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Infrared Filter Radiometers for Thermodynamic Temperature Determination below 660 °C

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Abstract At the Physikalisch-Technische Bundesanstalt (PTB), absolutely-calibrated filter radiometers based on silicon photodiodes are routinely used for thermodynamic temperature determinations of blackbodies in the range from the zinc fixed point (FP) (419 °C) up to 3,000 °C. To extend the temperature range down to the tin FP (232 °C), we have designed two new filter radiometers based on indium gallium arsenide (InGaAs) photodiodes with center wavelengths at 1,300 nm and 1,550 nm. For the absolute calibration of the spectral irradiance responsivity of the new InGaAs filter radiometers, the spectral responsivity measurement in the near-infrared (NIR) spectral range has been significantly improved. With a newly developed tuneable laser and monochromator-based cryogenic radiometer facility, the relative standard uncertainty of the NIR spectral responsivity has been reduced from 0.17 % to about 0.03 %. By using the calibrated InGaAs filter radiometer in conjunction with the large-area double sodium heat pipe of the PTB, the first results for the difference between the thermodynamic temperature T and the ITS-90 temperature T_{90} in the temperature range from the zinc FP up to the aluminum FP (660 °C) are presented. The values for $T - T_{90}$ determined with the new InGaAs filter radiometers are consistent within their relative standard uncertainty of about 30 mK at 419 °C to about 60 mK at 660 °C.

Keywords Filter radiometer · Infrared · Radiometry · Thermodynamic temperature · Spectral responsivity

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1 Introduction

For more than 10 years, the Physikalisch-Technische Bundesanstalt (PTB) has measured the thermodynamic temperatures of blackbodies with absolutely-calibrated filter radiometers based on silicon photodiodes in the range from about 3,000 °C down to temperatures around the zinc fixed point (FP) at 419 °C [1].

The traceable absolute calibration of the filter radiometers is performed in a two-step procedure against a cryogenic radiometer that is the primary standard for the measurement of radiant power. The first step is the calibration of transfer detector standards (i.e., single photodiodes or trap detectors) against the cryogenic radiometer [2–6]. The spectral responsivity of the transfer detectors to radiant power is determined at this step. The second step comprises the measurement of the spectral irradiance responsivity of the filter radiometers by comparison with the calibrated transfer detector standards using the spectral comparator facility of the PTB [7]. The transfer detectors are provided with an additional precision aperture during this measurement.

The accurate measurement of thermodynamic temperatures with silicon photodiode-based filter radiometers near the Zn-FP becomes difficult due to the low signal-to-noise ratio, even at center wavelengths of about 1,000 nm. Therefore, the PTB has developed an InGaAs photodiode-based filter radiometer with a center wavelength at 1,595 nm and a bandwidth (FWHM) of 100 nm [1] as a first step to extend the range of radiometric high-accuracy thermodynamic temperature measurements down to temperatures as low as the Sn-FP (232 °C). This filter radiometer was absolutely-calibrated in terms of spectral irradiance responsivity and applied to thermodynamic temperature determinations of a blackbody at 419 °C, 457 °C, and 600 °C. The results presented in [1] are based on an interpolated scale of spectral responsivity in the wavelength range from 0.95 μm to 1.65 μm maintained with InGaAs photodiodes as transfer detector standards [2]. However, the uncertainty of this interpolated scale is more than one order of magnitude higher than the spectral responsivity scale maintained with trap detectors consisting of silicon photodiodes in the wavelength range from 500 nm to 900 nm [3]. The uncertainty of the spectral responsivity of the near-infrared (NIR) transfer standards dominated the uncertainty budget of the InGaAs filter radiometer calibration, and the standard uncertainty of thermodynamic temperature determination when applying this filter radiometer at the gas thermometry reference temperature (457 °C) of the ITS-90 [8] was about 104 mK. Due to this relatively large uncertainty, thermodynamic temperatures measured with the InGaAs filter radiometer were not helpful in investigating the thermodynamic accuracy of the ITS-90.

To overcome this problem, the uncertainty of the PTB spectral responsivity scale in the wavelength range from 0.95 μm to 1.65 μm was significantly reduced (see Sect. 2). Furthermore, two new InGaAs filter radiometers were built. These filter radiometers were optimized with respect to their bandwidth and center wavelength for a calibration with the lowest possible uncertainties, which is mandatory for high-accuracy radiometric temperature measurements (see Sect. 3).

2 Improved Realization of Near-Infrared Spectral Responsivity

2.1 High-Accuracy Calibration of InGaAs Transfer Detectors

Hitherto, the spectral responsivity scale between 950 nm and 1,650 nm was realized by calibrating InGaAs photodiodes at four laser lines using the PTB laser-based radiation thermometry cryogenic radiometer (RTCR) and interpolating the spectral responsivity with thermal detectors [2]. However, the interpolation with conventional thermal detectors is very time-consuming and of limited accuracy. Modeling of the spectral responsivity between widely separated laser-based calibrations, as is the case for Si trap detectors in the visible [3], is not possible because of the lack of an accurate model of the responsivity for the detectors commonly used in the NIR wavelength range.

Therefore, calibration against a cryogenic radiometer throughout the spectral region of interest has been chosen to reach higher accuracy. Furthermore, the lowest possible uncertainties can be reached by using laser radiation. Consequently, a new cryogenic radiometer facility has been established by combining tuneable laser radiation in certain wavelength regions with monochromator-based radiation that is available over the entire NIR spectral range. Initial investigations [4,5] have shown that, by using tuneable diode laser radiation in combination with a cryogenic radiometer, significantly smaller uncertainties could be achieved compared with monochromator-based calibrations. This is not only of interest for radiation thermometry, but also for optical communication [6].

2.2 Apparatus

The new facility consists of a prism-grating double monochromator, a mirror imaging system, a cryogenic radiometer (CryoRad II manufactured by Cambridge Research & Instrumentation), and a positioning system (Fig. 1). Originally, the system was optimized for calibrations in the UV range [9]. In order to perform calibrations in the NIR, only the radiation source, the grating, and the monitor detector have to be changed. A tungsten halogen lamp serves as a radiation source. A power of 1 μW to 2 μW within a bandwidth of 8.3 nm is available at wavelengths between 900 nm and 1,820 nm. The facility also allows direct radiation through a fiber into the final imaging stage. Thus, a tuneable diode laser can be attached to the system so still lower uncertainties are possible. Different tuneable lasers with wavelength ranges from 1,260 nm to 1,370 nm, 1,460 nm to 1,580 nm, and 1,520 nm to 1,620 nm have been used up to now.

2.3 Calibration of the Spectral Responsivity

The detectors are calibrated by measuring their electrical signal when inserted into the beam from the monochromator or the tuneable laser at the same position where the radiant power of the beam is determined by the cryogenic radiometer. A monitor detector is used to correct for variations of the radiant power between the radiometer and the detector measurements. Any polarization effects are corrected by measurements at

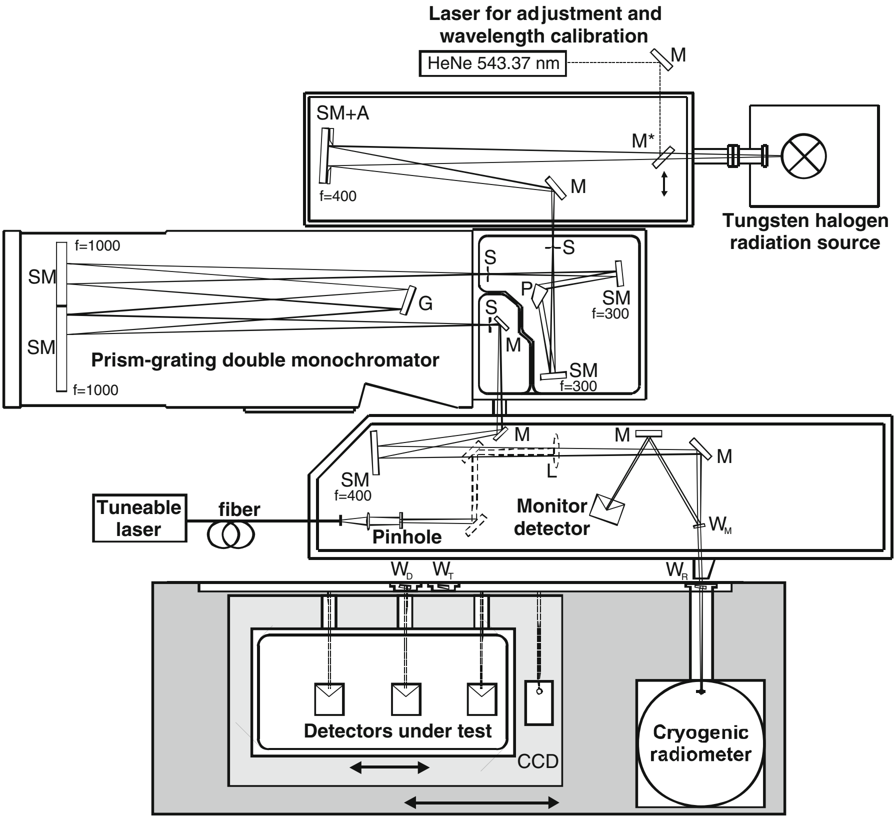

Fig. 1 Schematic diagram of the detector calibration facility. Labeling: M: plane mirrors; SM: spherical mirrors (focal lengths are stated in mm); M*: removable mirror only in use for adjustment and wavelength calibration; A: f/40 aperture in front of the collecting mirror; S: circular apertures of 1.25 mm diameter used as monochromator slits; P: Pellin-Broca prism made of fused silica; G: NIR grating; W: wedged windows of the same type where W_M is used to couple out the monitor beam, W_R is the vacuum sealing window in front of the cryogenic radiometer which is rotated by 180° with respect to W_M, W_D is an additional window to obtain the same optical path at the cryogenic radiometer and the detectors under test; W_T is the position in which W_R is placed for measuring the ratio of the window transmittances W_D to W_R. The tuneable radiation of the diode laser can be used instead of the monochromatized radiation of the tungsten halogen lamp. Additional mirrors and an achromatic lens are used in this case

three different angles of detector rotation. The detectors are calibrated at a controlled temperature.

Single InGaAs photodiodes are used as transfer standards for the spectral responsivity. They are calibrated from 950 nm to 1,650 nm with a relative standard uncertainty of 0.1 % by using the monochromatized radiation from a tungsten halogen lamp. The uncertainty of this calibration is dominated by the cryogenic radiometer instability ascribed to a drift of typically not more than 20 nW in 10 min and noise of typically 6 nW. The contribution to the overall relative uncertainty decreases with increasing radiant power. The second largest contribution is the uncertainty associated with the window transmittance correction, which is measured before and after each calibration

Table 1 Typical uncertainty budget for the calibration of the spectral responsivity of an InGaAs photodiode at 1,550 nm when using monochromatized radiation of a tungsten halogen lamp and tuneable laser radiation

Source of uncertainty	Radiation source	
	Tungsten halogen lamp (%)	Tuneable diode laser (%)
Instability of cryogenic radiometer (noise, drift)	0.075	0.011
Uncertainty in wavelength	0.030	0.001
Window transmittance	0.030	0.010
Uncertainty of electric power measurement	0.015	0.015
Detector temperature	0.005	0.005
Cavity absorptance and inequivalence of power measurement	0.003	0.003
Stray light	0.002	0.002
Combined relative standard uncertainty of spectral responsivity at beam position	0.088	0.022

The uncertainty increases significantly near the wavelength of the InGaAs bandgap. Furthermore, the uncertainty contribution due to the non-uniformity of the detector is dependent on the wavelength and the beam profile actually used

at each wavelength. A window is used to seal the vacuum around the radiometer cavity. A second similar window is placed in front of the detector under test to obtain the same optical path. Furthermore, the uncertainty of the wavelength of the monochromatized radiation gives a significant contribution.

In addition, a calibration of the InGaAs photodiodes can be performed with tuneable diode laser sources throughout limited wavelength ranges. The much higher power and the narrow bandwidth reduce the uncertainty of the measurement of the spectral responsivity at the position of the laser spot to 0.02 % to 0.03 %.

The uncertainty budget for the measurement of the spectral responsivity at 1,550 nm using the radiation of a halogen lamp and laser radiation is shown in Table 1. The uncertainty of the transfer detector's spectral responsivity is limited by the instability of the cryogenic radiometer when using halogen lamp radiation. With laser radiation, this uncertainty contribution decreases to about 0.01 %. Furthermore, the uncertainty of the window transmittance correction can be reduced, and the wavelength uncertainty can be neglected.

When using the transfer detectors to calibrate a filter radiometer, the uncertainty associated with the non-uniformity of the detector must additionally be taken into account. The non-uniformity of the detector's spectral responsivity is separately measured, and the associated uncertainty is numerically calculated (see Sect. 3.3). This calculation takes into account the difference in beam size and beam profile at the spectral responsivity calibration facility and at the filter radiometer calibration facility. Furthermore, the calculation takes into account the weighting of the uncertainty due to the filter transmittance. The contribution of the uncertainty of the spectral responsivity of the transfer detector to the uncertainty of the filter radiometer calibration has to be calculated for each individual filter radiometer.

3 Infrared Filter Radiometers

3.1 Design

Two new InGaAs filter radiometers have been built following the design of the InGaAs filter radiometer presented in [1]. The basic components are a precision aperture, an interference filter as the wavelength selecting element, and a windowless InGaAs photodiode as the optical radiation detector. A schematic cross section of the new filter radiometers is given in Fig. 2. The aperture is diamond-turned with a knife edge and has a diameter of 3 mm. The center wavelengths and bandwidths were selected to fulfil the three following conditions: tuneable laser radiation has to be available in the wavelength region of the filter bandpass for the lowest possible calibration uncertainty of the transfer standards, water-vapor absorption when applying these filter radiometers in front of a blackbody has to be minimized, and the bandpass of the filter has to be of sufficient distance from the bandgap wavelength of the InGaAs photodiode to minimize the temperature dependence of the spectral responsivity of the filter radiometer (Fig. 3). To fulfil these conditions, we used custom interference filters with a center wavelength of 1,310 nm or 1,550 nm (respectively), a spectral bandwidth of about 50 nm (FWHM), and an out-of-band blocking of more than five orders of magnitude. With these filter parameters, the corrections due to water-vapor absorption remain below 4×10^{-4} (1,310 nm) and 4×10^{-5} (1,550 nm), respectively, and the temperature coefficient (TC) [2,10] and nonlinearity of the spectral responsivity of the filter radiometer are minimized. The InGaAs photodiodes used in the

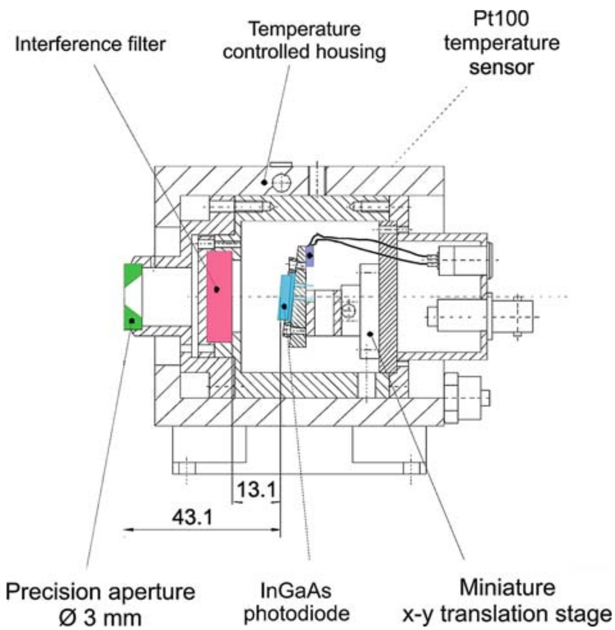

Fig. 2 Schematic view of an InGaAs filter radiometer

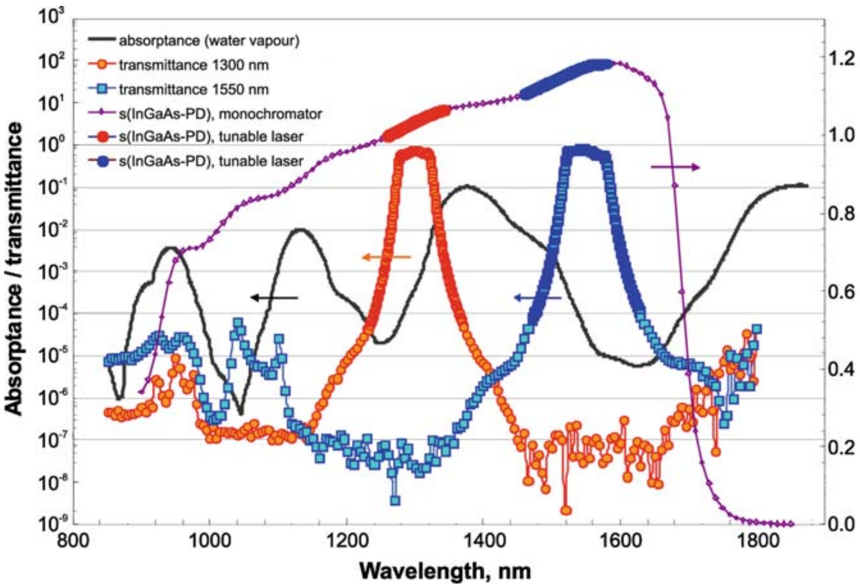

Fig. 3 Measured transmittance ("transmittance", left-hand scale) of the interference filters used for the filter radiometers FR1300 nm and FR1550 nm together with an absorption curve of a 2 m thick layer of air (23 °C, 1,013 hPa, 50 % rh) due to water vapor ("absorption", left-hand scale). The absorption curve was calculated by convolving the absorption lines in air with a 50 nm normalized bandwidth instrumental function of the filter radiometer. Also shown is the spectral responsivity of an InGaAs photodiode ("spectral responsivity", right-hand scale) used as a transfer standard; the thick regions of the responsivity curve denote the wavelength intervals where tunable lasers were used for its calibration. (The arrows on the curves indicate the position of the corresponding scale of the respective curves)

filter radiometer were selected from a batch of InGaAs photodiodes previously characterized with respect to their shunt resistance and the homogeneity of their spectral responsivity at 1,300 nm and 1,550 nm (Fig. 4).

The InGaAs photodiode is tilted by 5° with respect to the optical axis to avoid inter-reflections between the photodiode and the interference filter. Due to the small difference between the diameter of the sensitive area of the tilted photodiode (5 mm) and the diameter of the precision aperture (3 mm), their alignment to each other in the filter radiometer is critical. Therefore, to obtain the best concentricity, the photodiode was mounted on a miniature x–y translation stage and aligned by means of a collimated beam. The housing of the filter radiometer is temperature controlled within ±50 mK. The temperature is monitored by a Pt100 sensor near the photodiode.

3.2 Calibration of the Spectral Irradiance Responsivity

The filter radiometers are calibrated in terms of their spectral irradiance responsivity by comparison to transfer standard detectors at the spectral comparator facility of the PTB [7]. The transfer standards used were two single InGaAs photodiodes

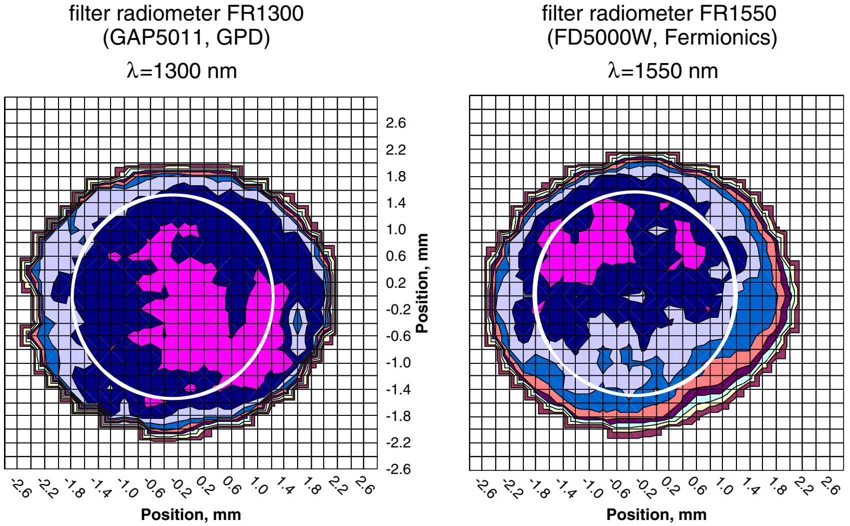

Fig. 4 Mapping of the spectral responsivity of the InGaAs photodiodes used for the filter radiometers FR1300 ($\lambda = 1,300$ nm) and FR1550 ($\lambda = 1,550$ nm). The measurements were performed with the spectral comparator applying a spot with a diameter of 0.3 mm. One change in color represents a relative change of 1×10^{-3} in spectral responsivity; the white circles denote the area of 3 mm diameter that is used during the filter radiometer calibration/application

(GAP5000—Germanium Power Devices, FD5000W—Fermionics) with a 5 mm diameter sensitive area and previously calibrated in terms of spectral power responsivity against the cryogenic radiometer CryoRad II at the new spectral responsivity calibration facility (see Sect. 2.2). For the calibration at the spectral comparator facility, the sensitive area of the transfer standards for spectral power responsivity is limited with a precision, diamond-turned aperture with a nominal diameter of about 3 mm. The diameter of the aperture has been separately measured with the method outlined in [11]. By this means, these transfer standards are transferred into transfer standards of spectral irradiance responsivity. At the spectral comparator facility, a grating with 651 lines $\cdot$ mm^{-1} was used, which gives a spectral dispersion of 4 nm $\cdot$ mm^{-1}. For measurements within the bandpass of the filter radiometer, the spectral bandwidth of the monochromator was set to 1 nm; the out-of-band measurements were performed with a spectral bandwidth of 6 nm. To take account of the polarization sensitivity of the transfer detector and the filter radiometer, both detectors were rotated successively by 90° about their optical axis. The mean value of the four measurements, consisting in each case of three runs over the bandpass, was taken as the result for the spectral irradiance responsivity. The repeatability of the integrated spectral irradiance responsivity after a complete new alignment of the optical path and the detectors was within 2×10^{-4}. The spectral irradiance responsivity of the InGaAs filter radiometers is shown in Fig. 5.

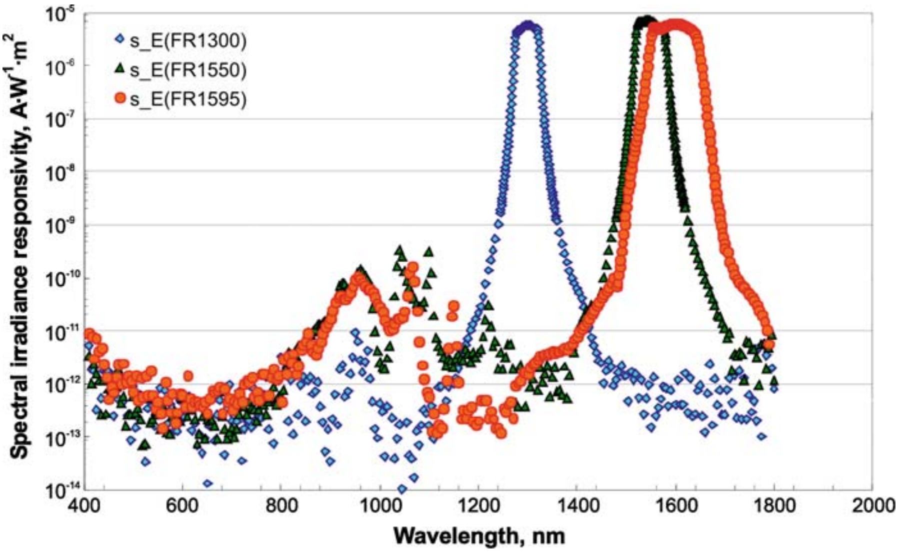

Fig. 5 Spectral irradiance responsivity of the InGaAs filter radiometers FR1300, FR1550, and FR1595

Table 2 Uncertainty budget for the spectral irradiance responsivity of the InGaAs filter radiometers

Source of uncertainty	Filter radiometer $\Delta S_E/S_E\,(\times 10^4)$		
	FR1300	FR1550	FR1595
Calculated contribution of the uncertainty of the transfer detector	4.1	3.9	13.0
Repeatability	2.0	2.0	2.0
Aperture area of the transfer detector	2.7	2.7	2.7
Diffraction correction at the transfer detector aperture	1.0	1.0	1.0
Distance from the exit slit monochromator	0.5	0.5	0.5
Temperature coefficient of the filter radiometer	0.2	0.2	0.2
Stability of the tungsten lamp	0.2	0.2	0.2
Monochromator bandwith effect	0.5	0.5	0.5
Homogeneity of the spectral comparator beam	0.2	0.2	0.2
Uncertainty of center wavelength (25pm, 419 °C)	2.1	1.4	1.3
Combined relative standard uncertainty	5.8	5.5	13.6

3.3 Uncertainty Budget of the Filter Radiometer Calibration

The uncertainty budget for the calibration of the filter radiometers FR1300, FR1550, and FR1595 in terms of spectral irradiance is presented in Table 2. The uncertainty of the spectral responsivity of the transfer standard over the bandpass wavelength region is not constant due to the fact that the calibration against the cryogenic radiometer was performed using both a tuneable laser and monochromator radiation. Therefore, the Monte-Carlo method presented in [12] was used for the calculation of the uncertainty component arising from the transfer standard. The uncertainty component due to the TC of the filter radiometers was calculated by using the measured values of the corresponding TCs and from the assumption that the temperature of the filter radiometers can be controlled within ± 50 mK. The uncertainty associated with bandwidth effects of the monochromator was estimated according to [13]. The uncertainty contribution from the inhomogeneity of the spectral comparator beam was calculated by convolving the measured beam inhomogeneity with the measured inhomogeneity of the photodiodes (Fig. 4).

4 First Results of the Thermodynamic Temperature Measurement and $T - T_{90}$ in the Range from 419 °C to 660 °C

Directly after their calibration, the InGaAs filter radiometers were used to determine the possible deviation between the thermodynamic temperature T and the ITS-90 temperature T_{90} with the large-area, double sodium heat-pipe blackbody (LABB) of the PTB as a high-accuracy source of spectral irradiance. The experimental setup and the measurement procedure are described in detail in [14]. The investigation was performed for several temperatures in the interval between the Zn-FP and the Al-FP, namely, at 500 °C, 550 °C, 600 °C, 660 °C, 457 °C, and 419 °C. To verify the reproducibility of the obtained T–T_{90} results, the measurement at 660 °C was repeated twice, with a complete shutdown of the furnace in between. The thermodynamic temperature measurements of both filter radiometers agreed within less than 10 mK. In order to prove the accuracy of the diffraction correction and to identify additional systematic effects (e.g., the angular dependence of the interference filter transmission), the aperture distance between the LABB and the filter radiometers was varied from 750 mm to 1,750 mm in steps of 250 mm. The ITS-90 temperature of the blackbody was sensed at the bottom of the cavity with three calibrated 0.25 Ω high-temperature standard platinum resistance thermometers (HTSPRT).

Table 3 gives the standard uncertainty for the $T - T_{90}$ determination, consisting of the contributions from the geometry, the thermodynamic temperature determination, the filter radiometer calibration, and the determination of the ITS-90 temperature. The conversion into a temperature equivalent was performed via the Wien approximation of Planck's law. The uncertainty arising from the aperture distance determination was calculated assuming an absolute uncertainty of 50 μm for a distance of 1 m. The uncertainty associated with the aperture diffraction correction has two components, namely, the LABB aperture and the filter radiometer aperture. The main contribution to the uncertainty of the T_{90} determination is caused by the stability of the HTSPRTs, which was monitored by measuring their water-triple-point resistance before and after the thermodynamic temperature determinations.

The results for the $T - T_{90}$ measurements are shown in Fig. 6. The measured differences between the thermodynamic temperature T and the ITS-90 temperature T_{90} determined with the new InGaAs filter radiometers agree within 20 mK at all

Table 3 Uncertainty budget for the $T - T_{90}$ determination with the InGaAs filter radiometers FR1300, FR1550, and FR1595, calculated for $T_{90} = 419\,°C$ (Zn-FP) and $T_{90} = 660\,°C$ (Al-FP)

Source of uncertainty	Filter radiometer $\Delta S_E/S_E\,(\times 10^4)$		
	FR1300	FR1550	FR1595
Geometry			
Aperture area	0.4	0.4	0.4
Thermal expansion aperture	0.3	0.3	0.3
Distance of the apertures	1.0	1.0	1.0
Diffraction correction blackbody (LABB) aperture	1.0	1.0	1.0
Measurement of T			
Photocurrent noise	0.5	0.5	0.5
Calibration feedback resistors	1.0	1.0	1.0
Calibration DVM	0.2	0.2	0.2
Refractive index n	0.3	0.3	0.3
Boltzmann constant k	0.2	0.2	0.2
Numerical integration	0.5	0.5	0.5
Emissivity LABB	0.8	0.8	0.8
Homogeneity LABB	2.0	2.0	2.0
Filter radiometer calibration			
Calibration spectral comparator	5.8	5.5	13.6
Diffraction correction filter radiometer aperture	1.0	1.0	1.0
Combined relative standard uncertainty	6.6	6.3	13.9
Temperature equivalent	$u(T)$, mK		
419 °C	29	33	74
660 °C	52	59	134
Measurement of T_{90}	$u(T_{90})$, mK		
419 °C	7	7	7
660 °C	10	10	10
$u(T - T_{90})$, mK$(k = 1)$			
419 °C	29	33	74
660 °C	53	60	135

investigated T_{90} temperatures, which is well within their standard uncertainties. In order to underpin the results of the thermodynamic temperature determinations with the improved InGaAs filter radiometers, independent results for the $T - T_{90}$ determinations at 600 °C and 660 °C are also displayed. They were obtained with an absolutely-calibrated silicon photodiode-based filter radiometer with a center wavelength of 900 nm (FR900). The results for this filter radiometer are consistent with the results of the new InGaAs filter radiometers as well as with the result for the same filter radiometer presented in 2002 [1]. The values for $T - T_{90}$ determined with the InGaAs filter radiometer FR1595 agree within their uncertainty with the results determined with the

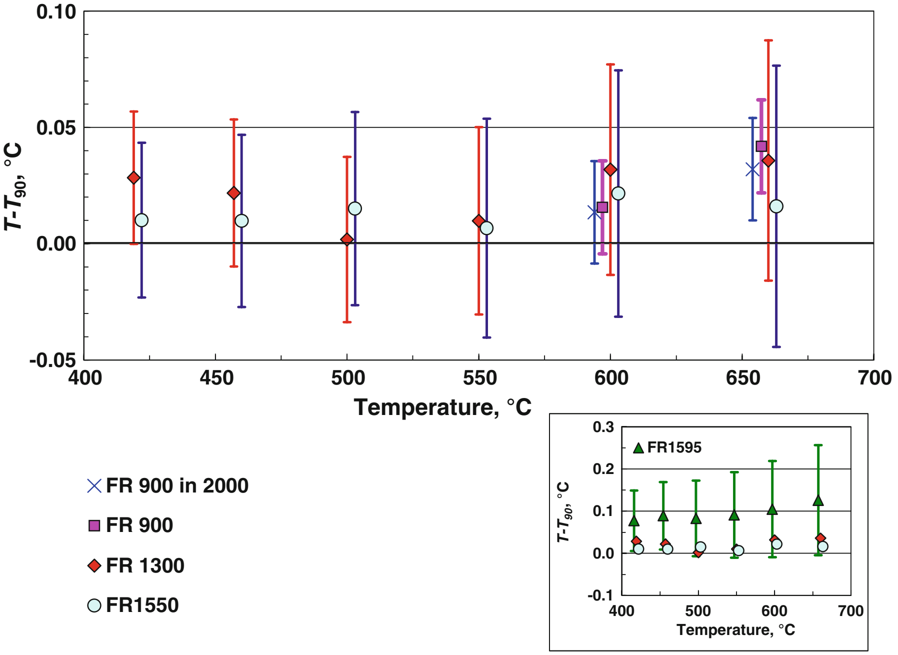

Fig. 6 Results for the $T - T_{90}$ measurements in the range from 419 °C to 660 °C with the new InGaAs filter radiometers FR1300 and FR1550, the InGaAs filter radiometer FR 1595 (displayed in the small inset for a better visualization due to its larger uncertainty), and the silicon-based filter radiometer FR900. Also shown are the results measured at the PTB with the FR900 in 2000 at 600 °C and 660 °C. (The positions of the data points for the $T - T_{90}$ results for each investigated temperature have been slightly expanded along the temperature axis to facilitate the identification of individual results for a certain filter radiometer.) The uncertainty bars denote the standard uncertainty

new InGaAs filter radiometers, but the uncertainty is about three times higher due to the considerably higher uncertainty of the spectral responsivity scale in the bandgap wavelength range of InGaAs. All results indicate that the thermodynamic temperature is systematically higher than the ITS-90 temperature.

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