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CALIBRATION OF RADIATION SOURCES AND DETECTORS OVER A BROAD RANGE OF MEASUREMENT OF THE ENERGY OF OPTICAL RADIATION

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A method of calibration of devices used to measure energy by means of a calorimeter and reference photodiode is described. Experimental results of the calibration are presented. Through the use of the method, energy meters, photodetector devices, and radiation sources may be calibrated over a range more than 10^8 times the measured radiant energy with the use of time conversion.
Keywords: *calibration, energy, detector, energy source.*

Through classical methods of transmission of radiant energy it is possible to calibrate devices whose measurement range differ from standards by not more than 10^5 or 10^6 times the measured radiant energy [1, 2]. Devices for conducting calibration of these methods have error of 4–5% in the best case [3]. The basic problem that has to be overcome in the construction of the devices is to eliminate scattered light in the measurement circuit [4]. The upper limit of the linearity of the conversion characteristic of photoelectric radiation detectors used in instruments that measure radiant energy does not exceed $1 \cdot 10^{-7}$ J. Calibration of photodetectors at lower energy levels may be performed by comparison with a reference photodiode. A range of measurement of energies greater than 10^{-3} J is achieved by calibrations performed by means of calorimeters [5].

Special methods are needed in calibration of measuring instruments in the range 10^{-7}–10^{-3} J. Most of these methods are used in calibration of instrument used to measure energy in other ranges as well. There is a method of transmitting the units of energy and power in the dynamic range to 10^9 times the measured energy [6, 7]. The unit of power is transmitted to a comparison photometer containing a photoelectric radiation detector and load circuit from a resistor R to a capacitor C, one of the well-known methods according to State Standard GOST 17333–80, *Photoelectronic Devices. Methods for Measurement of the Spectral Sensitivity of Photoelectric Cathodes*. The absolute spectral sensitivity of a photodetector device with source of continuous radiation is also measured. It is only necessary to multiply the resulting value of the sensitivity expressed in units of power by the time constant of the RC circuit of the photodetector in order to obtain the sensitivity expressed in energy units. The unit of energy is transmitted by a comparison photometer to a pulsed source of radiation, for example, a light-emitting diode (LED) with sufficiently short length of the pulse characteristic. The LED is a source of a δ-pulse of radiation for the comparison photometer and the calibrated photodetector devices. A working standard of low-level energy with error in the transmission of the unit 2–3% may be obtained by this method. The method is used to calibrate primary series-produced pulse photoelectric photometers [8]. In the method which is being considered here, the sensitivity S of the photodetector device, expressed in units of radiant energy, is found in the case of measurements of the maximal value in the output pulse using the formula

$$S = S_{det}/C, \tag{1}$$

where S_{det} is the sensitivity of the detector expressed in units of power, and C is the capacitance of the integrating capacitor in the photodetector circuit [9].

One version of the present method of calibration is based on a transition from average power to the energy of a semiconductor laser [10]. The energy of a single pulse in a regular sequence of radiation pulses is calculated from the results of measurements of the average power and the pulse repetition frequency. The product of these two quantities yields the value

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of the energy of each pulse in the sequence. A drawback of the method lies in the greater requirements imposed on the linearity of the calibrated detectors relative to current in the pulse as a consequence of the large relative pulse duration.

Method of calibration with time conversion. Let us now consider a version of a previously proposed method [6] using a light-emitting diode functioning in a pulse regime and radiating a rectangular pulse of power P with known duration t and energy $W = Pt$. The present source of radiation is used as a comparison source in the transmission of the unit of radiant energy from a calorimeter with time constant greater than the pulse length to a photodiode with integrating capacitance and back. The maximal length of the photodiode is selected with the use of a calorimeter and the minimal length, by a photodiode, so that the radiant energy not exceed the upper measurement limit of the photodetector. The measured ratio of the length of the pulses characterizes the variation of the radiant energy.

In [9, 11], it is proposed that the fundamental pulse be modulated by means of auxiliary pulses for digital processing of measurement results in a calibration performed by the present method. The drawback of the method lies in the decrease in the dynamic range of calibration by a factor equal to the relative duration of the modulating pulses. Another drawback is that in the case of short pulses and high currents the amplitude of the modulating pulses is not established immediately, but instead grows by an exponential law, leading to an additional measurement error. In order to obtain the maximal range of calibration it is best to use the entire length of the pulse. In this case, the calibration range is expanded, which makes it possible to compare two detectors that differ in terms of sensitivity by more than 10^6 times the measured energy by means of direct measurements. The magnitude of the energy may be converted into the value of the power of the pulse relative to its length.

An additional systematic measurement error is due to the finite nature of the calorimeter's time constant in the case of the greatest pulse length. At the end of an input radiation pulse, the calorimeter's detecting element succeeds in partially cooling down, which leads to a decrease in the output electric signal. Cooling occurs according to an exponential law, which may be replaced by a linear law with a small additional error. The systematic component of the measurement error is determined experimentally. For this purpose, two pulses are successively fed to the generator of the radiation pulses, one of maximum length with the length of second pulse one-half as great. The results of a measurement differ by less than half the value of the error δ_τ that arises in the interval of time between the ends of the short and long pulses:

$$\delta_\tau = 2n_1 - n_2,$$

where n_1 and n_2 are the readings of the energy for the short and long pulses.

Such an error appears during the short pulse. A regular reading n, where the long pulse is used is given as $n = n_2 + 2\delta_\tau$, i.e., $n = n_2 + 2(2n_1 - n_2)$. Finally, we obtain

$$n = 4n_1 - n_2. \tag{2}$$

The difference between the computed n and the measured n_2 values of the radiant energy defines the correction to the measurement result. Similar corrections may also be introduced for the short pulses. In this case the error is related to the finite lengths of the front and a section of the radiation pulse. This may be caused by the response time of the radiators or the generators of the electric pulses. The correction is determined in similar fashion. An additional pulse with length a known multiple of the fundamental pulse is generated and the ratio of the readings of the radiation energies for these pulses is checked. If it does not coincide with the ratio of the lengths of the pulses, a correction to the result of the calculation of the radiant energy is calculated. No law defining the decrease in the reading in the case of a short pulse is now known, hence the correction is calculated only with respect to the length of the pulses.

Sources of comparison. A sufficiently powerful radiator is needed to calibrate thermal radiation detectors and detectors used as a comparison source. An additional attenuator is used when working with photoelectric radiation detectors. Such a source may contain LEDs in a regime of stable radiation power and precise variation of the length of the current pulse through the light-emitting diode. Where the radiant energy possesses sufficient stability, the source may be used as a reference for calibration of ordinary detectors and photodetector devices by means of direct measurements. If precise values of the lengths of the pulses of radiation pulses with constant radiated power are specified, the linearity of the scale of the detectors in a radiant energy measurement regime may be specified. Digital generators of the pulse length with stabilization of the reference frequency by a quartz oscillator may be used for this purpose. Such a generator may be fabricated on the base of a

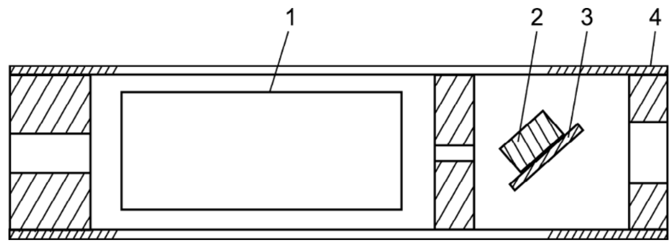

Fig. 1. Schematic diagram of piezoelectric detector of measuring transducer PIP 1–3: *1*) compartment for placement of amplifier; *2*) radiation detector; *3*) detecting surface of screen; *4*) integrating cavity of radiation attenuator.

triggered multivibrator [9]. The output pulse of the multivibrator is generated as a result of a reading of a series of auxiliary pulses with repetition frequency stabilized by a quartz oscillator. The length of the output pulse of the multivibator varies in steps by factors of 4, 16, 64, and 256.

Still another principle underlying the generation of pulses of precise length consists in division of the frequency of a quartz oscillator by means of additional frequency dividers and subsequent addition of the resulting time intervals in the logic elements. A programmable controller that generates the required time intervals is sometimes used. Since such generators are fabricated in individual models, the use of a controller is not economically justified. A stabilized quartz oscillator at a frequency of 1048.57 kHz for expanding the range of pulse lengths to $8 \cdot 10^{-6}$–1 s was used in experimental studies by the present author, which made it possible to vary the energy of the radiation pulses 10^5-fold.

An additional power amplifier produces a selected operating regime of the light-emitting diode based on the linear dependence of the radiated energy on pulse length [6]. Structurally, the radiator should be fabricated in the form of a small autonomous head to enable access to different parts of the calibrated device or plant. To reduce electrical induction in the detector produced by current pulses travelling through the light-emitting diode, the power amplifier is situated in direct proximity to the diode. For this purpose, a head with optical system by means of which the distance between the radiator and the detector may be increased and a beam of radiation of required diameter formed in the detector was used [11]. In a second variant of the head, a semiconductor laser with radiation wavelength 660 nm was used in place of a light-emitting diode. A pulse generator with avalanche transistor and light-emitting diode by means of which a radiation pulse 120 ns in length with maximal power 0.5 W could be generated was used [12].

Comparison detectors. A measuring transducer of the power and energy of pulsed radiation for a broad spectral range was fabricated on the base of a piezoelectric and a pyroelectric radiation detector containing three optical heads for different ranges of measurement of energy.

In the least sensitive head of measuring transducer PIP 1–3 (range of energy measurement $1 \cdot 10^{-3}$–$1 \cdot 10^{-1}$ J), an optical attenuator (cf. Fig. 1) is situated in front of the detecting element. The optical attenuator is in the form of an aluminum cylinder *4* within which an aluminum plate *3* is mounted oblique to the optical axis. Radiation detector *2* measuring 4 × 4 × 6 mm in dimension is glued to the opposite side of the plate. A portion of the radiation is incident on the detecting element following multiple repeated reflections by the casing. In such a construction, the radiation is attenuated roughly 100-fold. More precise adjustment of the attenuation is produced by varying the sensitivity of the electronic circuit in compartment *1*.

In the head of average sensitivity of measuring transducer PIP 3–5 (range of measurement of energy $1 \cdot 10^{-5}$ to $1 \cdot 10^{-3}$ J), a detecting element 8 mm in diameter is coated with a black matte stain and mounted directly in front of the inlet window. The nonuniformity of the sensitivity of the stained element does not exceed 1% in the spectral band 0.2–1 μm. Its sensitivity decreases continuously in the infrared range of the spectrum by 10–15% at a wavelength of 11 μm. Due to the low degree of sensitivity of the radiation detector, its selectivity cannot be determined by direct measurements, hence the reflection factor is measured by the detecting surface. A 300-MΩ resistor in the feedback circuit of a specially developed amplifier serves as the detector load. Through the use of feedback, it becomes possible to partially compensate the capacitance of the radiation detector and the input capacitance of the amplifier. The resulting value of the rise time constant of the signal $1 \cdot 10^{-4}$ s determines the speed of the detector. In the case of lengthy radiation pulses, the detector functions as a device that measures

TABLE 1. Measured Values of Energy and Computed Values of Power of Radiation Pulses of Different Lengths Obtained as a Result of Calibrations of LED Radiator with the Use of an IMO-2N Calorimeter and FD288 Photodiode

Date of calibration	Device	Energy, J	Power, mW	Divergence, %	Length, s
12.28.2016	IMO-2N	$1.800 \cdot 10^{-2}$	21.96	–1.8	1
	FD288	$2.560 \cdot 10^{-7}$	22.36		$12 \cdot 10^{-6}$
01.09.2017	IMO-2N	$10.650 \cdot 10^{-3}$	13.00	–7.7	1
	FD288	$1.070 \cdot 10^{-7}$	14.00		$8 \cdot 10^{-6}$
02.01.2017	IMO-2N	$13.250 \cdot 10^{-3}$	16.20	–20.2	1
	FD288	$2.320 \cdot 10^{-7}$	20.30		$12 \cdot 10^{-6}$
02.02.2017	IMO-2N	8.900	10.86	+7.8	1
	FD288	$1.220 \cdot 10^{-7}$	10.07		$12 \cdot 10^{-6}$
03.09.2017	IMO-2N	$9.780 \cdot 10^{-3}$	11.90	–7.0	1
	FD288	$0.975 \cdot 10^{-7}$	12.78		$8 \cdot 10^{-6}$

the power with sensitivity of around 3 V/W, and in the case of shorter pulses, as a device that measures energy with sensitivity roughly $1.5 \cdot 10^4$ V/J. The threshold energy amounts to $5 \cdot 10^{-8}$ J. Structurally, the radiation detector and amplifier are situated in a common metallic case. The device is connected to a standard oscillograph.

The high-frequency head of measuring transducer PIP 5–7 (range of measurement of energy $1 \cdot 10^{-7}$–$1 \cdot 10^{-5}$ J) utilizes a pyroelectric radiation detector 4 × 4 mm in dimension situated in a metallic case.

For all the heads, the greatest repetition frequency of the measured radiation pulses depends on the integration time constant and amounts to 100–1000 Hz with output voltage $1 \cdot 10^{-3}$–5 V and voltage of the power source 7–12 V. The overall dimensions of the heads are as follows: diameter 22 mm, length 87 mm, and mass 0.5 kg.

The IME-1 low-energy measuring device (threshold energy $1 \cdot 10^{-13}$ J in the spectral range 0.8–1.6 μm) is used to calibrate detectors in the range of nanosecond pulses with radiant energy 10^{-10}–10^{-12} J in the spectral range 0.4–1.8 μm. The device constitutes a measuring transducer with output to an oscillograph. The diameter of the detecting site of the germanium photodiode of the measuring transducer is 3 mm, the sensitivity of the energy measuring device $1 \cdot 10^{10}$ V/J, and the time constant $1 \cdot 10^{-5}$ s. The IME-1 device may be situated in a collimeter 60 mm in diameter. The use of a built-in 3-V power source produces a reduction in electromagnetic leakage in the transducer.

Experimental results. Experimental verification of the newly developed method of calibration of a photodetector device was conducted with the use of two standards, an IMO-2N calorimeter and FD288 reference photodiode. Two sources of radiation were used in the experiments, an AL107B light-emitting radiator with wavelength 0.92 μm with minimal pulse lengths 7.8125 and 11.448 μs for different operating regimes and maximal length 1 s, and a semiconductor laser with radiation wavelength 660 nm in the circuit of a pulse generator with the same pulse lengths and in a continuous operating regime. The radiant energy of the light-emitting diode was selected in accordance with the results of preliminary tests and the recommendations of [6]. The pulse length could be varied precisely two-fold.

The reference photodiode is calibrated annually as a first-order working standard. The IMO-2N calorimeter functions in a regime of energy measurement and average power. The calorimeter in the regime of measurement of average power was compared to a calorimeter calibrated relative to electric power by an Rs 5900 pyroelectric radiometer (Laser Precision Corp., United States) [2] using a laser as a comparison source. Results of measurements by a radiometer of 1.69 mW and by a calorimeter of 1.78 mW were obtained with divergence of 5.3%. The radiant energy of the LED radiator measured by the IMO-2N calorimeter with pulses of lengths 0.5 and length 1 s amounted to 5.94 and 10.7 mJ, respectively. The final result of the measurement of the radiant energy for a pulse of length 1 s determined by formula (2) is as follows: $n = 4 \cdot 5.94 - 10.7 = 13.06$ mJ. The absolute error (correction) then amounts to 2.36 mJ or 22% of the measured magnitude. A coefficient of 1.22 was used for the subsequent measurements and calculations.

Table 1 presents the results of a calibration of a LED radiator with the use of an IMO-2N calorimeter and FD288 photodiode (a sensitivity of $1.64 \cdot 10^7$ V/J at a wavelength 0.92 μm was calculated by formula (1)). The measurements were performed over the course of three months in different operating regimes of the diode. On average, the divergence of the results of the calibration of the comparison source amounted to 8.9%. The dynamic range of the calibration was equal to the ratio of the lengths of the pulses (in the present experiment, 131072-fold for a pulse length 8 μs). It could be increased ten-fold (to 10^6) by varying the clock frequency of the quartz drive oscillator ten-fold if a correction due to the finite length of the front and the pulse edge is introduced. The correction is determined similar to the correction associated with the finite time constant of the calorimeter. The pulse length should not be decreased further due to the limitation on the speed of the light-emitting diode. The pulse characteristic of the AL107B light-emitting diode used in the experiments has a length of 150 ns.

The dynamic range of the calibration may also be expanded by reducing the capacitance in the photodiode circuit. This method was used in calibration of the IME-1 low-energy meter used in the plant to verify the sensitivity of the detection channels of laser range finders. An FD263 photodiode with 3 × 3 mm detection site and sensitivity 0.48 A/W was calibrated. The total capacitance of the FD263 photodiode together with the capacitance of the connecting cable amounted to 675 pF. A sensitivity of the IME-1 in terms of energy $1.82 \cdot 10^7$ V/J at a wavelength of 920 nm was obtained, i.e., the parameter increased 35-fold. The total dynamic range of the calibration may reach $5 \cdot 10^7$. An LED comparison source with generator of a 300-ns current supply pulse was fabricated with the use of an avalanche transistor to calibrate the IME-1 device. A supply voltage amounting to several dozen volts is needed for normal operation of an avalanche transistor, hence a voltage pulse is generated, with amplitude close to the voltage of the supply source, making it possible to successively connect two or more light-emitting diodes. Such a circuit assures that the ratio of the radiant powers of the light-emitting diodes will remain constant as the external factors (supply voltage, temperature, etc.) are varied and makes it possible to use the diodes as radiation attenuators. Attenuation of the radiant energy is produced with the use of diaphragms glued to the light-emitting diodes. For AL107B LEDs with radiation wavelength 0.92 μm and diaphragm 1.2 mm in diameter, a radiant energy of $2 \cdot 10^{-9}$ J was obtained, while with a diaphragm 0.3 mm in diameter, the radiant energy decreases 28-fold. In the calibration process, the radiant energy of a LED with 1.2-mm diaphragm was measured by a photodetector device with FD263 LED, while with a 0.3-mm diaphragm, by an IME-1 device. A 28-fold expansion of the calibration range can be achieved by this method, with the overall range amounting to 10^9 times the measured radiant energy. The measured sensitivity of the IME-1 device amounted to $1.07 \cdot 10^{10}$ V/J and the threshold energy, $1 \cdot 10^{-13}$ J.

The IME-1 device was compared twice in terms of scale division to a PD10-C device (Ophir, Israel) with germanium photodiode as radiation detector (as in the IME-1). The interval between the comparisons amounted to several months. The scale division of the devices differ by factor of 10^2. The energy of the radiation source amounted to around $1 \cdot 10^{-9}$ J, a value that corresponds to the upper measurement limit of the IME-1 device and approximately to the lower measurement limit of the PD10-C device. The radiation of the LED enters through diaphragms, one 1.2 mm in diameter and the other 0.3 mm in diameter, correspondingly, the PD10-C device and the IME-1 measuring device. The difference between the readings of the IME-1 meter and the PD10-C device amounted to 16 and 2.1% in the first and second comparisons of the devices' readings.

Glass attenuators that are neutral over the entire spectrum with optical density in the range 3–4 could be calibrated through the use of a set of detectors and comparison sources developed by the present author. The use of these attenuators expands the functional range of the radiation sources from $1 \cdot 10^{-12}$ to $1 \cdot 10^{-16}$ J, which is entirely sufficient for the purpose of generating signals in the linear range of operation of high-sensitivity photodetector devices, for example, laser range finders and detecting systems.

The method of calibration of devices used to measure the energy of pulse radiation does not require the use of expensive plants or special compartments as well as making it possible to quickly perform a calibration in a dynamic range up to 10^8–10^8 times the measured radiant energy. By combining the present method with a method that uses optical attenuators, the range of measurement may be additionally expanded 10^3–10^4-fold. The error in measurements performed by this method is within the requirements of the measurement chains of standards for working measuring instruments, i.e., GOST 8.275–2013, *State System for Assurance of the Uniformity of Measurements. State Measurement Chain for Instruments for Measurement of the Average Power of Laser Radiation and Energy of Pulse Laser Radiation in the Range of Wavelengths from 0.3 to 12 μm*; GOST 8.195–2013, *State System for Assurance of the Uniformity of Measurements. State Measurement Chain for Instruments* *for Measurement of the Spectral Density of Radiance, Spectral Density of Radiant Intensity, Spectral Density of Irradiance, Radiant Intensity, and Irradiance in the Range of Wavelength from 0.2 to 25.0 μm*; and GOST 8.023–2014, *State System for Assurance of the Uniformity of Measurements. State Measurement Chain for Instruments for Measurement of Optical Quantities of Continuous and Pulse Radiation*. Coupling coordinating calibrated measurement instruments with standards operating on the basis of different physical principles increases the reliability and precision of measurements. Through the use of the proposed method of calibration it is possible to pass from radiant energy to power in a radiation pulse.

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