27-fs, 166-MW pulses at 98 W average power from highly efficient thin-disk oscillator driven nonlinear compressor

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Abstract: We demonstrate efficient nonlinear compression of a high-power thin-disk oscillator based on a two-stage (multi-pass-cell and multiple-plate) compression setup, achieving 98-W average power with 27-fs pulses at 13.4 MHz, resulting in 166-MW peak power.
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1. Introduction

Ultrafast thin-disk lasers (TDLs) have consistently been at the forefront of progress in the performance of high-average power ultrafast laser sources in the last decades. Among the different ultrafast disk architectures, compact one-box modelocked TDL oscillators are particularly attractive for applications requiring MHz repetition rates and high average powers. Average powers of several hundreds of watts and pulse energies approaching 100 µJ have been demonstrated [1], surpassing any other modelocked oscillator technology. However, one drawback of this technology for scientific applications remains the rather long pulse duration directly achievable out of these oscillators. The main difficulty is that broadband gain materials such as $CaGdAlO_4$ suitable for the TDL geometry remain unsuitable for high-power operation, and although many efforts continue to be made in this direction, sub-100 fs pulse remain undemonstrated with average powers of > 20 W. Alternative approach is to use external pulse compression. At these high repetition rates and moderate pulse energies, high compression efficiency is of utmost importance, therefore only few techniques are suitable. So far, high-power modelocked TDLs have been efficiently compressed using (1) gas-filled Kagome-type fibers, where 2.4 MHz, 70 W(29 µJ), 870 fs (peak power P_{peak} = 29 MW) pulses were compressed to 108 fs with 105-MW peak power and a throughput of η = 66%, [2], (2) multi-pass cells, where (a) 10 MHz, 500 W(50 µJ), 850 fs (P_{peak} = 52 MW) pulses were compressed to 170 fs with a peak power of 160 MW and η = 75% [3], and (b) 15.6 MHz, 80 W(5.1 µJ), 190 fs and a peak power of 24 MW pulses were compressed to 40 fs with 67 MW peak power and η=94%, respectively [4].

Here, we demonstrate a simple and efficient pulse compression setup from a 13.4 MHz, 123 W(9 µJ), 534 fs (P_{peak} = 16 MW) thin-disk oscillator down to 27 fs at 98 W average power, reaching 166 MW of peak power at 80% overall efficiency. The compressor is based on two stages, one multi-pass cell to reduce the pulse duration to 88 fs and subsequent compression to 27 fs using the multiple-plate technique [5]. To the best of our knowledge, this is the highest peak power demonstrated from a MHz-repetition rate amplifier-free based source. Additionally, this is the first time that the multiple-plate technique has been applied to a 100-W class MHz source with sub-10 µJ input pulse energy, showing the versatility of this technique. The demonstrated source is very promising for further compression to the few-cycle regime, for oscillator-driven HHG at high repetition rate or for the generation of very broadband THz radiation at high average power.

2. Experimental setup and results

A scheme of the experimental setup is shown in Fig. 1a. The driving TDL used for the compression setup has been described in detail in [6]. It is a SESAM-soliton-modelocked Yb:YAG TDL delivering up to 123 W of average power in 534 fs pulses, at a repetition rate of 13.4 MHz. This results in an input peak power of 16 MW.

The first compression stage is a Herriott-type multi-pass cell (MPC) consisting of two concave mirrors with a radius of curvature (ROC) of 300 mm, separated by 540 mm. The beam undergoes 42 passes through a 12 mm thick AR-coated fused-silica (FS) plate in the center of the MPC. One of the two concave mirrors is dispersive with a group delay dispersion (GDD) of -350 fs^2, which compensates for the material dispersion of the FS plate. To compress the spectrally broadened pulses, dispersive mirrors with a total GDD of -13200 fs^2 are further applied. From the first compression stage, we achieve clean nearly transform-limited (TL) 88-fs pulses with 112 W of average power, a peak power of 80 MW and an excellent beam quality of M^2 < 1.15.

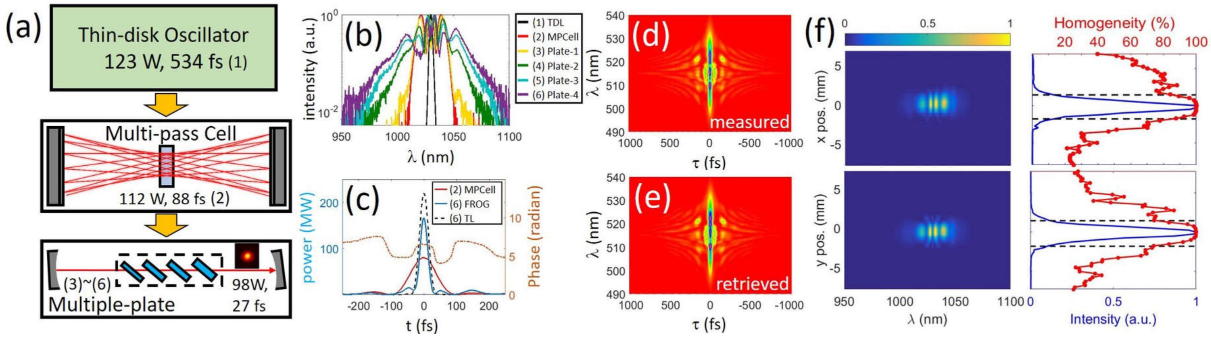

Fig. 1. (a) Experimental setup. (b) Power spectra measured along the setup as labelled in (a). (c) Pulse after the MPC compressor (red-solid), TL pulse after multiple plates (black-dashed), and temporal intensity (blue-solid) and phase (brown-solid) by FROG retrieval. (d-e) Measured and retrieved FROG traces of the final compressed pulses. (f) Homogeneity measurement after the multi-plate stage.

The output of the MPC stage seeds a second compression stage based on the multiple-plate technique, consisting of 4 FS plates (thickness of 1/2/2/3 mm). With a combination of concave mirrors, we reach a peak intensity of ~1.2 TW/cm^2 on the surface of the first plate. Other plates are strategically placed to maximize spectral broadening. Figure 1b shows the power spectra measured using an integrating sphere at the output of the TDL, MPC, and after each plate in the multiple-plate stage. The final output spectrum with 4 FS plates spans from 950 nm to 1100 nm, supporting a 30-fs (FWHM) TL pulse (black-dashed, Fig. 1c). A set of dispersive mirrors with a total GDD of -800 fs^2 compensate for the residual spectral phase resulting in 98 W of transmitted average power. We get excellent agreement between measured (Fig. 1d) and retrieved (Fig. 1e) FROG traces (FROG error of 4×10^{-3} at 512×512 grid). The final compressed pulse has 27-fs duration (FWHM) and 166-MW peak power (blue line, Fig. 1c), about 19 times shorter and with > 10 times higher peak power than the input. Note that FWHM becomes a misleading metric in this case, where the TL pulse with the highest peak power of 219 MW corresponds to a broader FWHM value of 30 fs (black-dashed, Fig. 1c). The TL peak power was not reached because of residual phase, which remained uncompensated by the dispersive mirrors available at the time of the experiment. Me measured an excellent beam quality of $M_x^2 = 1.13$ and $M_y^2 = 1.4$ with a small degradation in the y direction. This can be attributed to the wedged plates, available at the time of the experiment. We further verified this by replacing the plates with unwedged ones with the same total thickness. The beam quality factors improved as expected with an $M_x^2 = 1.13$, $M_y^2 = 1.24$ for the same broadening. Figure 1f shows the additional spectral homogeneity characterization of the beam (beam width $\omega_{1/e2} = 1.7$ mm) after the multi-plate stage using the approach described in [7]. A single-mode fiber is used to measure 60 spectra along the x- and y-axis with a totally range of 15 mm. For each measurement point, we calculate a homogeneity value V. The homogeneity values V are > 80% over 1/e^2, with an intensity-weighted average V_{avg} of 97% (x-axis) and 96% (y-axis) over the full 15 mm range, indicates an excellent spatial quality of the beam. The output power of the system was stable, with 0.6% fluctuation (root-mean square value) measured over 170 minutes (102000 data points).

3. Conclusions

We demonstrate pulse compression of a high-power modelocked thin-disk oscillator to 98 W, 27 fs, and 166 MW, enhancing the peak power of our oscillator by over an order of magnitude. These results confirm the potential of the multiple-plate technique for compression of high average power laser systems at high repetition rate. The performance in terms of peak power is the highest so far from an amplifier-free high average power source. In the near future, we will exploit the unique parameters offered by our setup for broadband THz generation and explore an additional multiple-plate setup to reach the few-cycle regime.

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