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Modelling of reproduction process for power laser radiation

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The model and algorithms for analysis of the laser photoinduced processes were developed using numerical simulations. A statistics of the process was carried out by averaging over a hundred laser pulses. A special correction algorithm was created. A standard uncertainty of the results from the output laser signals without any correction was equal to 0.003527, while for the expected value was equal to about 1.000510. After correction procedure standard uncertainty of results was 0.000479 for the expected value equal to 0.999955. Due to the applied correction methodology of laser signal analysis, the uncertainty can decrease by one order of magnitude. The proposed approach may be used for describing photoinduced nonlinear optical processes with time duration from nanosecond to microsecond.

Keywords: reproduction process, transfer process, average power of laser radiation.

1. Introduction

Standards in detection of average laser radiation powers are necessary for correct metrological measurements and transformation of laser pulses [1, 2]. The most important parameter of a standard is uncertainty for reproduction and transfer of a unit portion of laser power. The uncertainty concerns all the elements of a standard system. These elements include standard measuring converter (SMC), control converter (CC), analogue-to-digital converters (A/D) of electric signals, and the laser as a source of radiation. To design a standard system for determination of uncertainty u_w, analysis of uncertainty for particular elements is needed. Thus, in the present work we will develop a mathematical model describing corresponding basic operation. To create a complete mathematical algorithm, appropriate synthesis of basic structural elements should be carried out.

The control of the laser parameters is very crucial during studies of the photo-induced optical and nonlinear optical properties [3, 4]. The principal requirement of such kinds of experiments is reliable reproduction of optical parameters [5, 6].

Section 2 of this paper describes a mathematical model of reproduction and transfer processes of average power of laser radiation. The basic algorithms are given in Section 3.

2. Mathematical model of reproduction and transfer processes for single pulses of laser radiation

Let us consider measurements in an SMC-A/D converter system devoted to measurement of an average power of laser radiation for different variants of standards [7–10].

It is assumed that incident laser radiation is constant P_0 and does not change with time. The output signal of the measuring converter is described as

$$F(t) = \int_0^t \mathrm{d}t' P(t') g(t-t') \tag{1}$$

where $g(t) = \frac{1}{\tau - \tau'}\left[\exp\left(-\frac{1}{\tau}\right) - \exp\left(-\frac{1}{\tau'}\right)\right]$ is the unit pulse power weight function for the measuring converter with time constant $\tau' \sim 0.1\,\tau$, $P(t) = P_0$.

Conversion of a signal in the measuring converter and its measurement with A/D converter is carried out with the known value of the standard uncertainty u_c. For the given value u_c, for each of the measuring centres, a function of density distribution for error probabilities is formulated.

Traditionally three types of probability distribution functions are assumed: even distribution, triangular distribution or a normal one. During measurements, the function of error distribution of measuring converter includes a drift to the high values with constant velocity γ.

Calculation of a standard uncertainty for a measuring system is made through the generation of the F_j random numbers, according to the given probability distribution function for each instrument in a system. Nonlinear processing of the conversion function to the given $h(x)$ distribution function is used. For a subjected function of a measuring converter, the F_j numbers are randomly generated. A basis for generation of F_j numbers is a random y value with an even distribution in the interval (0, 1) which is obtained using the generator of pseudorandom numbers. The set searched for the random F_j values, with a probability determined by the $h(x)$ density distribution function, is found by solving the equation $y_j = G(F_j)$, where $G(F) = \int_{-\infty}^{F} \mathrm{d}x h(x)$ is a probability of finding the $F_j < F$ number; $\lim_{F \to \infty}[G(F)] = 1$. The obtained values are shown in a histogram. Signal average value and a standard uncertainty are also determined.

It was stated that a form of the distribution function for measuring system errors is defined using a distribution function of measuring converter errors. Thus, the same mathematical form for error distribution function is taken into consideration in calculations for both instruments.

It is also assumed that for the required total value of uncertainty for the measuring system, the parameters of measuring procedure and of the instruments used can be evaluated. At least five most important parameters should be considered: u_p, $u_{A/D}$, the uncertainty of the measuring converter and A/D converter, respectively, the number of N readouts, the measurement time Δt, and a drift velocity γ.

In order to find the values of these parameters, the $u_c(\gamma = 0)$ relationship for the value τ should be formulated and the $u_c(\gamma = 0) = (u_p^2 + u_{A/D}^2)^{1/2}$ relationship should be used. Because the basic element of the system is the measuring converter, first its metrological characteristics should be determined, and next the required conversion uncertainty for A/D converter.

Let us consider the influence of instability of laser radiation power on the result of reproduction of the unit average power of laser radiation and its value transfer. The instability in laser radiation power is determined from the dependence which is a superposition of power jump, fluctuation, and drift [11–14]

$$P(t) = P_0\Big[1 + A\Theta(t - t_0)\Theta(t - t_1) + \alpha S(t) - \gamma_L t\Big] \tag{2}$$

where A is the relative value of a jumping amplitude, t_0 is the time of jump occurrence, $t_1 = t_0 + \Delta t$, Δt is the jump duration, $\Theta(t) = 0$ for $t < 0$, for $\Theta(t) = 1$ for $t \geq 0$; $\alpha = A'/S_{max}$, A' is the maximum relative amplitude for laser radiation fluctuation, S_{max} is the maximum value of a component of development of the $S(t)$ function, and γ_L is the velocity of laser radiation drift.

The output signal of the measuring converter is described by Eq. (1). The process of thermal balance stability should be assumed to last at least about 10τ. Afterwards,

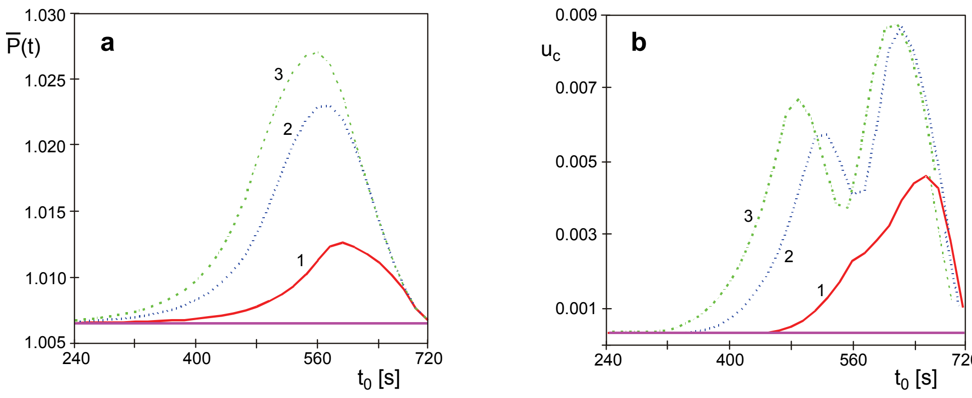

Fig. 1. Average value of the system signal (**a**) and system standard deviation (**b**) vs. the time of jump occurrence t_0, $\Delta t = 30$ s (curve 1), $\Delta t = 90$ s (curve 2), and $\Delta t = 120$ s (curve 3).

within the time of 2τ, the signal at the output of the measuring converter is measured many times and at equal time intervals by A/D converter.

Figure 1 shows dependences of an average value of the system's $\overline{P}$ output signal as a function of the t_0 time during a jump occurrence. A chart of standard uncertainty of the system as a function of jump occurrence time is shown in Fig. 1**b**.

The results obtained from investigations demonstrated that when a jump occurs directly before the measurements start, the signal at the measuring converter output carries information concerning the jump and its influence on the whole measuring process.

3. Algorithm for measurement data analysis

Two methods were developed to minimise uncertainty during reproduction of the unit of average power of laser radiation, with regard to power jump of laser radiation.

The first method is as follows: for the given value of the u_r deviation of an average value of the $\overline{P}$ power of laser radiation, when the measuring signal is $\overline{P}_0$ without laser radiation, a series of curves for the various values of the jump duration $0.1\tau \le \Delta t \le 10\tau$ are drawn (Fig. 2). For each time, the jump amplitude is taken in such a way as to fulfil the inequality

$$\frac{\overline{P}}{\overline{P}_0} \le 1 + u_r \tag{3}$$

The maximum value of a jump amplitude is searched for with a constant step within the range of $0 < A \le A_{max}$. If the ratio is $\overline{P}/\overline{P}_0 > 1 + u_r$, the previous value of jump amplitude is taken as the maximum one and the next one is recorded. A set of the maximum values of the amplitude is shown in Fig. 3, viewed in 3D.

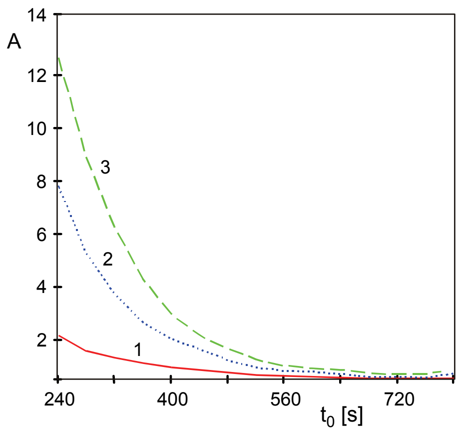

Fig. 2. Maximum jump amplitude vs. the time of its occurrence t_0 for the constant deviation value u_r, $\Delta t = 30$ s, $u_r = 0.01$ (curve 1), $u_r = 0.03$ (curve 2), and $u_r = 0.1$ (curve 3).

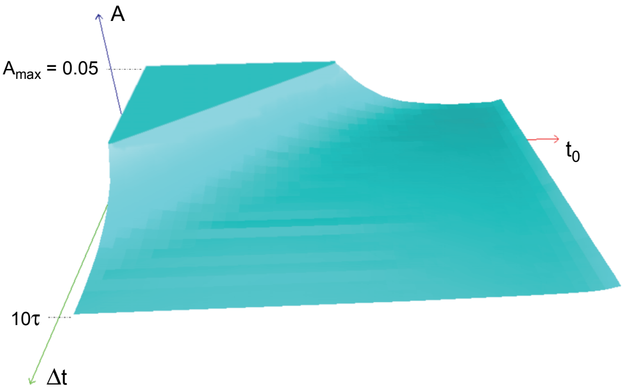

Fig. 3. A chart of the maximum values of power jump found for $u_r = 0.0005$.

Data handling is performed according to the following scheme:

– The point $A(\Delta t, t_0)$, the coordinates of which are closest to the experimental values Δt and t_0, is found at the surface of Fig. 3;

– A plane parallel to the plane $(\Delta t, t_0)$ is drawn through this point;

– The plane crossing the axis A determines the possible maximum value of a jump amplitude.

If the experimental value of the jump amplitude is lower than the maximum value found, *i.e.*, the found point is inside the volume limited by the surface from Fig. 3, the measurement result is the proper one. Due to the methodology presented here, errors of a measuring process can be detected and be avoided when the final result is being determined.

In the second method, uncertainty of reproduction of the unit of power of laser radiation can be minimised by taking into account the influence of a jump (the time of jump occurrence, its length and amplitude) on the conditions of operation of SMC-A/D converter system.

Using this method for the real P_{exp} values of the power, the corrected P'_{exp} value is calculated using the expression

$$P'_{exp} = \frac{P_{exp}}{1 + u_r} \tag{4}$$

where P_{exp} is the average experimental value of the power with the jump.

The concept of this method is similar to the one described above for the first method. A data set for various u_r values is formed. The deviation u_r value is chosen from the $(u_{r_{min}}, u_{r_{max}})$ range with a constant step. Adequate u_r value corresponds to each set of parameters of the power jump. Among the calculated data, the values t_0, Δt, and A are the same as the experimental ones. The value u_r which corresponds to the data with the jump parameters is introduced into Eq. (4) and next the P'_{exp} power value is calculated.

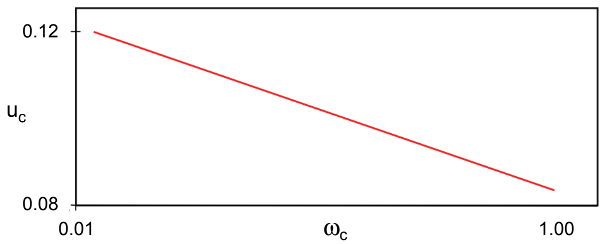

Fig. 4. Dependence of the relative standard deviation of the system u_c on fluctuation frequency ω_c.

It has been determined that using the mathematical model, the spread of the power values is higher when some fluctuations decrease. Figure 4 shows the dependence of relative standard uncertainty for the system as a function of fluctuation frequency. It is obvious, from the results obtained, that for the system with the time constant of the measuring converter $\tau = 60$ s, low frequency fluctuations significantly affect the measured results.

Figure 5 shows the permissible fluctuation frequency $\omega_{\min}$ as a function of the time constant τ of the measuring converter $u_{r_{\max}} = 0.03$.

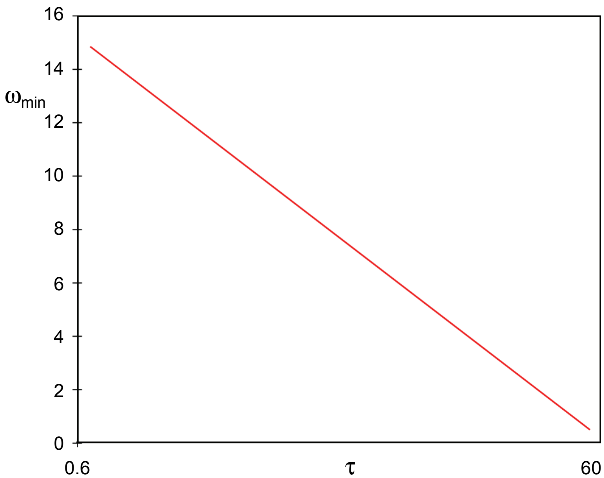

Fig. 5. Permissible fluctuation frequency $\omega_{\min}$ as a function of the time constant of the measuring converter $u_{r_{\max}} = 0.03$.

It has been determined that a drift of laser radiation significantly affects the spread of values for the system's output laser signal. A drift of laser radiation, together with a drift of the measuring converter signal, can enhance the measurement errors for drifts of the same directions, *i.e.*, if the order of the drift values is not $10\gamma_L \gg \gamma_P$ or $\gamma_P \gg 10\gamma_L$ or decreases the measurement errors if $10\gamma_L \sim \gamma_P$.

For thermal converters, mathematical descriptions of this operation and control receiver operation are identical.

The integrand $g(t)$ from Eq. (1) sufficiently smoothes the signal jumps caused by instabilities. Thus, to obtain the required information on instabilities of laser radiation, a fast control receiver is needed. A measurement process of the output signal for a control receiver starts at the time 2τ, before the start of measurement process of standard measuring converter. This is indispensable for the complete description of instability appearing, especially in the case when a power jump of laser radiation appears just before the start of the measurement process. After time 2τ, the measurement process of the output signal of a control receiver proceeds simultaneously.

As a filter of the noise resulting from statistical character of the signal, at the output of the control receiver–A/D converter system, a discrete filter is used with the characteristic expressed as

$$F'(t) = \sum_{n = -n_L}^{n_R} C_n F_n \tag{5}$$

where F' is the filtered signal, F_n is the signal including noise, C_n is the filter coefficient, n_L is the lower limit of the filter cut-off, and n_R is the upper limit of the filter.

The method relies on the division of the output signal into blocks of determined values in which a signal is approximated with the polynomial of the given order, according to a criterion of root-mean-square error.

To obtain, from the filtered signal, the signal originating from laser radiation, the component which is responsible for the receiver drift γ_P (the drift velocity γ_P is given in the device characteristic) is calculated. Next, the first order Walter integral equation with known nucleus $g(t)$ is solved. This equation can be transformed into a convenient form of the second-order Walter equation. Finally, the following expression is obtained

$$P(t) + \int_{t_0}^{t} \mathrm{d}t' \frac{g_t''(t-t')}{g_t'(0)} P(t') = \frac{F''(t)}{g_t'(0)} \tag{6}$$

The value of radiation power at each step is calculated from Eq. (6) using the method of successive approximations

$$P^{(0)}(t_i) = \frac{F''(t_i)}{g'(0)} \tag{7a}$$

$$P^{(n)}(t_i) = \frac{F''(t_i)}{g'(0)} + \sum_{j = t_1}^{t_i} \frac{g''(t_i - t_j)}{g'(0)} P^{(n-1)}(t_j) \tag{7b}$$

where n is the step number.

To properly analyse the signal, using this method, application of a control receiver is necessary. This receiver should be characterized by a low level of uncertainty. Thus,

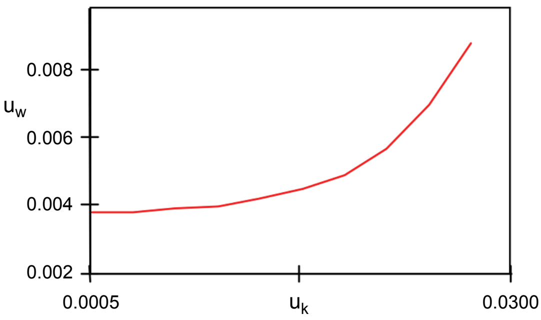

Fig. 6. Dependence between u_w and u_k.

calculations of uncertainty u_w of the measurement as a function of u_k were performed. The corresponding calculation results are shown in Fig. 6.

Examples of results of calculations for a measuring system providing reproduction of a signal shape with the uncertainty not lower than 0.005 are depicted in Fig. 7. The presented laser radiation power signals correspond to the control receiver of $u_k = 0.01$. Figure 7**a** shows the input power signal of laser radiation on the control receiver, Fig. 7**b** a signal at the system's output. Figure 7**c** presents laser radiation power signal reproduced using the methodology developed.

Such an approach is exceptionally powerful for analysis of the photoinduced laser processes with pulse duration within 1 ns–100 ms. This is caused by the fact that during

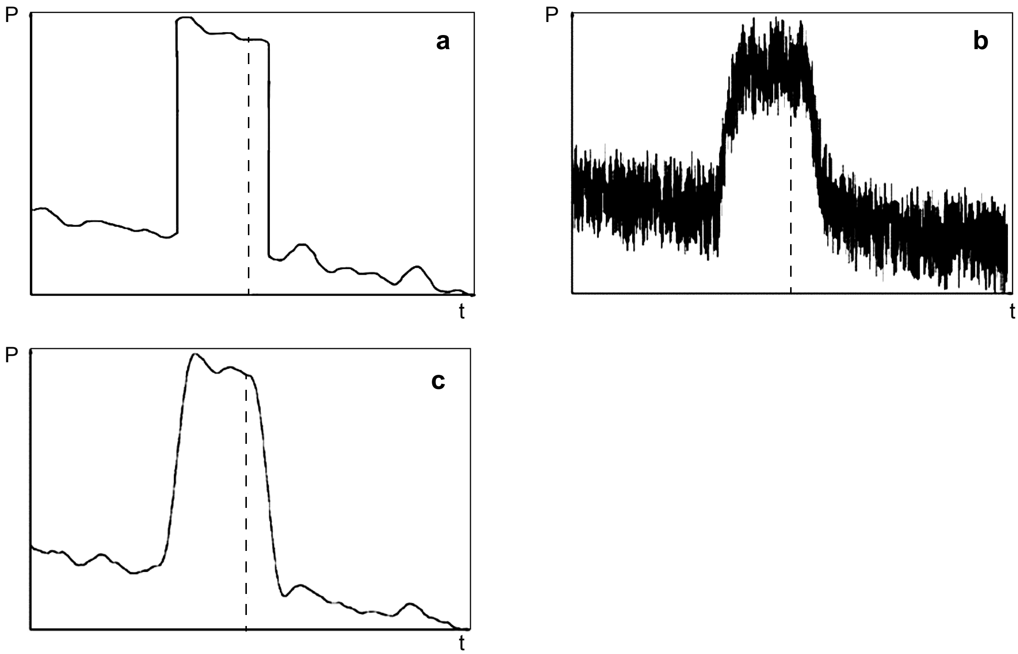

Fig. 7. Laser radiation power signals.

such processes the photoinduced phonons with similar realization times begin to play the principal role [15–17].

The consecutive stage is the correction of the reproduction result for the average power of laser radiation and of its value transfer using the correction algorithm. The corrected value of the average $\overline{P}_{\mathrm{corr}}$ power of radiation is obtained from

$$\overline{P}_{\mathrm{corr}} = \frac{\overline{P}}{1+m} \tag{8}$$

where $\overline{P}$ is the average value of power at the output of SMC in one measurement process and corrected considering a measuring converter drift. The coefficient m, for low values of the corrections, can be given in the form

$$m = \frac{\overline{P} - \overline{P}'_{\mathrm{corr}}}{\overline{P}'_{\mathrm{exp}}} \tag{9}$$

where $\overline{P}'_{\mathrm{corr}}$ is the average power of a laser radiation calculated using control receiver (when the fluctuations and power jumps of laser radiation are excluded), $\overline{P}'_{\mathrm{exp}}$ is the average power observed experimentally with power jump during the measuring process using the control receiver.

4. Conclusions

The formulated model and algorithms for analysis of results were verified by a numerical test. When determining the average power of laser radiation, one hundred measurement runs selected at random were analysed by means of the presented algorithms and compared with the hitherto obtained results, without a correction process. A standard uncertainty of the results from the output signals of SMC, with no correction, was 0.003527 whereas the expected value was 1.000510. Next, a standard uncertainty of the corrected results was 0.000479 whereas the expected value was 0.999955. It is obvious from the results obtained that for the system with the time constant of the measuring converter $\tau = 60$ s, low frequency fluctuations significantly affect the measured results. Due to the applied methodology of signal analysis for a converter of laser radiation, the result uncertainty of reproduction of transfer of the unit of average power of laser radiation can decrease by one order of magnitude. The proposed method may be used for analysis for the photoinduced nonlinear optical processes within the nanosecond and microsecond time durations.

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