The problem of reproducing thermodynamic temperatures above 5000 K and generating intense infrared radiation to achieve them

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Abstract. The feasibility of the operation of reproduction and transfer of a unit of thermodynamic temperature at the level of 5000 K in the metrology of temperature measurements is analyzed. A brief analysis of the current capabilities of temperature metrology is presented, the reality of reproducing high temperature and generating intense infrared radiation for its implementation is shown. The theoretical justification of the methods, schemes for their implementation, as well as brief descriptions of hardware systems are presented.

1. Introduction
The development and implementation of new high-temperature technologies, complex technogenic systems and facilities with extreme operating conditions requires knowledge of their energy state, the most important characteristic of which is thermodynamic temperature. It can be confidently predicted that in the near future temperature control at the level of 5000–10000 K and higher will be in demand [1]. Modern reference radiation thermometry provides an upper limit of the reproducible temperature equal to 3473 K, therefore, temperature measuring instruments are calibrated and applied only to a given temperature [2,3]. This, first of all, is connected with the ultimate capabilities of infrared radiation sources, with the help of which the calibration of measuring instruments is carried out. In particular, the well-known models of an absolutely black body provide reproduction of the maximum thermodynamic temperature, which does not exceed 3200 K [4]. Other sources of infrared radiation, for example, such as solid-state lasers, light-emitting diodes, gas-discharge or mercury-xenon lamps, have not found their application in this field of thermal measurements [5]. This is due to the facts:
- sources provide the generation of quasi-monochromatic radiation of a given high intensity and with a given spectrum, but do not provide the required stability,
- sources provide the generation of quasi-monochromatic radiation with a given high energy stability, with a given spectrum, but do not provide a high radiation intensity,
- sources provide the generation of monochromatic radiation with a given intensity and stability, however, the spectrum of this radiation is not exactly known and cannot be accurately measured (monochromatic lasers).
Thus, currently there are no infrared sources that can provide the generation of quasi-monochromatic radiation with a spectral intensity of more than 30 mW nm\(^{-1}\) mm\(^{-2}\) (which is equivalent to the emission of a black body with a temperature of \(\approx 5000\) K) and energy stability of no worse than 99.99\% (power fluctuations are not more than 0.01\%). When reproducing and transmitting a unit of thermodynamic temperature, as a rule, the principle of equivalence of spectral energy brightness of a radiation source to its thermodynamic temperature is used, i.e. the so-called direct method \([6,7,8]\). With this method, the generation of high temperatures (above 3473 K) requires the generation of very powerful radiation, which is a serious problem. This article briefly discusses our proposed method for generating high-power stable quasi-monochromatic radiation, intended for the direct method. An alternative method for reproducing heat is also proposed, alternative to the conventional direct method. The proposed method is based on the principle of virtual equivalence of spectral energy brightness and thermodynamic temperature, in which the surface radiation flux density of the source is virtually associated with a specific thermodynamic temperature. In this case, to achieve a high temperature, the generation of less powerful radiation is required and this problem is solved.

2. Generation of stable high-intensity infrared radiation

To expand the dynamic range of the direct temperature reproduction method, it is proposed to generate high power quasi-monochromatic radiation in the following way. It is proposed to mix two radiations: the first radiation is a low-stability background radiation of high intensity, the second radiation is a controlled highly stable radiation of low intensity. The resulting total radiation is characterized by high power and high stability, which is achieved due to the ability to adjust the power of the second radiation according to the parameter of its fluctuation component. The structural diagram of the device that generates this radiation is shown in fig.1. As a result of applying such a technical solution, the instability of the background high-power radiant is significantly improved due to the stabilization system of the second radiant. In this case, for example, a xenon or mercury-xenon lamp can be used as a background radiant, whose broadband radiation is filtered by a band-pass optical filter of a given nominal value. These emissions are mixed in a special optical integrator-mixer, for example, in the integrating sphere, or in the so-called Ulbricht’s sphere, a photometric sphere. In this case, the integrating sphere simultaneously performs two functions - the mixing of radiation and their spatial integration. At the output of the integrating sphere, there is a stream of total radiation uniformly distributed over its output aperture, the spectral intensity of which is equal to:

\[
I_x (\lambda, \tau) = k_2 \left( I_1 (\lambda, \tau) + I_2 (\lambda, \tau) \right),
\]

and its power in a given spectral range (in the wavelength band \(\lambda_1 < \lambda_2\)) is equal to:

\[
P_x (\tau) = \int_{\lambda_1}^{\lambda_2} \left( I_1 (\lambda, \tau) + I_2 (\lambda, \tau) \right) d\lambda = \int_{\lambda_1}^{\lambda_2} I_2 (\lambda, \tau) d\lambda,
\]

where \(k_2\) - the transmittance of the mixer-integrator (integrating sphere); \(I_1(\lambda, \tau)\) - the spectral intensity of the first (background radiant); \(I_2(\lambda, \tau)\) - the spectral intensity of the second radiant; \(I_x(\lambda, \tau)\) - the total spectral intensity of the mixed radiation, \(F\) - the area of the output aperture of the integrator-mixer. The flux power of the resulting total radiation at the output of the integrating sphere, in another way, can be represented as the sum of the constant and variable (fluctuation) components:

\[
P_x (\tau) = P_x^c + P_x^v (\tau),
\]

where \(P_x^c\) - the constant component of power, \(P_x^v (\tau)\) - the time-variable (fluctuation) component of power. The fluctuation component of the radiation flux power \(P_x^v (\tau)\) - a negative feedback signal for the second radiant, it controls the power of the second radiant, as a result of which the power of the total radiation is stabilized, while its fluctuation component is reduced to the minimum value of \(P_x^{v\ min}\).
Thus, as a result of regulation at the output of the integrating sphere, there will be a radiation flux characterized by power:

\[ P_\Sigma (\tau) = k_2 \int A_1 (\lambda, \tau) + I_2 (\lambda, \tau) d\lambda = P_\Sigma + P_\Sigma^{\text{min}} (\tau), \]

and radiation stability, characterized by the ratio \( P_\Sigma^{\text{min}} / P_\Sigma \), which should be no more than \( 10^{-4} \) (<0.01%).

It should be noted that the ratio of the initial powers and spectral intensities of the radiant must be chosen on the basis of the following condition: the power of the second radiant \( P_2 \) must be sufficient to fully compensate for fluctuations in the power \( P_1 \) of the background radiant, or, in other words, the amplitude of the fluctuations must be significantly less than the power of the second radiant. If the amplitude of the fluctuations in the background radiant power is denoted by \( A_1 \), then this condition has the form:

\[ A_1 = n_1 P_1 \ll P_2, \]

where \( n_1 \) - the instability of the background radiant, expressed in relative units, which usually is \( n_1 = 6 \times 10^{-3} \pm 2 \times 10^{-2} \). It has been established that for practical use it is most optimal when the power of the second radiant is not less than 10 times the amplitude of fluctuations of the background radiant. The most optimal power ratio of the first and second radiant is established experimentally when setting up a specific device that implements this method.

As elements of a device that implements this method, for example, the following elements and devices can be taken.

Background radiant 1 (fig.1) - mercury-xenon lamp company "Hamamatsu Photonics K.K." (Japan), model L8288 in an E5421 package with a consumed electric power of \( P_1 = 500 \text{ W} \), which, together with a band-pass optical filter of a given nominal value in a given spectral range, for example, in the range \( \lambda = 640-660 \text{ nm} \), provides a quasi-monochromatic collimated radiation flux with a spectral density of \( I_1 = 80 \text{ mW nm}^{-1} \text{ mm}^{-2} \). As a band-pass optical filter, for example, an FBH650-10 band-pass optical filter with an effective passband \( \Delta \lambda = 10 \text{ nm} \) and a central wavelength of \( \lambda_0 = 650 \text{ nm} \) can be used. Moreover, the instability of the lamp radiation intensity is \( n_1 = 2 \times 10^{-3} \), or \( A_1 = n_1 I_1 = \pm 0.16 \text{ mW nm}^{-1} \text{ mm}^{-2} \).

The second radiant 2 - a solid laser manufactured by NKT Photonics (Denmark), model SuperK EXTREME EXR-20, working in conjunction with a tunnel acousto-optical filter, model SuperK VARIA, provides a maximum radiation spectral density of \( I_2 = 6.4 \text{ mW nm}^{-1} \text{ mm}^{-2} \). Since this type of lasers has options for adjusting power, central wavelength, and emission bandwidth, they therefore provide quasi-monochromatic radiation of a given denomination in a wide dynamic range. Lasers also have an input to control their power through a negative feedback signal. As is known, laser power stabilization systems built on the principle of negative feedback provide relative fluctuations in the radiation power of no worse than \( 10^{-4} \) or 0.01% [9]. These lasers with a feedback system provide instability no worse than \( n_2 = 3 \times 10^{-5} \) or \( A_2 = n_2 I_2 = \pm 2.10^{-4} \text{ mW nm}^{-1} \text{ mm}^{-2} \).

Integrator mixer 3, for example, the Hydra model of optical signals with an integrated sphere with a diameter of 20 mm, with a transmittance of \( k < 0.9 \).

Optical negative feedback devices 4 include a neutral absorption filter, a photodetector (for example, a silicon photodiode) and an amplification-conversion unit connected to a laser device (second emitter). As such devices, standard optical elements can be taken, for example, manufactured by Thorlabs, USA.

Preliminary calculations show that when using these elements, it is possible to obtain radiation with an intensity of \( 7.78 \times 10^{13} \text{ W m}^{-3} \), which corresponds to the thermodynamic temperature of an absolutely black body equal to \( T = 5910 \text{ K} \). In this case, the stability of the total radiation can be achieved no worse than \( 10^{-4} \). According to our estimates, using this method, it is possible to obtain high-intensity quasi-monochromatic radiation in the wavelength range \( \lambda_0 = 400-2000 \text{ nm} \) with a bandwidth \( \Delta \lambda = 5-100 \text{ nm} \).
3. An alternative method for reproducing and transferring a unit of thermodynamic temperature

The proposed method is based on the advantage of monochromatic lasers over other sources — their high power. A block diagram illustrating the method is presented in fig. 2. It is proposed to reproduce and transfer a unit of thermodynamic temperature by transferring the surface density of the radiation flux from the monochromatic laser 1 to the measuring device - radiation thermometer 9 and to equate it with the equivalent temperature. Since the surface density of the radiation flux is directly related to the thermodynamic temperature through the Planck’s formula, the transfer of the surface density of the radiation flux to the measuring device simultaneously means the transfer of the value of the thermodynamic temperature to it, i.e. its units (kelvin) at the selected temperature level. To implement the method, it is necessary that monochromatic radiation be uniformly distributed in a given section and uniformly propagate from a given section into half-space (into a solid angle equal to \( \omega = 2\pi \text{ sr} \)), i.e., that the radiation is similar to the radiation of a Lambert’s source.

According to the proposed method, in the process of transmitting a temperature unit in a given section, a predetermined surface radiation flux density from a monochromatic laser 1 is created, it is measured, for example, using a photo-detector 6, and it is virtually considered equal to the surface flux density of an absolutely blackbody in a specific spectral range in the same given section. Then, the Planck formula is used for the spectral energy brightness of an absolutely blackbody and the desired thermodynamic temperature corresponding to the specifically measured surface density of the radiation flux from a monochromatic laser is calculated from it. These operations are described by the following relationships:

\[
q_m = \int_0^\infty \tau(\lambda)L_{b,\lambda}(\lambda, T) d\lambda, \quad (1)
\]

where \( q_m \) - the measured surface density of the radiation flux created by the monochromatic laser 1; \( \tau(\lambda) \) - the spectral transmittance of the band-pass optical filter 4, which sets the radiation spectrum, perceived from a completely black body; \( L_{b,\lambda}(\lambda, T) \) - the spectral energy brightness of a completely black body, which is calculated according to the Planck’s formula; \( \lambda \) - the radiation wavelength; \( T \) - the thermodynamic temperature.

The ratio for the spectral energy brightness according to the Planck’s formula for the emission of a blackbody in air (normal conditions) has the form:

\[
L_{b,\lambda}(\lambda, T) = \frac{2hc^2}{n^2\lambda^5} \exp\left(-\frac{hc}{n\lambda kT}\right), \quad (2)
\]

where \( h \) - the fundamental Planck’s constant, \( c \) - the speed of light in vacuum, \( n \) - the refractive index of air, \( k \) - the fundamental Boltzmann’s constant. The calculation of the thermodynamic temperature \( T \) is performed according to the relations (1),(2). Then, after measuring the surface radiation flux density \( q_m \) and calculating the thermodynamic temperature, the response of the radiation thermometer 9 to the indicated radiation is recorded and the calculated value of the thermodynamic temperature is put in correspondence with this response. In this transfer of the temperature unit at a given temperature level is carried out.

To create monochromatic radiation, which is uniformly distributed and evenly distributed into a half-space in a solid angle of \( 2\pi \text{ sr} \) in a given section, a combination of the following series-optically connected elements is used: monochromatic laser 1, laser beam expander 7, iris diaphragm 13,
photometric sphere 2, calibrated diaphragm 3. Using a photometric sphere 2, the monochromatic radiation power is evenly distributed over the cross section of the first calibrated diaphragm 3, while the radiation from its cross section propagates into half-space similarly to Lambert’s radiation. Using the calibrated diaphragm 3 mounted on the output port of the photometric sphere 2, within the specified accuracy, the cross section of the radiation beam with a diameter $d_1$ is set. The laser beam expander 7 allows you to change (in particular, expand) the original diameter of the laser beam and at the same time performs two functions:

1. When the aperture of the iris diaphragm 13 is greater than or equal to the diameter of the input port of the photometric sphere 2, expanding the diameter of the laser beam significantly reduces the energy density at the place the laser beam first hits the photometric sphere — this significantly reduces the overheating of the photometric sphere and ensures its normal functioning.

2. When changing the aperture of the iris diaphragm 13 from a certain minimum value to a value equal to the diameter of the input port of the photometric sphere 2, the laser beam expander 7 provides the possibility of wide-range adjustment of the power of the laser radiation supplied to the photometric sphere. For example, with a multiplicity of increase equal to $\eta=10^x$, the power can vary on 100 times, with a multiplicity equal to $\eta=16x$ – on 256 times.

The specified combination of the above devices allows with a given accuracy to reproduce a given surface density of the radiation flux. This radiation flux density is virtually assumed to be equal to the surface density of the radiation flux of a completely blackbody in a given spectral range, and it is numerically equal to the integral of the spectral energy brightness of a completely blackbody over a given spectrum. Thus, a specific thermodynamic temperature $T$ is associated with the indicated surface radiation flux density $q_m$. As a result, the dependence of the thermodynamic temperature $T$ on the surface flux density $q_m$ generated by a particular monochromatic laser 1 is obtained.

As follows from relations (1), (2), in order to find the desired thermodynamic temperature $T$ by the Planck’s formula, it is necessary to know the surface density of the radiation flux of the monochromatic laser $q_m$ and the spectral transmittance of the optical system $\tau(\lambda)$. The spectral transmittance $\tau(\lambda)$ is completely determined by the spectral transmittance of the band-pass optical filter 4, which is installed on the input port of the radiation thermometer 9. Obtaining numerical values of $\tau(\lambda)$ does not present any difficulties - they are accurately measured in advance by existing spectrum analyzers. The measurement of the surface flux density of a monochromatic laser radiation $q_m$ is also not a problem - for measuring $q_m$, for example, a quantum trap-detector 6 with a known quantum efficiency $[10, 11]$ is used, the value of which was previously, previously and once measured, for example, using the absolute cryogenic radiometer. The calculation of $q_m$ is performed according to the ratio:

$$q_m = \frac{hc}{QED\lambda_m e GF} I_{TR}, \quad (3)$$

where $QED$ - the quantum efficiency of the trap-detector 6, measured under normal conditions in the air; $e$ - the electron charge; $\lambda_m$ - the radiation wavelength of the used monochromatic laser; $G$ - the configuration factor, $F=\pi r^2/4$ - the cross-sectional area of the first calibrated diaphragm 3; $I_{TR}$ - the measured signal of the trap detector (photocurrent). In the case when it is required to reproduce a very high temperature, the equivalent surface density of the laser radiation flux may turn out to be so high that it will exceed the maximum allowable for the trap-detector and radiation thermometer. In this case, the band-pass optical filter 4 is equipped with a neutral optical filter 8, further attenuating the radiation, while the attenuation coefficient of this filter 8 is considered known with a given accuracy.

As a result of the above operations, the surface radiation flux density $q_m$ in the cross section of the first calibrated diaphragm 3 is determined with a given accuracy and the specific thermodynamic temperature $T$ corresponds to it, i.e. it is reproduced, equal to a specific number of units of kelvin, which can then be transferred to a specific means of measurement - radiation thermometer 9. The power $P_L$ monochromatic laser 1, which is required to reproduce kelvin at a given thermodynamic temperature, is determined as follows. Based on the given thermodynamic temperature, the required
surface radiation flux density $q_m$ is calculated from relations (1),(2), and previously known values of $\tau(\lambda)$ are used. Then, the laser power is calculated by the ratio:

$$P_L = q_m F/ (\tau_R \tau_F),$$

(4)

where $\tau_R$ - the transmittance of radiation by the laser beam expander 7, $\tau_F$ - the transmittance of radiation by the photometric sphere 2.

Figure 3 presents examples of graphic dependences of the power $P_L$ calculated on the ratio (4) on the required thermodynamic temperature for spectra of different widths $\Delta \lambda = 1$ nm, $\Delta \lambda = 3$ nm. The calculations were performed for the wavelength of laser radiation equal to $\lambda_0 = 532$ nm, the diameter of the first calibrated diaphragm 3, equal to $2r_1 = 2$ mm, and the parameter values equal to $\tau_R = 0.8$ were adopted; $\tau_F = 0.5$. Figure 4 shows an example of the dependence of the maximum thermodynamic temperature $T_{max}$ on the bandwidth of a given spectrum $\Delta \lambda$, which can be achieved using a laser with a specific power $P_L = 5$ W at a laser wavelength of $\lambda_0 = 532$ nm, the diameter of the first calibrated diaphragm 3 equal to $2r_1 = 2$ mm; $\tau_R = 0.8$; $\tau_F = 0.5$. It was found that the maximum thermodynamic temperature $T_{max}$ is inversely proportional to the fourth power of the bandwidth, i.e. $T_{max} \sim \Delta \lambda^{-1/4}$.

Depending on the type of equipment used at the current level of technological development, the proposed method for the estimates made provides the total relative standard uncertainty of reproduction and transmission of kelvin in the range from $5 \times 10^{-4}$ to $10^{-3}$.

4. Conclusion
The above-considered problem of accurate reproduction of high temperatures and the concomitant problem of generating high-power radiation, in our opinion, can be solved with the help of our technical solutions. We hope that specialists in the field of temperature measurements will duly appreciate the practical significance of the proposed methods.

References
[1] Pronin A N 2019 The evolution of the international system of units (SI) requires new standards (Chief Metrologist № 1) pp 32-38
[2] GOST 8.558-2009 (RU) State verification scheme for temperature measuring instruments
[3] GOST 8.566-2012 (RU) State system for ensuring the uniformity of measurements. Blackbody radiant. Verification and Calibration Technique
[4] Ogarev S A, Khlevnoy B B, Samoilov M L et al. 2015 High-temperature blackbody models for photometry, radiometry, and radiation thermometry (Measuring Technique № 11) pp 51-55
[5] Martin M J, Mantilla J M, D del Campo, Hernanz M L, Pons A & Campos J (2017) *Performance of Different Light Sources for the Absolute Calibration of Radiation Thermometers (Int. J. Thermophys* vol 38 № 9) pp. 138-151

[6] Saunders P, Woolliams E, Yoon H and al. 2018 *Uncertainty estimation in primary radiometric temperature measurement (www.bipm.org)* 70 P

[7] Klaus A, Graham M *Thermodynamic temperature by primary radiometry (Phil. Trans. R. Soc. A* 374: 20150041) 17 p [http://dx.doi.org/10.1098/rsta.2015.0041]

[8] Khodunkov V P 2017 *Problem aspects of high temperature referral metrology (Journal of Physics: Conf. Series* vol 891) 7 P

[9] Klimkina Yu Yu, Bilenko I A 2012 *Unsteady fluctuations in the intensity and direction of radiation of a YAG laser (Bulletin of the Russian Academy of Sciences. Physical Series* vol 76 № 12) pp. 1431-1433

[10] Meelis Sildoja, Farshid Manoocheri, Mikko Merimaa et al. 2013 *Predictable quantum efficient detector: I. Photodiodes and predicted responsivity (Metrologia 50)* pp. 385–394

[11] Khodunkov V P *Quantum trap detector* RU patent № 2659329 bul №19 (2018)