Problem aspects of high temperature referral metrology

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Abstract. The main problematic aspects of the reproduction and transmission of a unit of temperature by a direct method are considered. The methodology and hardware for its implementation are considered. An estimate of the expected uncertainty in the measurement of the thermodynamic temperature is given.

1. Introduction

The problem of increasing the sensitivity and accuracy of measurements of physical quantities is becoming more and more topical in order to ensure reliable and early diagnosis of various processes and complex technical systems, and to meet the requirements for product quality.

One of the most promising ways to solve this problem is the use of refined values of fundamental physical constants on the basis of macroscopic phenomena of quantum physics, which are the subject of research in such fields of science as quantum thermophysics and quantum metrology [1, 2]. This approach will significantly increase the accuracy of the standards of basic and derived SI units and will give a powerful impetus to the development of precision instrumentation. Quantum metrology and quantum thermometry, in particular, has such a great potential that it requires close attention of specialists. Some of its sections, especially those related to the reproduction and transfer of temperature units, are developing rapidly abroad, as a result of which new types of precision measuring converters, devices and systems are being created. Quantum and thermodynamic processes in macroscopic quantum systems that involve the use of predictable and controlled quantum (radiation) flows lie at the basis of the developed methods and means of measuring quantum thermometry.

The modern progress achieved in photonics allows us to hope that in the next few years controlled radiation streams will be created with an exactly defined number of photons per second. This gives impetus to the development of metrology, based on new quantum standards and new quantum calibration methods [3-9]. The forthcoming approval in 2018 of a new definition of the temperature unit - Kelvin - can be regarded as an extremely important step in the future of photometry and radiometry and in the emergence of a new thermophysical direction, discipline - quantum thermometry. As planned, the new formulation of Kelvin will be in harmony with the proposed redefinitions of four of the seven basic units of the SI system (kilogram, ampere, candela and mole) in terms of fundamental constants.
2. Methodology

2.1. Description of the problem

In the classical radiometry of high-energy flows, the primary optical radiation scale for sources and receivers is based on an absolute cryogenic radiometer with a traceable connection to the SI unit system through electrical units. For the ultraviolet and infrared regions of the spectrum, primary scales are based on calculated sources, such as the synchrotron or Planck radiator with traceability to the SI unit system through units of thermometry, electricity and length [3-4].

One of the problems of modern radiometry is caused by the breadth of the range of radiometric measurements. The dynamic range of radiometry extends more than 13 orders of magnitude, so different types of instruments and different physical principles are used for its implementation. In this connection, for radiometric quantities and radiometric units, communication with the SI unit system is more complex, especially for establishing such a connection in the full dynamic range. Solving these problems involves working out three main issues.

1. Improvement of the measurement procedure using an absolute cryogenic radiometer (calorimeter) to implement a direct method of reproducing a unit of temperature.
2. Improvement of the measurement procedure using quantum trap-traps based on photodiodes with 100% internal quantum efficiency due to fundamentally new designs and taking into account additional components of the measurement error.
3. Practical realization of the approximation to the method of counting photons (quanta of radiation energy) due to the joint use of high-precision laser and trap-trap.

2.2. Hardware high-temperature radiometry

Absolute radiometer - receiver with calibration by the method of substitution by electric power, is a tool that allows to detect and estimate the level of incident infrared radiation and compare it with the equivalent effect of an electrical signal, i.e. Get a binding to the electrical units of the SI system. The principle of operation of an absolute radiometer is to compare the thermal efficiency of the power of infrared radiation with the corresponding amount of electrical thermal power, which is now commonly called electrical substitution (ES). The basis of the concept of ES is that the thermal effect from the action of substituting electrical energy is directly equivalent to the thermal effect from the effect of the measured optical (infrared) power, i.e. the heat flux and thermal paths from each energy source are directly equivalent.

Unfortunately, the ideal equivalence of the absolute radiometer is not yet achieved, which is due to the following reasons:
- loss of power of optical radiation due to its incomplete entry into the receiving element;
- the presence of the band characteristic of the receiving element (the dependence of the output signal on the location of the beam in the receiving element and the relative distribution power over the beam cross section);
- the equivalence of the replacement of the optical power of the electric power due to the difference in the conditions of propagation of the heating energy, due to the influence of current-carrying wires, etc;
- the influence of background illumination and other sources of interference.

The absolute radiometers - the cryogenic radiometer (ACR) [10], which is used for a power level of several milliwatts, and the calorimeter [11], which is used for power levels on the order of several watts or even a few kilowatts, are most widely used. The most frequently used sources in absolute radiometry are blackbody models and synchrotron radiation sources (synchrotrons) based on electron accelerators. These photon sources create optical radiation in a wide spectral range, and their output power can be calculated from fundamental principles based on the knowledge of certain physical parameters. The source based on the black body model is used to obtain a connection between the
level of its radiation and its temperature, i.e. to obtain traceability to the International Temperature Scale. In this regard, according to a number of researchers, a promising direction is the use of an absolute cryogenic radiometer together with a radiator based on the model of an even body tied to a triple point of water.

Advances in the field of laser engineering make it possible to look with optimism at the possibility of using lasers stabilized in frequency and power in radiometry and photometry, i.e. to use the space of a laser stabilized in frequency and amplitude placed in joint with the ACR. The advantages of ACR include high sensitivity of the device, low background of parasitic radiation and, as a result of all this, potentially high accuracy of measurements. Among the main shortcomings of ACR are:

- low level of measured signals and their narrow dynamic range;
- necessity of vacuuming the device;
- necessity of use liquid helium during operation.

All this significantly complicates and increases the cost of the measurement process with the use of ACR. In addition, ACR is inherent in many components of the measurement error characteristic of calorimetric meters. These are the above-described error components due to the band characteristic, the nonequivalence of substitution, and the like. Since the cryogenic radiometer is a complex measuring instrument associated with the basic units of the SI system and has the potential for unknown and, accordingly, unrecorded systematic errors, which can then be extended to all other radiometric quantities [4]. Therefore, the development of alternative measurement methods with a comparable level of uncertainty, ideally associated with fundamental constants, will allow for more reliable independent comparisons and ensuring the reliability of reproduction of radiometric and photometric units.

Another, promising development of methods is the use of so-called predictable quantum effective detectors (PQED), which are predicted to be able to completely replace the absolute radiometer. The combination of ACR, a model of an absolutely black body (ABB), a quantum detector, and a laser stabilized in amplitude and frequency is based on the following fundamental conclusions and relationships.

2.3. Theoretical relationships

It is well known that any matter with a temperature above absolute zero emits electromagnetic energy. For special types of bodies, or so-called absolutely black bodies, the radiated energy can be calculated according to the Planck radiation law, which describes the spectral density of the energy brightness of the ABB as a function of its thermodynamic temperature [12]:

\[
L_{b,\lambda} = \varepsilon(\lambda, T) \left( \frac{C_1}{\lambda^2} \exp\left(\frac{C_2}{\lambda T}\right) - 1 \right) = \varepsilon(\lambda, T) \left( \frac{2\pi^2 \lambda^3}{C_2} \frac{1}{\lambda^2} \exp\left(\frac{C_2}{\lambda T}\right) - 1 \right),
\]

where: \(L_{b,\lambda}\) - spectral density of energy brightness, W/m\(^3\) or W/(m\(^2\)×nm); \(\varepsilon(\lambda, T)\) is the spectral emissivity of the ABB (\(\varepsilon(\lambda, T) \approx 0.9995\)); \(\lambda\) is the length of the electromagnetic wave, m; \(h=(6.6260755\pm0.00023)\times10^{-34}\) - Planck constant, J×s; \(c=1.602176462(65)\times10^{-19}\) is the elementary charge, (A×s); \(c=2.99792458\times10^8\) - speed of light in vacuum, m/s; \(k=1.38064852\times10^{-23}\) is the Boltzmann constant, J/K; \(C_1=2\pihc=3,74177118\times10^{-16}\) - the first coefficient in the Planck law, W×m\(^2\); \(C_2=\frac{hc}{k}=1.4387752(25)\times10^2\) - the second coefficient in the Planck law, m×K; complex \(hc/e = (1239.84193 \pm 0.00005)\), W×nm/A; \(T\) is the thermodynamic temperature, K.

According to Planck's quantum theory, the spectral power of the radiation flux of the ABB \(P_b\) can be expressed in two ways. In the first method - through the spectral density of energy brightness:

\[
P_b = L_{b,\lambda} \times \lambda \times A_1,
\]

In the second method - through the number of photons emitted per unit time and the photon energy:

\[
P_b = N_{ph} \times \frac{hc}{\lambda},
\]

Where \(A_1\) is the area (aperture) of the emitting surface of the ABB, m\(^2\); \(N_{ph}\) - the number of photons emitted per unit time from the surface \(A_1\), photon/s; complex \(hc/\lambda\) is the energy of one photon, J.

The first of these two, the relation (2), is used in the measurement (reproduction) of the
thermodynamic temperature of the ABB with an absolute cryogenic radiometer (ACR), whose operation is based on converting the energy of the incident photon into phonon energy, i.e., the electromagnetic wave into a sound wave, as a result which, according to the quantum theory of the heat capacity of Einstein, changes (increases) the heat capacity of the body to which radiation falls. The change in the heat capacity of the body (the receiving element of the ACR) causes an increase in its temperature, which is measured on the basis of the principle of electric power substitution. With this method of measuring the thermodynamic temperature, its main design formula is found from the relation connecting the power of the $P_{in}$ radiation incident on the receiver to the spectral density of the energy brightness of the ABB $L_{b,\lambda}$, measured by the method of electrical substitution:

$$P_{in} = I_{CR}/S_{CR}(\lambda) = L_{b,\lambda} \times \lambda \times A_1 \times F_{A1-A2} \times \epsilon_{CR}(\lambda, T) \times \eta_{OS}(\lambda), \quad (4)$$

where $I_{CR}$ is the electric current of the cryogenic radiometer ACR, $A$: $S_{CR}(\lambda)$ is the spectral sensitivity of ACR, $A/W$: $F_{A1-A2}$ - the configuration factor of the optical measurement system (Figure 1); $\epsilon_{CR}(\lambda, T)\approx 0.9999$ is the spectral absorption coefficient of the emission of the receiving element of the ACR [10]; $\eta_{OS}(\lambda)$ is the transmittance of monochromatic radiation by the optical system. The configuration factor $F_{A1-A2}$ in its physical essence determines the regularity of the energy density decrease with increasing distance from the radiation source is found as the ratio of the 2 solid angles inscribed inside the input and output apertures of the optical system and is determined by their geometric parameters: radii and the distance between them (Figure 1):

$$F_{A1-A2} = \frac{1}{2} \left\{ (r_1^2 + r_2^2 + d^2) - \sqrt{(r_1^2 + r_2^2 + d^2)^2 - 4d^2r_2^2} \right\} / r_1^2. \quad (5)$$

In the considered problem of reproducing a unit of thermodynamic temperature and constructing a temperature scale, the main role is played by a radiometric system, the main components of which are: a radiation source - ABB and a radiation receiver - either an absolute cryogenic radiometer, or, as suggested by a number of researchers, a predictable quantum effective detector with a known (predicted) spectral sensitivity. In general, the schematic structure of such a radiometric system has the form shown in Figure 2.

Reproduction and transmission of a unit of temperature by thermal radiation by the radiation direct method is performed in four stages:

1. Measurement of the power of the stabilized laser by an absolute cryogenic calorimeter.
2. Calibration of a special radiation detector (trap-detector, PQED) with a power laser.
3. Calibration of a special radiation source (laser with an integrating sphere) by a power trap-detector.
4. Transmission of a unit of temperature calculated from the power of a special radiation source (laser with an integrating sphere), a reference radiation thermometer.
In the case of using as a radiation detector of the PQED, the spectral power of the incident \( P_n(\lambda) \) incident on it, expressed in terms of a photocurrent \( I_{\text{photo}} \), is determined by the relationship:

\[
P_n(\lambda) = I_{\text{photo}}/S_0(\lambda),
\]

where \( S_0(\lambda) \) is the spectral sensitivity of the detector PQED, A/W; \( I_{\text{photo}} = I_{\text{photo}}^* - I_{\text{dark}} \); \( I_{\text{photo}}^* \) - registered photocurrent, A; \( I_{\text{dark}} \) - dark current of photodiode, A.

The derivation of the relation connecting the thermodynamic temperature of the radiator of the ABB and the detected photocurrent strength of the PQED. The recorded power of the pin incident on the photodetector is:

\[
P_n = P_b \times F_{A1-A2} \times \eta_{OS}(\lambda) \times QED = N_{ph} \times F_{A1-A2} \times \eta_{OS}(\lambda) \times QED \times h\nu/\lambda,
\]

where \( QED \) is the quantum efficiency of the photodetector (for PQED \( QED = 0.99995 \)). We artificially multiply the right-hand side of the relation by \( c/e \) (\( e \) is the elementary charge), we obtain:

\[
P_n = N_{ph} \times e \times F_{A1-A2} \times \eta_{OS}(\lambda) \times QED \times h\nu/e,
\]

In this ratio two complexes are distinguished:

\[
I_{\text{photo}} = N_{ph} \times e \times F_{A1-A2} \times \eta_{OS}(\lambda) \times QED
\]

and \( S_0^{*(\lambda)} = h\nu/e, \)

which are consistent with the relation (6), in which: \( S_0^{*(\lambda)} \) is the spectral sensitivity of an ideal photodetector with \( QED = 1.0 \); complex \( N_{ph} \times F_{A1-A2} \times \eta_{OS}(\lambda) \times QED = N_{phin} \) is the number of photons incident on the photodetector surface per unit time. Expressing the parameter \( N_{ph} \) from the relation (9) and substituting it into the relation (3), we obtain the ratio for the power of the radiation flux of the ABB:

\[
P_b = N_{ph} \times h\nu/\lambda = I_{\text{photo}} \times h\nu/e \times F_{A1-A2} \times \eta_{OS}(\lambda) \times QED.
\]

Solving equation (10) together with (2) and (1) with respect to the temperature \( T \), we obtain the required relation:

\[
T = \frac{C_2}{\lambda \cdot \ln \left( 1 + \frac{2\pi \cdot e \cdot QED \cdot \eta_{OS} \cdot A_1 \cdot F_{A1-A2}}{\lambda^3 \cdot I_{\text{photo}}} \right)},
\]

which, taking into account the values of the physical constants \( c, e, C_2 \), takes the form:

\[
T = \frac{1.4387752 \cdot 10^{-2}}{\lambda \cdot \ln \left( 1 + 3.017942 \cdot 10^{-10} \frac{QED \cdot \eta_{OS} \cdot A_1 \cdot F_{A1-A2}}{\lambda^3 \cdot I_{\text{photo}}} \right)}.
\]

3. Estimation quantum efficiency of the PQED and standard uncertainty of measuring the thermodynamic temperature

The system of equations (1), (2) and (10) physically means that the power measured by the quantum detector is equivalent to the power incident on the receiver from the Lambert radiator at the same wavelength in the given solid angle and the viewing direction, or else the recorded photocurrent is a measure of the spectral energy brightness of monochromatic radiation and, ultimately, a measure of the desired thermodynamic temperature.

Let us analyze the physical quantities included in the calculated relation (11). The most important from the point of view of minimizing the measurement uncertainty is the exact knowledge of the parameter - the quantum efficiency of the photodetector \( QED \), which is close to \( QED = 0.99995 \) at room temperature. \( QED \) is the physical quantity characterizing the photosensitivity of the detector, equal to the ratio of the number of photons, the absorption of which by the receiving element of the detector caused the formation of charge carriers, to the total number of absorbed photons. The quantum efficiency of a photodetector is expressed in % or in relative units and is calculated by the ratio:

\[
QED = [1 - \delta(\lambda)] \times [1 - \rho(\lambda)],
\]

in which: \( \delta(\lambda) \) is the coefficient of spectral losses due to the internal quantum deficit of photodiodes; \( \rho(\lambda) \) is the coefficient of spectral losses due to the reflection of the \( QED \).

Another important characteristic of the PQED, which is included in the practical design formula for
temperature (see relations (10), (11)) is the a priori predicted spectral sensitivity $S_{Dp}(\lambda)$, which is calculated by the relation:

$$S_{Dp}(\lambda) = e^\delta hf \times QED = e^\delta hf \times [1 - \rho(\lambda)] \times [1 - \rho(\lambda)],$$

(14)

Taking into account the specific values of the fundamental constants and in view of the smallness of the coefficients $\rho(\lambda)$, $\delta(\lambda)$, relation (14) can be represented as:

$$S_{Dp}(\lambda) = \lambda \times [1 - (\delta(\lambda) + \rho(\lambda))] / 1239.8493.$$  

(15)

For an example, we give the quantitative values of the spectral sensitivity of the PQED $S_d(\lambda)=S_{Dp}(\lambda)$ for two wavelengths - 532 nm and 800 nm, obtained experimentally by the developers of the PQED for room temperature [13]:

- wavelength $\lambda=532$ nm; $\rho(\lambda)=6.62\pm0.05$ ppm, $\delta(\lambda)=9+130-7$ ppm $\rightarrow S_d(\lambda)=0.429080 \text{ A/W};$
- quantum efficiency of PQED $QED=0.99998$;
- wavelength $\lambda=800$ nm; $\rho(\lambda)=37\pm16$ ppm, $\delta(\lambda)=11+180-9$ ppm $\rightarrow S_d(\lambda)=0.645212 \text{ A/W};$
- quantum efficiency of PQED $QED=0.99995$.

Thus, we can assume that the standard uncertainty of measuring the thermodynamic temperature due to the components of $S_d(\lambda)$ and $QED$ when using the PQED does not exceed 100 ppm. In this connection, it can be expected that a comparison of the developed PQED with a cryogenic radiometer will give a low uncertainty of about 30 ppm [14]. The determination of the limits of the reproduced temperatures depends entirely on the expected level of the measured current signal of the photodiodes forming the trap detector and their actual dark current. The values of the dark currents applied in the photodiode PQED are within $I_{\text{dark}}=16-30 \text{ nA}$, and their maximum values can reach $I_{\text{dark,max}}=1200 \text{ nA}$. That is why the investigation of dark currents of the PQED is one of the most important and urgent tasks solved within the framework of the problem of creating a new standard of temperature. On this depends the subsequent selection of the sizes of optical elements - the diameters of the apertures and the distance between them, in turn, determining the power of the radiation flux incident on the PQED and the photocurrent generated by it.

Another important aspect of the application of quantum detectors is the choice of optimal wavelengths. In contrast to the cryogenic radiometer, when using the PQED as a reference, the spectral composition of the incident radiation significantly affects the accuracy of the measurements. Mainly, this influence consists in the clearly expressed spectral dependence of the reflectivity of the PQED, the function of the reflecting plate, the current generated by it is too small for accurate recording. Therefore, it seems that the wavelengths $\lambda=532 \text{ nm}$ and $\lambda=950 \text{ nm}$, traditionally used in radiometry, for which $I_{\text{photo}}/I_{\text{phot2}}=5 \div 6$, are optimal from the point of view of a compromise between the reflective losses and the signal-to-noise ratio of the PQED.

4. Conclusions

Above we briefly show only some of the modern aspects of quantum thermometry. An analysis of the achieved level of development of quantum thermometry revealed the following priority tasks, subject to an early resolution:

- Development of primary standards for absolute radiometry with an uncertainty of 1 ppm in the visible and infrared wavelengths using predictable quantum detectors, the optimization of measurements at low temperatures due to:
  - improving the quality of modeling and accounting for the loss of charge carriers of quantum detectors;
  - design and manufacture of special photodiodes with close to unity internal quantum efficiency, for example - new-generation photodiodes based on the application of a nanostructured surface providing a quantum yield of a single photodiode of $\sim 96\%$ [15];
- expected ultra-low measurement uncertainty using advanced cryogenic radiometers based on the principle of electrical substitution;
- estimates of the stability of quantum detectors for a long time.

- Establishment of traceability to spectral radiometry using primary standards operating at room temperature, including:
  - traceability of radiometry and photometry at uncertainty of 100 ppm;
  - development of models and issues related to the polarization of radiation;
  - wide dynamic range of quantum detectors;
  - evaluation of the reliability of standards and their stability over time;
  - assessment of ease of use;
- extending the use of predictable quantum room temperature detectors to metrological institutions that do not have access to cryogenic radiometers, and to the industry to reduce the chain of traceability at the regional and international levels.

According to the results of scientific research and development it is expected that it will be possible to achieve uncertainty values well below 0.1% at room temperature, i.e. such uncertainty as is currently required for most radiometric applications in health, environmental and industrial control.

Thus, the radiometric community is ready to develop new self-calibrating devices, which potentially reduces the need to remove instruments from their application for calibration.

5. References

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