, and V. I. Sapritsky, “International comparison of radiation-temperature measurements with filtered detectors over the temperature range 1380 K to 3100 K,” Metrologia **35**, 283-288 (1998).

40. H. W. Yoon, P. Sperfeld, S. Galal Yousef, and J. Metzdorf, “NIST-PTB measurements of the radiometric temperatures of a high-temperature black body using filter radiometers,” Metrologia **37**, 377-380 (2000).

41. B. B. Khlevnoy, N. J. Harrison, L. J. Rogers, D. F. Pollard, N. P. Fox, P. Sperfeld, J. Fischer, R. Friedrich, J. Metzdorf, J. Seidel, M. L. Samoylov, R. I. Stolyarevskaya, V. B. Khromchenko, S. A. Ogarev, and V. I. Sapritsky, “Intercomparison of radiation temperature measurements over the temperature range from 1600 K to 3300 K,” Metrologia **40**, S39-S44 (2003).

42. T. M. Hunt, N. P. Fox, W. S. Hartree, and N. M. Durant, “Evaluating the performance of filter radiometers as a means of improving the uncertainty of ultraviolet measurements,” Metrologia **35**, 345-351 (1998).

43. N. P. Fox, E. Theocharous, and T. H. Ward, “Establishing a new ultraviolet and near-infrared spectral responsivity scale,” Metrologia **35**, 535-541 (1998).

44. T. Saito, K. Katori, M. Nishi, and H. Onuki, “Spectral quantum efficiencies of semiconductor photodiodes in the far ultraviolet region,” Rev. Sci. Instrum. **60**, 2303-2306 (1989).

45. T. Saito, K. Katori, and H. Onuki, ”Characteristics of semiconductor photodiodes in the VUV region,” Phys. Scripta **41**, 783-787 (1990).

46. N. M. Durant and N. P. Fox, “Evaluation of solid state detectors for ultraviolet radiometric applications,” Metrologia **32**, 505-508 (1995/96).

47. T. Saito, M. Yuri, and H. Onuki, “Polarization characteristics of semiconductor photodiodes,” Metrologia **32**, 485-489 (1995/96).

48. P. S. Shaw, K.R. Lykke, R. Gupta, T. R. O’Brian, U. Arp, H. H. White, T. B. Lucatorto, J. L. Dehmer, and A. C. Parr, “Ultraviolet radiometry with synchrotron radiation and cryogenic radiometer,“ Appl. Opt. **38**, 18-28 (1999).

49. P. S. Shaw, T. C. Larason, R. Gupta, S. W. Brown, R. E. Vest, and K. R. Lykke, “The new ultraviolet spectral responsivity scale based on cryogenic radiometry at Synchrotron Ultraviolet Radiation Facility III,” Rev. Sci. Instrum. **72**, 2242-2247 (2001).

50. T. Saito, ”Difference in the photocurrent of semiconductor photodiodes depending on the polarity of current measurement through a contribution from the photoemission current,” Metrologia **40**, S159-S162 (2003).

51. http://www.hamamatsu.com.

52. K. Solt, H. Melchior, U. Kroth, P. Kuschnerus, V. Persch, H. Rabus, M. Richter, and G. Ulm, “PtSi–*n*–Si Schottky-barrier photodetectors with stable spectral responsivity in the 120–250 nm spectral range,” Appl. Phys. Lett. **69**, 3662-3664 (1996).

53. T Kübarsepp, *Optical radiometry using silicon photodetectors*, Thesis for the degree of Doctor of Technology, (Helsinki University of Technology, Metrology Research Institute, Espoo, Finland 1999).

54. S. Nevas, F. Manoocheri, and E. Ikonen, “Gonioreflectometer for measuring spectral diffuse reflectance,” Appl. Opt. **43**, 6391 (2004).

55. F. Manoocheri and E. Ikonen, “High accuracy spectrometer for measurement of regular spectral transmittance,” Appl. Opt. **34**, 3686-3692 (1995).

56. http://kcdb.bipm.org/.

57. T. M. Goodman, J. E. Martin, B. D. Shipp, and N. P. Turner, ”The manufacture and measurements of precision apertures,” in Proceedings of the second international conference on new developments and applications in optical radiometry, N. P. Fox and D. Nettleton, Ed. (Institute of Physics, Bristol, United Kingdom, 1989) pp. 121-128.

58. J. Fischer and M. Stock, “A non-contact measurements of radiometric apertures with an optical microtopography sensor,” Meas. Sci. Technol. **3**, 693-689 (1992).

59. A. Lassila, E. Ikonen, and K. Riski, “Interferometer for calibration of gradual line scales with a movind CCD camera as a line detector,” Appl. Opt. **33**, 3600-3603 (1994).

60. J. B. Fowler and G. Dezsi, “High accuracy measurement of aperture area relative to a standard known aperture,” J. Res. Natl. Inst. Technol. **100**, 277-283 (1995).

61. J. B. Fowler, R. S. Durvasula, and A. C. Parr, "High-accuracy aperture-area measurement facilities at National Institute of Standards and Technology," Metrologia **35**, 497-500 (1998).

62. E. Ikonen, P. Toivanen, and A. Lassila, "A new optical method for high-accuracy determination of aperture area," Metrologia **35**, 369-372 (1998).

63. J. Geist, E. F. Zalewski and A. R. Schaefer, "Spectral response self-calibration and interpolation of silicon photodiodes," Appl. Opt. **19**, 3795-3799 (1980).

64. J. Geist, D. Chandler-Horowitz, R. Köhler, A. M. Robinson and C. R. James, "Numerical modelling of short-wavelength internal quantum efficiency," *Metrologia* **28**, 193-196 (1991).

65. J. Geist, A. M. Robinson and C. R. James, "Numerical modeling of silicon photodiodes for high-accuracy applications Part III: Interpolating and extrapolating internal quantum-efficiency calibrations,"J. Res. Natl. Inst. Stand. Technol. **96**, 481-492 (1991).

66. P. Kärhä, A. Lassila, H. Ludvigsen, F. Manoochehri, H. Fagerlund and E. Ikonen, "Optical power and transmittance measurements and their use in detector-based realization of the luminous intensity scale," Opt. Eng. **34**, 2611-2618 (1995).

67. L. P. Boivin and A. A. Gaertner, "Analysis of the uncertainties involved in the realization of a spectral irradiance scale in the infrared at the NRC," Metrologia **28**, 129-134 (1991).

68. R. L. Rusby, R. P. Hudson, M. Durieux, J. F. Schooley, P. P. M. Steur, and C. A. Swenson, "Thermodynamic basis of the ITS-90," Metrologia **28**, 9-18 (1991).

69. P. Saunders and D. R. White, "Physical basis of interpolation equations for radiation thermometry," Metrologia **40**, 195-203 (2003).

70. P. Saunders and D. R. White, "Interpolation errors for radiation thermometry," Metrologia **41**, 41-46 (2004).

71. Y. Yamada, H. Sakate, F. Sakuma, and A. Ono, "High-temperature fixed points in the range 1150 ºC to 2500 ºC using metal-carbon eutectics," Metrologia **38**, 213-219 (2001).

72. V. I. Sapritski, S. A. Ogarev, B. B. Khlevnoy, M. L. Samoylov, and V. B. Khromchenko, "Development of metal-carbon high-temperature Fixed-point blackbodies for precision photometry and radiometry," Metrologia **40**, S128-S131 (2003).

73. R. Goebel, Y. Yamada, and M. Stock, "Thermodynamic temperature measurements of metal-carbon eutectic fixed points," *in Proceedings of TEMPMEKO'04*, (2005) (in press).

74. Y. Yamada and P. Bloembergen, "On the properties of hyper-eutectic metal-carbon fixed points," *in Proceedings of TEMPMEKO'04*, (2005) (in press).

75. E. R. Wooliams, B. B. Khlevnoy, S. R. Montgomery, N. J. Harrison, D. Lowe, N. P. Fox, S. A. Ogarev, V. B. Khromenko, and V. I. Sapritski, "Measurements of the melting and freezing plateaus of Re-C eutectic fixed-point blackbodies," *in Proceedings of TEMPMEKO'04*, (2005) (in press).

76. B. B. Khlevnoy, V. I. Sapritsky, S. A. Ogarev, M. K. Sakharov, M. L. Samoylov, and Yu. A. Pikalev, "Development of fixed points above 2700 K based on M-C and MC-C eutectics at VNIIOFI for radiation thermometry and radiometry," *in Proceedings of TEMPMEKO 2004*, (2005) (in press).

77. D. Lowe and G. Machin, "Development of metal-carbon eutectic based high-temperature fixed points for reproducibility studies," *in Proceedings of TEMPMEKO'04*, (2005) (in press).

78. *Traceability in infrared radiation thermometry from -50* ºC *to 800* ºC, *Final report on the TRIRAT project (EUROMET project SMT4-CT-96-2060)* (2002).

79. ISO/CIE 10526, *CIE standard colorimetric illuminants*, (International Organization for Standardization, Genève, Switzerland, 1991) 9 p.

80. S. Galal Yousef, P. Sperfeld, and J. Metzdorf, "Measurement and calculation of the emissivity of a high –temperature black body," Metrologia **37**, 365-368 (2000)

81. A. V. Prokhorov, "Monte Carlo Method in Optical Radiometry," Metrologia **35**, 465-471 (1998).

82. G. Bauer and K. Bischoff, "Evaluation of the emissivity of a cavity source by reflection measurements," Appl. Opt. **10**, 2639-2643 (1971).

83. A. Fresnel, *Memoir on the diffraction of light, Paris 1819. Translated in Wave theory of light and spectra*, *H. Crew et al., eds.,* Arno Press, New York (1981).

84. E. Lommel, "Die Beugungserscheinungen einer kreisrunden Oeffnung und eines kreisrunden Schirmschens theoretisch und experimentell Bearbeitet," Abh. Bayer. Akad. **15**, 233 (1885).

85. L. P. Boivin, "Diffraction corrections in radiometry: comparison of two different methods of calculation," Appl. Opt. **14**, 2002-2009 (1975).

86. W. H. Steel and J. A. Bell, "Diffraction corrections in radiometry," J. Opt. Soc. Am. **62**, 1099-1103 (1972).

87. E. L. Shirley, "Revised formulas for diffraction effects with point and extended sources," Appl. Opt. **37**, 6581-6590 (1998).

88. E. L. Shirley and M. L. Teraciano, "Two innovations in diffraction calculations for cylindrically symmetrical systems," Appl. Opt. **40**, 4463-4472 (2001).

89. P. Edwards and M. McCall, "Diffraction loss in radiometry," Appl. Opt. **42**, 5024-5032 (2003).

90. G. Eppeldauer and J. E. Hardis, "Fourteen-decade photocurrent measurements with large-area silicon photodiodes at room temperature," Appl. Opt. **30**, 3091-3099 (1991).

91. J. Fisher and Fu Lei, “Photodiode nonlinearity measurement with an intensity stabilized laser as a radiation source,” Appl. Opt. **32**, 4187-4190 (1993).

92. *Expression of the Uncertainty of Measurements in Calibration,* Publication of the European co-operation for Accreditation, EA-4/02, 1999.

93. J. L. Gardner, “Correlations in primary spectral standards,” Metrologia **40**, S167-S171 (2003).

94. J. L. Gardner, “Uncertainties in interpolated spectral data,” J. Res. Natl. Inst. Stand. Technol. **108**, 69-78 (2003).

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

96. R Goebel, S Yilmaz, and R Pello, “Polarization dependence of trap detectors,” Metrologia **33**, 207-213 (1996).

97. A. Lamminpää, M. Noorma, T. Hyyppä, F. Manoocheri, P. Kärhä, and E. Ikonen, ”Characterization of germanium detectors for applications of spectral irradiance measurements,” *accepted for publication at the 2005 NCSLI Workshop & Symposium in Washington, DC August 7-11, 2005.*

Abstracts of publications

I. **"Characterization of GaAsP trap detector for radiometric measurements in ultra violet wavelength range,"** *Rev. Sci. Instrum.* **76**, 033110 (2005).

A trap detector was constructed of three Schottky-type 10×10 mm^2 GaAsP photodiodes. The spectral reflectance of the trap detector was calculated from the measured spectral reflectances of a single GaAsP photodiode in the wavelength range between 240 and 600 nm, and compared to the measured spectral reflectance of the trap detector at three laser wavelengths. The absolute spectral responsivity of the trap detector was measured. The internal quantum efficiencies (IQE) of the trap detector and a single photodiode were calculated in the wavelength region between 250 and 400 nm from the spectral reflectances and responsivities. The comparison revealed reduction of the apparent IQE of the trap detector as compared to the single photodiode at the level of 10 %. The spatial uniformity of the responsivity of the trap detector was measured, and the corresponding uncertainty component at 325 nm was calculated to be 4×10^{-4}. The effect of moderate ultraviolet exposure at the level of 50 mJ/cm^2 on the stability of the responsivity of GaAsP photodiode was studied and found to be below 2×10^{-3} at all used wavelengths.

II. **"Characterisation of filter radiometers with wavelength tuneable laser source,"** *Metrologia* **40**, S220-223 (2003).

Results of filter radiometer characterisation with wavelength-tuneable Ti:Sapphire laser in the wavelength band around 900 nm are presented. 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 characterised with a relative standard uncertainty of 9×10^{-4} using the scanning method. The results agree well with more conventional monochromator-based measurements.

III. **“Absolute detector-based radiometric temperature scale,“** *Accepted for publication in Proceedings of TEMPMEKO 2004.*

A high accuracy filter radiometer with an absolute calibration is used to measure the thermodynamic temperature of a blackbody in irradiance mode. A copper fixed point cell is used as the blackbody source and the measurement results are compared with the defined freezing-point temperature of copper, 1084.62 °C. We show that the straightforward two-aperture configuration is practical for the measurements of a blackbody with small opening area even at relatively low temperatures. The standard uncertainty of the measurements is between 0.17 K and 0.20 K.

IV. **“Radiometric temperature measurements with absolutely characterized filter radiometers in irradiance mode,”** *Metrology Research Institute Report* **24/2005**.

The absolute characterization of filter radiometers for radiometric determination of the thermodynamic temperatures of blackbody sources in irradiance mode is described. Two different methods are used to calibrate four filter radiometers at different wavelengths between 600 and 900 nm. The freezing temperatures of silver and copper are measured and compared with the defined values of the International Temperature scale of 1990 (ITS-90). The deviations of the measured temperatures from the defined values of the ITS-90 are 122 mK and 120 mK for silver and copper, respectively. The standard uncertainties of the comparison are 110 mK and 123 mK, respectively. The agreement between the temperature measurements at different wavelengths is further investigated at the temperatures up to 1500 °C with a variable temperature blackbody. The results obtained at different wavelengths are mostly within the standard uncertainty limits, which vary between 110 mK and 186 mK with wavelength and temperature.