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Combined Method of Energy and Power Meters Calibration in Optical Range

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Abstract:

Method of calibration using calculation of measured optical power radiation in units of the radiation energy and backward is presented. The novelty of the paper is using different kinds of electrical attenuators in calibration that allows escaping the influence of scattering light in measurements. The method permits calibration of energy and power meters in range of 8 – 10 orders of magnitude. Comparison detector allows calibrating energy and power meters and radiation sources via self-calibrated photodiode by the LED comparison source with the radiation power 10^{-7} – 10^{-5} W.

Keywords: Measurement; Radiation Power; Energy of Radiation; Calibration; Photodetector.

DOI:

INTRODUCTION

The processes of various researches, adjustment and repairs of optical and electronic devices require the measurements of the radiation energy and power. It is not always possible using standard measuring instruments. They may not fit owing to the limits of the measurement or a design and dimensions of optical unit of a measuring instrument. For the measurements in hard-to-reach places of systems and devices, special detectors with a suitable design are often made. Measurements should be carried out in the absolute units of the radiation energy and power. Measurement required limits of such devices are often 6 or more orders of the magnitude of radiation energy and power. Calibration of such meters by the classical methods is time-consuming and requires using of complex and expensive equipment and dark rooms. Construction of meter's receiving parts can be different. Standard electrical measuring devices and oscilloscopes are used for recording.

In the classical methods the expansion of calibration limits is reached by attenuating the radiation flux of a reference source [1]. The inverse-square law or a set of neutral light filters are used [2, 3]. Expansion of calibration does not exceed 4 –6 orders of magnitude due to additional influence of scattering light and a big measurement error [4]. The method of the transformation in time [5], using duration change of radiation pulse, had been proposed for energy radiation calibration in wide limits. Power calibration was performed within a wide range by the method of an additional attenuator [6].

2. METHOD OF CALIBRATION

Combined method permits transfer calibration from power units to energy units and backward for increasing limits of the calibration. The calibration is performed in accordance with the calibration scheme (Fig. 1) in three stages. Firstly, the spectral responsibility of a photodetector PD with a load capacitor C and a parallel resistor R was measured in continuous radiation mode by comparison with the standard photodetector. Self-calibrated photodiode was used as a reference detector in the visible region of spectrum. The capacitance was selected according to the required energy measuring limits and the time constant of the detector. The PD to calibrate and the standard one were alternately connected to the recording device (Fig. 2) containing an operational

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amplifier with resistors in the feedback loop switching limits of measurement within three orders. The resistors in the feedback loop are also the load resistors of the PD. The LED red emitter (Fig. 3) with a power of 1 – 2×10^{-5} watts was used as a source of comparison. The responsibility of PD SP was measured in A/W. The measurement range of the PD with the recording device is about 10^{-5} – 10^{-9} watts given by one order within the scale of instrument. The responsibility S_w in V / J was calculated according to the equation $S_w = S_p / C$. Approximate responsibility of the PD is 10^7 V/ J for the wavelength 650 nm. The PD was connected to the oscilloscope and, in this case, was used as a power or energy meter. The limits of energy measurement are 10^{-7} – 10^{-9} J.

At the second stage, the PD was used as a secondary standard both in energy and power units. Red semiconductor laser with a power of several mW was used as a comparison source. The energy of the laser's radiation was measured. The laser can operate in continuous and pulsed mode with the same power. Pulse duration can vary within three orders of magnitude. With the pulse duration of 10 μs and the laser power of 1 mW, the energy was 1×10^{-8} J. The laser power was calculated using the measured by the PD laser's energy value and known pulse duration. The laser calibrated this way in terms of the power, further was used as a source of comparison both in power and radiation energy units. The radiation energy could be increased from two to three orders of magnitude to several micro joules by precisely increasing pulse duration. Using this source of comparison, the pyroelectric energy meters operating in a wide range of the spectrum were calibrated using the comparison method. Thus, the secondary standard of radiation energy in the wide band of spectrum and the limits of energy measurements 1×10^{-5} – 1×10^{-3} J was obtained.

Such a simple way two calibrated source of power radiation, two calibrated source of energy and two secondary standard detectors were obtained. Measurement limits of these secondary standards vary from 10^{-9} to 10^{-5} W and 10^{-3} – 10^{-9} J in the band of spectral responsibility of photodiodes.

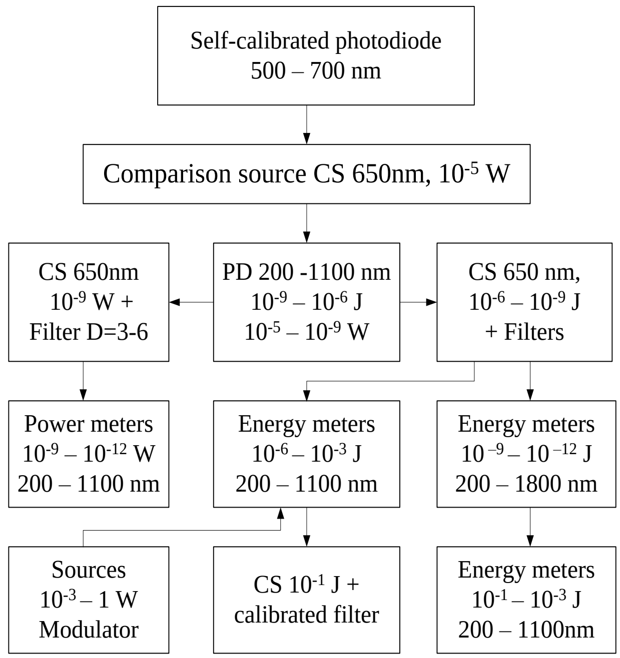

Figure 1. The calibration scheme.

At the third stage transmittance of a filter with an optical density of 3…4 and attenuation coefficient of a photometric sphere was measured by the PD with measurement range of 10^{-5} – 10^{-9} W. Verification of the filter transmittance measurement was carried out in an energy mode by increasing pulse duration by using a filter. In this case, measurement errors could be avoided due to possible nonlinearity of the PD. The measurement limit is extended on 3 orders of magnitude of the measured power till 10^{-12} W and J with an additional filter. Another filter with an optical density of 5, 6 was measured with an additional absorber [6] and above-mentioned laser radiation source. Using PD together with the low-power comparison sources and these light filters allows spreading measurement limits of power and energy from lower values up to threshold values. The same filters were used to calibrate the sources of comparison of higher power and radiation energy. Further, these sources could be used for calibrating energy meters at large levels. A pyroelectric energy meter and a mechanical modulator can calibrate a continuous emission laser with a power up to 1 W.

Calibrated 1, 2 mW comparison source could be measured using a standard calorimeter or electric current calibrated pyroelectric radiometer RS-5900. In this case,

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the calibration is checked. Based on the results of comparison, the calibration error was estimated.

Combined method covers operations in the spectral band determined by the spectral responsibility of using photodiode. The spectrum is expanded by using non-selective pyroelectric sensor, which is calibrated in energy units.

3. CHOICE OF A STANDART

There are three commonly used standards for calibration power meters: thermal radiation detector for large power levels, self-calibrated photodiode in the spectral band of 0.5 – 0.7 μm for lower levels and electric current -calibrated pyroelectric detector for average power levels (model Rs-5900, Laser Precision Corp.). A number of auxiliary comparison sources with a set of optical attenuators to obtain required measurement limit or the photometric method using the inverse square law [3] are used for calibration. Calibration in units of energy performed by similar methods or the time-converted method [6]. Standard calorimeter and pyroelectric radiometer are expansive devices and require qualified service personnel. The most convenient and affordable standard is a self-calibrated photodiode. In the case of low precision measurements, any photodiode with a calibrated spectral responsibility could be applied.

Self-calibrated photodiode has 100 percent quantum efficiency of absorbed power and there is no band unevenness of the responsibility. The reflection of such photodiodes is close to 30 %. Construction description of the standard detector called Trap detector [1], in which photodiode absorbs reflected by other photodiodes flux was made. Signal from all photodiodes is summarized to compensate the reflection loss. It was observed that the reflectance indicatrix is 10…20 degrees, when reflection from the receiving surface of the photodiode was measured. The specula reflection for four measured photodiodes of type FD-288 ("quantum") was 65 % of the total reflection. The measured quantum efficiency of these diodes was 95 %. The design of Trap detector with such photodiodes is not suitable since a great part of the reflected from photodiode flux does not fall on the next photodiode. Therefore, a single photodiode with the measured total reflection by a sphere photometer should be used as a standard. The photodiode spectral responsibility was calculated by the absorbed power.

4. COMPARISON PHOTODETECTOR

In the scheme (Fig. 2) the load of photodiode is parallel connection of a resistor R and a capacitor C. In the experimental system, the capacitance C includes capacitances of the photodiode, connecting cable and the input capacitance of an oscilloscope and is 22 nF at the supply voltage of 6 V.

The capacitance was measured being supplied by power source, while the capacitance meter was connected through separating capacitors with a capacity of more than 10 μF. In this way, the supplying voltage of the photodiode does not affect on operation of the capacitance meter. The resistance R was selected from the ratio 0.1 RC greater or equal to the duration of measured radiation pulse. Effect of electromagnetic interference on connecting cables and effect of scattering light on a photodiode is growing with R. The responsibility St is $St = Sp/C = 1.36\times10^{7}$ V/J in mode of measuring radiation energy for the photodiode responsibility Sp is 0.3 A/W in the continuous mode at the wavelength 650 nm and capacity $C = 2.2\times10^{-8}$ F.

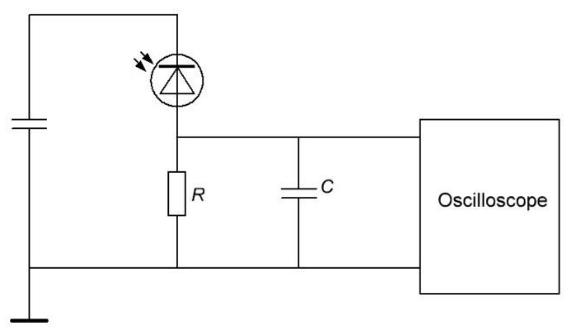

Figure 2. The photodetector PD circuit.

Measurement limits of the photodetector using an oscilloscope with a responsibility is 1 mV/div, photodiode supply voltage 6 V and the wavelength 650 nm are varying from 2.5×10^{-8} to 1×10^{-5} W and from 1×10^{-9} to 3×10^{-7} J consequently. Upper limits correspond to the linearity limit of the photodiode conversion characteristic.

5. RECORDING DEVICES

Photoelectric detectors are current sources for recording devices. Recording devices measure electric current and have large input resistance. However, devices are susceptible to the electromagnetic interference through connecting wires. Therefore, portable photodetector probes with a small output resistance are used. Current –

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voltage converters CVC are built in probes. Widespread voltmeters and oscilloscopes that measure CVC voltage have measurement dynamic range within 3 orders. In practice, oscilloscopes are the most commonly used. The lower limit of measurement is determined by the noise. The voltage of CVC power supply determines the upper limit.

The method is based on a wide linear dynamic current range of detectors. A circuit with an operational amplifier without additional bias on a photodiode supplies the voltage on it constant with high accuracy while the current is changing through the photodiode. This provides a linear scale within all limits of measurement and minimum dark current, which determines the lower limit of the measurement. The saturation current of a photodiode, which does not exceed 10 – 20 μA for most silicon photodiodes, confines the upper limit. Measurement limits in the electric circuit of the PD are switched by resistances in the feedback loop of the operational amplifier, which are load resistors of photodiode in the same time. Resistances changes in range of 100 kOhm…5 MOhm for all photodiodes and 50…100 MOhm for photodiodes selected by the dark current. Such radiometer has the responsibility of 2–5×10^{10} mV / W with a silicon photodiode and commonly used voltmeter-tester VM 830. This corresponds to indication of 100 divisions. The upper limit of measurement in a linear range is 5×10^{-5} Watts. The dynamic range of such radiometer is 10^5 [6]. In radiation energy meters photodiode load is a capacitance. Switching of capacitors and load resistors must be done simultaneously to maintain required constant time integration of a received signal. The upper limit of linear mode of energy meter is limited by photodiode saturation current and does not exceed 10^{-7} J. The lower limit is divided by parasitic capacitances of switching circuit and capacity of photodiode.

The upper limit of photodiode linearity may be small during energy calibration and consequently an oscilloscope signal may also be small. In this case, using an additional matching amplifier between a detector PD and an oscilloscope is required (Fig. 3). The frequency band of PDs is narrow comparing to the frequency band of commonly used oscilloscopes. This permits reducing a measurement lower limit by oscilloscope with an additional amplifier in 30 – 50 times.

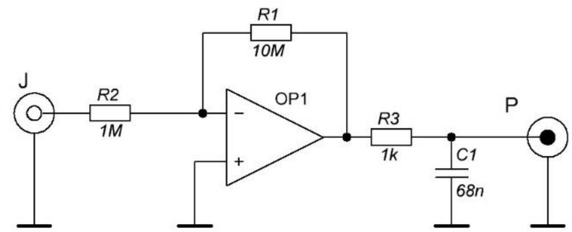

Figure 3. Matching amplifier, gain = R_1/R_2, time constant = R_3C_1.

Another way to increase sensitivity in radiation energy measurement mode is to reduce a capacity and increase a resistance simultaneously. In the case of using matching amplifier, integration time constant could also be increased with odd resistor in an input of an amplifier. In this case, time constant in detector circuit increases without gain increasing. Photodiode should have a small dark current. An additional resistor is placed in detector housing. The same amplifier is used in both cases of energy and power measuring.

6. OPTICAL ATTENUATORS

A glass neutral light filter or a photometric sphere can be used as an attenuator. In practice, to achieve required optical density a set of few filters with lower density are often used. As shown in [4] a set of filters poorly reproduce transmittance at re-installation and change of position of a single filter. When the total optical density of a set of filters is more than 3…4, the error in total transmittance, due to the reflections between faces of single filters, could reach several hundred percent. Therefore, one light filter of required density was used for the calibration. Transmittance of such filter could be measured using energy and power meters. In case of using radiation energy meter, pulse duration of the comparison source and the energy of its radiation increase by 128 - 256 times. The filter with an attenuation of 200…500 times had been applied and radiation energy was measured behind the filter. According to the measurement results, attenuator transmittance was calculated with additional error from the time constant of the detector. In the present case, the additional error is -1.2 percent.

The photometric sphere according to the standard [7] was used for measuring the power of LED radiation. The sphere of 35 mm diameter with inlet and outlet holes of 5 mm diameter and an internal screen was used in

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measurements. Power measurement of the radiation was carried out with a standard photodiode.

The calibration of the sphere was carried out as follows: readout n1 was obtained on the PD without sphere at the coarse limit of measurement with the load resistance of 100 kOhm from the LED emitter with diaphragm. Then photodiode radiometer was placed behind the outlet hole and the LED with diaphragm was placed on the opposite side of the sphere, the load resistance R was increased in p times and readout n2 was obtained. An attenuation coefficient of radiation by the sphere k is $k = n_2 / p\ n_1$. The measured attenuation coefficient of the sphere was 0.0030.

Flat constructions of the attenuators (Fig. 4) allow them to be installed in hard-to-reach places of a device or a system. Measured attenuation coefficient of the designed construction was 0.002 with the reception area of photodiode 1×1 mm and 0.0001 with the aperture diameter 0.2 mm in front of the photodiode. The attenuator was made of aluminum. The inner surface of the case was treated mechanically without application of an abrasive.

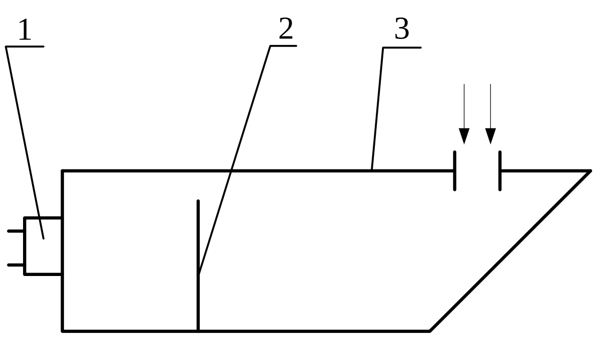

Figure 4. Flat detector: 1 – photodiode, 2 – screen, 3 – aluminum case. Absorption coefficient 0,0001, aperture 5,5 mm, silicon photodiode 1×1 mm, size 35×25×8 mm.

7. COMPARISON SOURCES

A low-power semiconductor laser from a pointer with the wavelength of 650 nm could be used as a source of comparison for calibrating the spectral responsibility of a photodiode. Laser supply current is set up 50…100 mA and stabilized. Semiconductor laser is changing the radiation power within 15 – 30 minutes after switching on due to the high power current density, which is heating an emitting element. The article [4] presents these changes measured by four different devices simultaneously. The average radiation power decreased by 6, 8, 9.4 and 10 % in 2, 5, 10, 15 and 20 minutes respectively after switching on relative to the value obtained in 2 minutes after switching on. Measurement indication was taken at the same time intervals after the laser had been switched on. In the pulse mode of the laser, these changes are much smaller. The reducing of supply current does not lead to noticeable improvement in laser operation; with significant current decrease, generating radiation breaks down. The half-width of the spectral radiation curve of such laser is 30 nm. The LED with the same radiation power is more stable due to the lower power density. Radiation in it comes from larger emitting surface. Therefore, the optical system fails to form a parallel beam of light as it is done in the laser. To reduce divergence of the radiation formed by an optical system, it is necessary to reduce power of LED radiation with diaphragms. Thus, for elimination of scattering light, not less than 2 diaphragms must be applied. The using of lens permits to form an image of an emitting surface of a LED at a distance from output end of it. This makes possible obtaining it on receiving elements of detectors, located in the depth of a device. In modern LEDs, radiation power is 2 – 3 orders of magnitude higher than upper limit of linearity of silicon photodiodes, which allows using considered radiation beam formation schemes. The spectral curve of Chinese red LED (Fig. 5) has the half width of 45 nm, which is close to the characteristics of the laser.

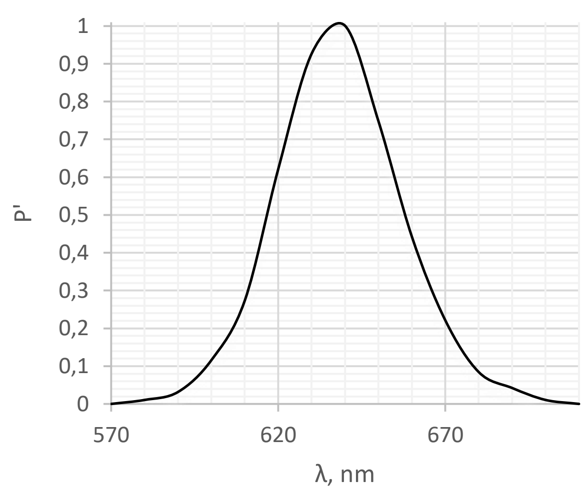

Figure 5. The spectral curve of LED.

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Table 1. Comparison of laser power measurement results by the calorimeter and the photodetectors with measurement results of the pyroelectric radiometer

Detector	Pyroelectric radiometer	Calorimeter	Photodetector	Standard photodiode
Average definition, %	0	+8.6	+11.8	+7.9
Error, %	0	±5	±2	±1.7

The spectral curve of standard photodiode is close to a straight line in the region of LED and laser radiation spectrum, so there is no additional calibration error from the wide spectral range of the LED radiation. The spectral responsibility, in this case, is taken into account at the maximum radiation of the LED.

In a pulse mode, the calibration is performed with a pulse generator or a pulse shaper of precise duration and constant power of a radiation source. Power supply remains the same for the LED and the laser. Current supply generator is produced through a transistor key, which allows source operating in pulse and continuous modes.

In presented system pulse durations were chosen 1 second, 2 milliseconds and 8 microseconds [5]. This system allows reducing non-selectively radiation energy by 1.25×10^5 times, providing calibration of LED emitter with the calorimeter and the reference photodetector PD. At the same time, it becomes possible to transfer unit of energy and power from both standards to the non-selective high-sensitivity pyroelectric detector for calibrating source or detectors in a wide range of the spectrum.

8. THE EXPERIMENTAL RESULTS

The results of laser power measurements (table) show coincidence of measured values. The calorimeter and the radiometer work within the main limits of measurement. The reference photodiode was calibrated at the Russian Institute of standards of optical and physical measurement with an error within ± 4%. During photodetector calibration, four independent measurements were carried out within four orders of magnitude of laser power variation. According to the metrology laws, the total error of all these measurements is 2 - 3 times more than error of the standard and in our case it is not less than 10 %. With this in mind, obtained discrepancy between the results of comparing PD with other devices can be considered small.

9. CONCLUSION

The combined method of measuring energy and power optical radiation is simple, does not require expensive equipment and special means. The method makes it possible calibrating a significant part of common and specially manufactured for specific tasks detectors and sources of optical radiation. The method does not require dark rooms. Calibration error of the considered method is sufficient to solve practical problems. Methods of measuring the attenuation coefficient in units of energy and power can reduce the radiation flux or energy by 4 – 5 orders of magnitude. Measurement in units of radiation energy has a number of advantages:

1. No requirements for parallelism of a radiation beam and, consequently, non-point sources such as LEDs and gas-discharge lamps are possible to use.
2. More stable operation of the radiation source due to absence of overheating.
3. Work in lit rooms.

The combination of these methods and implements allows extending range of measurement in both directions, to higher and to lower values.

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