28-W, 217 fs solid-state Yb:CALGdO₄ regenerative amplifiers

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A new high-performance Yb:CaAlGdO₄ (Yb:CALGO) regenerative amplifier is demonstrated. Pumped by 116 W at 980 nm and seeded by means of a 92 fs oscillator, it generates as much as 36 W of average output power with chirped pulses, and 28 W with 217 fs compressed pulses at 500 kHz repetition rate. This corresponds to 56 μJ of pulse energy and 258 MW peak power. The compressed pulses have a time–bandwidth product of 0.69 and could be shortened further with an improved compressor setup. © 2013 Optical Society of America

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High-power sources of femtosecond pulses at repetition rates up to a few megahertz are required for fast, high-precision micromachining in industry and biomedicine [1].

Extremely high powers up to the kilowatt level have been demonstrated with direct amplification of high-repetition-rate oscillators, achieving 1.1 kW of average power at 20 MHz repetition rate with 615 fs pulses using the Innoslab Yb:YAG concept [2], and 830-W trains of 640 fs pulses at 78 MHz [3] by employing large-mode area Yb-doped fiber amplifiers.

Pulses at lower repetition rates, typically ≈100 kHz up to a few megahertz, with substantially higher energy and peak power are preferred for many applications. These pulse trains can be generated conveniently with bulk solid-state, diode-pumped regenerative amplifiers (RAs).

Thin-disk laser oscillators (TDLs) have also been proven to be able to generate power as high as 275 W with 583 fs pulses at 16.3 MHz, employing Yb:YAG [4]. However, with respect to long-cavity, low-repetition-rate TDLs, RAs offer greater flexibility in tuning the repetition rate according to the particular application, especially when a sub-megahertz pulse frequency is required.

The highest output power reported to date for RAs is 10 W in an Yb:KYW TDL operating at 20 kHz, with 185 fs pulses [5]. A much higher repetition rate of 200 kHz and 8 W output power was reported for a bulk Yb:KYW RA employing two differently cut Yb:KYW crystals, providing broadening of the gain bandwidth and 181 fs pulses [6].

An Yb:YAG TDL RA yielded as much as 160 W at 800 kHz, although with significantly longer 750 fs pulses [7]. Yb:CaAlGdO₄ (Yb:CALGO) is considered a very promising material owing to its excellent thermo-mechanical properties and broad fluorescence bandwidth [8], allowing generation of pulses as short as 40 fs [9]. Ultrafast oscillators with output power as high as 12.5 W and 94 fs pulses have been demonstrated [10]. Lately, an Yb:CALGO TDL has been reported with 28 W output power and pulses as short as 300 fs, at 23 MHz [11].

In this Letter, we report the experimental results of an Yb:CALGO RA generating the highest average power (36 W) to the best of our knowledge, with a compressed pulse width of ≈200 fs at 28 W output.

The conceptual scheme of the system layout is shown in Fig. 1. A diode-pumped Yb:CALGO oscillator provides the seeding of the Yb:CALGO RA. Pulse stretching occurs in the RA cavity, over many round trips. A grating compressor is employed at the RA output in order to recover the femtosecond pulse.

The Yb:CALGO crystal employed in the RA was 4 mm long and 2% doped, antireflection-coated on both faces for the pump and the laser wavelengths, and was mounted in a water-cooled holder. The crystal was cut for pumping with polarization parallel to the π axis, whereas laser oscillation occurred along the σ axis.

The fiber-coupled pump laser diode provided as much as 116 W at ≈980 nm out of a 200 μm fiber. The pump and the laser beam diameters in the crystal were ≈400 and ≈310 μm, respectively.

The femtosecond Yb:CALGO seeder delivered approximately 650 mW of output power, with 92 fs Fourier-limited pulses at 63 MHz repetition rate. The pulse spectrum was 12.5 nm wide (FWHM) and centered at ≈1050 nm.

After passing through a Faraday isolator, the oscillator beam was injected into the RA. The isolator was employed to protect the seeder from dangerous back-reflections and, at the same time, for separating the amplified output pulse from the seed oscillator.

The RA setup chosen for this experiment is quite common, employing a 40-mm-long double-BaB₂O₄
(BBO) Pockels cell for pulse switch-in and switch-out, and relying on pulse stretching through propagation in intracavity dispersive media over multiple round trips. Depending on the exact number of round trips, usually ranging between 50 and 100, the pulse was stretched to >6 ps during amplification and prior to recompression. The beam radius in the Pockels cell was ≈0.6 mm to minimize self-phase modulation (SPM).

Actually, considering the intracavity material dispersion, the injected pulse should have been stretched further to about twice this value, if there was no gain narrowing.

For the experiments, the repetition rate was chosen to be 500 kHz, in order to not damage the intracavity components due to excessive peak intensity at a lower pulse frequency.

Preliminary investigations at reduced pump power showed that saturation of energy extraction from the amplifier occurred after about 70 round trips (Fig. 2). Furthermore, gain narrowing reduced the pulse spectrum moderately, from 12.5 to 9 nm.

In the next step, the input–output characteristic of the Yb:CALGO setup was measured up to full pump power (Fig. 3) for the RA, whereas the continuous wave (CW) curve with a 15% output coupler is shown for comparison. The difference in slope efficiency is due to higher losses in the more complex RA cavity and a number of round trips inferior to that required for optimum power extraction. Pumped by 116 W, the RA generated up to 36 W at 500 kHz, corresponding to 72 µJ per pulse. The observed roll-off above 100 W is most likely due to the thermal drift of the pump wavelength off the maximum crystal absorption peak with increasing pump power. This could be compensated for by either improved heat management of the actual pump diode or by using a wavelength-stabilized pump diode.

At the output of the RA, the beam was expanded by means of a telescope and sent through the grating compressor setup. The compressor design [12] consists of a high-efficiency transmission grating with 1250 lines/mm employed in a folded configuration for maximum compactness. Folding was achieved through a retro-reflective prism element and a highly reflective mirror. Total transmission efficiency was measured to be 78%.

After recompression we measured 28 W of average power. Second-harmonic generation (SHG)-FROG diagnostic [13] yielded 217 fs pulse width (Fig. 4), in close agreement with a separate second-order, noncollinear

![Fig. 2. Preliminary results of amplification before compression (red dots) and pulse spectrum FWHM (blue diamonds) as a function of the number of round trips for 34.5 W pump power.](image)

![Fig. 3. Amplified output power before compression, after 50 round trips in the RA, and CW performance.](image)

![Fig. 4. Retrieved FROG trace (top), retrieved pulse and temporal phase (center), and retrieved spectrum and spectral phase (bottom).](image)
autocorrelation measurement. The SHG-FROG measurement has been performed with a grid size of \(128 \times 128\), giving a FROG error of 0.0187.

Assuming the third-order refractive nonlinearity of the BBO Pockels cell to be \(\approx 7.4 \times 10^{-16} \text{ cm}^2/\text{W}\) [14], which is mostly responsible for the intracavity nonlinear chirp, we estimated an integrated nonlinear phase of \(\approx \pi/10\) rad over 50 round trips. Indeed, the pulse spectrum does not carry typical distortions due to significant SPM. The difference between the measured compressed pulse and the ideal transform-limited pulse corresponding to the spectrum with constant phase (i.e., \(\approx 136\) fs from inverse Fourier transformation) appears mostly due to the unbalanced stretcher–compressor design in terms of higher order dispersion. Indeed, it turns out that numerical pulse compression optimization with pure second-order dispersion, taking into account the measured spectrum and phase reported in Fig. 4, yields only 198 fs, quite close to the pulse width measured actually. We concluded that shorter pulses could be obtained only by employing a different stretcher–compressor design for better management of higher order dispersion terms, although this might imply a more complex and therefore not so compact layout.

The output beam quality was also analyzed and the results are displayed in Fig. 5. The beam was nearly TEM\(_{00}\) up to full pump power, with \(M^2\) parameters of 1.13 and 1.09 along \(x\) and \(y\)-axis, respectively.

In conclusion, we have demonstrated, to the best of our knowledge, the first RA based on Yb:CALGO. Furthermore, we are not aware of a higher output power achieved up to date in other sub-300-fs RAs employing Yb-doped crystals. Pulses as short as 217 fs with 28 W average output power at 500 kHz repetition rate have been obtained in this experiment.

The output power has the potential to be improved significantly since thermal lensing does not introduce significant distortions and limitations yet, as the excellent beam quality suggests.

A refined compressor design, with lower losses and a larger tuning range for chirp removal, with small higher order dispersion terms, should also contribute to higher throughput and shorter pulses, paving the way toward gigawatt peak power-level pulses, which are very attractive for many applications.

References