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New PTB Setup for the Absolute Calibration of the Spectral Responsivity of Radiation Thermometers

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Abstract The paper describes the new experimental setup assembled at the PTB for the absolute spectral responsivity measurement of radiation thermometers. The concept of this setup is to measure the relative spectral responsivity of the radiation thermometer using the conventional monochromator-based spectral comparator facility also used for the calibration of filter radiometers. The absolute spectral responsivity is subsequently measured at one wavelength, supplied by the radiation of a diode laser, using the new setup. The radiation of the diode laser is guided with an optical fiber into an integrating sphere source that is equipped with an aperture of absolutely known area. The spectral radiance of this integrating sphere source is determined via the spectral irradiance measured by a trap detector with an absolutely calibrated spectral responsivity traceable to the primary detector standard of the PTB, the cryogenic radiometer. First results of the spectral responsivity calibration of the radiation thermometer LP3 are presented, and a provisional uncertainty budget of the absolute spectral responsivity is given.

Keywords Radiation thermometer · Spectral responsivity · Thermodynamic temperature measurement

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1 Introduction

To improve the obtainable uncertainty of the high-temperature part of the International Temperature Scale of 1990 (ITS-90) by novel high-temperature fixed points, the melting and freezing temperatures of these fixed points have to be measured independently of, and with lower uncertainties than, the ITS-90. An independent method to measure thermodynamic temperatures is the application of thermal radiation detectors with spectral responsivities traceable to electrical units via the cryogenic radiometer. At PTB, the measurement of thermodynamic temperatures using absolutely calibrated interference-filter radiometers in the irradiance mode is well established since the early 1990s [1]. However, due to the limited performance of the available high-temperature furnaces, the temperature gradient in the cavity heating the high-temperature fixed points is quite steep. Proper application of fixed points, on the other hand, requires a homogeneous temperature distribution over the length of the fixed-point cell to ensure homogenous melting and freezing of the fixed-point material.

Consequently, fixed-point cells with small dimensions are less sensitive to temperature gradients inside a furnace cavity and are therefore widely used as temperature fixed-points in radiation thermometry. However, to obtain sufficiently high emissivities with a short fixed-point cell cavity, only small radiating apertures can be realized. For the best operation of the high-temperature fixed-points, the radiating aperture of these cavities is restricted to 3 mm in diameter. Such small apertures prevent irradiance measurements with lens-free filter radiometers, and require lens-based radiation thermometers with small measuring spots instead. To measure the thermodynamic melting and freezing temperatures of the high-temperature fixed points with small apertures independently of the ITS-90, the absolute spectral responsivity of the imaging radiation thermometers has to be measured. In contrast to the calibration of non-imaging filter radiometers, which is well established at the PTB based on the highly accurate spectral responsivity scale of the PTB [2,3], calibration of the spectral responsivity of radiation thermometers requires different prerequisites. In particular, an extended source of accurately known spectral radiance, closely matching the characteristics of the source to be measured, is required. It has already been described in [4] that an integrating sphere can be used to generate a uniform extended source. However, due to the multiple diffuse reflections inside an integrating sphere, a radiation source of high spectral power has to be used, i.e. a monochromator as a source for the integrating sphere is not easily applicable.

To overcome this limitation, a laser tunable over the whole wavelength range of the filter transmission has been applied [4]. Usually, the applied radiation thermometers use interference filters for wavelength selection. Calibration of the spectral responsivities of interference filter-based devices with small bandwidth radiation sources is problematic. Special precautions are necessary to detect possible small variations of the spectral responsivity caused by the interference layers of the filter. Usually, the bandwidth of the laser is below 1 pm, consequently requiring a step size of about 1 pm to detect all possible variations caused by the interference layers. This results in at least 20,000 measurements for an interference filter with a 20 nm FWHM bandwidth. Such a large number of single measurements is impractical. To avoid this problem, a different approach was followed here.

The relative spectral responsivity is measured by a conventional monochromator-based setup with a spectral bandwidth of about 0.5 nm. The absolute measurement using the laser-based integrating sphere source is subsequently made at only one laser wavelength with a scan of about ±100 pm around this wavelength. This approach significantly reduces the time needed for a calibration and does not increase the overall uncertainty. In Sect. 2 of this paper, the integrating sphere source and the results of its characterization are presented. In Sect. 3, the radiation thermometer and its interference filter are briefly described. In Sect. 5, an uncertainty estimate is given.

2 Experimental Setup

2.1 Integrating Sphere Source

The integrating sphere is shown in Fig. 1, and it has the following dimensions: diameter of the sphere about 5 cm, diameter of the radiating opening 6 mm. Two perpendicular openings of the sphere can be used; one is the input port to supply the radiation to the integrating sphere, and the other is the output port which is the source of the homogeneous field of radiation. On the left side of Fig. 1, the optical fiber leading the laser radiation into the integrating sphere can be seen. The radiating opening, defined by a precision aluminium aperture of 5 mm in diameter, can be seen in the middle of the integrating sphere.

The spatial homogeneity of the radiating opening has been measured by scanning the measuring spot of the LP3 radiation thermometer across the opening and recording the obtained photocurrent. The result of such a measurement is shown in Fig. 2. As can be seen in Fig. 2, the variation of the spectral responsivity of the integrating sphere source is of the order of 0.5 % across the inner opening of the aperture.

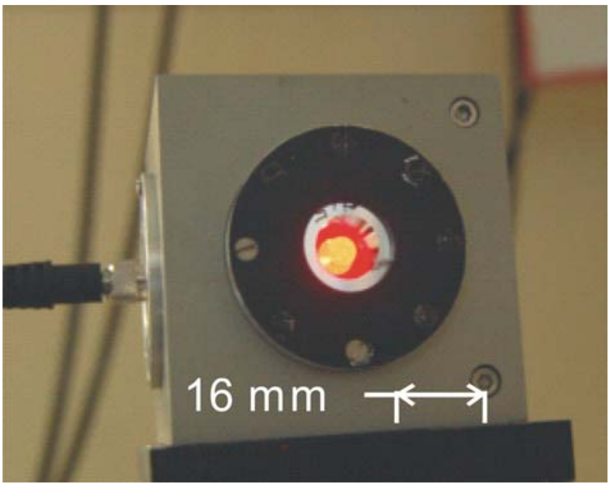

Fig. 1 Photograph of the integrating sphere with the approximate dimensions

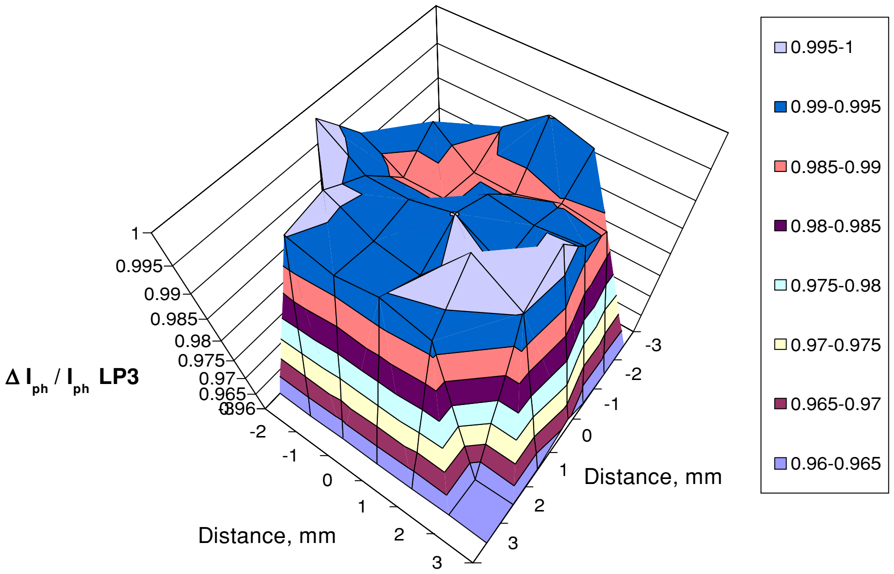

Fig. 2 Variation of the spectral radiance across the radiating opening of the integrating sphere at a laser wavelength of approximately 650 nm

2.2 Radiation Thermometer

The radiation thermometer under investigation was an LP3-8005 manufactured by KE Technologie GmbH in Stuttgart (Germany).[1] The LP3 comprises a selected silicon photodiode and a set of interference and neutral density filters. The electronic amplification system has been optimized for high-accuracy metrological applications. Special care has been taken to minimize non-linear effects. A schematic of the LP3 can be seen in Fig. 3. The main characteristics of the LP3 radiation thermometer are: a 0.8 mm measuring spot diameter at a measurement distance of 700 mm; measurable photocurrent ranging from 50 pA to 800 nA; response time less than 0.2 s; and reproducibility better than 0.2 %. The filters used in the LP3 8005 are interference filters with center wavelengths around 650 nm and 950 nm, with a bandwidth (FWHM) of about 20 nm. For the measurements of high temperatures, only the interference filter with a center wavelength around 650 nm is used. Therefore, only this wavelength has been used for the absolute calibration.

2.3 Laser Diode

The laser diode was obtained from Thorlabs Inc. (see footnote 1) and has a maximum output power of about 5 mW at a wavelength of about 650.1 nm at a temperature of 20 °C. The laser diode is operated using a low-noise power supply and temperature

[1] References to commercial products are provided for identification purposes only and constitute neither endorsement nor representation that the item identified is the best available for the stated purpose.

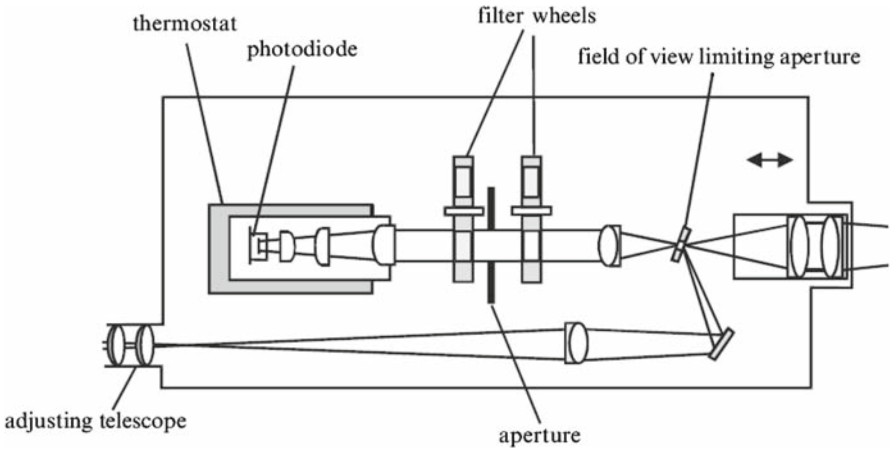

Fig. 3 Schematic of the LP3 radiation thermometer

controller, typically with 70 mA at 2.4 V. With the aid of an optical spectrum analyzer, the stability of the laser diode was found to be critically dependent upon the electrical power and temperature settings. Here, marginal changes to the settings caused drastic changes to the lasing modes of the diode, ranging from a single mode to up to three modes of similar optical power within 1.5 nm. Only after a sufficient settling time was the optical power found to be stable within a few parts per thousand.

A 200 cm long optical fiber is used to couple the laser radiation into the integrating sphere. To reduce the speckle, a portion of the optical fiber was immersed in an ultrasonic bath. A fiber core diameter of 0.2 mm was chosen to guarantee a sufficient bending radius in the chamber of the ultrasonic bath, and the jacket lining and buffer of the fiber were removed over a length of 100 cm, leaving only the core and cladding, for optimum mechanical coupling to the ultrasonic bath.

2.4 Monochromator-Based Spectral Comparator

The monochromator-based spectral comparator is described in detail in [2]. A schematic of the spectral comparator setup can be seen in Fig. 4. For the relative calibration of the spectral responsivity, the imaging optics of the LP3 has been removed to ensure stable overfilling of the field stop of the LP3. This aperture defines the measurement area of the instrument; with the imaging optics, the line-shaped light beam from the monochromator only partly overfills the aperture and results in an unstable measurement signal.

In the first section of the optical path, the exit slit of the monochromator is imaged with a magnification ratio of about two onto a variable aperture set to an approximate diameter of 0.25 mm. In the second section of the optical path, the overfilled aperture is then imaged with a magnification ratio of about 1.8 onto the LP3 aperture (and subsequently the trap detector). The calibration was performed using a grating with 651 lines $\cdot$ mm^{-1} and a reciprocal dispersion of 4 nm $\cdot$ mm^{-1}. Within the bandpass

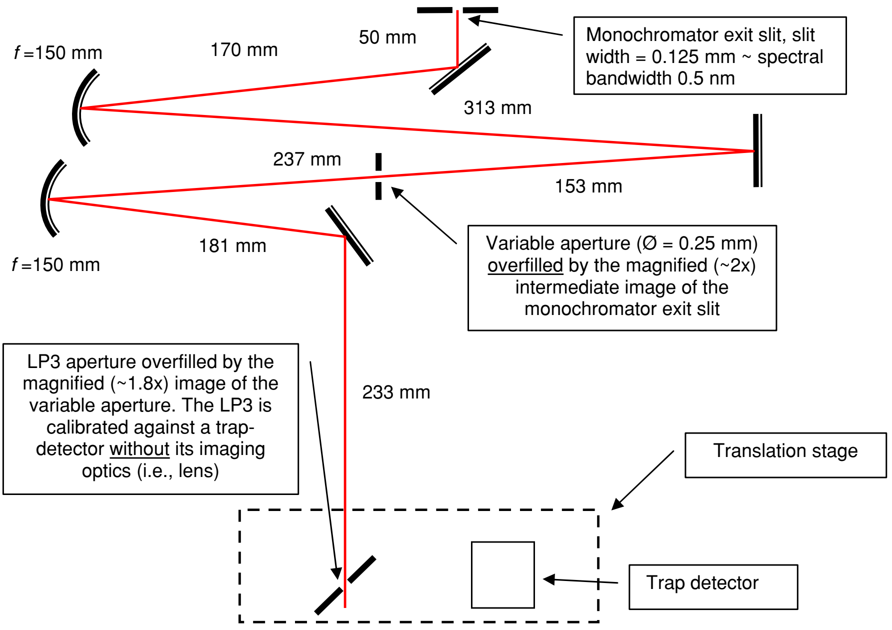

Fig. 4 Optical setup for the calibration of the relative spectral responsivity of the LP3

of the interference filter, i.e., from 620 nm to 680 nm, the spectral bandwidth of the monochromator was equal to 0.5 nm and the wavelength step for the calibration was set to 0.5 nm. Four runs over the bandpass were performed. The maximum relative difference between an individual run and the mean of all runs in the integral spectral responsivity was about 1.6×10^{-3}; the center wavelength differed by no more than 40 pm. For the measurement of the blocking regions of the interference filter (420 nm to 620 nm and 680 nm to 1,200 nm), the spectral bandwidth was 6 nm and the wavelength step for calibration was 5 nm. The resulting relative spectral responsivity of the LP3 is shown in Fig. 5.

3 Results

The laser radiation was injected into the integrating sphere by a fiber optic, as can be seen in the schematic of the experimental setup in Fig. 6. This simple injection leads to a so-called speckle pattern as can be seen in Fig. 7. The speckle pattern is highly unstable, changing with thermal and mechanical noise. These changes result in a variation of the spectral radiance at the output aperture of the integrating sphere that critically influences the overall noise of the measured signal. This is particularly critical when viewing the aperture of the integrating sphere source with detectors having different spot sizes. The cause of the speckle pattern is the coherence of the laser radiation emitted by the laser diode. Removing the speckle pattern requires a distortion of the coherence of the laser radiation. Several approaches are reported in the literature. Our first attempt to reduce the speckle pattern by guiding the laser radi-

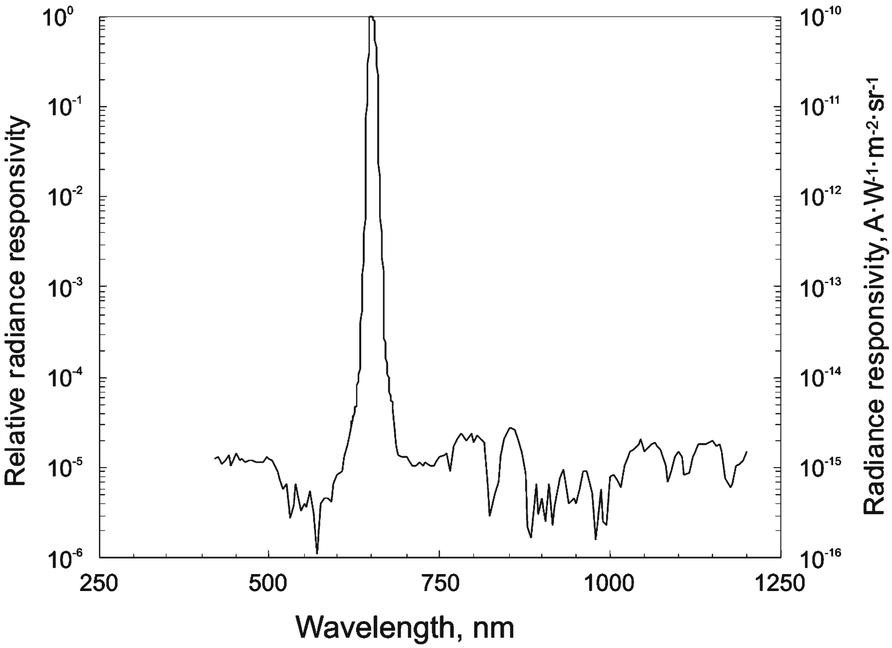

Fig. 5 Relative spectral responsivity and the radiance responsivity of the LP3 radiation thermometer measured using the monochromator-based setup

ation through a rotating glass disc of varying thickness did not improve the situation. Only by putting a length of the glass fiber inside an ultrasonic water bath was the speckle pattern removed completely, as can be seen in Fig. 8. After removing the speckle pattern, the temporal stability of the spectral radiance emitted by the integrating sphere source was measured by a trap detector over a time scale of several hours. A schematic of the measurement geometry can be seen in Fig. 9, where the geometry and the relevant dimensions are shown. The results of these measurements are shown in Fig. 10. It can be seen that the temporal variation of the spectral radiance emitted by the integrating sphere source was within 0.3 % over 5 h. To account for the remaining variation, the absolute calibration of the radiation thermometer was performed by viewing the integrating sphere source alternately with the radiation thermometer and the trap detector. The wavelength of the laser radiation and its spectral bandwidth were measured with a wavemeter. The obtained wavelength was 650.12 nm. Using the known spectral responsivity of the trap detector and the geometrical data, the spectral irradiance of the integrating sphere source was determined to be 2.902×10^{-5} W · m^{-2}. As the radiation thermometer senses spectral radiance, the spectral irradiance E_λ was transformed into spectral radiance L_λ using the formula,

$$E_\lambda(\lambda, d) = \frac{2\pi r_1^2}{r_1^2 + r_2^2 + d^2 + \sqrt{(r_1^2 + r_2^2 + d^2)^2 - 4r_1^2 r_2^2}} L_\lambda(\lambda) \qquad (1)$$

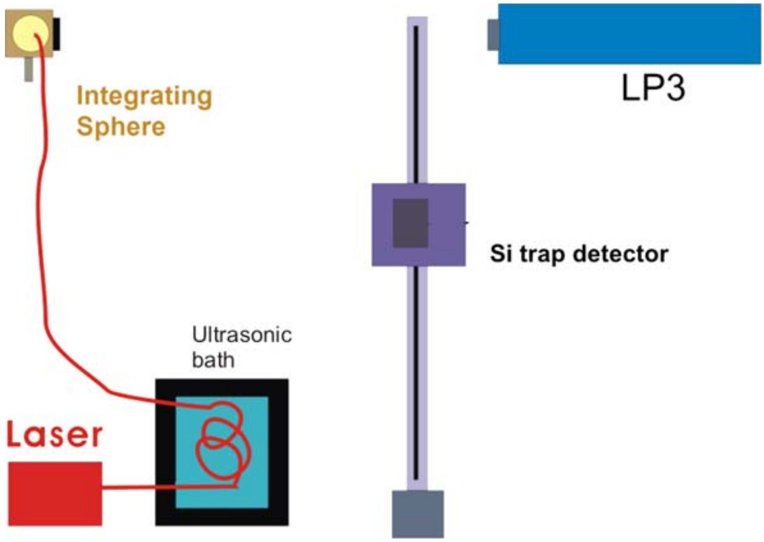

Fig. 6 Schematic of the experimental setup

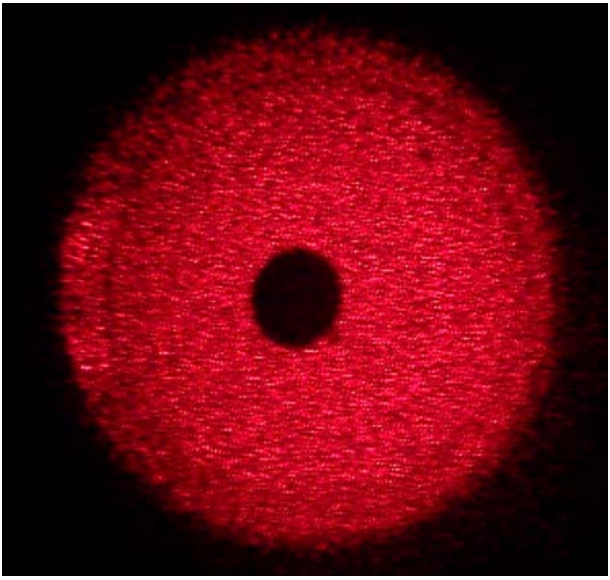

Fig. 7 View of the opening of the integrating sphere source with the LP3 optics when injecting the laser radiation directly into the integrating sphere. The speckle pattern can clearly be seen

with r_1 and r_2 being the radii of the source and the trap apertures, respectively, and d the distance between the source and trap apertures (see Fig. 9). The resulting radiance is $3.6586 \times 10^{-1}\,\mathrm{W \cdot m^{-3} \cdot sr^{-1}}$. At this radiance, the measured photocurrent of the radiation thermometer is 3.691×10^{-11} A.

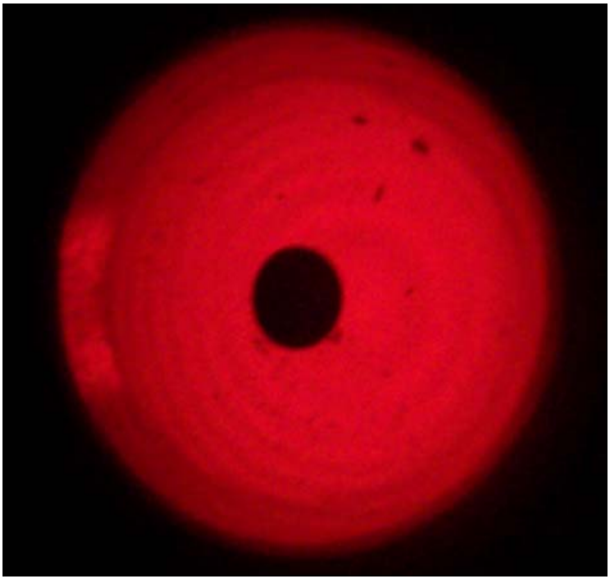

Fig. 8 View of the opening of the integrating sphere source with the LP3 optics when injecting the laser radiation into the integrating sphere after passing the glass fiber through an ultrasonic bath. The speckle pattern is completely removed

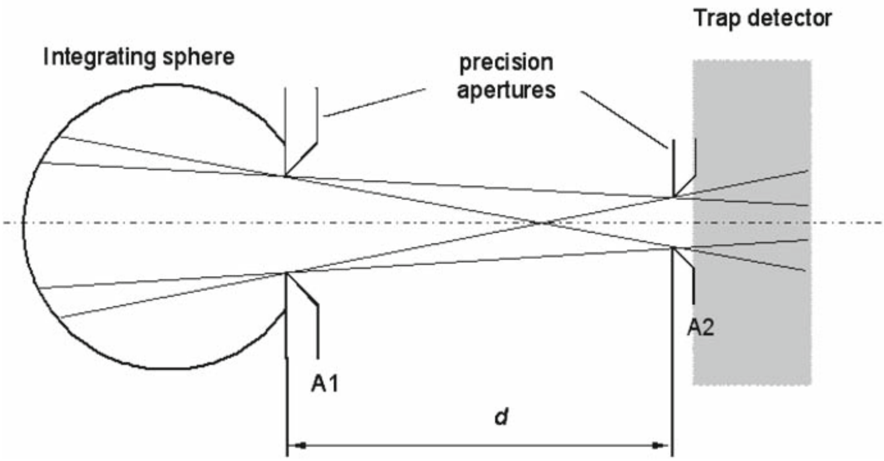

Fig. 9 Sketch of the measurement geometry showing the relevant dimensions

Combining the relative spectral radiance responsivity of the radiation thermometer LP3 shown in Fig. 5 with the absolute radiance responsivity at 650.1 nm, the final radiance responsivity can be calculated and is shown in Fig. 5.

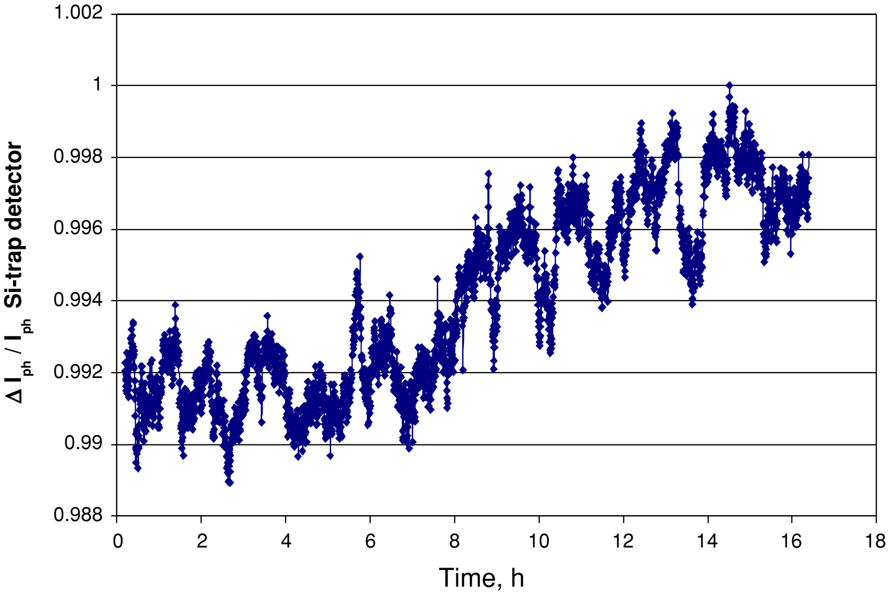

Fig. 10 Stability of the spectral responsivity emitted by the integrating sphere source as measured by the trap detector

4 Uncertainty Estimation

The components contributing to the overall uncertainty of the measured absolute spectral responsivity of the radiation thermometer are: the dimensions of the source aperture, the distance between the source aperture and the trap detector aperture, the spectral responsivity of the trap detector, the spatial and temporal homogeneity of the spectral radiance at the integrating sphere output, and the stability and noise of the LP3 radiation thermometer. In the present setup, the following factors contribute most to the overall uncertainty: the temporal stability of the laser radiation, which is of the order of 0.3 % over 5 h, and the homogeneity of the spectral radiance across the opening of the integrating sphere source of 0.5 %. As the time delay between the measurement of the trap detector and the radiation thermometer under investigation is about 2 min, this accounts for an uncertainty contribution of 0.05 % for the temporal instability of the laser radiation. As only the central part of the integrating sphere is seen by the radiation thermometer and the trap detector, the inhomogeneity of the radiance across the source aperture accounts for about 0.25 %. The uncertainty of the spectral irradiance responsivity of the trap detector is about 0.04 %, and the uncertainty of the source aperture area is about 0.02 %. The distance between the source and detector apertures is about 500 mm and is measured with an uncertainty of about 0.05 mm, accounting for an uncertainty contribution of 0.02 %. The stability and noise of the LP3 radiation thermometer is about 0.05 %. The relative uncertainty contributions are summarized in Table 1. The overall uncertainty of this preliminary setup is about 0.26 % ($k = 1$) of the determined spectral responsivity of the radiation thermometer. By improving the

Table 1 Summary of the relative uncertainty contributions of the spectral responsivity of the radiation thermometer

Contribution	Current relative uncertainty (%)	Future relative uncertainty (%)
Laser stability	0.02	0.02
Spatial homogeneity	0.25	0.05
Spectral responsivity of trap	0.04	0.04
Source aperture	0.02	0.02
Distance	0.02	0.02
LP3 stability and noise	0.02	0.02
Squared sum	0.26	0.08

homogeneity to a value of 0.05 %, which is straightforward, the overall uncertainty will reduce to 0.08 %.

5 Discussion and Outlook

The described measurement schemes and setups represent a first approach to the difficult and demanding task of a direct absolute radiometric calibration of a radiation thermometer. The instruments and devices presented were chosen because they allow us to gain an understanding of, and solve, the specific physical and experimental problems at low cost and with easy applicability.

A larger integrating sphere will significantly improve the spatial uniformity across the output aperture, but this will require a more powerful laser source in order to obtain the same radiance output level. Additionally, the current solid-state-diode-based laser system is limited in its operational stability, and no optical feedback channel is included in the integrating sphere to optimize the laser output. For this reason, we plan to equip a larger integrating sphere with a monitor diode, and to use an Ar^+ laser and, in a second stage, PTB's tunable laser facility TULIP [5] as monochromatic light sources.

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References

1. D.R. Taubert, J. Hartmann, J. Hollandt, J. Fischer, in *Temperature, Its Measurement and Control in Science and Industry*, vol 7, part 1, ed. by D. Ripple (AIP, New York, 2003), pp. 7–12
2. D.R. Taubert, R. Friedrich, J. Hartmann, J. Hollandt, Metrologia **40**, S35 (2003)
3. L. Werner, J. Fischer, U. Johannsen, J. Hartmann, Metrologia **37**, 279 (2000)
4. H.W. Yoon, Metrologia **43**, S22 (2006)
5. A. Sperling, O. Larionov, U. Grusemann, S. Winter, in *Proceedings of the 9th International Conference on New Developments and Applications in Optical Radiometry (NEWRAD)*, ed. by J. Groebner (PMODWRC, Davos, Switzerland, 2005), p. 93