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Diode-pumped thin-disk Yb:YAG regenerative amplifier

C. Hönninger[1], I. Johannsen[2], M. Moser[3], G. Zhang[1], A. Giesen[4], U. Keller[1]

[1] Ultrafast Laser Physics Laboratory, Institute of Quantum Electronics, Swiss Federal Institute of Technology, ETH Hönggerberg, HPT, CH-8093 Zürich, Switzerland (Fax: +41-1/633 10 59, E-mail: clemens@iqe.phys.ethz.ch, WWW: http://iqe.ethz.ch/ultrafast/Welcome.html)
[2] Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V., Institut fur Technische Physik, Pfaffenwaldring 38–40, D-70569 Stuttgart, Germany
[3] Paul Scherrer Institute, PSI, Zürich, Switzerland
[4] Institut fur Strahlwerkzeuge, Universität Stuttgart, Pfaffenwaldring 43, D-70569 Stuttgart, Germany

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Abstract. A passively modelocked 750-fs Yb:YAG oscillator is used as the seed laser for a diode-pumped thin disk Yb:YAG regenerative amplifier. Pulse energies of 180 μJ are obtained at repetition rates of up to 750 Hz, and 120 μJ pulses were achieved at 1 kHz. The amplified pulse duration was 2.3 ps, resulting in a pulse peak power of 78 MW. The increase in pulse duration during amplification is attributed to gain narrowing in the amplifier material rather than to intracavity dispersion.

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Compact sources of ultrashort laser pulses at microjoule to millijoule energy levels are of interest for several applications, such as medical surgery, industrial machining, or nonlinear frequency conversion. The development of powerful laser diodes, matching the absorption wavelengths of many solid state materials, made it possible to build compact and efficient modelocked oscillators and regenerative amplifiers. Typical pulse durations of diode-pumped passively modelocked oscillators range from below 100 fs to a few ps [1]. However, most experiments on diode-pumped regenerative amplifiers have been performed in the regime of 10 ps and more. For example, pulse energies of 90 μJ and 750 μJ were extracted from cw diode-pumped Nd:YLF regenerative amplifiers with 2 W and 15 W of pump power, respectively[2, 3]. Furthermore, 2.5 mJ pulses were achieved by pumping with a Nd:YLF crystal using two 60 W, microlens-collimated, quasi-cw diode bars [4]. As a result of the limited gain bandwidth, the pulse duration of the amplified pulses in Nd:YLF is typically 10–20 ps. Using Nd:YAG, millijoule level pulses were demonstrated with pulse widths of 25 ps [5] and about 1 ns [6]. Amplified pulses in the femtosecond regime can currently be obtained only through chirped-pulse amplification (CPA) [7] since most optical materials and coatings cannot withstand the high peak intensities associated with microjoule or millijoule energies concentrated in the short time window of a femtosecond pulse.

In addition to an oscillator and an amplifier, CPA needs a temporal stretcher for the seed pulse and a compressor for the amplified pulse to regain femtosecond pulse duration. Recently, 24-μJ, 850-fs pulses at 1 kHz repetition rate have been demonstrated from a diode-pumped Nd:glass regenerative amplifier based on CPA [8]. In the regime of intermediate pulse durations of a few picoseconds, compact microjoule energy regenerative amplifiers without the need for stretching and compression can be built by using a gain medium with a sufficiently broad gain bandwidth.

Over the past few years, diode-pumped ytterbium-doped lasers have gained increasing interest because of their small quantum defect, the broad absorption and emission bandwidth, and the long fluorescence lifetime. Efficient continuous-wave operation of Yb:YAG has been demonstrated [9–11] as has modelocking with pulse durations as short as 340 fs [1, 12]. The broad gain bandwidth of ≈ 5.3 nm at 1030 nm provides the possibility to amplify 5 to 10 times shorter pulses than with Nd:YLF or YAG. This is interesting for high-peak-power applications. Additionally, the long fluorescence lifetime (≈ 1 ms) and the small emission cross section are beneficial for pulse amplification. This results in a large saturation fluence of $\approx 8\ \mathrm{J/cm^2}$ of the amplifier material. However, the low gain makes it difficult to extract the stored energy efficiently from a Yb:YAG amplifier within a reasonable number of cavity roundtrips.

In this paper, we report, to our knowledge for the first time, a diode-pumped Yb:YAG regenerative amplifier. The amplifier is seeded by a passively modelocked 70 MHz Yb:YAG oscillator emitting at 1.03 μm, similar to the one described in [1, 12]. Instead of a 5%-doped Yb:YAG crystal, we used a doping of 11%, resulting in a pulse duration that is 2 times longer (750 fs). For this experiment, we pumped the Yb:YAG crystal with a Ti:sapphire laser tuned to 968 nm. The extension to diode-pumping has been demonstrated with a diode-pumped Yb:phosphate glass laser with which we obtained 60-fs pulses at an average output power of 44 mW and a repetition rate of 110 MHz [13]. This demonstrates that we can substitute the Ti:sapphire pump by a diode pump without suffering an increase in pulse duration. This is important be-

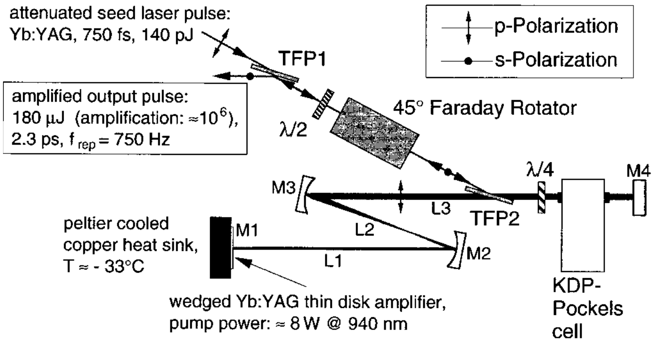

Fig. 1. Experimental set-up of the diode-pumped Yb:YAG thin-disk regenerative amplifier. M1 is a Yb:YAG thin disk used as "active" mirror; L1 = 47 cm; M2 has a 20-cm radius of curvature (ROC); L2 = 32.7 cm; M3 has a ROC of 40 cm; L3 = 62 cm; M4 is a flat highly reflecting end mirror; TFP's are thin film polarizers; $\lambda/4$ is a quarter-wave plate, $\lambda/2$ is a half-wave plate

cause mode matching between the pump and laser mode is more critical for these quasi-three-level laser materials than for ideal four-level materials. Therefore, we refer to our regenerative amplifier as an all-solid-state amplifier since there is no fundamental problem in building a diode-pumped femtosecond Yb:YAG seed oscillator. As the amplifier we used a diode-pumped 11%-doped Yb:YAG thin-disk laser amplifier head [10]. The 300-μm thin gain medium is pumped by seven fiber-coupled 1-W Siemens laser diodes at 940 nm imaged to a pump spot diameter of 450–500 μm. This results in approximately 8 W of incident pump power corresponding to ≈ 6.5 W absorbed pump power after four double passes through the Yb:YAG disk.

The experimental set-up of the regenerative amplifier is shown in Fig. 1. The amplifier cavity has a repetition rate of 110 MHz, corresponding to a roundtrip time of 9.4 ns, and contains a mirror telescope for pump-to-laser mode matching inside the Yb:YAG crystal and for avoiding damage problems at the thin-film polarizer (TFP), the quarter-wave plate and the Pockels cell. The gain medium is placed at one end of the cavity and the size of the laser mode is calculated to be 400 μm × 380 μm by using ABCD matrix formalism. The mode diameter in the second arm of the cavity is ≈ 2 mm. For pulse switching, we inserted a TFP, a zero-order 1030-nm quarter-wave plate and a Pockels cell. The Pockels cell contains a 20-mm long KD*P crystal. The Pockels cell and the driver (DR-85) are from Medox Electro-Optics. The clock signal for the driver is derived from the 70-MHz seed laser. The "p" polarization of the seed pulses is rotated to "s" polarization when the pulses pass through a 1030-nm half-wave plate and a 7-mm-aperture Faraday rotator (Electro-Optics Technology Inc.), each of them providing a 45° polarization rotation. The s-polarized pulses are injected into the amplifier by reflection at the thin-film polarizer (TFP2). For the regeneratively amplified pulses, the Faraday rotation is canceled by the half-wave plate, resulting in reflection at the external polarizer (TFP1).

The cavity is first optimized without any intracavity elements by using a 1% output coupler as the end mirror (M4). We then inserted the thin-film polarizer and the zero-order 1030-nm quarter-wave plate, both adjusted for minimum insertion loss by optimizing the output power. The thin-film polarizer introduced a single-pass loss of 2.1% for the transmitted p-polarized light. No measurable loss was introduced by the quarter-wave plate when inserted at zero retardation. As the next step, we installed a highly reflective end mirror (M4) to configure the system for amplification. We rotated the quarter-wave plate by 45° and placed the Pockels cell inside the cavity. The single-pass loss of our KD*P Pockels cell was measured to be ≈ 2%. To optimize the alignment we operated the Pockels cell in the Q-switching mode and minimized the build-up time of the Q-switched laser pulse. The build-up is monitored with a photodiode behind M4.

With no voltage applied to the Pockels cell the incoming seed pulse train circulates through the amplifier cavity once: the polarization is rotated by 90° because of the double pass through the quarter-wave plate and because the Pockels cell introduces no retardation at zero voltage. Then the pulse train is transmitted through the thin-film polarizer (TFP2), amplified in the pumped thin disk gain medium, again rotated by 90°, and finally ejected by reflection at the polarizer (TFP2). The ejected pulse train can be measured at the output of the regenerative amplifier. This results in a constant background power level that has to be subtracted when measuring the amplified pulse energy.

We determined the small signal gain per roundtrip by measuring the average power of the ejected seed pulse train with and without pumping of the amplifier medium and then taking the ratio. For a pump power of about 8 W we obtained a roundtrip small signal gain of 1.3. The seed pulse energy was 140 pJ.

The pulse switching with the Medox Pockels cell system operates as follows [14]. Initially the switch is off, allowing the seed pulse train to double pass once through the amplifier as described above. When the quarter-wave voltage is applied to the Pockels cell, the pulse circulating in the cavity is trapped, whereas the incoming seed pulse train experiences a full-wave retardation from the static quarter-wave-plate/Pockels-cell combination and is ejected from the amplifier cavity directly by reflection at the thin film polarizer. After the amplification period, the trapped pulse is cavity dumped by applying the half-wave voltage to the Pockels cell. The build-up of the trapped pulse is monitored by using the same photodiode behind M4 as described above. The output pulse was monitored with a second photodiode. The photodiode output is measured by using a 400-MHz analog oscilloscope. Optimization of the overlap between the cavity and seed beams is achieved by setting the Pockels cell driver for a long quarter-wave voltage period and then minimizing the build-up time of the amplified pulse. The reduction in the pulse build-up time for the seeded amplifier in comparison to the unseeded amplifier (only Q-switching) is 15–20%.

For repetition rates up to 750 Hz we achieved 2.3 ps pulses with pulse energies of 180 μJ, corresponding to a pulse peak power of 78 MW. At a 1-kHz repetition rate we obtained 120 μJ pulses. The pulse energies actually extracted from the amplifier disk are about 50% higher, i.e. 270 μJ and 180 μJ, respectively. This is due to imperfect reflectivity of the TFPs and the loss introduced by the Pockels cell and Faraday rotator during the final pass of the pulse through these elements. We calculated the maximum extractable pulse energy by using the Lowdermilk and Murray theory for multipass amplifiers [15]. For our single-pass gain of 1.14 and single-pass losses of ≈ 4% we determined a peak extractable fluence of 350 mJ/cm^2. The laser mode area of about 0.001 cm^2 at the

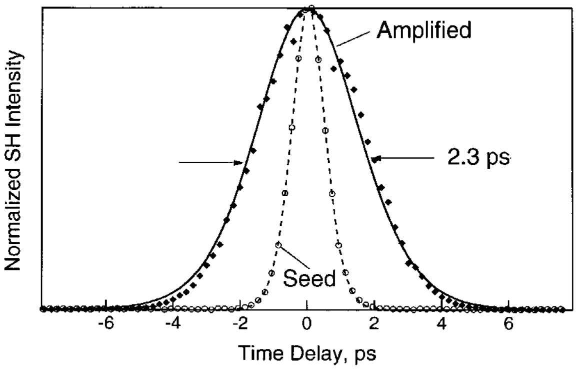

Fig. 2. Normalized slow-scan autocorrelations and fits (assuming hyperbolic secans pulse shape) of the 750-fs seed pulse (*circles*) and the 2.3-ps amplified pulse (*squares*) at a 1-kHz repetition rate

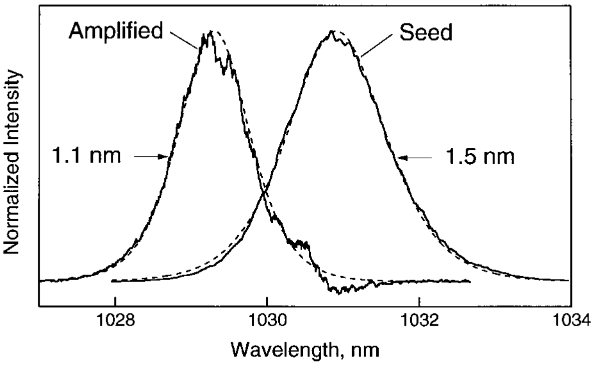

Fig. 3. Measured (*solid line*) and sech^2-fitted (*dashed line*) pulse spectra of seed (*right*) and amplifier output (*left*) at a 1-kHz repetition rate, showing the effect of gain narrowing

amplifier disk results in a maximum extractable pulse energy of 350 μJ. With an uncertainty of 1% in our intracavity gain or loss taken into account, this value is in good agreement with our maximum obtained pulse energy of 270 μJ. The extraction efficiency of our regenerative amplifier with respect to the stored optical energy of about 5.6 mJ (6.5 W absorbed pump power times 0.951 ms upper state lifetime times 0.91 quantum efficiency) is 5%. This value is consistent with the formula derived by Naito et al. [6].

Figure 2 shows the intensity autocorrelation traces of the seed pulse and the amplified pulse at a 1-kHz repetition rate, both measured with a slow-scan autocorrelator. The increase in pulse duration from 750 fs to 2.3 ps during amplification can be explained by gain narrowing in the Yb:YAG amplifier material [16, 17]. As an approximation we assume Gaussian pulses. An unchirped Gaussian pulse with a temporal envelope of the form $\exp(-at^2)$ is temporally spread to a new envelope $\exp(-a't^2)$ after an amplifier with finite bandwidth. The full width at half maximum (FWHM) of the intensity is given by $\tau_{\mathrm{FWHM}} = (2\ln 2/a')^{1/2}$. Applying a parabolic approximation for the gain profile and neglecting saturation effects in the amplifier, we derive the following relation between a' and a

$$a' = \frac{a}{1 + \frac{8N \ln G_0}{\Delta\omega_{\mathrm{a}}^2} a},$$

where N is the number of roundtrips in the amplifier, G_0 is the roundtrip small signal gain at line center, and $\Delta\omega_{\mathrm{a}}$ is the FWHM amplifier bandwidth. From fluorescence measurements with Yb:YAG we extracted a FWHM amplifier bandwidth of 5.3 nm at 1030 nm. The number of roundtrips in our regenerative amplifier was typically 85, corresponding to a pulse build-up time of about 800 ns. Inserting the measured roundtrip small signal gain of 1.3, we calculate an amplified pulse duration of 1.8 ps, which agrees quite well with our measurements. The small deviation may arise from the use of a Gaussian pulse envelope instead of a hyperbolic secans and from neglecting saturation effects in our calculations. From the dispersion data of KD*P we calculated a temporal spreading to less than a 760-fs pulse duration after 85 roundtrips. Therefore, we believe that the temporal stretching of our amplified pulses is mainly the result of gain narrowing.

Figure 3 shows the normalized spectra of the seed pulse and the amplified pulse. The shift of about 1.6 nm to shorter wavelengths from the seed to the amplified pulse spectrum is due to the seed oscillator and amplifier having different spectral gain distributions. This originates from the "Q-switched" operation of the amplifier. In this mode of operation, the gain is much higher than the losses and re-absorption is negligible. Therefore, the Yb:YAG amplifier can be treated as an ideal four-level laser and the spectral gain distribution corresponds to the fluorescence curve. However, for cw mode-locked operation of the oscillator, the saturated gain is determined by the interplay of steady-state inversion and re-absorption. For this reason, the effective gain profile of the seed oscillator is slightly shifted to longer wavelengths, where the gain is still high but the re-absorption is lower. A second contribution to the wavelength shift may arise from the cooling of the thin-disk amplifier. The copper heat sink temperature is kept at −33 °C. Cooling the amplifier results in lower re-absorption at the laser wavelength compared to that of the oscillator, which is operated at room temperature without any cooling. For the amplifier, this leads to a small shift in the effective gain to shorter wavelengths. From our simplified calculations, we derive a gain narrowing of the amplified pulse bandwidth to 0.8 nm when seeding with a bandwidth of 1.5 nm. This is in good agreement with the experiment, where we measured an amplified bandwidth of 1.1 nm. Self-phase modulation inside the Pockels cell during the last few roundtrips may have a small effect on the pulse shaping as well, resulting in a slight reduction in the gain narrowing.

The limit of the pulse repetition rate at approximately 1 kHz was due to the 1-ms upper state lifetime of Yb:YAG and an increase in losses introduced by the Pockels cell for higher repetition rates. The increased loss is caused by the onset of acousto optic ringing and of thermal problems resulting from the higher average power. This resulted in a longer amplification time of more than 1 μs, which was too long for the Pockels cell to maintain the quarter-wave voltage. This problem can be solved by designing a regenerative amplifier with no voltage applied to the Pockels cell during amplification.

In a second experiment, we used a $\mathrm{LiNbO_3}$ Pockels cell instead of KD*P. We obtained an amplified pulse duration of approximately 10 ps. The $\mathrm{LiNbO_3}$ Pockels cell introduced higher loss (2.5% single pass), which results in longer build-up times (186 roundtrips) and slightly lower pulse energies compared to the experiments with KD*P. The temporal stretching during amplification was mainly due to dispersive pulse broadening in the highly dispersive 25-mm-long

$LiNbO_3$ crystal. Some gain narrowing contributes as well since the amplified bandwidth is narrowed to ≈ 1 nm. However, the long pulse duration cannot be explained by this effect alone.

In conclusion, we have demonstrated a compact all-solid-state hundred-microjoule-level Yb:YAG regenerative amplifier operating in the few-picosecond regime. No additional pulse stretching and compression is needed. For quasi-three-level amplifiers, which typically exhibit a low gain cross-section, a low-loss amplifier cavity is desirable to efficiently extract the stored energy. By reducing the intracavity losses, e.g. by using a thin-film polarizer with higher transmission or a BBO Pockels cell instead of KD*P, and increasing the small signal gain, e.g. by optimizing the pump-to-amplifier mode matching or using a pump source with higher brightness, an increase in extraction efficiency and in the achieved pulse energy should be possible. For example, a single pass intracavity loss of only 2.5% and a roundtrip small signal gain of 1.5 would result in a 1-mJ pulse energy.

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