Device for wideband ratio pyrometry

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Abstract. In this article we present procedures of creation, verification, and application of a device for contactless measurement of object’s temperature in vacuum. In contrast to conventional dual-wavelength pyrometers, it does not rely on spectral filtering and makes use of the intrinsic bandwidth parameters of photodetectors. In theory the device is capable of measuring values of temperature ranging from room temperature to several thousands kelvins. The verification was performed using a reference thermometer. Also, in-field measurements of the sample’s temperature in vacuum were conducted, which show efficiency of the proposed system.

1. Introduction

Accurate surface temperature measurements are crucial for modern surface science (see eg. [1–5]). Among the non-destructive methods of surface temperature measurements optical methods have a huge advantage over others. Optical thermometers do not require physical contact with object of interest, provide fast response on temperature change and ensure locality of the measurements. They require, though, careful mapping of heat radiation, registered by pyrometer, to thermodynamic temperature. There are several points that must be taken into account: ambient temperature, sensor housing temperature, presence of radiation absorption by medium between sensor and the sample (including air and viewport window), geometry of the experiment, noise characteristics of detectors and amplifiers, etc. Each optical thermometry method falls in one of the following categories:

(i) Single wavelength pyrometry;
(ii) Total radiation pyrometry (both thermal (bolometers) and photoelectric);
(iii) Dual- and multi-wavelength pyrometry:
   (a) Monochromatic;
   (b) Wideband.

In general, accuracy and application capabilities of these devices tend to raise from the former to the latter, as well as device complexity and cost. Single-wavelength pyrometers are cheap, handy and are able to measure temperature of surfaces of known emissivity. Multiband pyrometers are sophisticated setups capable of measuring temperatures of non-gray surfaces with unknown, non-constant, and time-varying emissivity.
This research is focused on development, verification and testing of a device for measurements of the sample surface temperature in vacuum, which is in principle an intermediate device between dual wide-band pyrometers and total radiation pyrometers. It features the simplicity of design and low cost while being capable of measuring temperatures of grey bodies of unknown emissivity.

2. Methodology and devices

2.1. Methodology

Upon being exposed to the IR radiation of heated body, the photodiode (PD) generates the photocurrent, which is then amplified, converted to the digital signal and processed. The magnitude of the photocurrent is

\[ I(T) \propto A_{PD} F_{PD \rightarrow obj} \int_{0}^{\infty} L_e(\lambda, T) R(\lambda) d\lambda = A_{PD} F_{PD \rightarrow obj} \Sigma(T), \]  

where \( A_{PD} \) is the PD sensor’s area, \( F_{PD \rightarrow obj} \) is a view factor (i.e. fraction of the PD’s field of view that is occupied by the body), \( L_e(\lambda, T) \) is spectral radiance of the body, \( R(\lambda) \) stands for the spectral responsivity of sensor, and \( \Sigma(T) \) is short for the integral in RHS. In the gray-body approximation, the spectral radiance of body is defined by the Planck law:

\[ L_e(\lambda, T) = \varepsilon L_b(\lambda, T) = \varepsilon \frac{2hc^2}{\lambda^5} \left( \exp \frac{hc}{\lambda k_B T} - 1 \right)^{-1}, \]  

where \( \varepsilon \in [0, 1] \) stands for the body emissivity, \( h, c, \) and \( k_B \) for Planck constant, speed of light in vacuum, and Boltzmann constant, respectively.

The expression in the RHS of equation 1 is a monotonous function of \( T \) (see figure 2 (a)). Thus, for given \( \varepsilon \), the temperature of any object may in theory be unambiguously inferred from equation 1 after the calibration with a black-body reference. This gives the foundation to the total radiation pyrometry (see pp. 184 – 191 of [6]). In practice, however, \( \varepsilon \) is seldom certainly known; moreover, it may be non-constant across the object surface or time-varying, therefore reducing measurement to nothing.

Both the need of pre-calibration and the influence of \( \varepsilon \) may be eliminated if the ratio of two signals is considered instead of the single PD signal. This strategy was first exploited by two-color manual pyrometry [7], and later by two-wavelength automated pyrometry (see the review in [6]). Most radiation thermometers measure intensity of light in narrow bands of spectrum, using interference filters or monochromators. These narrowband methods have several advantages, but the detected power is at least two magnitudes smaller [8] compared to an unfiltered PD. In this work, a full-spectrum measurements were considered. To distinguish the bands, the PDs with different spectral responsivities were chosen instead of using filters.

Let \( I_1 \) and \( I_2 \) be photocurrents of different PDs with sensor areas \( A_1 \) and \( A_2 \) and spectral responsivity \( R_1(\lambda) \) and \( R_2(\lambda) \) respectively; both diodes are exposed to the same heat radiation. Then

\[ \frac{I_1(T)}{I_2(T)} = \frac{A_1 \varepsilon \int_{0}^{\infty} L_b(\lambda, T) R_1(\lambda) d\lambda}{A_2 \varepsilon \int_{0}^{\infty} L_b(\lambda, T) R_2(\lambda) d\lambda} = \frac{A_1}{A_2} \mathcal{R}(T). \]  

Here

\[ \mathcal{R}(T) = \frac{\int_{0}^{\infty} L_b(\lambda, T) R_1(\lambda) d\lambda}{\int_{0}^{\infty} L_b(\lambda, T) R_2(\lambda) d\lambda}. \]  

is ratio function of two PDs. This function can be calculated from the equation 2 and $R_i(\lambda)$ from i-th device datasheet.

In this way, the thermometric measurement comes down to evaluating

$$T = R^{-1} \left( \frac{(A_2 I_1)}{(A_1 I_2)} \right) = R^{-1} (j_1/j_2),$$

where $j_1$ and $j_2$ are photocurrent densities and $R^{-1}$ stands for the inverse of $R$. The inversion procedure may be implemented in several ways, such as

(i) linear search in a pre-calculated array of $R(T)$ and further interpolation between the nearest found entries (used in this work; relatively coarse and fast, with potential use in embedded systems);

(ii) numerically solving equation $R(T) = R^{exp}$ (more accurate but time-consuming).

Before using equation 5, its reliability should be checked for the given set of PDs. Also temperature ranges where the evaluation of $R(T)$ is feasible should be obtained. In this work a reference thermometer was used for this purpose.

2.2. Devices

![Figure 1](image_url)

Figure 1. (a) Spectral responsivity of PD 1 and PD 2 for different wavelength (dashed green line indicates the spectral responsivity of an ideal photodetector) [9]. (b) Ratio function (equation 4) for these diodes.

For the current study following photodiodes without filters were selected:

(i) InGaAs (PD 1) [10]: near-infrared (0.5 – 2.15 µm) photodiode.

(ii) InAsSbP/InAs (PD 2) [11]: mid-infrared (1.8 – 3.8 µm) photodiode.

The spectral responsivities of chosen PDs and $R(T)$ for them are shown on figures 1 (a) and (b) respectively. Small signal detection required high feedback resistance, so almost all photogenerated current could flow via the low shunt impedance of the PD itself, generating close-to-zero output voltage. To prevent this effect, the impedance of these PDs was virtually increased by using bootstrapping circuit suggested in [12].

The setup for the verification procedure included PD fixture and diaphragm (optional), digital IR reference thermometer [13] and ceramic plate (a part of BGA rework system) as a thermal radiation source. All devices were mounted upon the optical bench. The diaphragm holder was placed at the distance of 2.5 cm from the sensor. Two apertures were tested, with diameters 0.25 cm and 0.15 cm, limiting the angle of view to 200 mrad and 120 mrad correspondingly.
3. Results and Discussion

3.1. Verification measurements

![Diagram showing PD signals for different field of view: (a) full aperture, (b) 0.25 cm aperture, (c) 0.15 cm aperture](image)

**Figure 2.** PD signals for different field of view: (a) full aperture, (b) 0.25 cm aperture, (c) 0.15 cm aperture

The verification sequence was following:

(i) The signal—temperature series for each PD were acquired, separately for unbounded Field of View (FOV) and for different smaller apertures;

(ii) The ratio function $R_{exp}^T$ was evaluated for each temperature $T$;

(iii) $R_{exp}^T$ were compared to the theoretical curve (equation 4);

(iv) Regions where the ratio function evaluation is feasible were determined.

The results of the procedure are depicted in figure 2 and figure 3. Here, full-aperture acquisition provides high signal level, and the good correspondence to the equation 4 holds for a wide range of temperatures, starting from as low as 640 K. Small apertures cause smaller signal and smaller signal-to-noise ratio (SNR) and drastically raise the lower limit of temperature that can be measured via the setup. This lower boundary was determined as the point where extrapolated trend line for $R_{exp}^T$ meets the theoretical $R(T)$, and is estimated to be at 828 K ($R = 4.3$).

![Diagram showing the temperature dependence of ratio functions obtained experimentally](image)

**Figure 3.** The temperature dependence of ratio functions obtained experimentally. Starting from approximately 640 K, the $R_{exp}^T$ acquired with full aperture neatly follows the $R(T)$. The ambient influence is linearly decaying with $T$ and is expected to become negligible at high temperatures.
3.2. Vacuum measurements

The idea of the last experiment was to verify work of the setup at higher temperatures by measuring the Curie temperature of a FeNi$_3$ magnetic sample inside vacuum. Experiment involved two PDs (PD holder was fixed on the vacuum viewport flange) with aperture 0.25 cm, allowing to study 1.8 cm$^2$ fragment of the sample at the distance of 18 cm from the PDs. The heating device was fixed beneath the sample so that by passing a current through the heater it is possible to vary the temperature of the sample in a wide range. The Curie temperature of that sample was determined in a previous study [14] by independent measurement method. So, if one determines heater current, corresponding to the disappearance of the sample’s surface magnetic order, one can postulate that at this heater current surface temperature is 863 K.

Spin-polarized electron spectroscopy [15–18] (SPES) was used to map the sample’s secondary electrons polarization to the heater current. Experimental results are shown on the figure 4 (c). From approximation of the results by Curie-Weiss law, heater current that leads to loss of magnetic ordering in the sample, “Curie current”, was found equal to 1.96 A.

![Figure 4](image)

**Figure 4.** Time dependence of the ratio function (a) and temperature (b) during measurements in vacuum. Note: blue (orange) horizontal line shows value 4.3 (828 K) which is upper (lower) boundary for our device. Black vertical lines divide (i), (ii) and (iii) time intervals. (c) Polarization – Temperature dependence obtained from results of SPES measurements.

To verify work of the presented pyrometer, following experimental sequence was proposed:

(i) for 600 s sample was heated with heater current exceeding “Curie current”;
(ii) for next 600 s heater current was fixed at “Curie current” value;
(iii) then heater current was set to zero – the sample was left cooling in vacuum.

The experimental results of the above procedure are shown on figures 4 (a) and (b). On figure 4 (a) ratio function on time dependence is shown, blue line shows the highest ratios that should lead to correct measurement results. Figure 4 (b), in mean time, shows the temperature corresponding to the ratio function above. As one can notice, sample heats up quickly and stays in measurable region until the current is turned off. By analyzing the curve one can deduce that temperature, that corresponds to the “Curie current”, is equal to 867 K. The latter value coincides with independently measured one [14] within the accuracy of the “Curie current” measurements made by SPES.
3.3. Discussion

As the verification measurements have shown, small apertures result in small SNR and relatively high lower boundary of measurable temperature range. To account for these effects, it is needed to add one more term to the equation 1:

\[ I = A_{PD} \left[ F_{PD\rightarrow obj} \Sigma_{obj}(T_{obj}) + (1 - F_{PD\rightarrow obj}) \Sigma_{amb}(T_{obj}, T_{amb}, t, ...) \right], \]  

(6)

where \( \Sigma_{obj} = \int_{0}^{\infty} L_{\lambda}(\lambda, T_{obj}) R(\lambda) d\lambda \) is the useful signal and \( \Sigma_{amb}(T_{obj}, T_{amb}, t, ...) \) is ambient noise, i.e. radiation emitted by the diaphragm and reflected from its surface. When using full aperture \( (F_{PD\rightarrow obj} \sim 1) \), one can neglect \( \Sigma_{amb} \) and confidently evaluate \( R_{exp} \), but when aperture attenuates the useful signal \( (F_{PD\rightarrow obj} \ll 1) \), \( \Sigma_{amb} \) becomes dominant unless temperature is high enough. To overcome this complication one can develop different strategies, such as using the cooled blackened apertures resulting in decreased ambient noise. Lock-in amplification is also an attractive option for recovering the useful signal. It should also be mentioned that by using focusing IR optics one can shift lower limit to the lower temperatures.

Another difficulty for accurate measurements of the sample temperature in vacuum is the wavelength-dependent transmission of the vacuum chamber’s viewport. It was found that the signal of the PD 2 starts to be unstable (noisy) at higher temperatures than it used to, when measurements were held without viewport in the way. This effect was attributed to the substantial absorption of the IR radiation by the viewport’s glass. Therefore, the measurements of the low temperatures (i.e., with greater impact of the long wavelengths on the measurement) should be corrected; e.g., by explicitly adding the transmission factor as \( \tau(\lambda) \) to the both integrals in \( R(T) \) (equation 4). In case of unknown or varying transmission, the other techniques were proposed [19].

Finally, it should be mentioned that real bodies, especially metals, are not gray. It was shown [6] that \( \varepsilon \) has weak dependence on \( \lambda \). To take this into account one should fall back to using a set of multiple narrow-band diodes (see pp. 204 – 206 in [6] and [20]), but such strategy will compromise the overall sensitivity and dramatically increase the setup cost.

4. Conclusions

A ratio pyrometry device was constructed, with its temperature sensing abilities defined solely by the responsivity curves of the used photodetectors. As the verification measurements have shown, there exists a boundary temperature (in our case 828 K) below which the measurements become unreliable unless special care was taken of the ambient noise. Vacuum chamber measurements have shown that the presented device is able to accurately measure sample surface temperature from outside of the vacuum chamber, but at low temperatures (< 800 K), the wavelength-dependent transmission of the viewport should be accounted for.

References

[1] Tripathi M, Mittelberger A, Mustonen K, Mangler C, Kotakoski J, Meyer J C and Susi T 2017 Phys. Status Solidi 11 1700124
[2] Luckman G 1988 Studies of surface segregation kinetics by Auger electron spectroscopy (Academic Press Boston)
[3] Korenyugin D G, Martsinovsky A M and Orlov K E 2009 Technical Physics Letters 35 944
[4] Andronov A, Budyлина E, Shkitun P, Gabdullin P, Gnuchev N, Kvashenina O and Arkhipov A 2018 J. Vac. Sci. Technol., B 36 02C108
[5] Kuznetsov M, Zemlyakov E, Toporkov A, Kurakin A and Arkhipov A 2018 1109 012038
[6] Michalski L, Eckersdorf K, Kucharski J and McGhee J 2001 Temperature measurement (John Wiley & Sons)
[7] Forsythe W 1923 J. Opt. Soc. Am. 7 1115–1121
[8] Andor G 1995 Metrologia 32 709–711 URL https://doi.org/10.1088/0026-1394/32/6/64
[9] Wang W C 2011 Seattle: Department of Mechanical Engineering-University of Washington URL http://courses.washington.edu/me557/optics-detector.pdf
[10] LASER COMPONENTS GmbH 2016 Extended InGaAs 2200 nm URL https://www.lasercomponents.com/fileadmin/user_upload/home/Datasheets/lcdgi/ig22-series.pdf
[11] LED Microsensor NT LLC 2017 Mid-Infrared (MIR) Photodiode rev. 041017 URL http://lmsnt.com/datasheets/PD/Lms36PD-03_Lms36PD-03_T03_rev041017.pdf
[12] Makai J P and Makai T 2014 J. Mod. Opt. 61 1187–1194
[13] Melexis 2018 MLX90614 family URL https://www.melexis.com/-/media/files/documents/datasheets/mlx90614-datasheet-melexis.pdf
[14] Reinmuth J, Donath M, Passek F and Petrov V 1998 J. Phys.: Condens. Matter 10 4027
[15] Fishkova T Y, Mamaev Y A, Ovsyannikova I, Petrov V and Shpak E 1994 Nucl. Instrum. Methods Phys. Res. A 348 56–60
[16] Petrov V, Grebeshkov V, Grachev B and Kamochkin A 2003 Rev. Sci. Instrum. 74 1278–1281
[17] Petrov V, Galaktionov M and Kamochkin A 2001 Rev. Sci. Instrum. 72 3728–3730
[18] Pavlov A, Ustinov A and Petrov V 2018 J. Electron. Spectrosc. Relat. Phenom. 223 62–66
[19] Lowe D, Bourson F, Journeau C, Machin G, Parga C and Sadli M 2013 Int. Congress of Metrology p 15003
[20] Felice R A 2006 Foundry Management and Technology 134 40–41