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NONLINEAR OPTICAL PHENOMENA

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Power limitations and pulse distortions in an Yb : KGW chirped-pulse amplification laser system

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Abstract. **We have studied self-action effects (self-focusing and self-phase modulation) and stimulated Raman scattering in an Yb : KGW chirped-pulse amplification laser system. The results demonstrate that self-focusing in combination with thermal lensing may significantly limit the chirped pulse energy in this system (down to 200 μJ) even at a relatively long pulse duration (50 ps). Nonlinear lenses in the laser crystals in combination with thermal lenses bring the regenerative amplifier cavity in the laser system to the instability zone and limit the average output power at pulse repetition rates under 50 kHz. Self-phase modulation, a manifestation of self-action, may significantly distort a recompressed femtosecond pulse at energies near the self-focusing threshold. Stimulated Raman scattering in such a laser has a weaker effect on output parameters than do self-focusing and thermal lensing, and Raman spectra are only observed in the case of pulse energy instability.**

Keywords: *solid-state lasers, diode pumping, ultrashort pulses, nonlinear effects, self-action, self-focusing, stimulated Raman scattering, thermal lensing.*

1. Introduction

Ytterbium-doped tungstate crystals, Yb^{3+} : $KY(WO_4)_2$ (Yb : KYW) and Yb^{3+} : $KGd(WO_4)_2$ (Yb : KGW), are promising materials for compact and efficient laser systems because they possess good optical, spectral and gain characteristics [1, 2]. The large gain bandwidth of Yb : KGW/Yb : KYW crystals enables the generation and amplification of pulses shorter than 500 fs with high average power and energy [3–5], sufficient e.g. for micromachining applications.

To eliminate undesirable nonlinear effects in the amplification process, e.g. optical breakdown and self-action, such amplification systems typically use the chirped-pulse amplification (CPA) technique [6]. In this approach, a short broadband pulse is first stretched in time by several hundred times, then amplified and finally compressed. The duration of a stretched chirped pulse in compact laser systems is usually limited to 50–100 ps because of the small dimensions of the pulse stretcher. At such pulse durations, parasitic nonlinear effects can be only partially suppressed.

Self-action, which includes self-focusing and self-phase modulation, may in principle have a significant effect on laser emission parameters of KGW/KYW crystals, which have a relatively high nonlinear refractive index: $n_2 \approx (1-2)\times 10^{-15}$ cm^2 W^{-1} [7, 8].

In the 1970s, self-action was shown to have a significant impact on oscillators with self-starting longitudinal mode locking [9–12]. The importance of taking into account self-phase modulation in laser systems with chirped-pulse amplification was investigated e.g. by Perry et al. [13].

KGW/KYW crystals possess, in addition to high Kerr nonlinearity, a large Raman gain coefficient [14, 15]. Stimulated Raman scattering (SRS) in laser crystals may bring the lasing wavelength beyond the gain band, limiting the output energy at the fundamental wavelength. The use of chirped broadband pulses raises the SRS threshold but does not completely suppress the SRS process [16].

This paper addresses the above-mentioned nonlinear effects in an Yb : KGW CPA laser system at various pulse repetition frequencies.

2. Experimental setup

Figure 1 shows the laser system configuration. The system includes a femtosecond Yb : KGW master oscillator, a stretcher–compressor integrated module based on one transmissive diffraction grating, and a regenerative amplifier containing two Yb : KGW crystals. In addition, the system includes an isolator for protecting the master oscillator from the amplified light and a Faraday rotator, which brings out the light amplified by the regenerative amplifier. The self-mode-locked master oscillator, described elsewhere [5], operated at 76 MHz with an average output power of 1.6 W. The spectral width of the pulses was 12 nm and their duration was 100 fs.

The cavity of the regenerative amplifier contains two Yb : KGW crystals (LC1 and LC2) with an ytterbium content of 3%, which allows the output power to be increased relative to a single-crystal configuration. Typically, we used crystals of different orientations: N_g and N_p cuts. At an appropriate polarisation of the amplified light, this allowed the gain band to be considerably extended [3, 4]. To this end, the cavity mode was polarised vertically, along the N_p axis in the former crystal and along the N_m axis in the latter. The use of relatively long Yb : KGW crystals, 2×2×5 mm in dimensions, with a low doping level makes it possible to distribute heating and stress along their longitudinal axis, thereby reducing the specific load. Pumping at 981 nm with a spectral width of

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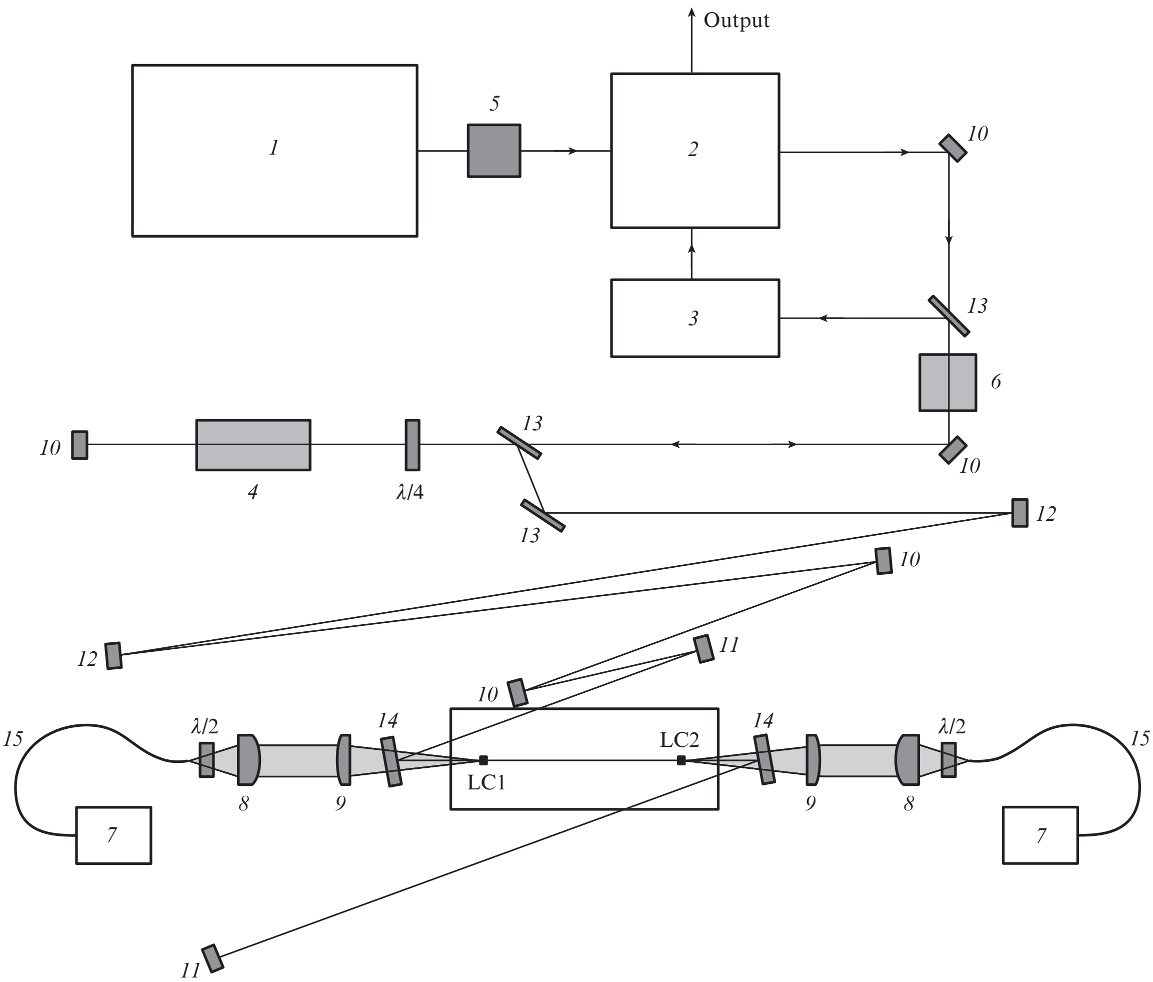

Figure 1. Laser system configuration: (*1*) master oscillator, (*2*) stretcher–compressor module, (*3*) Pockels cell optical switch, (*4*) Pockels cell, (*5*) Faraday isolator, (*6*) Faraday rotator, (*7*) diode laser bars, (*8*, *9*) collimating and focusing doublet lenses, (*10*) flat dielectric mirrors, (*11*, *12*) concave dielectric mirrors, (*13*) thin-film dielectric polarisers, (*14*) dichroic mirror, (*15*) optical fibre, (LC1, LC2) laser crystals.

~4 nm was ensured by two 70-W diode laser bars. To minimise depolarisation, which is necessary for maximising the absorption of pump light polarised along the N_m axis, the pump light was delivered through short pieces of fibre (30 cm length, 200 μm diameter, NA = 0.22). The pump beams were first collimated and then focused by doublet lenses through dichroic mirrors to a spot diameter of about 320 μm. The total power loss in the pump channels was ~14%, and the absorption during amplification was ~70%. To achieve a high energy deposition efficiency, the cavity design was such that the mode diameter approached the pump beam diameter. To ensure a sufficiently large cavity length (~200 cm), which is necessary for operation of the Pockels cell, we used flat and spherical broadband high-reflectivity mirrors.

The pulses amplified in the regenerative amplifier were separated from the input pulses by a Faraday cell and directed to another Pockels cell (*3*), which served to enhance the temporal pulse contrast with respect to pre- and post-pulses. The chirped pulses of 50-ps duration were then directed to a compressor, where they were compressed to the shortest possible duration. The net loss in the latter Pockels cell and compressor was about 40% of the output power. The total gain in the regenerative amplifier was varied by changing the time gate of cell *4*, which determined the number of cavity round trips. Under the conditions of this study, the time gate was 400–500 ns and was determined by amplifier saturation. In contrast to our previous work [4], no Lyot filter was used to shape the spectrum before the regenerative amplifier, which allowed us to obtain the shortest possible pulse duration (~180 fs) after compression because of the narrowing of the spectrum during regenerative amplification.

3. Experimental results and discussion

We measured the output power, spectrum, and pulse autocorrelation function at the output of the laser system. Figure 2 shows the output power as a function of incident pump power at different pulse repetition rates. It is seen that the output power increases monotonically at pulse repetition rates $f_{rep} >$ 50 kHz and saturates at $P_{av} \approx 7.5$ W when the repetition rate is 50 kHz. At high repetition rates (f_{rep} = 100–500 kHz), the highest average power reached 10–12 W at a pump power above 100 W and a 400-ns time gate of the Pockels cell. The average power was then 13–16.6 W before the compressor and 16–20 W behind the Faraday cell. This suggests that, by eliminating the rather high loss after the regenerative amplifier, e.g. by removing the contrast-enhancing Pockels cell, the average output power can be brought to 15 W.

The power limitation at a pulse repetition rate of 50 kHz may be caused by the rather high peak output power P_{peak},

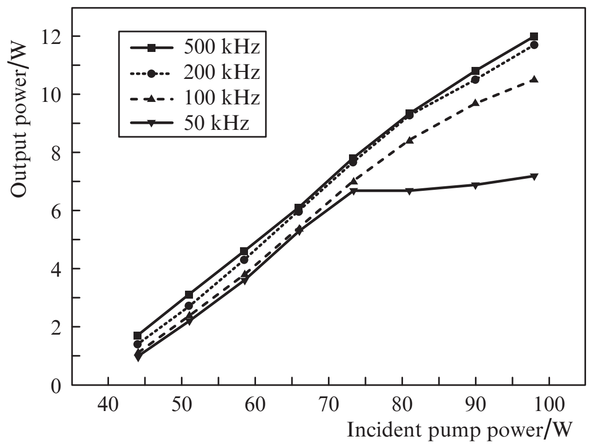

Figure 2. Output power as a function of incident pump power for the laser system at different pulse repetition rates.

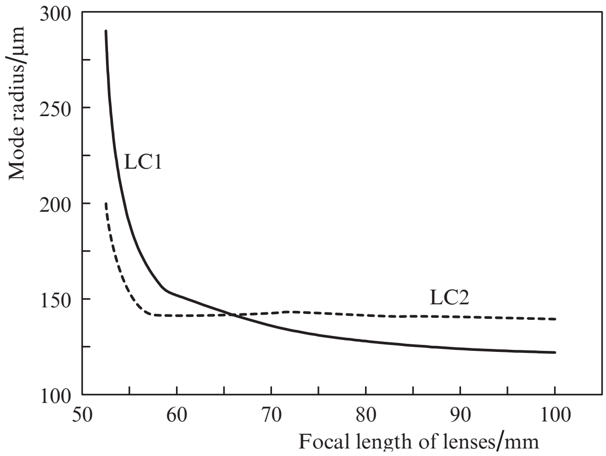

Figure 3. Mode radius in the LC1 and LC2 laser crystals as a function of the focal length of lenses induced in the crystals.

which reaches 4.7 MW at P_{av} = 7 W. This peak power is several times the critical power for self-focusing in KGW crystals: $P_{cr} = cn\lambda^2/(8\pi^2 n_2) \approx 0.65$ MW. This means that a nonlinear lens is induced in the bulk of the laser crystals, which potentially can disturb the stability of the regenerative amplifier cavity. The focal length of such a lens can be estimated using the following expression for the external self-focusing length in the aberrationless approximation [12]:

$$F_{sf} \approx \frac{\pi w^4}{4 n_2 l P_{peak}} = \frac{\pi^2 n w^4}{\lambda^2 l (P_{peak}/P_{cr})}, \qquad (1)$$

where w is the Gaussian laser beam radius; n is the refractive index; and l is the crystal length. Substituting appropriate parameters into this relation, we obtain $F_{sf} \approx 170$ mm at P_{peak} = 4.5 MW. Note that this estimate is only approximate, in particular because the exact value of the nonlinear refractive index is unknown.

To check conditions for cavity stability in the presence of lenses, we calculated the mode radius in the laser crystals as a function of the focal length of the lenses induced in the crystals using the ABCD method. The calculation results, presented in Fig. 3, demonstrate that the cavity has sufficiently good dynamic stability up to $F \approx 60$ mm. In the case of stronger lenses, the mode size in the crystals is much larger and the cavity is unstable.

An estimate of the optical power shows that nonlinear lenses taken alone are insufficient for bringing the cavity to the instability zone. At the same time, pumping produces not only nonlinear lenses but also a thermo-optic lens. Its dioptric power can be estimated using the following formula [17]:

$$D_{th} = \frac{1}{f_{th}} = \frac{\eta_h P_{abs}}{2\pi w_p^2 K_c}\left[\frac{\partial n}{\partial T} + (n_0 - 1)(1+\nu)\alpha_T + 2 n_0^3 \alpha_T C'_{x,y}\right]. \qquad (2)$$

Here, P_{abs} is the absorbed power; η_h is the absorbed power to heat conversion efficiency; K_c is the thermal conductivity; n_0 is the refractive index; $\partial n/\partial T$ is the temperature derivative of the refractive index; ν is Poisson's ratio; α_T is the thermal expansion coefficient; and $C'_{x,y}$ are photoelastic constants.

Substituting the relevant thermo-optic parameters from Refs [17–20] and P_{abs} = 30 W into (2), we obtain f_{th} values from 3 to 8 cm for the N_g-cut crystal and from –6 to 4 cm for the N_p-cut crystal. The experimental data in Refs [17–20] also exhibit such large scatter. It follows, however, from the experimental output power data in Fig. 2 that, at high pulse repetition rates (f_{rep} = 100–500 kHz), where the effect of Kerr nonlinearity is weak, the output power does not saturate, i.e. thermal lensing, taken alone, is insufficient for bringing the regenerative amplifier cavity to the instability zone: a combined effect of thermal and nonlinear lenses is necessary. Moreover, in contrast to a thermal lens, a nonlinear Kerr lens is 'fast', i.e. its focal length depends on the peak output power, which increases in the amplification process. As a result, the cavity stability conditions can be violated for only a part of the pulse near the highest peak power, and this leads not to regenerative amplification suppression but to output power saturation.

In addition to intracavity lenses, which influence the cavity configuration, there are other fundamental causes that limit the output power at high pump powers, e.g. upconversion-type excitation energy losses from the upper laser level or thermal population of the lower laser level. In ytterbium-doped laser media, however, parasitic excitation loss effects are much weaker in comparison with, e.g., Nd-doped media. Heating of a crystal in the pump zone, which may reach ~450 K according to our LASCAD simulations, may lead to thermal population of the lower laser level, which in turn would decrease the gain coefficient and output power. It is this effect which seems to be responsible for the nonlinear behaviour of the output power as a function of pump power at high pulse repetition rates (Fig. 2). The output power measurements for the regenerative amplifier operating in a Q-switched mode as an oscillator also showed that the output power deviated from linearity by about 20%, which was probably also caused by both the thermal population of the lower laser level and thermo-optic lensing. However, both in the case of picosecond pulse amplification at high repetition frequencies and in the case of Q-switched operation, there was no strong saturation of the output power. This leads us to conclude that it is the combined effect of self-focusing and thermo-optic lensing which limits the output power in the laser system under consideration at relatively low pulse repetition rates or relatively high picosecond pulse energies.

Note that thermo-optic effects had no significant influence on the spatial laser beam quality at the output of the system. In particular, beam quality factor measurements at pulse repetition rates in the range 100–500 kHz yielded $M^2 < 1.1$ at all power levels, indicating that the beam divergence approached the diffraction limit.

In addition to the self-focusing effect, another effect related to Kerr nonlinearity, namely, self-phase modulation, is of importance in ultrashort-pulse lasers. Typically, it increases the spectral width of pulses and may both increase the pulse duration [13] and decrease it [21] after compression in an optimally adjusted compressor [depending on the sign of the self-phase modulation (chirp) of the input pulse]. Self-phase modulation is commonly quantified by the phase shift, which coincides with the B-integral [22]:

$$B = \frac{2\pi n_2}{\lambda}\int_0^l I(z)\,\mathrm{d}z. \tag{3}$$

The total B-integral for regenerative amplification can be estimated, for example, in the small-signal approximation: $I = I_0\exp(\alpha\lambda)$ [23]. In this approximation, the B-integral for KGW/KYW crystals is given by

$$B_{\mathrm{total}} = 0.067\frac{1 - G^{-1}}{\alpha}I_{\mathrm{out}}, \tag{4}$$

where G is the total gain; α is the small-signal gain coefficient (cm^{-1}); and I_{out} is the output intensity (GW cm^{-2}). An estimate with this formula gives $B_{\mathrm{total}} \approx 2.15$ at the threshold for output power limitation by self-focusing at an energy E = 200 μJ. According to Perry et al. [13], this phase shift should change the spectrum and shape of the compressed pulses.

To examine the effect of self-phase modulation on output parameters, we measured spectra and autocorrelation functions of compressed pulses. In our measurements, the path length in the compressor was adjusted so as to minimise the autocorrelation trace width.

At a pulse repetition rate of 500 kHz and the corresponding low energy (~15 μJ), when the effect of Kerr nonlinearity was weak, the full width at half maximum (FWHM) of the spectrum was 7 nm and the autocorrelation trace width was 450 fs, which corresponded to a pulse duration of 267 fs for sech^2-shaped pulses. Under these conditions, the narrowing of the spectrum was influenced primarily by the limited spectral width of the gain band [24, 25] and the pulse duration was influenced by both this factor and aberrations in the compressor [4].

Figure 4 shows optical spectra and autocorrelation traces at low and high output powers and a pulse repetition rate of 50 kHz. It is seen that increasing the pulse energy changes the shape of the spectrum and slightly increases its width. This is due to the relatively low values of the B-integral ($B \approx 2$) [26, 27] and the competition from the narrowing of the spectrum during regenerative amplification [24, 25]. Nevertheless, the modification of the spectrum reflects changes in the shape of the autocorrelation trace: formation of extra peaks and broadening of the pedestal. As a result, the autocorrelation trace width increases by about 20% at the highest energy. Figure 5 shows the FWHM and 1/e^2 width of the autocorrelation trace as functions of the B-integral. It is seen that, whereas the FWHM of the autocorrelation trace remains essentially unchanged, the pedestal width increases considerably. This increase in the wings of the autocorrelation trace means that phase modulation results in a nonlinear time variation of the frequency because

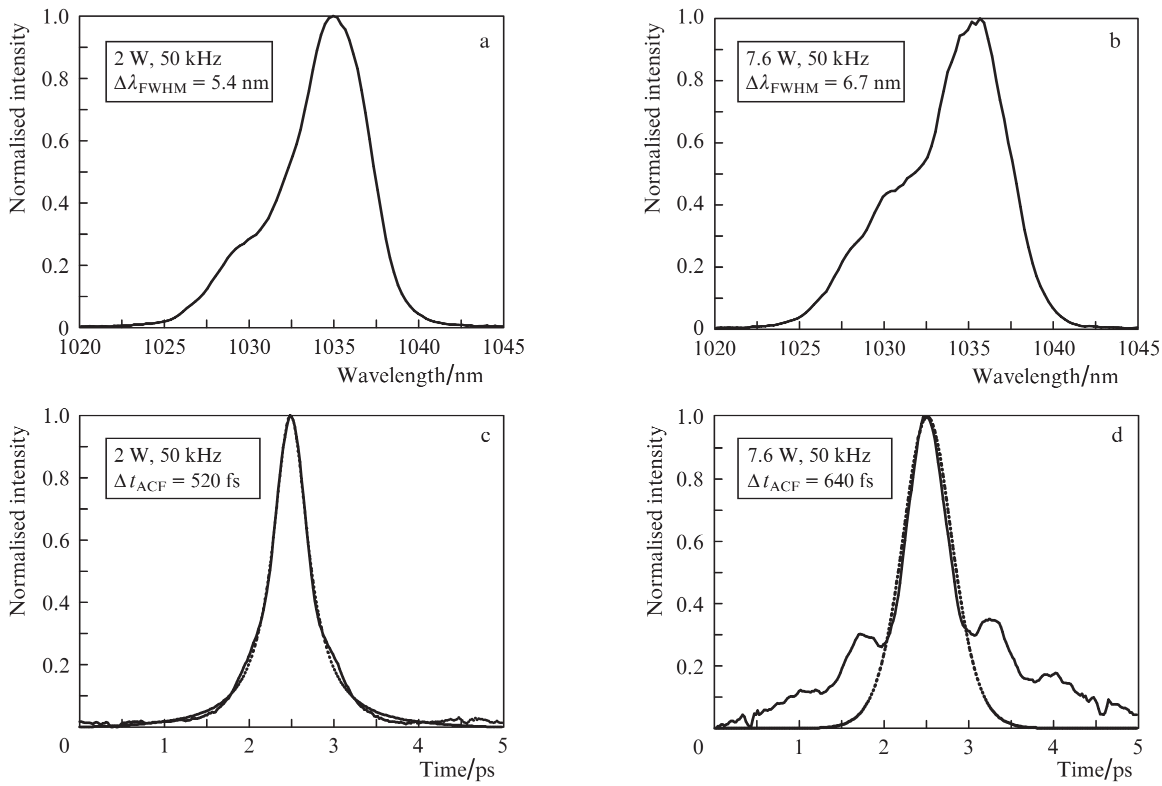

Figure 4. (a, b) Measured spectra and (c, d) autocorrelation traces at (a, c) low and (b, d) high output powers (solid lines); the dotted lines represent sech^2 fits to the autocorrelation functions.

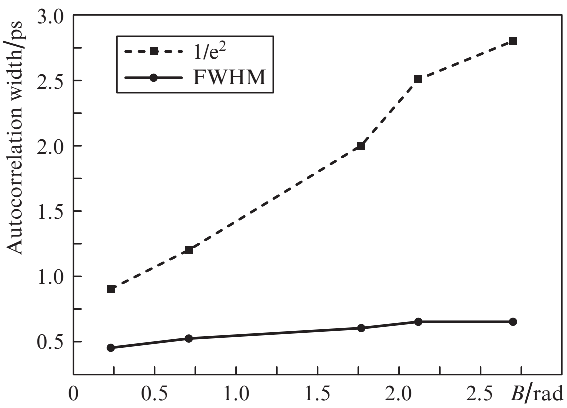

Figure 5. FWHM and $1/e^2$ width of the autocorrelation trace as functions of the *B*-integral for chirped 50-ps pulses in the regenerative amplifier.

the shape of the pulse being amplified is nonoptimal for stretching the spectrum [28].

In addition to self-action effects, another nonlinear process that may limit the output power of KGW/KYW lasers is stimulated Raman scattering, which has already been observed in an Yb : KGW CPA laser system [29]. An estimate of the Raman gain G_R using a steady-state Raman gain coefficient $g = 5.1$ cm GW^{-1} [14] yields $G_R = gIl \approx 20$ at a crystal length $l = 5$ mm and peak power $P_{peak} = 4.6$ MW, which approaches the threshold value of this parameter. However, in the case of chirped broadband pulses, the SRS threshold may be several times higher [16], which would lead to suppression of this effect. Indeed, no SRS spectra were observed at any power level when the pulse energy in the regenerative amplifier was stable. At the same time, in the case of pulse amplitude instability in the amplifier, the first and second Stokes SRS components with a shift $\Delta\nu = 901$ cm^{-1} emerged at wavelengths of 1140 and 1270 nm. We expressly brought about such instability [30] by varying the time gate of the Pockels cell in the regenerative amplifier. In this operation mode, the maximum pulse energy was about a factor of 1.5 higher than the average one. The emergence of Stokes components at this energy means that the Raman gain coefficient approaches its steady-state value, in contrast to what was reported by Zhavoronkov et al. [16]. We did not measure the efficiency of energy conversion to Stokes component. Note again that SRS spectra were only observed in the case of pulse energy instability in the regenerative amplifier. Under energy stability conditions, no such spectra were detected, which leads us to conclude that self-focusing plays a key role in limiting the energy of intense ultrashort pulses.

4. Conclusions

We have demonstrated a directly diode pumped Yb : KGW dual-slab regenerative amplifier. A laser system containing the amplifier generated femtosecond pulses shorter than 300 fs with an average power of up to 12 W at pulse repetition rates in the range 100–500 kHz with a beam quality factor $M^2 < 1.1$.

At a pulse repetition rate of 50 kHz, the output energy in the regenerative amplifier of the laser system was limited to about 200 μJ. In our opinion, the most likely cause of this limitation is the combined effect of large-scale self-focusing and thermal lensing in the gain elements, which disturbs the stability of the amplifier cavity. To increase the maximum pulse energy, self-focusing should be suppressed, which can be achieved e.g. by using shorter crystals and/or increasing the cavity mode diameter and pump power. In our case, it is more convenient to suppress this effect by reducing the pulse peak power and increasing the pulse duration (to above 100 ps), which will be the subject of further work in the nearest future.

Self-phase modulation in laser crystals does not limit the pulse energy but influences the shape and duration of compressed femtosecond pulses. To eliminate this effect when necessary, the nonlinear phase shift should be less than 1 rad, or specific spectral profiling should be made before amplification [31]. To suppress self-phase modulation, i.e. to reduce the *B*-integral, one can take advantage of the same methods as are used to suppress large-scale self-focusing.

Stimulated Raman scattering does not limit the output energy in the described laser system under stable operation conditions of the regenerative amplifier, but the maximum output energy approaches the SRS threshold.

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