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Nuclear-pumped laser operating in the master oscillator – amplifier regime

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***Abstract*. The efficiency of a master oscillator – amplifier scheme and the possibility of its using in multichannel nuclear-pumped laser systems are studied. The small-signal gain and saturation parameter are measured for the He : Ar : Xe = 380 : 380 : 1 mixture at a pressure of 1 atm at a wavelength of 2.03 μm. It is shown that the small-signal gain increases linearly with the specific pump power density and achieves 1.1 – 1.2 m^{-1} at a pump density of 40 W cm^{-3}. The saturation parameter is almost independent of the pump power and is equal to 70 – 90 W cm^{-2}. It is found that at the pump-pulse maximum (40 W cm^{-3}) the laser radiation power increases after amplification by 100 %.**

Keywords: *distributed loss coefficient, nuclear-pumped lasers, multichannel laser system, small-signal gain, master oscillator – amplifier scheme.*

1. Introduction

The development of high-power nuclear-pumped laser facilities [1] is related to the solution of the problem of reducing the number of light beams generated by the facility. This problem appears due to the specificity of nuclear-pumped lasers because any high-power cw laser facility should be multichannel. The problem can be solved by the following methods:

(i) The use of a master oscillator – amplifier scheme. This approach was realised in a nuclear-pumped optical amplifier at the State Research Centre, Physical Energy Institute [2].

(ii) The phasing of radiation from several laser channels by using the Talbot coupling or a nonlinear crystal (see review [3]). This method was used at the RFNC, VNIITF, where the partial phasing of radiation was achieved [4].

(iii) The use of schemes for sequential and parallel composition of laser channels proposed for nuclear-pumped cw lasers in [1]. The sequential composition of two identical laser channels was first realised in the LM-4 laser module in experiments [5]. The scheme of the parallel composition of channels was studied only numerically [6].

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This work is the first stage in the program for studying the efficiency of schemes for composition of nuclear-pumped laser channels and is devoted to the experimental investigation of a master oscillator – amplifier scheme in the two-channel LUNA-2M laser facility [7].

Note that a master oscillator – amplifier scheme upon pumping the active medium by uranium fission fragments was experimentally studied in papers [2, 8 – 12]. The main purpose of these papers, except [2], was the measurement of parameters of active laser media.

Our paper is devoted to the solution of two main problems: (i) the measurement of the small-signal gain and the saturation parameter of the active He – Ar – Xe mixture at a wavelength of 2.03 μm and comparison with experimental results [13, 14] obtained by the calibrated loss method and (ii) the study of the efficiency of the master oscillator – amplifier scheme. We studied the near- and far-field radiation distributions, determined the small-signal gain, investigated amplification in the saturation regime and found the efficiency of the oscillator – amplifier scheme.

2. Experiments

Experiments were performed on the nuclear-pumped two-channel LUNA-2M laser facility [7] with one of the channels used as a master oscillator and the other as an amplifier. The gas medium was excited by ^{235}U fission fragments escaping from a thin layer of uranium oxide – lower oxide irradiated by neutrons from the VIR-2M pulsed reactor [7]. The neutron duration (FWHM) was 3.2 ms and the energy release in the active zone of the reactor was 54 ± 2 MJ.

In the laser channels of the LUNA-2M facility, the ^{235}U oxide – protoxide layers with the surface density ∼ 3 mg cm^{-2} are used. The neutron flux density averaged over the channel length at the maximum of the reactor pulse recalculated to thermal neutrons was 2.2×10^{15} cm^{-2} s^{-1}. The specific pump power at the reactor pulse maximum averaged over the channel volume for the gas mixture under study was approximately 40 W cm^{-3}.

Figure 1 shows the optical scheme of the experimental facility. Laser radiation energy was detected with IMO-2N power meters and the radiation pulse shape was recorded by using FSA-G1 photoresistors and PD24-05 photodiodes. To verify the absence of interference that could be imposed on the useful signal by neutrons or gamma rays from the reactor, optical signals were modulated in one of the experiments.

Experimental studies of the parameters of active media

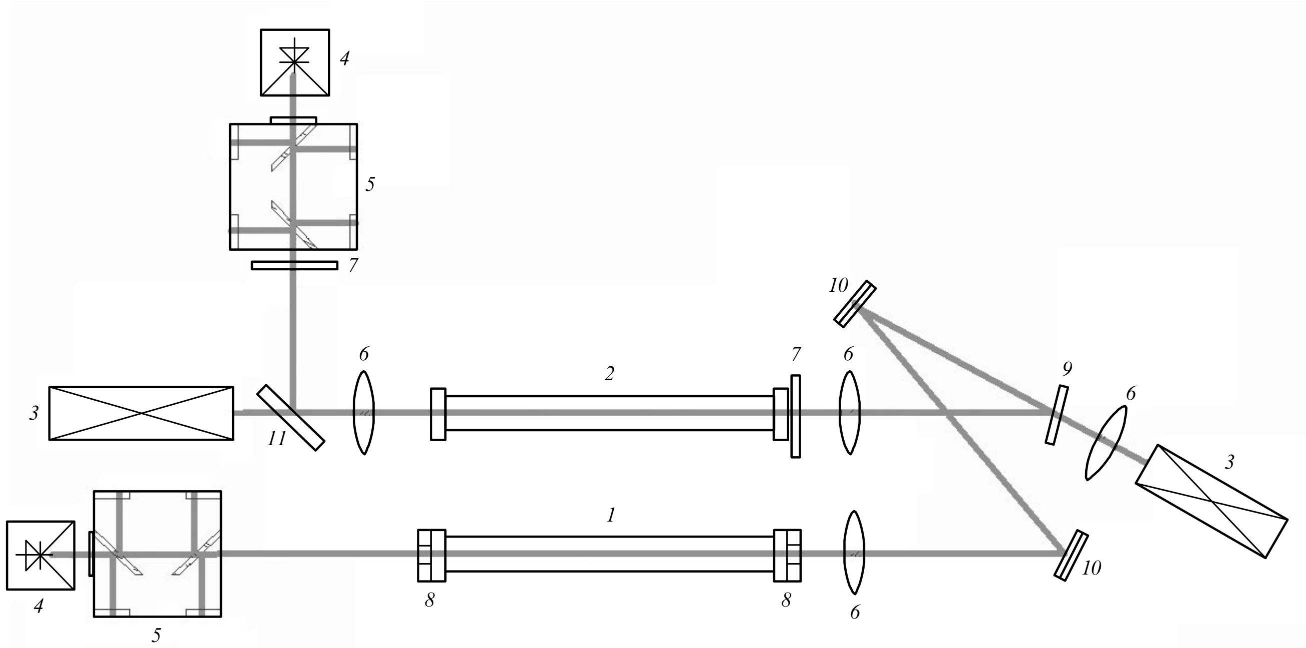

Figure 1. Scheme of the experimental setup: (*1*) oscillator; (*2*) amplifier; (*3*) IMO-2N power meter; (*4*) PD24-05 photodiode; (*5*) FSA-G1 photodetector unit; (*6*) focusing lens; (*7*) optical filters; (*8*) aperture; (*9*) optical wedge or a dielectric mirror; (*10*) aluminium mirror; (*11*) beamsplitter.

performed earlier on the LUNA-2M facility [13, 14] have shown that the maximum small-signal gains are $\sim 1\ \text{m}^{-1}$ and $\sim 2\ \text{m}^{-1}$ at wavelengths 2.03 and 2.65 μm, respectively, for the He : Ar : Xe = 380 : 380 : 1 mixture at a pressure of 1 atm. Because the absorption coefficient of water vapour at 2.65 μm ($\sim 0.3\ \text{m}^{-1}$ for the 50 % humidity of air under normal conditions) is much higher than that at 2.03 μm ($\sim$ 0.07 under the same conditions [15, 16]), we performed experiments at a wavelength of 2.03 μm. For this reason, in all experiments, except calibrations, both channels were filled with the He : Ar : Xe = 380 : 380 : 1 mixture at a pressure of 1 atm. In calibration experiments, the amplification channel was filled with helium at a pressure of 2 atm.

At the first stage of the investigation we measured the near- and far-field radiation distributions for the master oscillator. By using the Rogulsky wedge, we obtained from three to five images on carbon paper with the exposure ratios between successive images of $\sim 1:2$. Experiments showed that the near-field radiation distribution at the laser pulse maximum was almost uniform within a rectangular region of size 39×15 mm (at the $\sim 20\,\%$ intensity level), which is somewhat lower than the laser channel clearance (50×20 mm). The far-field divergence of the oscillator radiation in the horizontal and vertical regions was 7.5 and 5.5 mrad, respectively (at the $\sim 20\,\%$ intensity level).

Table 1 presents the energy parameters of radiation at the amplifier input and output obtained in ten experiments. One can see that radiation powers measured with photodiodes exceed radiation powers measured by using photoresistors. This can be explained by the nonuniform distribution of the radiation intensity on the photoresistor surface and the dynamic displacement of the laser beam in the plane of the photosensitive element of photodetectors.

3. Calculations

3.1 Mode composition and radiation propagation

The master oscillator resonator is formed by two mirrors (plane and spherical of radius 10 m) separated by a distance

Table 1. Energy parameters of laser radiation of the oscillator and amplifier.

Experiment number	W_{in}/mJ	W_{out}/mJ	P_{in}/W PR/PD	P_{out}/W PR/PD	Experimental method
1*	7.8	7.6	2.4/–	2.3/–	Calibrated
2*	8.3	8.2	2.6/–	2.5/–	Calibrated
3*	7.5	31	2.4/2.4	15/16.5	Small-signal gain
4*	2.7	15	0.9/0.9	8.3/9.3	Small-signal gain
5*	150	360	50/58	140/140	Saturation signal gain
6*	180	330	52/68	110/130	Saturation signal gain
7	1300	2300	400/450	650/–	Oscillator – amplifier
8	1200	1100	320/370	300/–	Calibrated
9	1200	1100	330/390	300/340	Calibrated
10	1200	2200	370/400	720/790	Oscillator – amplifier

Note: PR: photoresistor; PD: photodiode; W_{in}, W_{out}: input and output amplifier energies; P_{in}, P_{out}: input and output amplifier powers at the pump pulse maximum; * diaphragmed laser beam.

of 2.4 m. The cross section of the active volume is approximately rectangular of size 50×20 mm. The resonator Fresnel number for $\lambda = 2.03$ μm is $N \sim 50$. Estimates show that upon lasing in the mode mixing regime [17], the far-field radiation divergence of the master oscillator is determined by the divergence of the highest TEM_{mn} transverse mode with $m \approx 170$ and $n \approx 30$. Therefore, the far-field divergence angles along the x and y axes are 10 and 4 mrad, respectively, which is close to experimental values 7.5 and 5.5 mrad. This means that the oscillator radiation is partially coherent.

The dependences of the root-mean square radius of the amplitude distribution and the wave-front radius on the distance (along the x axis) for partially coherent beams in a linear optical system are described by expressions [18, 19]

$$w_x^2 = w_{0x}^2\left\{\left(A_x + \frac{B_x}{R_{0x}}\right)^2 + \left[\frac{\lambda B_x}{\pi (w_{0x}^{\rm g})^2}\right]^2\right\},$$
$$\frac{1}{R_x} = \frac{1}{B_x}\left[D_x - \frac{w_{0x}^2}{w_x^2}\left(A_x + \frac{B_x}{R_{0x}}\right)\right], \tag{1}$$

where w_{0x} and w_x are the root-mean-square radii of the amplitude distribution and R_{0x} and R_x are the wave-front radii at the input and output of the optical system; $A_xB_xC_xD_x$ is the transmission matrix of the optical system; and $w_{0x}^{\rm g}$ is the radius of the amplitude distribution for the equivalent Gaussian beam having the same far-field divergence as the initial beam.

It follows from experiments that the root-mean-square radii of the laser beam on the output resonator mirror along the x and y axes are 19.5 and 7 mm, while the radii of the amplitude distribution of the equivalent Gaussian beam are 1.8 and 1.3 mm, respectively. According to the notation of Siegman [20], we have the laser-beam propagation parameters $M_x = 10.6$ and $M_y = 5.5$.

3.2 Optical inhomogeneities and calculation of the optical scheme

Pump pulses produce optical inhomogeneities in the laser channels of the LUNA-2M facility, which can cause considerable changes in the cross section of a laser beam propagating in the amplifier. We calculated optical inhomogeneities by using the small energy input approximation [21], which is well fulfilled for helium-containing mixtures.

The energy input distribution was calculated by the method described in [22]. The results of calculations showed that the parabolic approximation of the energy input distribution describes its behaviour in the channel region -15 mm $< x < 15$ mm and -5 mm $< y < 5$ mm with the relative error no more than 3 %. The parabolic approximation of the energy input distribution allows us to describe the refractive index by using the second-order polynomial and matrix optics for calculating the propagation of partially coherent laser beams in the optical system by expressions (1).

The second derivative of the refractive index with respect to x in the axial region of laser channels is described by the expression [21]

$$n_{xx}(z;t) \approx -\frac{n_0 - 1}{\gamma\beta}\frac{q_{xx}(0,0)}{\langle q\rangle}\mu(z)\ln\left[\frac{P(t)}{P_0}\right], \tag{2}$$

where n_0 is the initial refractive index; γ is the adiabatic index; $\beta = V/V_0$ is the ratio of the active volume of a cell to the total volume ($\beta = 0.24$ for the LUNA-2M facility); $q(x,y)$ and $\langle q\rangle$ is the transverse energy input distribution and its average value, respectively; $\mu(z)$ is the relative distribution of the neutron flux over the amplifier length; $P(t)$ and P_0 are the gas pressure and its initial value, respectively.

After calculation of optical inhomogeneities, the parameters of the $ABCD$ transition matrix of the optical scheme and amplifier were determined by numerical integration of the ray equations in the paraxial approximation by the fourth-order Runge–Kutta method [23].

Calculations of the laser radiation propagation through the optical scheme and amplifier showed that the diaphragmed laser beam (∅1 cm) can pass almost without diffraction losses through the amplifier filled with helium at a pressure of 2 atm. The losses calculated for the non-diaphragmed beam propagating in the amplifier were ~ 10 %. These results are confirmed by calibration experiments (Table 1, experiment Nos 1, 2, 8, and 9).

The results of calculation of the propagation of a diaphragmed beam in the amplifier are presented in Fig. 2. A diverging lens (along the x axis) only slightly (by fractions of millimetre) expands the beam (not shown in Fig. 2). The influence of a focusing lens (along the y axis), on the contrary, is quite large: the beam waist is displaced to the amplifier input by ~ 0.5 m and the beam waist radius decreases from 4 to 1.5 mm.

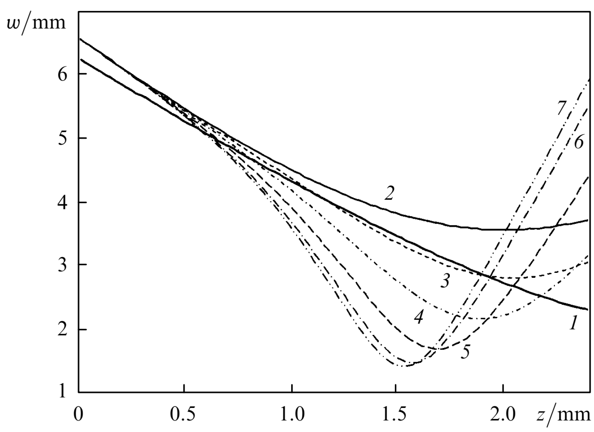

Figure 2. Distribution of the root-mean-square radius of a diaphragmed beam in the amplification channel along the x and y axes in a homogeneous medium (*1, 2*) and along the y axis at instants 5 (*3*), 6 (*4*), 7 (*5*), 8 (*6*) and above 9 ms (*7*).

3.3 Small-signal gain

The small-signal gain averaged over the amplifier length in the regime of stationary amplification of a laser beam is [24]

$$\langle\alpha_0\rangle = \rho + \frac{1}{L}\ln\left(\frac{P_{\rm out}}{P_{\rm in}}\right), \tag{3}$$

where $P_{\rm in}$ and $P_{\rm out}$ are the radiation powers at the amplifier input and output; ρ is the distributed loss coefficient; and L is the active medium of the amplifier ($L = 2$ m for the LUNA-2M facility).

Figure 3 shows radiation power pulses at the input and output of the amplifier in experiment No. 4. One can see that the output power of the amplifier at the reactor pulse maximum is approximately an order of magnitude higher than at the amplifier input. Calculations performed by expression (3) show that the small-signal gain at the reactor pulse maximum is approximately $0.9-1\ \mathrm{m}^{-1}$ in experiment No. 3 and $1.1-1.2\ \mathrm{m}^{-1}$ in experiment No. 4. A small difference between these results can be explained by a weak saturation effect in experiment No. 3.

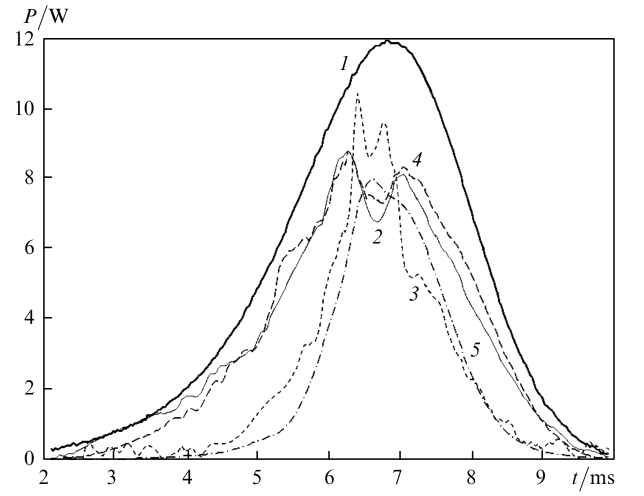

Figure 3. Small-signal gain in experiment No. 4 (diaphragmed beam, ∅1 cm): pump pulse shape (*1*) and the input (multiplied by 10 times) and output amplifier powers detected with a photodiode (*2, 3*) and a photoresistor (*4, 5*).

The dependence of the small-signal gain on the specific pump power in the range $8-40\ \mathrm{W\ cm}^{-3}$ is well described by a linear function of the type

$$\langle\alpha_0\rangle = \langle\alpha_0^{\max}\rangle\frac{\langle q\rangle}{\langle q_{\max}\rangle} - \rho, \tag{4}$$

where $\langle\alpha_0^{\max}\rangle$ is the small-signal gain at the pump pulse maximum averaged over the amplifier length; and $\langle q_{\max}\rangle = 40\ \mathrm{W\ cm}^{-3}$ is the maximum specific pump power. Table 2 presents the parameters of approximation (4) determined by the method of least squares from measurements obtained with a photodiode and a photoresistor. It follows from Table 2 that the distributed loss coefficient lies in the range from 2×10^{-3} to $6\times10^{-3}\ \mathrm{m}^{-1}$, in good agreement with data [14].

Table 2. Parameters of linear function (4).

Experiment number	Photodiode		Photoresistor	
	$\langle\alpha_0^{\max}\rangle/\mathrm{m}^{-1}$	ρ/m^{-1}	$\langle\alpha_0^{\max}\rangle/\mathrm{m}^{-1}$	ρ/m^{-1}
3	0.96	1.9×10^{-3}	0.94	3.7×10^{-3}
4	1.18	2.4×10^{-3}	1.10	6×10^{-3}

Figure 4 presents the dependences of the small-signal gain α_0 on the specific pump power obtained in [14] by the method of calibrated losses and in our paper by direct measurements (by the oscillator–amplifier method). One can see that in the case of the method of calibrated losses, a sharp jump of α_0 from ~ 0.2 to $\sim 0.8\ \mathrm{m}^{-1}$ is observed at the specific pump power $\sim 8\ \mathrm{W\ cm}^{-3}$, which is accompanied by the decease in the saturation parameter from ~ 80 to $\sim 20\ \mathrm{W\ cm}^{-2}$ [14]. This effect can be explained by the inapplicability of the Rigrod expression [25] for approximating the experimental results obtained at the pump power indicated above. Figure 4 also presents the values of the small-signal gain (squares) obtained by the method of calibrated losses for the fixed saturation parameter $80\ \mathrm{W\ cm}^{-2}$. One can see that in this case the results obtained by the two independent methods are in good agreement.

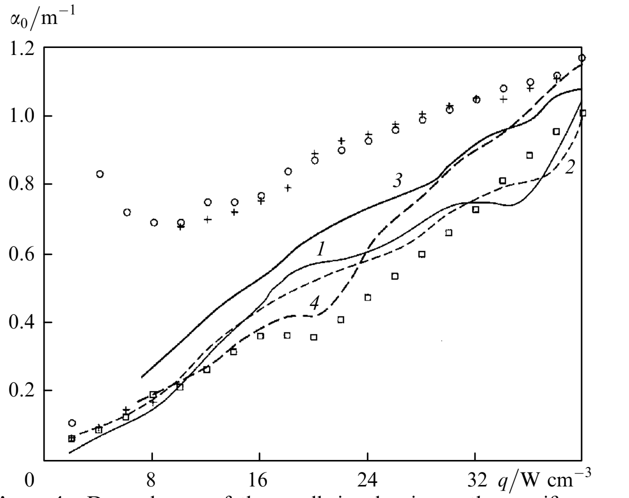

Figure 4. Dependences of the small-signal gain on the specific pump power determined by approximating experimental results by the method of least squares with the help of the Rigrod formula [14] (crosses and circles correspond to the left and right parts of the pump pulse, respectively; squares are the average of the left and right parts of the pump pulse; the saturation parameter is fixed at $80\ \mathrm{W\ cm}^{-2}$) and by the small-signal gain method by performing measurements with a photodiode and a photoresistor, respectively [experiment No. 3 (*1, 2*) and No. 4 (*3, 4*)].

3.4 Determination of the saturation parameter

The saturation parameter was determined by assuming that the radiation intensity is uniformly distributed over the laser beam cross section and the propagation of the root-mean-square radius of the amplitude distribution and the wave-front radius of the laser beam in the amplifier is described by expressions (1).

The radiation intensity at the amplifier output was determined from the expression [24]

$$I_{\mathrm{out}} = \frac{I_{\mathrm{in}}S_{\mathrm{in}}}{S_{\mathrm{out}}}\exp\left[\int_0^L \frac{\alpha_0(z)}{1+I_{\mathrm{s}}^{-1}I(z)}\mathrm{d}z - \rho L\right], \tag{5}$$

where I_{s} is the saturation parameter; I_{in} and I_{out} are the radiation intensities at the amplifier input and output, respectively; and S_{in} and S_{out} are the laser beam cross sections at the amplifier input and output, respectively.

The amplification of the diaphragmed laser beam (∅1 cm) in the saturated regime was measured in experiment Nos 5 and 6. Radiation power pulses at the amplifier input and output (experiment No. 5) presented in Fig. 5 show that the maximum output power of the amplifier is approximately three times higher than the input power.

The saturation parameter was determined from the best fit of experimental data by calculations. The radiation

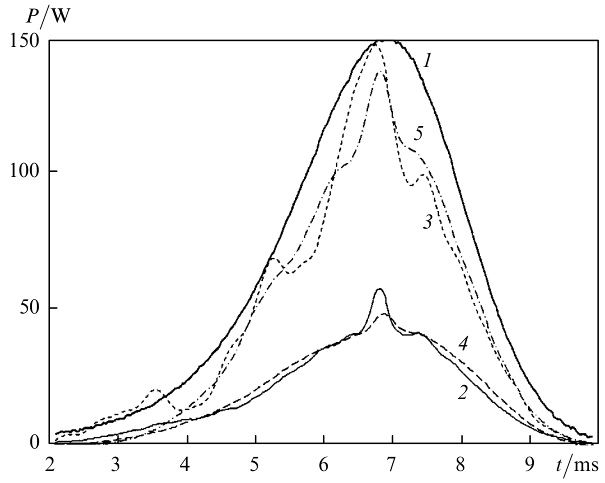

Figure 5. Saturated-signal amplification in experiment No. 5 (diaphragmed beam, ∅1 cm): pump pulse shape (*1*) and the input and output amplifier powers, respectively, measured with a photodiode (*2, 3*) and a photoresistor (*4, 5*).

intensity in the amplifier was calculated by expression (5) and the small-signal gain was measured in experiment No. 4. The calculations show that the saturation parameter is virtually independent of the pump power (tending to increase with increasing pump power) and is ~ 70 and 90 W cm^{-2} in experiment Nos 5 and 6, respectively.

3.5 Amplification of a non-diaphragmed beam

The operation efficiency of two laser channels of the LUNA-2M facility in the master oscillator – amplifier regime without laser beam diaphragming was studied in experiment Nos 7 and 10. As mentioned above, losses in these experiments caused by optical inhomogeneities and laser-beam 'diaphragming' on the amplification channel walls did not exceed 10 %.

Figure 6 presents laser power pulses at the amplifier input and output recorded in experiment No. 10. The output amplifier power at the pump pulse maximum (40 W cm^{-3}) achieves 700 – 790 W, which is approximately twice as large as the input power (370 – 400 W). The output amplifier power (2.2 J) in this experiment was approximately higher by 90 % than at the amplifier input (1.2 J).

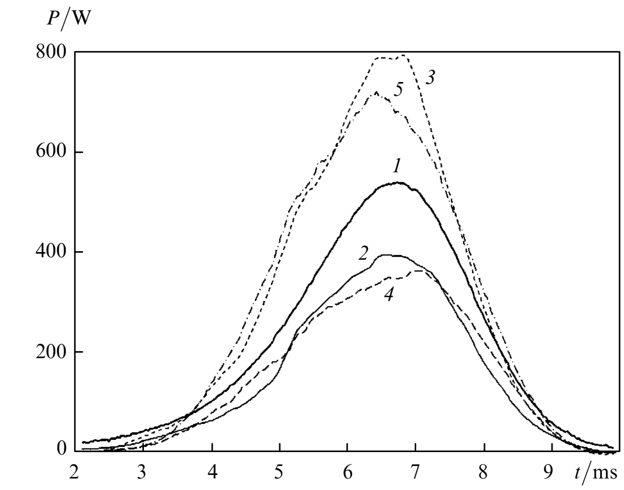

Figure 6. Saturated-signal amplification in experiment No. 10 (non-diaphragmed beam): pump pulse shape (*1*) and the input and output amplifier powers, respectively, measured with a photodiode (*2, 3*) and a photoresistor (*4, 5*).

4. Conclusions

By using the master oscillator – amplifier scheme in the nuclear-pumped two-channel LUNA-2M laser facility with the He : Ar : Xe = 380 : 380 : 1 mixture at a pressure of 1 atm, we have obtained the following results:

(i) The laser-beam cross section (at $\lambda = 2.03$ μm) behind the output resonator mirror is a rectangle of size 39×15 mm (at the ~ 20 % intensity level).

(ii) The far-field divergence of the oscillator radiation in the horizontal and vertical planes was 7.5 and 5.5 mrad, respectively (at the ~ 20 % intensity level). The calculations showed that such divergence corresponds to lasing in the mode mixing regime.

(iii) The small-signal gain almost linearly increases with increasing specific pump power and is 1.1 – 1.2 m^{-1} for $q_{max} = 40$ W cm^{-3}.

(iv) The distributed loss coefficient is between $2 \times 10^{-3}$and 6×10^{-3} m^{-1}.

(v) The saturation parameter is virtually independent of the pump power and is 70 – 90 W cm^{-3}.

(vi) Experiments on the amplification a non-diaphragmed laser beam have shown that the laser power and energy at the amplifier output at the reactor pulse maximum ($q_{max} = 40$ W cm^{-3}) were higher by ~ 100 % and 90 %, respectively, than at the amplifier input.

Note that in [2] a laser setup on the He : Ar : Xe = 600 : 200 : 1 mixture at a pressure of 1 atm (a wavelength of 2.03 μm) was studied. The parameters of this mixture should be close to those of the He : Ar : Xe = 380 : 380 : 1 mixture used in our experiments. It was found in [2] that the small-signal gain monotonically (but not linearly) increased with increasing pump power and achieved ~ 2 m^{-1} for $q = 180$ W cm^{-3}. In this case, the small-signal gain was 0.8 m^{-1} for $q = 30$ W cm^{-3}, in good agreement with our results (0.75 – 0.85 m^{-1}). However, the saturation parameter in [2] increased linearly with the pump power from 90 W cm^{-2} at the lasing threshold to 550 W cm^{-2} for $q = 180$ W cm^{-3}, which differs from the results of our paper.

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