A Lens-free InGaAs-Radiation Thermometer with improved Detectivity at 1.6 µm to cover the Temperature Range from 80 °C to 962 °C

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In the last decade the specific detectivity of InGaAs-photodiodes has improved significantly. Hence, the lower detection limit of InGaAs-photodiode based radiation thermometers at 1.6 µm can be extended. Here, an existing radiation thermometer was equipped with a state-of-the-art InGaAs-photodiode. The radiation thermometer was characterized and calibrated and a reference function has been compiled. The lower temperature limit could be extended from 150 °C down to 80 °C.

INTRODUCTION

The working group "Infrared Radiation Thermometry" of the Physikalisch-Technische Bundesanstalt (PTB) provides non-contact temperature measurements in the range from -170 °C to 962 °C at the highest metrological level. High-quality infrared radiation thermometers are used as transfer instruments as well as for comparison measurements. InGaAs-photodiode instruments are superior to instruments based on thermal detectors in terms of temporal stability and achievable uncertainties in the short wavelength range. However, wavelengths around 1.6 µm limit the minimal detectable temperature of InGaAs-radiation thermometers to typically 150 °C to 200 °C. In the last decade, the performance of InGaAs-photodiodes increased by several orders in magnitude in terms of specific detectivity. By using a commercial two-stage cooled InGaAs-photodiode, the minimal detectable temperature of a 15 years old lens-free radiation thermometer (LF-IRRT2) was improved from 150 °C to 80 °C.

Table 1. Specifications of the LF-IRRT3. See also Figure 1.

Component	Nominal specification
Aperture stop Ø	6.00 mm
Field stop Ø	3.706 mm
Distance aperture stop to field stop	243.8 mm
Detectivity (data sheet)	6.7×10^{13} cmHz$^{1/2}$/W
Bandpass of filter	1.55 µm - 1.65 µm
Maximum transmission of filter	81% at 1.6 µm

DESIGN OF THE RADIATION THERMOMETER LF-IRRT3

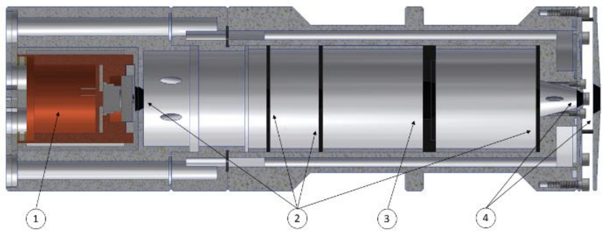

Figure 1 Cut presentation of the InGaAs-radiation thermometer LF-IRRT3. The main parts are listed in the text.

Figure 1 shows a cut presentation of the LF-IRRT3. The main parts are:

1. Water cooled detector housing including an interference filter and the field stop (see Table 1).
2. Set of stray light baffles in a water-cooled housing.
3. Motorized optical shutter.
4. Water-cooled front aperture (aperture stop) with additional heat-shield.

The photodiode is a two-stage cooled InGaAs-photodiode with an active area of 5 mm in diameter. The photodiode is operated at a temperature of approximately -20 °C ± 0.005 °C to reduce the wear and tear of the TE-cooler. The temperature is controlled by a custom-built temperature controller. The controller housing also includes a custom-built transimpedance amplifier, tailored for the photodiode. Gains can be set from 10^5 to 10^{10}. An additional voltage gain factor of 10 can be set at every gain to increase the signal level.

By means of a so-called reference function [2] the output signal is converted into a temperature reading.

The reference function is given by:

$$i = \frac{A_1 \cdot A_2}{D^2} \int_{\lambda_1}^{\lambda_2} L_\lambda(\lambda, t_{90}) \cdot s(\lambda) \cdot \tau(\lambda) \cdot d\lambda \quad (1)$$

with the photocurrent i, $A_{1,2}$ the active areas of the aperture stop and field stop, $\lambda_{1,2}$ the limiting wavelengths, $L_\lambda(\lambda, t_{90})$ the spectral radiance of the blackbody at the temperature t_{90}, $s(\lambda)$ the spectral responsivity of the photodiode, $\tau(\lambda)$ the transmission of the interference filter. Assuming a linear responsivity, the input values of Eq. (1) can be determined by measuring the photocurrent i at several known temperatures $t_{s,90}$ and applying a least square fit. In order to obtain a radiation temperature $t_{s,90}$ from the photocurrent i, the temperature is inversely calculated by comparing the measured photocurrent with the photocurrent according to Eq. (1).

CALIBRATION OF THE LF-IRRT3

The LF-IRRT3 has been calibrated at the Thermal Imager Calibration Facility (ThermICF) [1] (see Figure 2) of PTB. The ThermICF completely covers the temperature range from -60 °C to 962 °C by means of heatpipe blackbodies. Additional surface radiators are available in the temperature range from -15 °C to 500 °C for the full field of view characterization of thermal imagers.

The photocurrent of the LF-IRRT3 was measured at

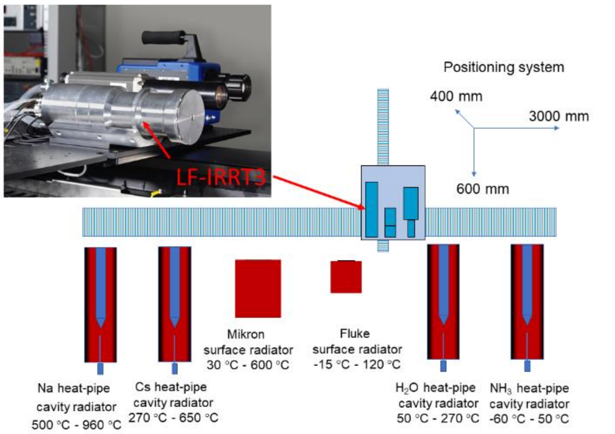

Figure 3 Schematic of the Thermal Imager Calibration Facility (ThermICF) of PTB. The facility uses four heatpipe blackbodies to provide radiation temperatures traceable to the ITS-90. The LF-IRRT3 is shown mounted on a long-range x-y-z-translation system in front of the heatpipe blackbodies and a surface radiator. The inserted photograph shows the LF-IRRT3 together with a pyrometer and a thermal imager.

several temperatures in the range from 80 °C to 960 °C and the input parameters for Eq. (1) were determined. The LF-IRRT3 together with the read-out electronics (DMM and transimpedance amplifier) was treated as a "blackbox", i.e. only the spectral radiance $L_\lambda(\lambda, t_{90})$ and the output signal were used for the calibration. However, in the observed temperature range, the photocurrent increases from $\approx 10^{-14}$ A to $\approx 10^{-6}$ A. Hence, the full range of gains of the transimpedance amplifier has to be used. The gain ratios were determined at four different temperatures to allow an overlap of different gain settings. To simplify the evaluation of the radiation temperature, an approximation of Eq. (1):

$$i = c \cdot \int_{\lambda_1}^{\lambda_2} L_\lambda(\lambda, t_{90})\, d\lambda \qquad (2)$$

with $c = A_1 A_2 \tau_0 s_0 / D^2$ is used. The resulting input parameters are given in Table 2.

Table 2 Input parameters for Eq. (2) obtained by calibration of LF-IRRT3 against high-quality heatpipe blackbodies of PTB.

Parameter (see text)	Value
Instrument const. c	$4.040989 \cdot 10^{-9}$ Am^{2}srW^{-1}
wavelength limit λ_1	$1.542945 \cdot 10^{-6}$ m
wavelength limit λ_2	$1.645718 \cdot 10^{-6}$ m

The resulting difference of the radiation temperature obtained according to Eq. (2) $t_{Instrument}$ and the radiation temperature $t_{s,90}$ is given in Figure 3.

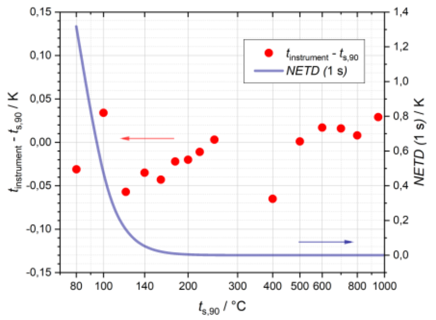

Figure 2 Difference of measured radiation temperature $t_{Instrument}$ and radiation temperature $t_{s,90}$ (red dots) and noise equivalent temperature difference / (NETD) (blue curve) for 1 s integration time plotted over the radiation temperature $t_{s,90}$.

CONCLUSION

The LF-IRRT3 was developed and calibrated against high-quality heatpipe blackbodies of PTB. The difference $t_{Instrument}$- $t_{s,90}$ is below 65 mK and within the expanded uncertainties of the blackbodies for all observed temperatures. However, the integration time increases for temperatures below 120 °C to approximately 5 minutes at 80 °C.

REFERENCES

1. I. Müller, et al., "Non-contact Temperature Measurement at the Physikalisch-Technische Bundesanstalt (PTB)" submitted to QIRT Journal
2. B. Gutschwager and J. Fischer, "An InGaAs radiation thermometer with an accurate reference function as transfer standard from 150 °C to 960 °C", in "Proceedings TEMPMEKO '99", edited by J. F. Dubbeldam and M. J. de Groot, 567-572, IMEKO/NMi Delft, 1999.