Contributed paper

OPTO-ELECTRONICS REVIEW **13**(3), 221–227

Investigations of a laser radiation energy meter with a photoacoustic converter

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The paper presents a measuring method of laser radiation energy using a photoacoustic converter. Mathematical-physical model of the converter and its numerical analysis are described. Influence of the selected design factors and operation conditions on a level of a voltage signal produced at a converter output was analysed. The results of theoretical investigations have been confirmed by the experimental ones. Development of a meter of laser radiation energy with a photoacoustic converter was a final results.

Keywords: photoacoustic converters, meters of laser radiation energy.

1. Introduction

For measurement of power or energy of optical radiation, absorption and transmission, the converters (detectors) are used. Absorption converters are placed at the end of a propagation path of the measured laser beam but transmission converters just at this beam path. Two basic groups of absorption converters can be distinguished, i.e., thermal and photonic ones [1,2].

To a separate group of the systems devoted to measurement of power or energy of laser radiation belong the systems with a radiation beam splitter. Accuracy of energetic parameters of optical radiation depends not only on a measuring instrument but also on accuracy of determination of a splitting coefficient of a radiation beam splitter. It is a disadvantage and such a disadvantage does not occur when the energy meter with a photoacoustic converter is used (Fig. 1). This converter consists of an optical element made of fused quartz and a thin-film piezoelectric detector (PVDF foil).

A laser beam entering an optical element, characterized by some absorption coefficient which is not equal to zero, causes local increase in a temperature as well as local increase in a medium volume. Next, an acoustic wave appears which influences a piezoelectric detector and produces a voltage signal at its output.

2. Mathematical-physical model and numerical analysis of a converter

A trial of numerical solution of equations describing acoustic phenomena in a photoacoustic converter has been undertaken. The formulated problem includes:

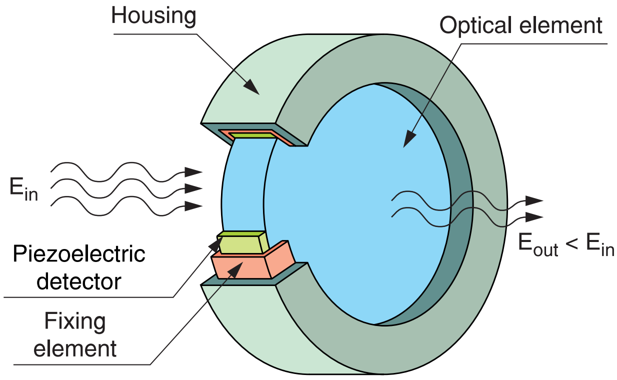

Fig. 1. Construction of a photoacoustic converter (after Ref. 3).

- equation of conservation of energy for precise modelling of an absorption process of laser pulse energy in an optical element,
- real equations of state of both media.

The Lagrange method was used to solve the equations of continuous media mechanics [4]. A problem of acoustic waves propagation was considered, assuming cylindrical symmetry of the occurring phenomena. One-dimensional model was taken for analysis, i.e., it was assumed that the medium is a homogenous one and only the waves propagating along the "*r*" axis are taken into account and the axis "*z*" is the same as direction of an incident laser beam (Fig. 2). The calculations were limited to modelling of the phenomena that occur in a thin layer of the medium of the thickness Δz (Fig. 3). For the above mentioned assumptions, a general system of equations for an elastic body takes the following form in the (r,z,θ) coordinates

$$\frac{d\rho}{dt} + \rho\left(\frac{\partial u}{\partial r} + \frac{u}{r}\right) = 0, \qquad (1)$$

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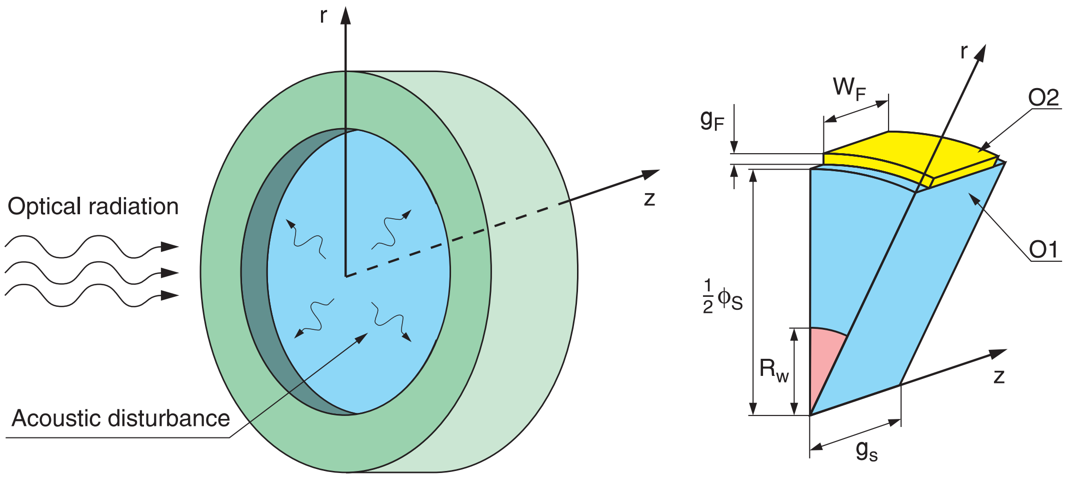


Fig. 2. Geometry of an photoacoustic converter taken for numerical analyses, where g_F is the thickness of a piezoelectric foil, w_F is the width of a piezoelectric foil, ϕ_S is the diameter of an optical element, g_S is the thickness of an optical element, R_W is the radius of a radiation beam, O1 is an optical element (medium 1), and O2 is the piezoelectric foil (medium 2).

$$\rho \frac{du}{dt} = -\frac{\partial p}{\partial r} + \frac{\partial S_1}{\partial r} + \frac{S_1 - S_2}{r}, \tag{2}$$

$$\rho \frac{d\varepsilon}{dt} = -p\left(\frac{\partial u}{\partial r} + \frac{u}{r}\right) + S_1 \frac{\partial u}{\partial r} + S_2 \frac{u}{r} + \alpha q, \tag{3}$$

$$\frac{dS_1}{dt} = 2\mu\left[\frac{\partial u}{\partial r} - \frac{1}{3}\left(\frac{\partial u}{\partial r} + \frac{u}{r}\right)\right], \tag{4}$$

$$\frac{dS_2}{dt} = 2\mu\left[\frac{u}{r} - \frac{1}{3}\left(\frac{\partial u}{\partial r} + \frac{u}{r}\right)\right]. \tag{5}$$

where r is the radial coordinate, ρ is the density, u is the mass velocity (along r), p is the pressure, ε is the internal energy per a volume unit, S_1 is the radial component of a stress deviator, S_2 is the peripheral component of a stress deviator, α is the absorption coefficient, q is the power density of a laser radiation pulse, and μ is the shear modulus.

The component S_3 can be determined from a dependence

$$S_1 + S_2 + S_3 = 0. \tag{6}$$

A medium's element which is considered in numerical calculations and the stresses influenced it are shown in Fig. 3.

It was assumed that the power delivered to the medium is described as

$$q = q_0 f_1(r) f_2(t), \tag{7}$$

where q_0 is the maxium power density, $f_1(r)$ is the dimensionless function determining a shape of a radiation pulse along a radius, $f_2(t)$ is the dimensionless function determining a shape of a radiation pulse v.s. time.

The components of stress tensor can be determined from a dependence

$$\sigma_1 = -p + S_1;\ \sigma_2 = -p + S_2;\ \sigma_3 = -p + S_3, \tag{8}$$

while the pressure p is determined from the equation of state [4]

$$p = K\left(1 - \frac{\rho_0}{\rho}\right) + \Gamma \rho \varepsilon, \tag{9}$$

where K is the bulk modulus, ρ_0 is the initial density, and Γ is the Gruneisen coefficient.

Using such a formulation, the model is correct in a wide range of the energy changes of laser radiation pulses. It was assumed in the proposed model that $f_1(r)$ and $f_2(t)$ are the Gaussian functions and they can be described by the following relations

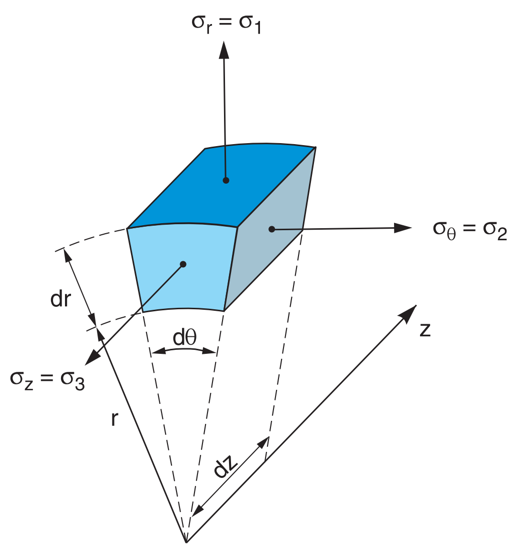


Fig. 3. Element of a medium taken for numerical calculations.

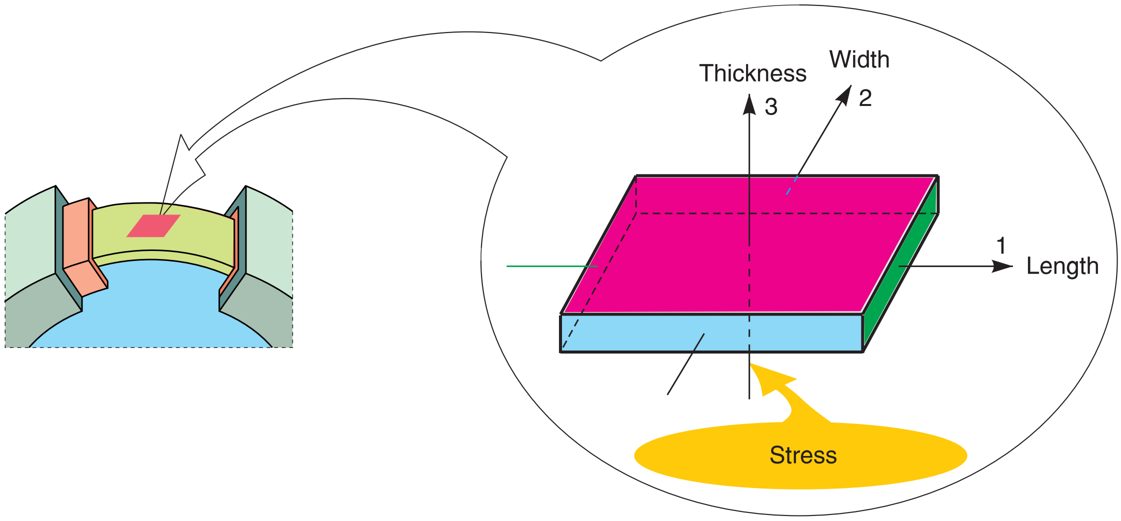


Fig. 4. Classification of the stresses registered in piezoelectric material.

$$f_1(r) = e^{-a_R\left(\frac{r}{R_W}\right)^2}, \quad f_2(t) = e^{-a_t\left(\frac{t-\tau}{\tau}\right)^2}, \tag{10}$$

and

$$f_1(r) = 0 \quad \text{for} \quad r > R_W, \quad f_2(t) = 0 \quad \text{for} \quad t > 2\tau$$

where α_R is the distribution coefficient, R_W is the radius of a radiation beam, α_t is the temporal distribution coefficient, and 2τ is the duration of a radiation pulse.

Due to introduction of adequate distribution coefficients, consideration of laser pulses of various shapes is possible. Two cases were considered: for $\alpha_R = \alpha_t = 1$ and for $\alpha_R = \alpha_t = 0$.

For $t = 0$, the following initial conditions have been assumed

$$\begin{aligned} &u(r,t) = 0, \quad \rho(r,t) = \rho_0, \quad p(r,t) = 0, \\ &S_1(r,t) = 0, \quad S_2(r,t) = 0, \quad \varepsilon(r,t) = 0 \end{aligned}. \tag{11}$$

The boundary conditions (for media boundary) are as follows:

for the external surface of a piezoelectric layer $r = R_3$

$$\sigma_1(r,t) = 0, \tag{12}$$

for media boundary (optical element and piezoelectric foil) $r = R_2 = 1/2\phi_S$

$$\sigma_1^{01}(r,t) = \sigma_1^{02}(r,t), \; u^{01}(r,t) = u^{02}(r,t), \tag{13}$$

where the indices "01" and "02" denote optical element and piezoelectric layer, respectively.

The above mentioned numerical model was used for determination of the force influencing a thin-film piezoelectric detector.

The data taken for numerical calculations are shown in Table 1.

Due to a small thickness of available PVDF foils (10–100 µm) and technology of manufactured electrodes, a voltage measurement on the direction $m = 3$ is possible (Fig. 4).

Thus, to determine a voltage signal, the piezoelectric coefficient g_{33} was taken.

Table 1. Data for numerical calculations (after Ref. 7).

Material constants						
	Density ρ_0 (kgm^{-3})	Poisson coefficient ν	Young modulus E (Gpa)	Bulk modulus K (Gpa)	Shear modulus μ (Gpa)	Gruneisen coefficient Γ
Glass	2510	0.208	45.42	26	18.8	0.53
PVDF foil	1780	0.18	8.30	4.3	3.5	1.64

Dimensions of main elements of a sensor			
Optical element glass		Piezoelectric detector – PVDF	
thickness g_S (mm) along z axis	7.0	thickness g_F (µm) along r axis	100
diameter ϕ_S (mm)	250	width w_F (mm)	5

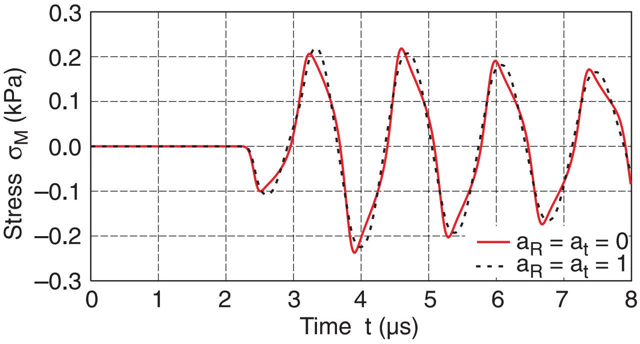


Fig. 5. Comparison of stress changes at the boundary of optical element and piezoelectric detector for various α_R, α_t, at E = 25 mJ, g_F = 100 μm, and t_i = 10 ns.

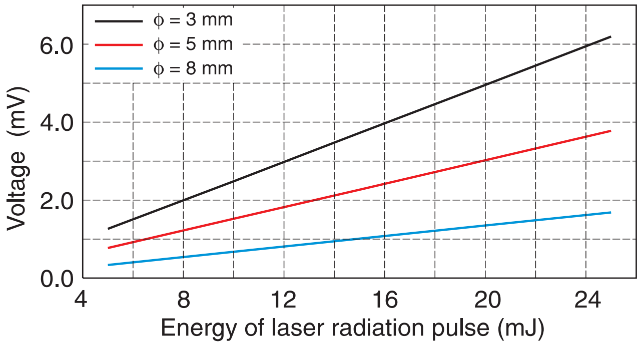


Fig. 7. Dependence of the voltage peak value at the output of a converter on laser pulse energy for three values of a diameter of a cross section of radiation beam ϕ, for t_i = 10 ns, g_F = 100 μm, and $\alpha_R = \alpha_t = 1$.

The voltage signal produced in a piezoelectric foil, that undergoes influence of the external stress, is described by the dependence [6]

$$V_0 = -g_{33}\sigma_M g_F, \tag{14}$$

where V_0 is the electrical voltage, g_{33} is the piezoelectric coefficient, σ_M is the stress at a contact of an optical element and a piezoelectric detector, and g_F is the foil thickness.

According to the boundary condition of Eq. (13), the following dependence is fulfilled

$$\sigma_M(t) = \sigma_1^{01}(r,t) = \sigma_1^{02}(r,t) \quad \text{for} \quad r = R_2. \tag{15}$$

In Eq. (15), a notation was accepted according to which a negative value of the stress corresponds to compression process and a positive one to tension of a medium material in which an acoustic wave propagates.

Figure 5 presents exemplary results of simulations illustrating the changes at the boundary of optical element and piezoelectric detector vs. time. It results from simulations that significant changes of temporal and spatial changes of a laser pulse insignificantly influence the shape of generated acoustic wave. Differences in maximal amplitudes of the appearing stresses and their temporal changes are negligible in practice. Thus, the proposed model can be used for simulation of interaction of laser pulses which spatial and temporal distribution of a power density are known only as approximated functions.

Figure 6 presents stress changes at the boundary of 01 and 02 media as a function of time, for various thicknesses of a piezoelectric foil. Increase in a thickness of a piezoelectric layer changes the shape of an acoustic wave. It results from longer propagation time of the wave in this layer. An initial part of the propagation course, including the first extremum (minimum stresses and corresponding to it the voltage signal maximum) does not change in the whole range of the simulated thicknesses of a piezoelectric foil.

Figure 7 presents dependence of a peak value of the voltage at the converter output on the laser pulse energy for the chosen diameters of a laser radiation beam. It results from the carried out analyses that, in the investigated range of energies (5–150 mJ), linear relationship between the peak voltage value at the converter output and the energy of laser radiation pulse occurs. Increase in a diameter of the incident radiation beam, when a constant value of energy is assumed, causes decrease in a value of voltage signal. Thus, it is important to know a diameter of a laser beam of incident radiation. It has to be taken into account during calibration of a measuring head (converter and preamplifier system).

Figure 8 presents dependence of the peak voltage value at the converter output on energy of a laser radiation pulse

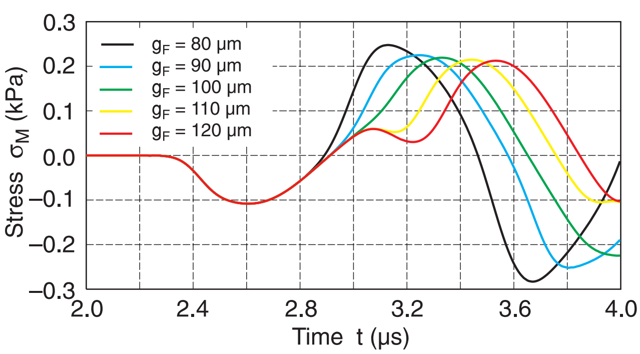


Fig. 6. Dependence of the stresses at the boundary of 01 and 02 media on time for selected thicknesses of a piezoelectric foil ($\alpha_R = \alpha_t = 1$, E = 25 mJ, t_i = 10 ns, ϕ = 3 mm).

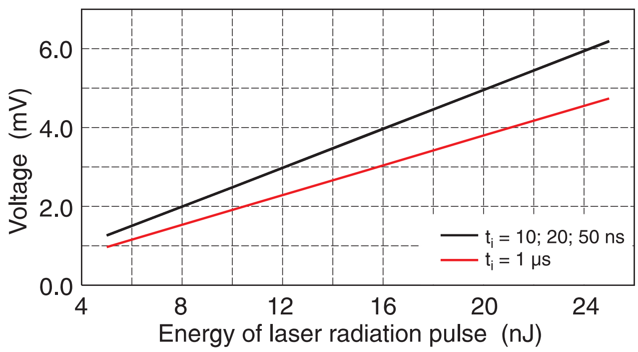


Fig. 8. Dependence of the voltage peak value at the output conversion on energy of a laser pulse for g_F = 100 μm, $\alpha_R = \alpha_t = 1$, and ϕ = 3 mm, for several values of t_i pulse duration of laser radiation.

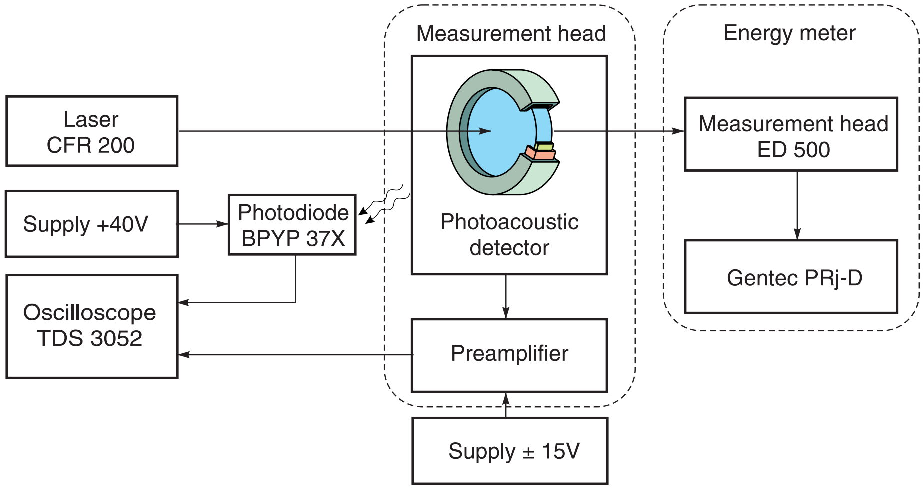


Fig. 9. Scheme of a measuring set-up used for registration of a shape of voltage signal received from a measuring head.

for several values of pulse duration. The change of duration of laser radiation pulse within the range of dozens of nanoseconds insignificantly influences the value of amplitude of the output voltage. Significant differences can be observed for the pulses of two orders of magnitude longer duration.

3. Testing of energy meter

3.1. Investigations of a measuring head

The proposed method for measurement of energy of pulse laser radiation was verified using TDS 3052 digital oscilloscope of the Tektronix firm. Figure 9 shows a scheme of a measuring set-up used for investigations. The oscilloscope was applied for observation of a shape of voltage delivered from a measuring head and for measurement of maximum value of an electric signal. A photodiode released a time base of the oscilloscope.

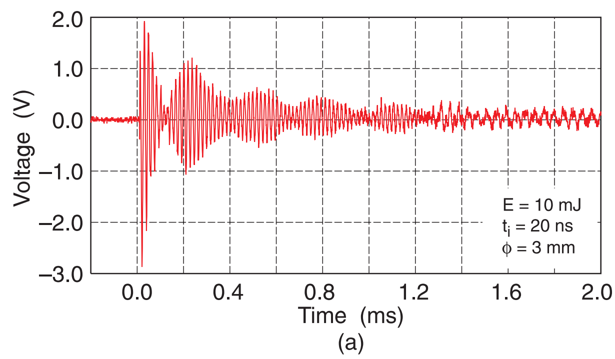
In order to determine a coefficient of detector conversion, the PRjD energy meter of pulse laser radiation with a measuring head (the Gentec firm of ED500 type) was used. Figure 10 presents typical course of voltage changes at the measuring head output for various time bases.

Comparison of experimental results with the results of numerical calculations is shown in Fig. 11. Geometrical parameters and material constants of the measuring head elements are consistent with those shown in Table 1.

As a result of the amplitude measurement of the first maximum of a voltage signal at the output of a measuring head, as a function of energy of pulse laser radiation, the chart shown in Fig. 12 has been obtained. On the basis of the above data, the detector conversion coefficient was calculated

$$w_p^i = \frac{V_i}{E_i}, \tag{16}$$

where V_i is the voltage at the preamplifier output and E_i is the laser pulse energy.



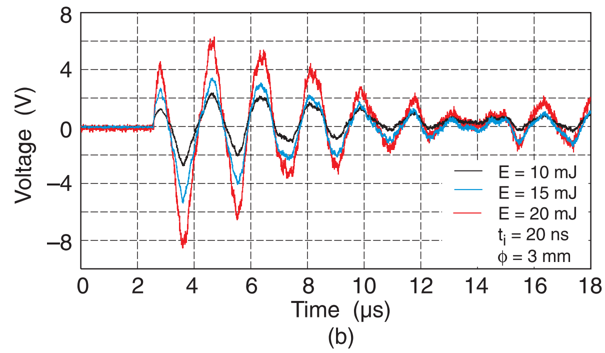


Fig. 10. Oscillograms of the voltages received from a measuring head for various time bases.

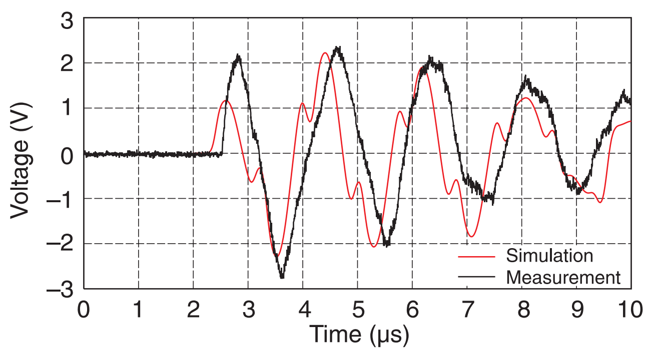


Fig. 11. Comparison of the voltage at the head output (measurement) with a course received from numerical simulation (simulation). Measurement conditions: $E = 10$ mJ, $t_i = 20$ ns, $\phi = 3$ mm.

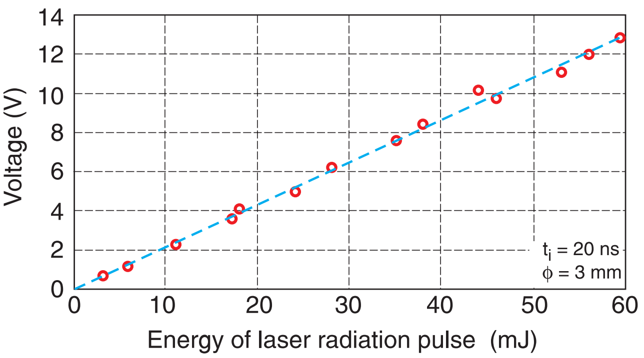


Fig. 12. Dependence of the amplitude of the first maximum of the output signal from a measuring head on energy of laser radiation pulse.

A characteristic of superficial sensitivity of a measuring head was measured at the measuring set-up, the scheme of which is shown in Fig. 13. The measurements were carried out for the energy of laser radiation pulse of 30 mJ, pulse duration 20 ns, and beam diameter of 3 mm. For each position of the measuring head, the measurements were performed that correspond to the first maximum of the observed course and energy of a laser pulse passing through an optical element.

Figure 14 presents a graphical image of the dependence of a detector sensitivity on a place of laser radiation beam incidence at the surface of optical element of the measuring head.

An average value of a conversion coefficient is 211 mV/mJ, but a standard uncertainty of the conversion coefficient is 8 mV/mJ. The differences of a conversion coefficient values result probably from heterogeneity of optical element's material.

3.2. Measurement of energetic characteristics of a meter

For the energy meter investigations, a measuring set-up shown in Fig. 15 was used.

The CFR 200 laser of the Big Sky Laser firm was applied for investigations. It generates laser radiation pulses with a repetition rate from 1 up to 30 Hz. Maximum energy of radiation pulse is 200 mJ for pulse duration of 15–20 ns. The manufacturer ensures that relative instability of energy of substitutive pulses, in series, is below 2%. A diameter of the emitted radiation beam is about 6 mm and its divergence is lower than 4 mrad.

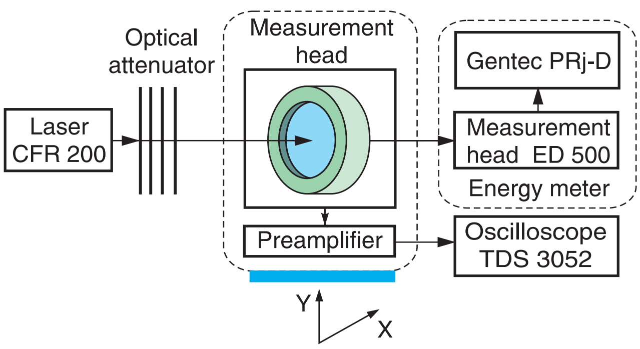


Fig. 13. Scheme of a set-up used for measurements of superficial characteristics of a measuring head. Measurement conditions E = 10 mJ, t_i = 20 ns, ϕ = 3 mm.

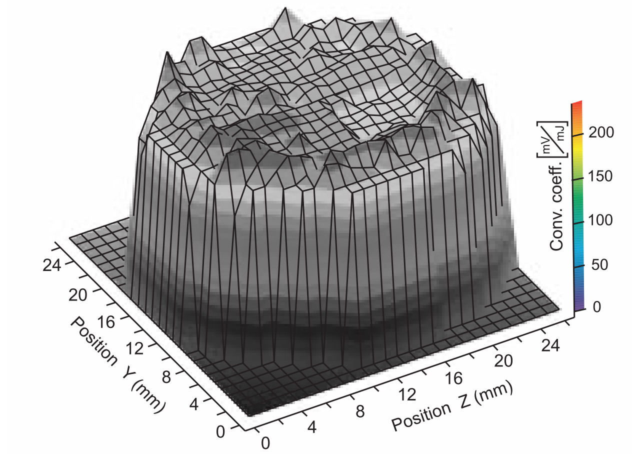


Fig. 14. Dependence of a conversion coefficient of the measuring head on a place of incidence of laser radiation beam.

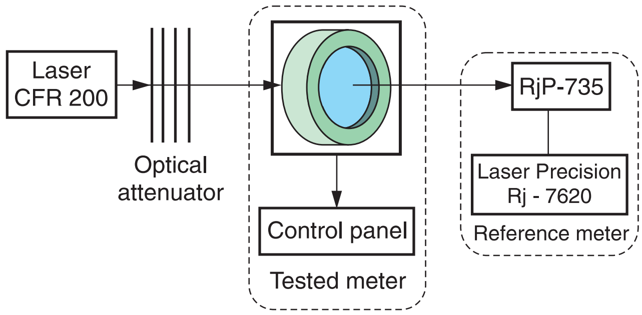


Fig. 15. Scheme of a set-up used for the meter examinations.

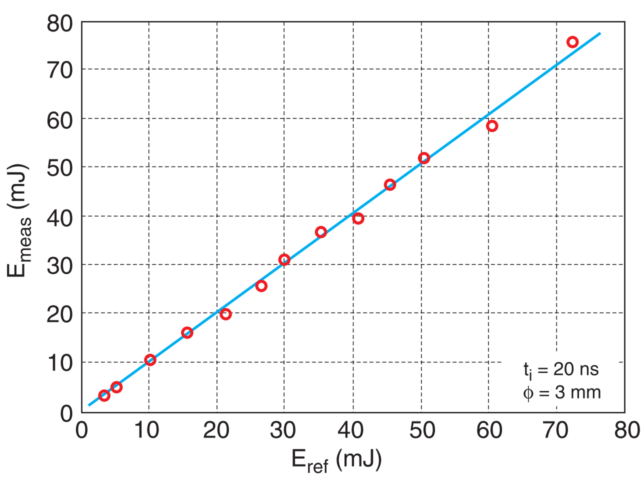


Fig. 16. Dependence of the energy measured with the designed meter on energy of laser radiation pulse measured with a standard meter.

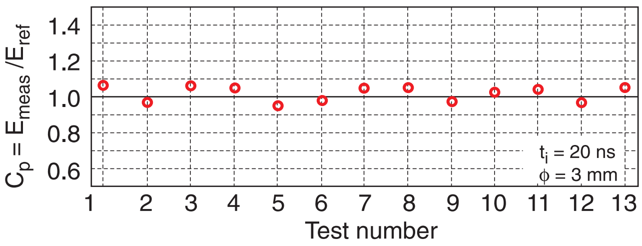


Fig. 17. Stability of indications of the performed model meter for various values of energy of laser radiation pulses.

To ensure satisfactory dynamics of changes of laser radiation energy, a set of optical attenuators was used. As a standard meter, the Rj – 7620 set of Laser Precision firm with the RjP – 735 measuring head was used. Figure 16 shows dependence of energy measured with a developed meter, vs. energy of a laser pulse measured with the standard meter.

Figure 17 shows the changes of a correction coefficient, which is a quotient of energy measured with the investigated meter to the energy indicated by a standard meter, for a series of laser radiation pulses. The measurements were carried out for various values of energy of laser radiation pulses according to Fig. 16. An average value of a correction coefficient was 1.015 and its standard uncertainty 1.2%.

4. Conclusions

The applied numerical model is proper for wide range of changes of laser pulse energy. The dependence connecting laser pulse energy with the peak value at the voltage output is a linear function in the whole range of energies (5–150 mJ). The peak voltage value decreases with increase in a diameter of a laser radiation beam. In applications of the proposed method for laser radiation energy measurement, influence of radiation beam on conversion coefficient of a measuring head should be taken into account.

The change of laser pulse duration, within a range of tens of nanoseconds, insignificantly influences the value of the output voltage amplitude. Experimental investigations included the measurements of a measuring head and a model of energy meter of laser radiation.

The obtained results of voltage measurement at the measuring head output are consistent with numerical calculations. Thus, the carried out experimental investigations confirm usefulness of the proposed numerical model for analyses of photoacoustic converters.

The characteristic of superficial sensitivity of a photoacoustic converter has been examined, too. Voltage sensitivity of a photoacoustic converter fluctuates slightly (5%-fluctuations) in dependence on a place where laser beam incidents on optical element's surface.

The meter has been investigated, too. The results obtained during its calibration show that the developed energy meter is characterised by a very good linearity of indications in the assumed, wide range of changes of the laser radiation energy (from several mJ up to 100 mJ). It results from the meter investigations that an average value of a correction coefficient is 1.015 but a standard uncertainty of this coefficient is equal to 1.2%.

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