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Femtosecond laser system based on thin rod Yb : YAG active elements with an output power of 110 W

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Abstract. **A three-stage laser amplification system based on thin Yb : YAG rods with diode laser pumping is developed and fabricated. In this system, the average power of a continuous train of femtosecond pulses from a Yb : KGW master oscillator with a pulse repetition rate of 80 MHz and initial pulse duration of 128 fs was raised by a factor of 100 to above 100 W. Preliminarily chirped laser pulses provided compensation of dispersion in optical elements of the system and obtaining 580-fs output pulses. The longer duration of output pulses relates to spectrum narrowing in the amplifiers.**

Keywords: *diode-pumped laser amplifier on Yb : YAG, high average radiation power, femtosecond pulses.*

1. Introduction

The use of thin rods with a diameter of about 1 mm as active elements substantially suppresses parasitic thermo-physical processes and, thus, increases an average radiation power as compared to active elements of greater diameter. As a result, the average power of lasers on thin Yb : YAG rods reaches hundreds of watts with a good beam quality [1]. A larger amplification in such elements due to a higher concentration of a pump power makes it possible to use a shorter gain medium and, consequently, to suppress partially the self-action of radiation, which limits the peak power of amplified ultrashort pulses. In turn, this allows one to amplify femtosecond pulses directly without using the chirped pulse amplification technique [1, 2]. However, amplification in such conventionally used medium as Yb : YAG with a sufficiently narrow gain leads to substantial spectral narrowing when laser pulses of duration 100 fs are amplified and makes the latter noticeably longer (up to 1000 fs) [1 – 4].

In the present work, direct amplification is thoroughly studied in the three-stage thin Yb : YAG rod amplifiers to the average power of above 100 W, as applied to a continuous train of 100-fs laser pulses from a Yb : KGW master oscillator operated at a pulse repetition rate of 80 MHz. The preliminary chirp introduced for compensating dispersion in elements of the amplifying system made it possible to obtain pulses shorter than 600 fs. Characteristics of some amplifiers on thin rods are described in [5] along with results of numerical simulation. Our earlier paper [4] briefly reported on the average power of 100 W.

2. Experimental setup

An optical schematic of the experimental setup is shown in Fig. 1. It comprises a femtosecond master oscillator (MO) based on an Yb : KGW crystal and three amplification units on thin rods from Yb : YAG crystals. The master oscillator was earlier used in our amplification system on Yb : KGW [6] and generated a train of laser pulses of duration 80 fs at a pulse repetition rate of 80 MHz. Although the centre radiation wavelength λ = 1035 nm of this Yb : KGW MO differs from the wavelength λ = 1030 nm, which corresponds to the gain maximum in Yb : YAG, the gain spectral profiles of these two media overlap, which provides efficient amplification.

The first two amplification stages operated by the double-pass scheme with a quarter-wave plate. In the first stage, the amplification unit was used with a conical active element of length 40 mm and the diameter varying from 0.8 to 0.3 mm developed at the Institute of Applied Physics (IAP) RAS [3]. The ytterbium concentration was 1 at.%. The amplifier was pumped by a laser diode bar with a fibre output of diameter 105 μm (JDSU Company) and the maximal radiation power of 150 W at a wavelength of 940 nm. The pump radiation was focused to a spot of diameter ~300 μm in a volume of the active element. The MO laser beam was also focused to the active element in such a way that the optimal overlapping with the pump beam was provided. The amplified laser radiation passed through a thin film polariser and was collimated by a spherical lens.

The second stage was also developed at the IAP RAS and comprised the active element (Shasta Company) of diameter 1 mm and length 30 mm with the ytterbium contents of 2 at.%. The amplifier was pumped by a semiconductor laser unit similar to that in the first stage according to the same optical scheme.

The third amplifying cascade based on the Taranis unit [7] with the active element having the diameter 1 mm and length of 40 mm was pumped by a semiconductor laser unit (nLight Company) with a maximal radiation power of 200 W at an output fibre of diameter 200 μm. The radiation power entering this stage was sufficiently high; thus, the amplifier operated in a single-pass regime.

Since the laser system gain was substantial (more than 100), self-excitation was restricted by using a Faraday isolator placed between the first and second amplifiers.

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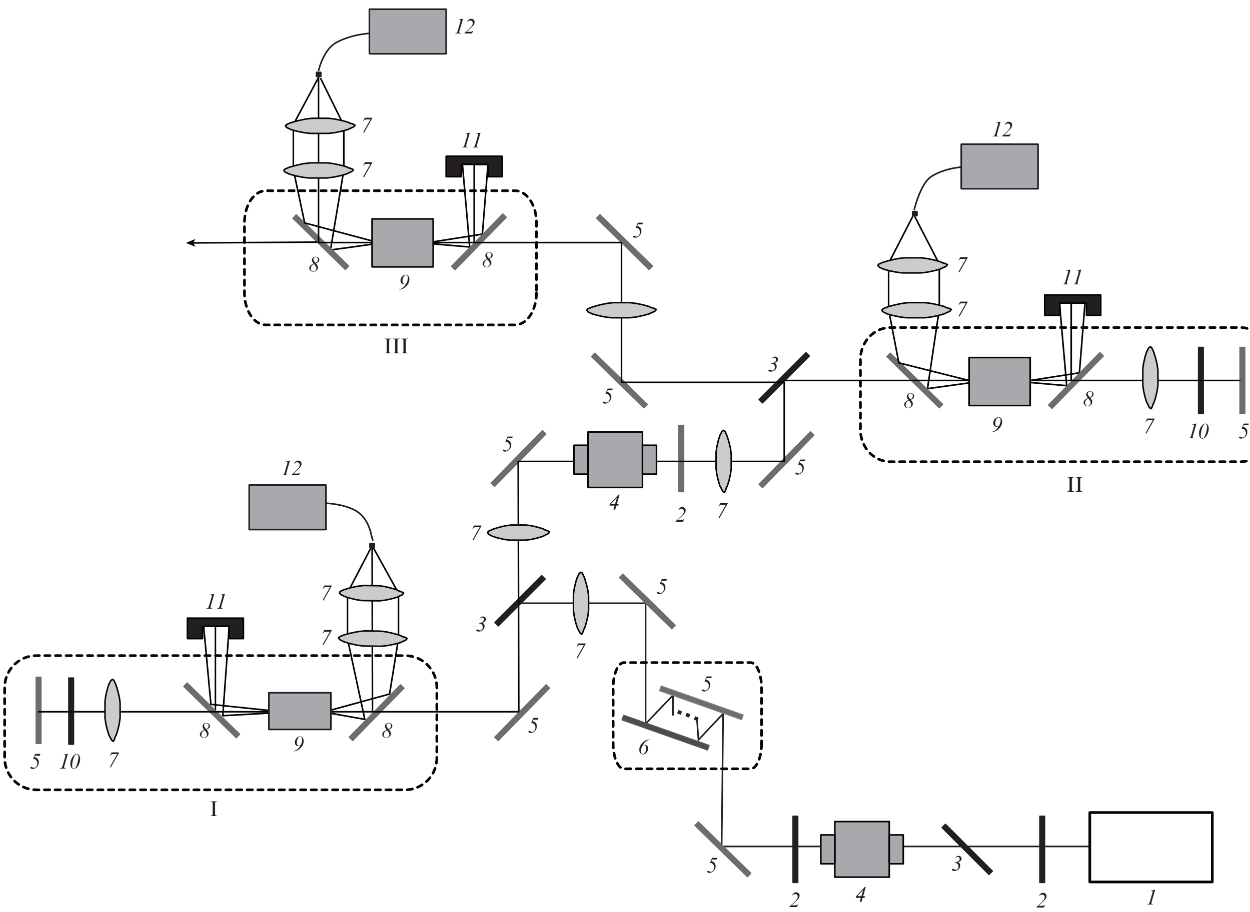

Figure 1. Schematic of the femtosecond laser system with an amplifier on thin rods: (I) and (II) first and second double-pass amplification stages, (III) third single-pass amplification stage; (*1*) Yb : KGW MO; (*2*) half-wave plates; (*3*) thin film polarisers; (*4*) Faraday isolator; (*5*) high-reflection mirrors; (*6*) chirped mirror; (*7*) lenses; (*8*) dichroic mirror; (*9*) thin rod active elements; (*10*) quarter-wave plates; (*11*) absorbers; (*12*) pump laser diode bars.

Dispersion spreading of pulses in the amplifying system was compensated by using a chirped mirror, which introduced a negative dispersion GDD $\approx$ –10000 fs^2 per single reflection. The total dispersion value was experimentally determined by varying the number of reflections from the chirped mirror that was used along with an ordinary high-reflection mirror.

3. Experimental results and discussion

An output power of the first amplifier is shown in Fig. 2 as a function of the pump power for the single- and double-pass amplification regimes. One can see that in the double-pass regime, the output power reaches 14 W and the overall gain is 14. The centre wavelength of the amplified radiation is 1030.4 nm at the spectrum (FWHM) width of 3.1 nm. Despite of the substantial suppression of thermo-optical effects in thin optical elements, a small depolarisation of radiation equal to 7.8 % per two transits was observed. The optical efficiency was relatively small (~10%) due to a small power of input signal.

A radiation power measured at output from the second amplifier is shown in Fig. 3 as a function of the pump power. In the double-pass regime, the output power exceeded 60 W, the optical efficiency of power extraction relative to the absorbed power reached 31 %. In this case, the spectrum narrowed to 2.5 nm and the duration of compressed pulse was 400 fs. Measurements showed that the beam had a sufficiently high quality ($M_x^2 = 1.21$, $M_y^2 = 1.25$), which indicates the absence of serious thermo-optical distortions.

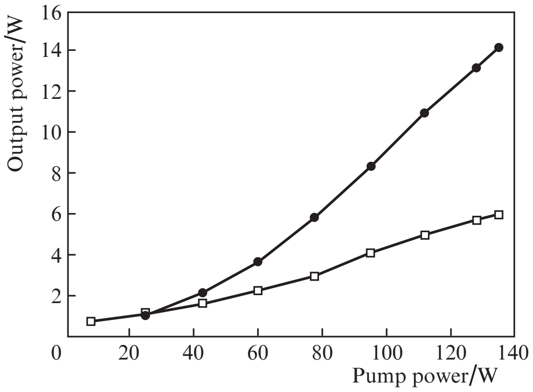

Figure 2. Output power of the first amplifier vs. the pump power for a (□) single pass and (●) double passes.

Data on the third amplification stage operated in a single-pass regime are presented in Fig. 4. The output power was above 110 W at the pump power of 180 W. Correspondingly, the conversion efficiency was 28 % (31 % with respect to the absorbed power).

A spectrum and autocorrelation function of femtosecond output laser pulses at the system output are shown in Fig. 5

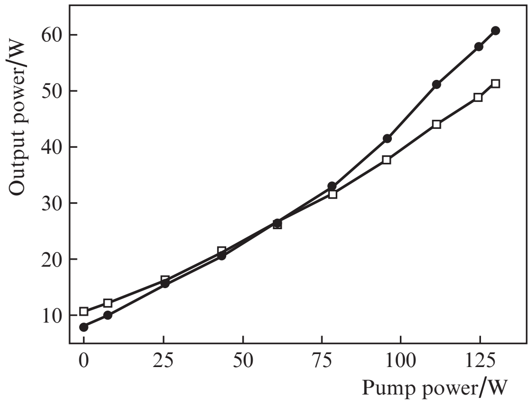

Figure 3. Output power of the second amplifier vs. the pump power for a (□) single pass and (●) double passes.

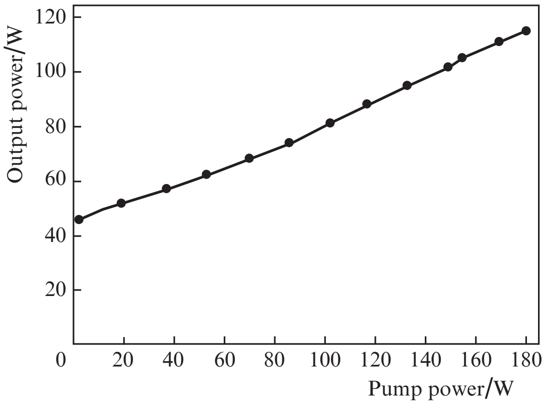

Figure 4. Output power of the third amplifier vs. the pump power.

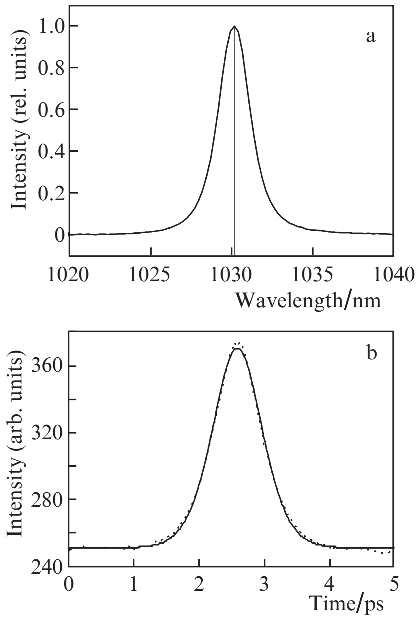

Figure 5. (a) Spectrum and (b) autocorrelation function of femtosecond laser pulses at output from the laser system. Dotted curve corresponds to the autocorrelation function of a sech^2-pulse.

One can see that the centre wavelength of the spectrum coincides with that of Yb:YAG-crystal luminescence, the initial spectrum narrows to 2.4 nm, and the pulse duration is 580 fs with the use of a chirped mirror. A product of the pulse duration and spectrum width yields the value of 0.39, which slightly differs from the limiting value of 0.315 for an ideal sech^2-pulse. If the radiation had no preliminary phase modulation, the duration of output femtosecond pulses was greater by approximately 1.25 times, which agrees with the measurement results given in [1].

The value of phase modulation (negative chirp) at the system input could be varied by changing the number of reflections from the chirped mirror. Measurements of the pulse duration after the second amplifier have shown that the minimal duration (500 fs) is observed after four reflections from the chirped mirror. This number of reflections was then used for the whole amplifying system.

A higher pump power resulted in a stronger thermo-optical lens with aberrations, which affected the beam quality. A standard radiation quality parameter M^2 measured at system output was $M_x^2 \times M_y^2 = 1.9 \times 1.8$ at the output power of 100 W. The beam quality can be improved in the second passage through the amplifier. However, it was not realised because of the self-excitation of the amplifying system as a whole. This can be realised in the future by using additional optical isolators for suppressing the self-excitation.

Possible development of the self-focusing, which is one of the main limiters of a peak power in solid-state laser systems [8] was also verified. As known, the development of a large-scale self-focusing requires an excess of the pulse peak power over the critical power P_{cr}. For development of a small-scale self-focusing, the value of B-integral should be greater than unity [8]. At the value of a nonlinear refractive index $n_2 = 6.9\times10^{-20}$ m^2 W^{-2} for the YAG crystal [9, 10] we obtain $P_{\mathrm{cr}} = 3.77\lambda^2/(8\pi n^2 n_0) \approx 1.9$ MW, which is comparable with the peak power of ultrashort pulses $P \approx 2.5$ MW at output of the amplifying system. Obviously, such a power may be sufficient for the development of the self-focusing. A stronger influence of self-focusing becomes possible at kilowatt powers or at a reduced pulse repetition rate when the average power is kept the same.

For determining the threshold energy values, at which the self-focusing reveals in the amplifiers, we measured a dependence of the light spot dimension on the pulse energy at a distance of ~1 m from the second amplifier. In this case, for increasing the pulse energy, the pulse repetition rate was reduced to 1 MHz by using an additional Pockels cell. The output power was varied by an attenuator comprised of polarisers and a half-wave plate placed at the system input. Dependences of the beam diameter on the output power are given in Fig. 6. One can see that the beam diameter noticeably increases starting from the power of ~3.5 W; this corresponds to the pulse energy of 3.5 μJ, which can be conditionally taken as the self-focusing threshold. The latter value corresponds to the peak power $P \approx 6$ MW. Measurements taken with a CCD-camera showed that under a further power increase up to 8 W the beam shape did not change. No destruction tracks were observed inside the active element that might indicate beam filamentation. Spectrum broadening, which might be related to self-phase modulation, has not been observed as well.

Note that the Kerr nonlinearity, which is responsible for the self-focusing, may also play a positive role in femtosecond laser systems resulting in self-modulation with the following pulse compression by chirped mirrors [11, 12]. However, a

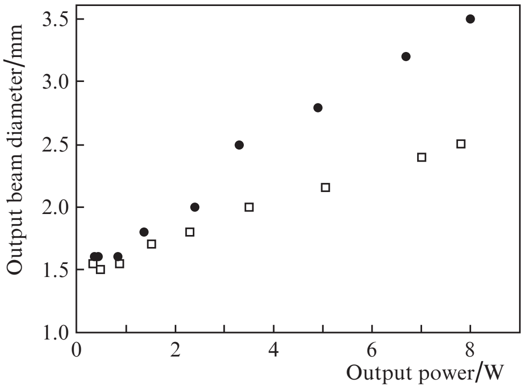

Figure 6. Laser beam diameter at the system output vs. the output power at the pulse repetition rate of (□) 80 and (●) 1 MHz.

possible employment of this effect in amplifying systems on thin rods with laser beam focusing into a volume of active medium requires further investigations, because filamentation of the radiation may occur in this case [13] and the material may be modified.

4. Conclusions

Results of the development of the femtosecond laser system with a 100-watt power based on three thin-rod amplifiers are presented. The total gain of the system in the saturation regime was above 100, which is comparable with gain in regenerative amplifiers. The output power exceeded 110 W at the optical efficiency of 26%, which provides the pulse energy of 1.38 μJ at the pulse repetition rate of 80 MHz. A limited spectral band of the crystal gain in Yb : YAG resulted in pulse stretching to 580 fs; however, this is substantially less than in the case without dispersion compensation (800 fs) [1]. The efficiency of correction is confirmed by the fact that the product of the spectrum width $\Delta\omega$ and pulse duration τ ($\Delta\omega\tau = 0.39$ under the assumption of a sech^2-shape of the pulse) is typical for a transform-limited pulse.

The main drawback of the developed amplifying system is the employment of a large number of isolators for preventing self-excitation. In our system, such isolators were realised as Faraday isolators.

In the future, the pulse repetition rate will be reduced to 1 MHz, which will increase the pulse energy to 100 μJ at the same average power. This, in turn, will require the employment of the chirped pulse amplification method [14] for suppressing self-focusing in thin rods.

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