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Femtosecond laser system based on thin rod active Yb:YAG elements with high average output power and pulse energy

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Abstract. **A three-stage laser amplifier system based on thin Yb:YAG rods with laser diode pumping has been developed and manufactured. A continuous train of femtosecond pulses from an Yb:KGW master oscillator with a repetition rate of 80 MHz and an initial duration of 150 fs is controlled by a Pockels cell to a frequency of 0.25–1 MHz and is amplified in the system by more than 6500 times to an average power of over 100 W. To suppress self-focusing, the pulses are lengthened in a stretcher on a volume Bragg diffraction grating, amplified, and then compressed to 947 fs. The energy of femtosecond pulses compressed after amplification exceeds 100–170 μJ at different repetition rates, which makes it possible to use them for efficient micromachining of various materials.**

Keywords: *laser Yb : YAG rod amplifiers, diode pumping, high average power and output energy, femtosecond pulses.*

1. Introduction

The use of thin rods with a diameter of about 1 mm as active laser elements makes it possible to significantly suppress parasitic thermophysical processes and thereby increase the average power and brightness of the generated or amplified radiation in comparison with active elements of a larger size. As a result, the average output power of lasers based on thin Yb:YAG rods ranges up to hundreds of watts with a good beam quality [1, 2]. Most of these lasers operate in a master oscillator–power amplifier (MOPA) configuration without using the chirped-pulse amplification (CPA) technique. Amplification in a medium such as Yb:YAG, which has a rather narrow amplification band, usually leads to a significant narrowing of the spectrum of amplified laser pulses with a duration of 100 fs and their significant (up to 1000 fs and more) lengthening [1–3]. Furthermore, the achievable pulse energy in direct amplification systems is limited by self-focusing at a level of several microjoules, which is insufficient for a number of applications, for example, for processing materials [4, 5].

In the present work, which is a continuation of Ref. [3], we studied in detail the amplification of a train of chirped 100-ps laser pulses with a repetition rate of 0.25–1 MHz in a three-stage Yb:YAG thin-rod amplifier up to an average power of more than 100 W. The lengthening of 150-fs pulses from the Yb:KGW master oscillator was carried out in a stretcher on a chirped volume Bragg diffraction grating. The same grating was used to compress the pulse to 947 fs. Such a relatively large increase in duration compared to the initial one is associated with the effect of spectrum narrowing in amplifiers with a sufficiently high gain [6], as well as with an insufficiently high quality of the diffraction grating. Nevertheless, compressed pulses of this subpicosecond duration possess all the advantages of ultrashort pulses for material processing [4, 5].

Some characteristics of individual thin-rod amplifiers and the results of numerical simulation of their parameters are described in Ref. [7]. Our earlier work [8] briefly reported on obtaining an average power of 100 W in a direct amplification system without CPA, and in Ref. [3] this direct amplification system was discussed in detail.

2. Experimental setup

The optical configuration of the laser system is shown in Fig. 1. The system consists of a femtosecond master oscillator (MO) based on a Yb:KGW crystal, a pulse picker based on a Pockels cell, a stretcher, three amplification modules based on thin Yb:YAG crystal rods, and a compressor. The master oscillator was previously used by us in an Yb:KGW amplifying system [9] and generated a continuous train of 120-fs laser pulses with a repetition rate of 80 MHz. The centre wavelength of the Yb:KGW oscillator, λ = 1035 nm, differs from the centre wavelength λ = 1030 nm of Yb:YAG amplifiers, which slightly reduces the gain, especially for a low signal. For this reason, we optimised the reflectance of the output mirror of the MO so as to shift its centre wavelength to λ = 1030 nm. The average output power of the modified MO was 2.6 W and the pulse duration was 150 fs. The average power of the radiation inputted to the amplifying system dropped to 5–20 mW with a decrease in the repetition rate to 0.25–1 MHz using a Pockels cell. In the amplification system, we partly used amplification modules with a geometry that differed from that described in Ref. [3].

The first two amplifying stages operated in a double-pass scheme with quarter-wave isolation. In the first stage, an amplifying Yb:YAG module with a 15-mm long active element 1 mm in diameter and with an ytterbium concentration of 2.5 at.% (Shasta), developed at the Federal Research Centre Institute of Applied Physics of the Russian Academy of Sciences (IAP RAS), was used [10, 11]. The amplifier was pumped with a 105-μm fibre-output laser diode array (JDSU) with a maximum output power of 150 W at a wavelength of

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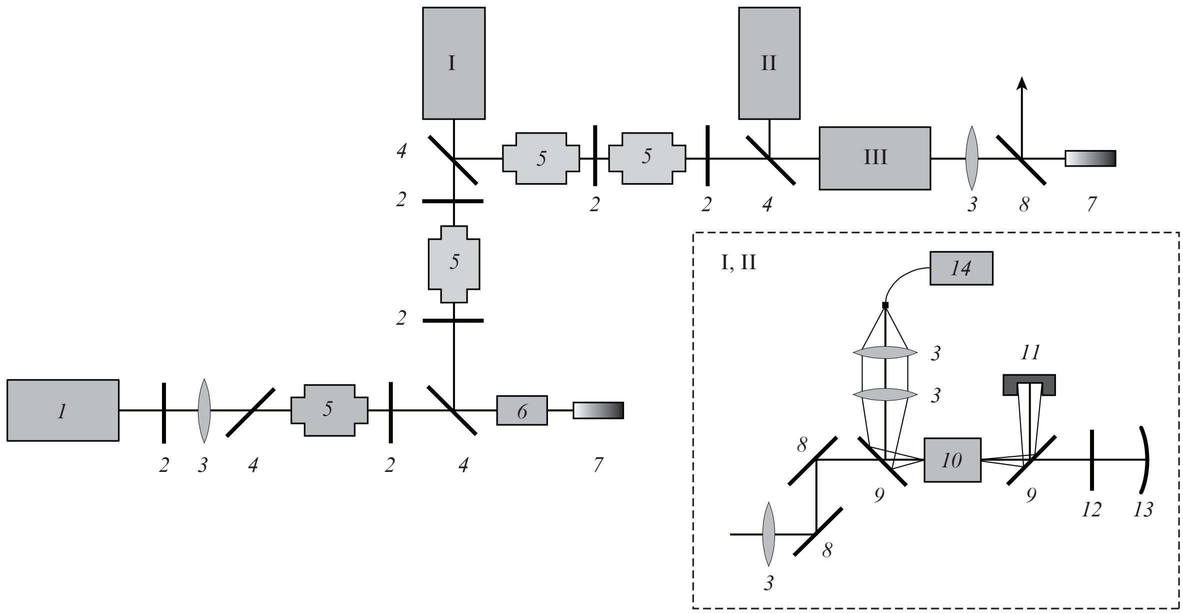

Figure 1. Schematic of a femtosecond laser system with a thin-rod amplifier: (I and II) first and second double-pass amplification stages; (III) third single-pass amplification stage; (*1*) Yb:KGW master oscillator; (*2*) half-wave plates; (*3*) lenses; (*4*) thin-film polarisers; (*5*) Faraday isolators; (*6*) Pockels cell; (*7*) chirped volume Bragg grating; (*8*) high-reflectivity mirrors; (*9*) dichroic mirror; (*10*) thin rod active elements; (*11*) radiation absorber; (*12*) quarter-wave plate; (*13*) concave mirror; (*14*) laser pump diode array.

940 nm. The radiation from the array was focused by a doublet of lenses into the volume of the active element into a spot approximately 300 μm in diameter. The laser beam from the MO was focused into the active element in such a way as to ensure its optimal overlap with the pump beam. The amplified laser radiation was collimated with a spherical lens after passing through a thin-film polariser.

The second stage, which was developed at the IAP RAS [10, 11], used an active element 1 mm in diameter and 19 mm in length with an ytterbium concentration of 2 at.%. The amplifier was pumped with the same semiconductor laser module as the first amplifier in this optical configuration.

The third amplifier stage based on the Taranis module [12] with a 30-mm long Yb:YAG active element 1 mm in diameter with an ytterbium concentration of 1 at.% was pumped by a combined module consisting of four semiconductor lasers (BWT); the power of each laser at the fibre output 105 μm in diameter was 150 W. The maximum power of the pump module was 600 W at the output of the 200-μm fibre. The third amplifier was operated in a single pass regime to prevent self-excitation of the high-gain amplifier system. The radiation power level at the input to the third amplifier was close to the saturation power density, which made it possible to extract a significant portion of the power stored in the amplifier.

Since the laser system possessed a significant gain (more than 6500), use was made of Faraday isolators installed after the MO and between the first and second amplifiers to prevent self-excitation of the system.

The pulse repetition rate was varied in the range 0.25–1 MHz using a Pockels cell based on a BBO crystal operating in a double-pass regime (see Fig. 1), where a volume Bragg diffraction grating served as a mirror. This technical solution made it possible to make the configuration more compact.

To implement the chirped pulse amplification regime, the initial laser pulse was lengthened using this diffraction grating, and after amplification it was compressed in a compressor based on a similar grating. In the stretcher and compressor, use was made of two types of volume Bragg chirped gratings (Optigrate) [13]. Gratings of the first type, according to the specifications, had a maximum reflection at a wavelength of 1034.9 nm, a spectral reflection bandwidth of 26.2 nm, a dispersion of 12.4 ps nm^{-1}, and a relatively low diffraction efficiency of 72.6%. The duration of the stretched pulse after the grating was about 100 ps for a spectrum width of 7.5 nm. Reverse compression of the pulse without amplification led to the lengthening of the original pulse from 120 to 192 fs, which characterises the quality and matching of the gratings used. In addition to these gratings, diffraction gratings with a maximum reflectivity at a wavelength of 1030 nm, a narrower (6.7 nm) spectral reflection bandwidth, a dispersion of 27 ps nm^{-1}, and with a higher diffraction efficiency of 95% were used in the stretcher and compressor. The stretching and recompression of the initial 120-fs pulse in the system of two such gratings increased its duration to 486 fs.

3. Discussion of experimental data and their comparison with the results of numerical simulation

The average radiation power at the output of the first amplifier during its operation in single- and double-pass regimes is shown in Fig. 2a as a function of the pump power for a pulse repetition rate of 1 MHz. As can be seen from the figure, in the double-pass amplification regime the average power amounts to 3.6 W with an amplification of more than 180. The amplifier operated in the amplification regime of a weak input signal, which led to a rather low optical energy extrac-

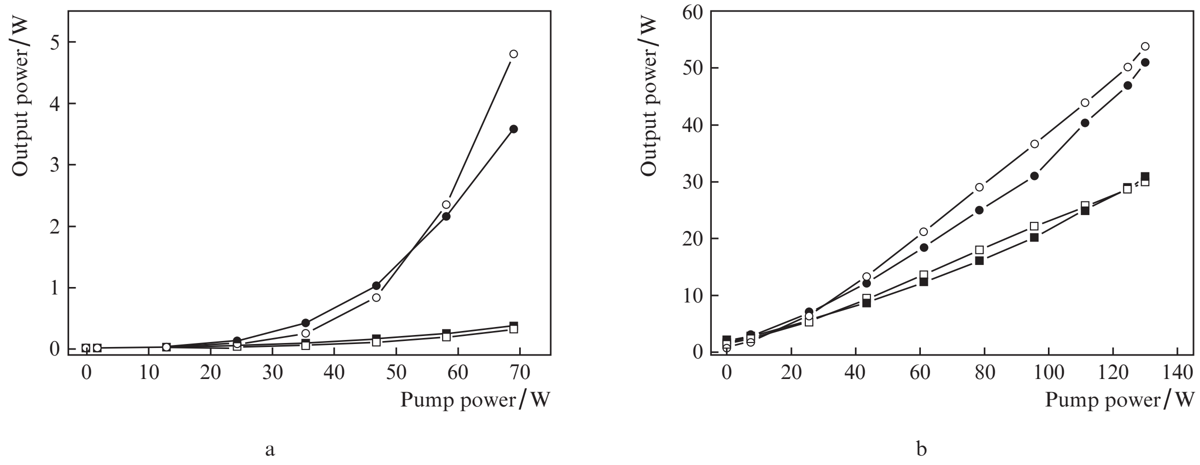

Figure 2. Experimentally recorded dependences of the output power of (a) the first and (b) second amplifiers on the pump power for (■) one and (●) two passes of the amplified radiation through the active element (□ and ○ are the simulation results for one and two radiation passes, respectively).

tion efficiency of about 5%. The beam quality was quite good, the parameter $M^2_{x,y} = 1.07 \times 1.16$, which is indicative of small phase distortions. The emission spectrum narrowed rather strongly (down to 2.17 nm) at half maximum, and the duration of the compressed pulse increased significantly, up to 600 fs.

The average output power of the second amplifier at a pump power of 130 W increased only up to 50 W (Fig. 2b). The drop in the total gain in the second pass as compared to the first one indicates a significant gain saturation due to a significant energy extraction, which amounted to 35.7%. The measured beam quality at the output of the second amplifier ($M^2_{x,y} = 1.09 \times 1.23$) only slightly deteriorated in comparison with the beam quality after the first amplifier, which again confirms the smallness of phase distortions. The emission spectrum narrowed to 1.82 nm, and the pulse duration after the compressor increased to 830 fs.

For numerical simulation of the parameters of thin-rod amplifiers and optimisation of the experimental configuration, we used the ASLD (Advanced software for laser design) software package [14]. For a more accurate calculation of the gain, we initially measured the transmission of pump radiation through a thin rod to determine the pump absorption coefficient. After input of the initial conditions, such as the input radiation power, the spectral parameters of the seed beam, the geometry and doping of the thin-rod crystal, as well as the parameters of the pump laser diode, the amplification conditions were optimised by calculating the output power in accordance with the positions of the pump and seed beams, the beam waist, the position of the concave mirror, etc. One can see from Fig. 2 that the simulation results are in good agreement with the experimental data.

Figure 3 shows an example of preliminary optimisation of the experimental configuration of a double-pass amplifier using numerical simulation. The results of calculating the output power in relation to the position of the concave mirror (Fig. 3a) show the presence of two output power maxima 1 and 2, due to good spatial overlap of the pump and amplified radiation beams of close size, for beams diverging and converging in the crystal, respectively. The experimentally found optimal position of the concave mirror was at a distance of 280 mm from the crystal, since the amplified beam is more focused after passing through the crystal in the case of incidence of the beam converging towards the crystal. The optimal beam size was also found when using a combination of

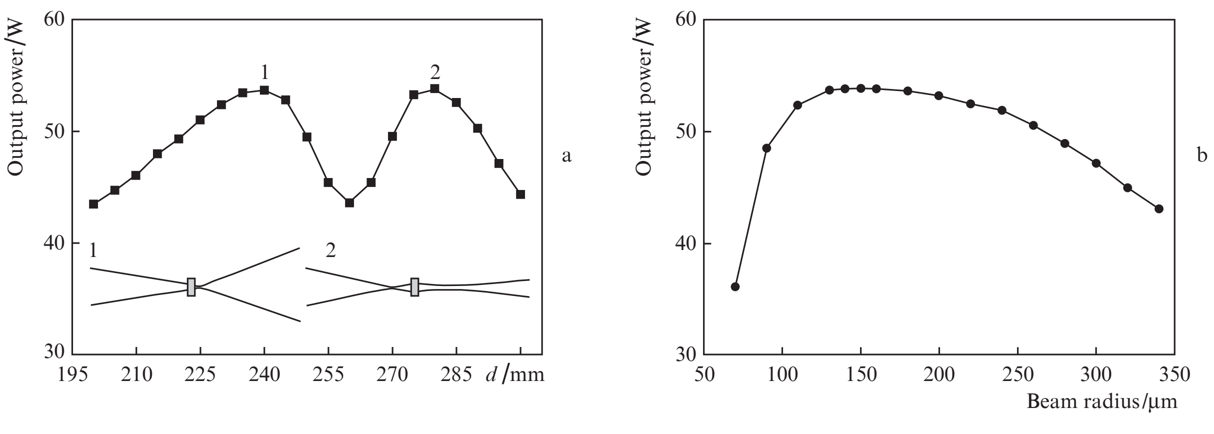

Figure 3. Simulation results for the second double-pass amplifier: dependence of (a) the output power on the distance d between the concave mirror and the thin rod and (b) of the output power on the transverse dimension of the seed beam. The lower part of Fig. 3a shows the seed-beam ray paths at maximum points 1 and 2.

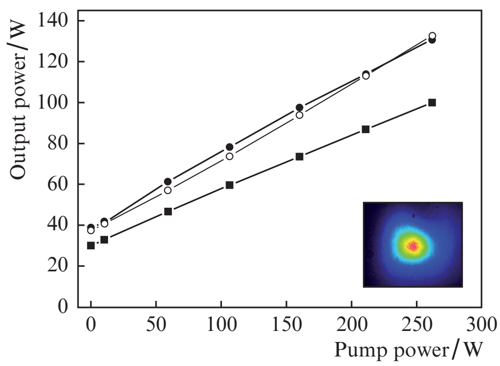

Figure 4. (Colour online) Output power of the third amplifier (•) before and (▪) after the compressor in relation to the pump power (○ = simulation results). The inset shows a near-field image of the laser beam.

lenses by calculating the dependence of the output power on the beam size (Fig. 3b).

Figure 4 shows the power at the output of the third amplifier before and after the compressor in relation to the pump power for a single-pass amplification regime. The output power was as high as 130 W for a pump power of 262 W. Therefore, the optical efficiency was 30.5%. The beam quality deteriorated: $M^2_{x,\,y} = 1.63 \times 1.90$, which was due to thermo-optical phase distortions.

The energy efficiency of compression with the use of the first diffraction grating was 76%, which provided an output power of 100 W. The emission spectrum narrowed to 1.72 nm, and the pulse duration increased to 947 fs (Fig. 5). The product of the spectrum width and the pulse duration was 0.46, which significantly exceeds the value of 0.315 obtained in the approximation of the pulse shape described by the sech^2 function, and indicates the presence of residual phase modulation.

The use of another volume chirped Bragg diffraction grating with a narrower reflection bandwidth (6.7 nm) and higher efficiency (95% instead of 72.6%) made it possible to obtain the same output power of 100 W, but at a significantly lower pumping power of the third amplifier: 194 W instead of 262 W. This, in turn, led to an improvement in the beam quality, $M^2_{x,\,y} = 1.46 \times 1.50$, due to a decrease in thermooptical aberrations with a decrease in the pump power. With the use of this grating, the compressed pulse duration increased somewhat – up to 1.11 ps – due to the narrower spectral reflection band.

Using these diffraction gratings, we studied the effect of the pulse repetition rate on the output radiation power after the first and second amplifiers. The corresponding dependences of the output power on the pump power are shown in Fig. 6. A significant increase in the output power is observed with an increase in the pulse repetition rate, which is due to the higher input average signal power: 20 mW at 1 MHz versus 5 mW at 250 kHz. However, due to gain saturation, this difference at the output of the second amplifier is smoothed out. For example, the total gain was 2800 at a repetition rate of 1 MHz and 8530 at a frequency of 250 kHz. In this case, the pulse energy in the latter case was as high as 167 μJ. The quality of the laser beam for all three repetition rates was close: $M^2_x = 1.25$, $M^2_y = 1.20 - 1.29$. With a decrease in the repetition rate, the pulse duration slightly increased, from 951 fs at a frequency of 1 MHz to 1020 fs at 250 kHz, because of the spectrum narrowing due to an increase in the overall gain.

In the course of experiments, we sometimes observed crystal destruction in the third amplifier at the maximum output

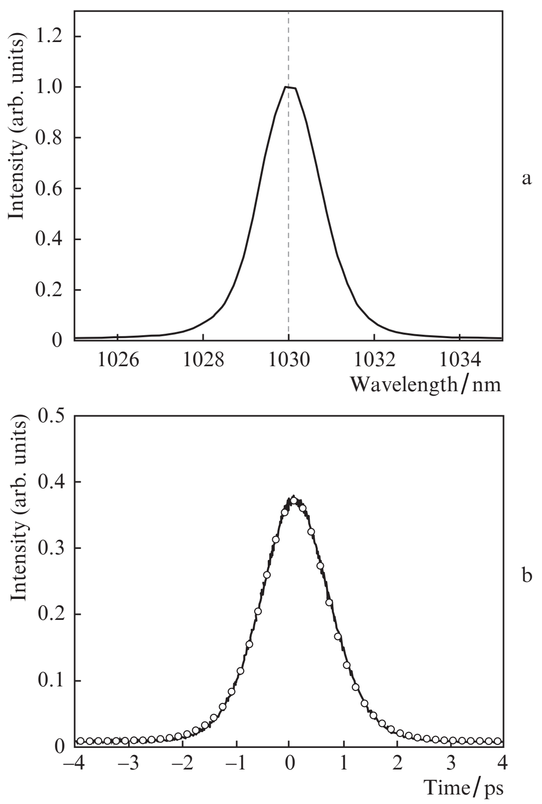

Figure 5. (a) Spectrum and (b) autocorrelation function of femtosecond laser pulses for an output power of 100 W (circles correspond to the autocorrelation function of a sech^2 pulse).

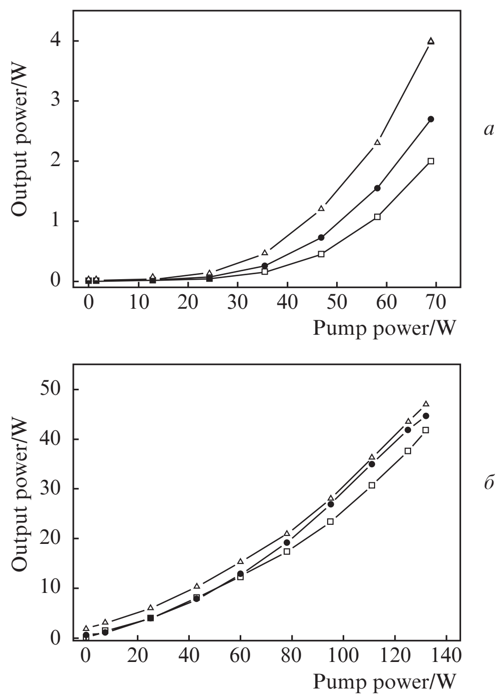

Figure 6. Output power of (a) the first and (b) second amplifiers as a function of the pump power for pulse repetition rates of (▫) 250 kHz, (•) 500 kHz, and (▵) 1 MHz.

power and pulse repetition rates of 1 and 0.5 MHz. The pulse energy amounted to 130 μJ with a chirped pulse duration of about 15 ps in the former case and 252 μJ with a pulse duration of about 50 ps in the latter case. The peak pulse power was approximately 5 MW in both cases. Note that the breakdown of an Yb : YAG amplifier crystal was observed in Ref. [15] at approximately the same peak power.

The simplest estimate of the maximum energy density in the beam yields 0.1 J cm^{-2}, which is significantly lower than the breakdown threshold of the YAG crystal for the indicated pulse durations [16], the peak power of 5 MW already exceeding the critical self-focusing power for the Kerr nonlinearity in this crystal [17, 18]. Under conditions of such an excess of the power, the beam diameter in the waist may significantly decrease, which will lead to an increase in the radiation intensity. In addition, a thermal lens can also contribute to the increase in intensity [11].

4. Conclusions

We have presented the results of the development of a femtosecond laser system with a 100-W average power based on three thin-rod Yb : YAG chirped pulse amplifiers. The pulse repetition rate was varied in the range 0.25 – 1 MHz using a Pockels cell, which separates these pulses from a continuous train of pulses from the Yb : KGW master oscillator. Pulse stretching and compression was performed in separate volume Bragg diffraction gratings with a dispersion from 12 to 27 ps nm^{-1}. The total gain of the system in the saturation regime was 2800 – 8500, depending on the pulse repetition rate. The output radiation power before compression exceeded 130 W for an optical efficiency of the system of 30.5 %, which corresponds to a pulse energy of 170 μJ at a repetition rate of 250 kHz at the output of the second amplifier. Due to the limited amplification frequency band of the Yb : YAG crystal, the spectrum narrowed to 1.7 nm. After pulse compression with the diffraction grating to a duration of 947 fs, the average power decreased to 100 W, which corresponds to a peak pulse power of 105 MW.

The use of a higher-efficiency diffraction grating made it possible to obtain the same output power at a lower pumping level of the amplifiers, which led to an improvement in the quality of the output beam M^2 by a factor of 1.1 – 1.25 to values $M_x^2 \times M_y^2 = 1.46 \times 1.50$. The system demonstrated a good output power stability at 0.8 % rms deviation from the mean over 60 min of operation. For a peak power of the amplified pulse exceeding 5 MW, a breakdown of the active element in the third amplifier was observed, which is probably associated with radiation self-focusing due to the Kerr nonlinearity and the thermal lens produced by the pump radiation. The most obvious method for suppressing self-focusing is to reduce the peak power of chirped pulses by lengthening them, while the thermal lens can be minimised by optimising the pumping system.

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