DOI 10.1007/s11018-019-01548-7
Measurement Techniques, Vol. 61, No. 11, February, 2019

COMPLEX OF TECHNICAL DEVICES FOR REPRODUCTION, STORAGE, AND TRANSMISSION OF THE UNIT OF PULSE DURATION OF LASER RADIATION IN THE RANGE $5{\cdot}10^{-11}$–$1{\cdot}10^{-9}$ s INCORPORATED INTO THE STATE PRIMARY SPECIAL STANDARD

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UDC 53.089.68

A complex of technical instruments for reproduction, storage, and transmission of the unit of duration of a laser radiation pulse in the range $5{\cdot}10^{-11}$–$1{\cdot}10^{-9}$ s is described. The complex has been introduced into State Primary Special Standard GET 187–2016 of the units of energy, distribution of energy density, duration of pulse, and wavelength of laser radiation.

Keywords: *standard, parameters of laser radiation, pulse duration.*

In pulse laser systems, the nature and intensity of the interaction of radiation with a substance are determined by the instantaneous radiation power. Therefore, in addition to the energy characteristics of pulse laser radiation, such as the average power and pulse energy, the temporal characteristics are also of great importance. The duration of a pulse of laser radiation is the most important temporal characteristic.

The generally accepted definition of the duration of a laser radiation pulse is given in international standard ISO 11554:2006 (GOST R ISO 11554–2008). On the basis of this document, the duration of a pulse is the maximal time interval between the two points on the time axis at which the power attains half the peak power.

GET 187–2010, the State Primary Special Standard of the units of energy, distribution of energy density, pulse duration, and wavelength of laser radiation comprises a complex of measuring instruments for reproduction and transmission of the unit of duration of a pulse laser radiation [1] that reproduces the unit of pulse duration in the range $1{\cdot}10^{-9}$–$1{\cdot}10^{-6}$ s.

The critical need for studies to improve GET 187–2010 for the purpose of expanding the time range into the picosecond band is due to the use of picosecond lasers in the GLONASS system and in medicine, scientific research, and the defense industry as well as for processing materials and other areas. Information about the temporal characteristics of a pulse (form, duration, rise time, and decay time) is needed in order to select the optimal radiation regime. In laser distance measurement, decreasing the duration of a probe pulse is a standard method of increasing measurement precision [2].

Measuring instruments of the approved type are needed for measurements of the time parameters of picosecond laser pulses. Equipment by means of which the time characteristics of laser radiation may be measured in the picosecond range do exist, but do not possess standardized metrological characteristics. An appropriate standards base must be created in order to normalize the metrological characteristics of instruments used in the measurement of the frequency-time characteristics of pulse laser radiation.

A complex of technical devices for reproduction, storage, and transmission of the unit of pulse duration of laser radiation in the range $5{\cdot}10^{-11}$–$1{\cdot}10^{-9}$ s (henceforth, "complex") was created as a result of an improvement in GET 187–2010. The newly introduced complex was introduced into the standard approved by Rossstandart Order No. 2089 (12.30.2016), *On Approval of the State Primary Special Standard of the Units of Energy, Distribution of Energy Density, Pulse Duration, and Wavelength of Laser Radiation,* with assignment of registration number GET 187–2016. The structural diagram of the complex is shown in Fig. 1.

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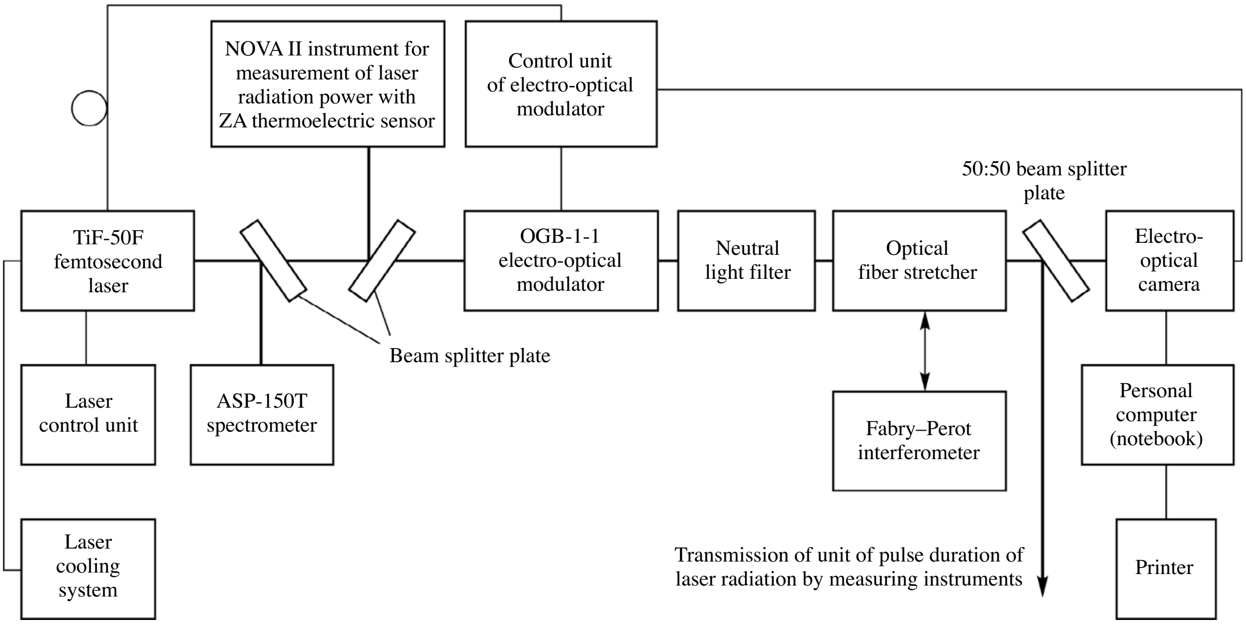

Fig. 1. Flow diagram of complex of technical devices for reproduction, storage, and transmission of the unit of duration of a laser radiation pulse in the range $5\cdot10^{-11}$–$1\cdot10^{-9}$ s.

The constituent parts of the complex comprise:

– system of optical equipment, including a TiF-50F femtosecond laser with control unit and cooling system, OG8-1-1 electro-optical modulator with control unit, Fabry–Perot interferometer, optical fiber stretcher, electro-optical camera, beam splitter plate, set of light filters made of NS colored optical glass (GOST 9411–91, Colored Optical Glass. Technical Conditions), and a set of optical and mechano-optical devices, and an optical table;

– system for control, recording, and documentation of measurements, including personal computer (notebook) and printer; and

– equipment for control of the complex' operating regime, including the NOVA II device for measurement of the power of laser radiation with ZA thermoelectric sensor, ASP-150T spectrometer, and IVA-6N thermohygrometer.

Through use of the software in the complex, it is possible to perform measurements and control and monitor the parameters of the equipment incorporated into the complex.

The complex reproduces the unit of pulse duration of laser radiation in the range $5\cdot10^{-11}$–$1\cdot10^{-9}$ s at the wavelength 0.755 μm. The unit reproduced by the standard is the duration of a single laser pulse generated by means of the basic technical devices incorporated into the standard, which includes a femtosecond laser, electro-optical modulator, system of mirrors, and an optical fiber stretcher. The duration of the generated pulse is measured by an electro-optical camera. The measurements begin after initiation of the steady-state generation regime of a femtosecond laser in which the radiation parameters, such as the average power, wavelength, and width of the spectral generation line, are all stable. The average radiation power of the laser is monitored by a thermoelectric sensor, while the wavelength and width of the spectral generation line, by a spectrometer. Control of the climate parameters in the compartment where the complex is situated is achieved by a thermohygrometer. The pulse duration measured in the experiment must correspond to the definition in GOST R ISO 11554–2008, i.e., the measurement technique employed presupposes that the points (moments of time) at which the power attains half the peak power are found from the recorded power dependence on time.

The value of the reproduced unit (duration of laser pulse) may be estimated from the formula

$$\tau_{\text{est}} = kx,$$

where k is the scan factor determined in the process of calibration of the time scale of the electro-optical camera, and x is the result of a measurement of the pulse duration on a photochronogram.

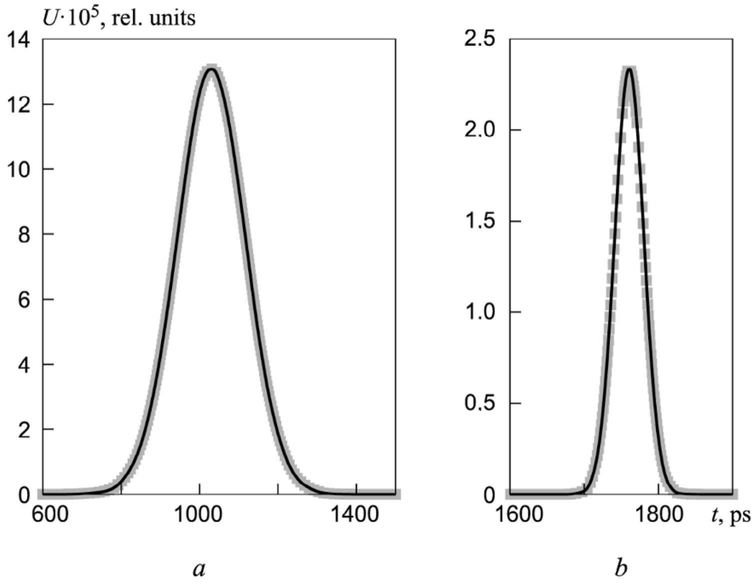

Fig. 2. Approximation of Gauss function of measured profile of pulse of laser radiation generated by complex (*a*) and time spread function of electro-optical camera measured as a response to a pulse of duration less than 50 fs (*b*): *t* is the measurement time.

The estimate thus computed differs from the true pulse duration, since in the general case the profile of the pulse intensity obtained by an electro-optical camera constitutes a convolution of the actual profile of the intensity and the camera's time spread function. To determine the true pulse duration, a deconvolution of the measured profile of the intensity from the time spread function must be performed.

The time spread function is a pulse characteristic of the electro-optical camera and may be experimentally measured as the camera's response to an ultra-short (femtosecond) laser pulse [3]. It has been established in experiments that the pulse generated by the complex and the time spread function of an electro-optical camera both exhibit a Gaussian form (Fig. 2). In this case, the correction of the systematic error associated with the finite duration of the time spread function may be realized through the introduction of a correction into the measurement equation, which as a result assumes the form

$$\tau = \sqrt{\tau_{\text{est}}^2 - \delta^2} = k\sqrt{x^2 - x_\delta^2}\,, \tag{1}$$

where τ is the duration of the pulse generated by the complex; δ, duration at the level of half the time spread function of the electro-optical camera; and x_δ, width at the level of half the camera' s time spread function on the photochronogram.

To reduce the influence of noise, the value of x is set equal to the arithmetic mean of the results of ten measurements.

The time scale of the electro-optical camera is calibrated by a method in which the time intervals are generated by means of a Fabry–Perot interferometer [4]. When a single femtosecond pulse of duration $\tau_p \ll T = 2nd/c$ (n is the index of refraction of air; d, base line of Fabry–Perot interferometer, i.e., thickness of intermediate ring; and c, speed of light in a vacuum) is fed to the interferometer, this results in a train of pulses which is recorded by the camera. The time interval between successive pulses in the train is the identical and equal to the duration T of a double passage of the laser pulse between the mirrors of the Fabry–Perot interferometer. Thus, the thickness of the base line of the interferometer specifies the time interval which is transmitted by means of a pulse of the femtosecond laser to the electro-optical camera in the course of calibration. The local values of the scan factor are calculated by means of the formula

$$k_i = T/(\Delta x)_i,$$

where $(\Delta x)_i$ are the intervals between successive pulses in the train in the photochronogram.

The sweep coefficient k is defined as the arithmetic mean of the local values, with a value k = 1.59 ps/pixel obtained as a result of calibration. The duration at the level of half the time spread function of the electro-optical camera is also

TABLE 1. Budget of Uncertainty of Reproduction of Unit of Pulse Duration of Laser Radiation by the Complex

Uncertainty component and its sources	Value, %
Type A standard uncertainty $u_A(\tau)$	1.52
Type B standard uncertainty $u_B(\tau)$, including:	1.53
discreteness of image of photochronogram $u_\mathrm{d}(\tau)$	0.34
uncertainty of calibration of time scale of electro-optical camera $u_\mathrm{c}(\tau)$	1.48
uncertainty of correction to value of pulse duration as a consequence of the finite duration of the time spread function of the electro-optical camera $u_\mathrm{cor}(\tau)$	0.17
Total standard uncertainty $u_\mathrm{tot}(\tau)$	2.15
Expanded uncertainty for conformance factor $k = 2$ ($P = 0.95$) $U_{0.95}(\tau)$	4.30

measured in the course of the camera's calibration as a response to an individual femtosecond laser pulse and amounts to $\delta = 49.0$ ps.

The standard uncertainties of the quantities occurring in measurement equation (1) was found as a result of metrological investigations of the complex. The budget of uncertainty of the reproduction of the unit of pulse duration of laser radiation by the complex is presented in Table 1.

Transmission of the unit from the complex to some other instrument for measurement of the pulse duration of laser radiation is accomplished by means of the femtosecond laser, electro-optical modulator, optical fiber stretcher, and beam splitter incorporated into the complex. The femtosecond laser, electro-optical modulator, and optical fiber stretcher are used to generate a light pulse with duration in the picosecond range. The beam splitter redistributes the light flux, directing some of it to the electro-optical camera in the complex, and the balance to the measuring instrument, by means of which the unit of pulse duration of laser radiation is transmitted. In this way, the measuring instrument and the electro-optical camera together measure the time characteristics of one and the same pulse. The value of the unit transmitted to the measuring instrument assumes the value of the pulse duration measured by the electro-optical camera in the complex. As a result of the use of the method of simultaneous measurements, the uncertainty of the transmission of the unit is equal to the uncertainty of the reproduction of the unit.

Conclusion. Through the use of GET 187–2016 it becomes possible to:

1) assure the uniformity of measurements of the time characteristics of pulse laser radiation in laser-based distance measurement, medicine, technologies employed in laser processing of materials, and the military sphere;

2) create conditions for expansion of the range of measurements of the time characteristics pulse laser radiation; and

3) create an inventory of instruments for measurements of the time characteristics of pulse laser radiation based on existing electro-optical cameras, autocorrelators, and high-speed photodetectors.

Studies and research efforts designed for further development of the standards base in the field of measurements of the time characteristics of pulse laser radiation for the purpose of expanding the range of reproduction of the unit of pulse duration and increasing measurement precision are continuing at the All-Russia Research Institute of Optophysical Measurements (VNIIOFI) [5].

The present study was completed with the use of equipment of the Center for collective use of high-precision measurement technologies in the field of photonics created on the base of VNIIOFI and supported by the Ministry of Education and Science of Russia within the framework of Agreement No. 14.595.21.0003 of 08.28.2017 (unique identifier RFMEFI59517X0003).

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