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. We achieve 98W average power with 27fs pulses at 13.4MHz, resulting in 166MW peak power.
OCIS codes: (320.6629) Supercontinuum generation; (140.3615) Lasers, ytterbium; (140.4050) Mode-locked lasers; (320.5520) Pulse compression; (320.7130) Ultrafast processes in condensed matter;

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, modelocked TDL oscillators are particularly attractive for applications requiring MHz repetition rates and high average powers, from a compact one-box oscillator. 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 major 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 suitable for the TDL geometry remain unsuitable for high-power operation, and although many efforts continue to be made in this direction, pulse durations <<100 fs remain undemonstrated with average powers of >20 W. An 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) 15.6 MHz, 80 W(5.1 µJ), 190 fs (P_{peak}=27 MW) pulses were compressed to 40 fs with a peak power of 67 MW and η=94% [3], and (b) 28.3 MHz, 100 W(3.5µJ), 220 fs and a peak power of 14 MW pulses were compressed to 16 fs with 60 MW peak power and η=60%, respectively [4].

Here, we demonstrate a simple and efficient pulse compression setup from a 13.4 MHz, 123 W(9µJ), 520 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. Our compressor is based on two stages, one multi-pass cell allowing us to reduce the pulse duration to 90 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 schematic of the experimental setup is shown in Fig. 1(a). The driving TDL used for the compression setup has been described in [6]. It consists of a SESAM, soliton-modelocked Yb:YAG TDL delivering up to 123 W of average power in 520 fs pulses, at a repetition rate of 13.4 MHz. This results in an input peak power of 16 MW.

In order to first reduce the pulse duration to sub-100 fs, we seed a Herriott-type multi-pass cell consisting of two concave mirrors with a ROC of 300 mm, with a 540 mm separation. The beam undergoes 42 passes through the 12mm thick AR coated fused-silica (FS) plate in the center of the MPC. One of the mirrors has a GDD of -350 fs², which compensates for the material dispersion of the plate. To compress the spectrally broadened pulses, the beam undergoes 24 reflections on two pairs of 2” dispersive mirrors with a GDD of -550 fs² per bounce. From this first compression stage, we achieve clean nearly transform-limited (TL) 90 fs pulses with 112 W of average power, a peak power of 80 MW and an excellent beam quality of M^2<1.15.

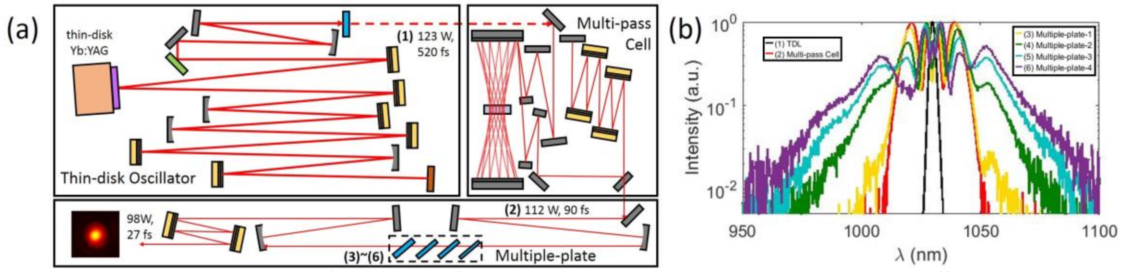

Fig. 1. (a) Experiment setup, with a near-field beam profile shown at the exit. (b) Power spectra measured at different places along the setup as labeled in (a), showing the very large spectral broadening achieved, in particular, the effect of each plate.

The output of the multi-pass cell seeds a second compression stage based on the multiple-plate technique, consisting of 4 FS plates with 1 mm, 2 mm, 2 mm and 3 mm in thickness. A plano/concave mirror (f=75 cm) delivers a peak intensity of ~1 TW/cm^2 on the surface of the first plate. Other plates are strategically placed to maximize spectral broadening. Four reflections on a set of dispersive mirrors (-200 fs^2 per bounce) compensate for the residual spectral phase resulting in 98 W of average power. Figure 1(b) shows the power spectra measured at the exits of the TDL, multi-pass cell, and different places in the multiple-plate stage. The final output spectrum spans from 950 nm to 1100 nm, supporting a 30-fs (FWHM) TL pulse. Figure 2 shows the results of SHG FROG, where the excellent agreement between measured and retrieved FROG traces [Fig. 2(a)] and power spectra [Fig. 2(b)] proves the fidelity of the retrieved temporal pulse shape [Fig. 2(c)]. The final compressed pulse has 27 fs duration (FWHM) and 166 MW peak power [blue, Fig. 2(c)], 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 corresponds to a broader FWHM value. We measured M_x^2=1.40, M_y^2=1.09 and a clean far-field pattern, confirming a good output beam quality. The slight degradation in one direction is most likely due to astigmatism introduced by the wedged plates used in this experiment, which we are currently investigating. The light source operates stably, with 0.6% power fluctuation (standard deviation divided by mean for 102,000 data points measured in 170 minutes).

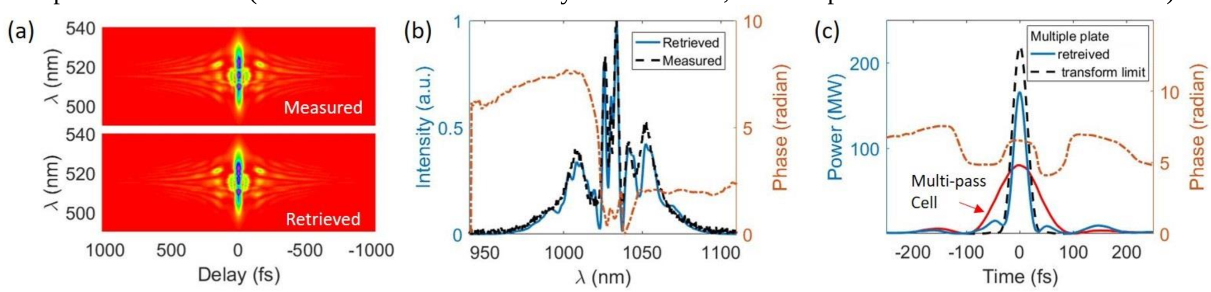

Fig. 2. (a) Measured and retrieved FROG traces of the final compressed pulse (FROG error of 0.007 at 512×512 grid). (b) Power spectra from optical spectrum analyzer (dashed) and FROG reconstruction (solid) and retrieved spectral phase (dashed-dotted). (c) Instantaneous powers of reconstructed pulses after the multi-pass cell (red), multiple plates (blue), and TL pulse after multiple plates (dashed).

3. Conclusions

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

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