Ultrafast Pulse Compression in Bulk with > 20 Times Spectral Broadening Factor from a Single Stage

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Abstract: We introduce the combination of multi-pass cell and multi-plate spectral broadening. We demonstrate the compression of 110-μJ pulses from 900-fs to 60-fs in a single stage and report broadening to 38-fs transform-limit by nonlinear mode-matching.

With the advent of ultrafast Yb-ion based disk, slab and fiber lasers, nonlinear pulse compression methods became indispensable for the generation of high average power sub-100 fs pulses. In particular, spectral broadening in bulk material located in a Herriott-type *multi-pass* cells (MPC) [1] has been established as a novel robust method for pulse compression in the 5 – 100 MW peak power range. The operation in the critical self-focusing regime becomes feasible through repetitive refocusing of the cell mirrors. Analogously, the *multi-plate* approach [2], which has mainly been used for broadband continuum generation, relies on the nonlinear refocusing of the Kerr media [3]. For both methods, only moderate compression factors not exceeding 10 have been reported so-far [4,5] (Fig. 1a). This enforced more complex setups with multiple stages and significant pulse pedestals [6,7]. Here, we introduce the hybridization of the multi-pass and multi-plate techniques, resulting in record-high single-stage compression factors of up to 15 and spectral broadening factors of up to 23. Our spectral broadening setup comprises only off-the-shelf optical elements. We report excellent spectrum stability, good beam quality and retrieved pulses with high compression quality.

The MPCs we set-up host multiple thin bulk plates (Fig 1b) instead of a single thicker one which was usually employed as nonlinear medium in bulk MPCs. Owing to the highly nonlinear impact of self-focusing with propagation length [3], our approach leads to reduced beam distortions within the Kerr media, and thus to less spatio-temporal coupling. This results in larger broadening factors and better compression quality. In our experiments, we compared spectral broadening in a single 3 mm thick silica window with broadening in three 1 mm thick silica plates. We used a laser system consisting of a home-built fiber laser front-end [8] and a commercial multi-pass Yb:YAG amplifier. The source delivered 10 Hz bursts of up to 800 pulses with on-average 110 ± 10 μJ energy, 900 fs duration and 1 MHz repetition rate. The pulse energy variation mainly originates from the fact that we have used two different lasers of the same type for the experiments. The about 350 mm long MPC was comprised of two standard quarter-wave-stack mirrors with 200 mm radius of curvature (Fig. 1b). Whereas we measured 66 μJ MPC output energy and a 65 fs

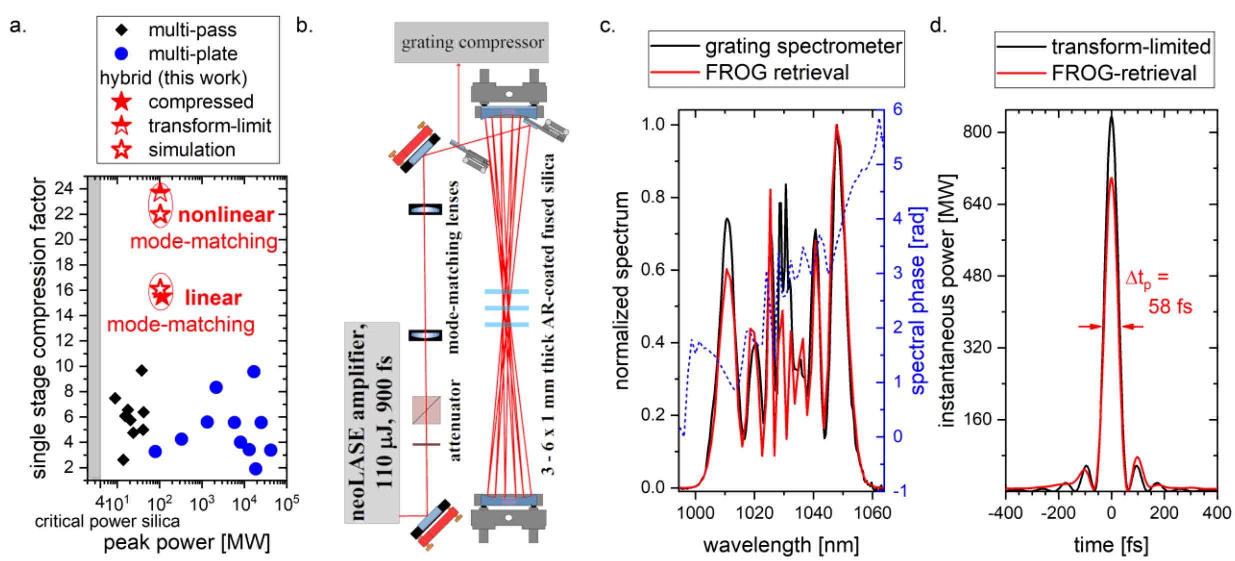

Fig. 1. a. Reported single stage compression factors of bulk multi-pass and multi-plate experiments in comparison to the results presented here (red marks). Encircled is the experimental 58 fs compression result (solid red star) and the benchmarking simulation (hollow star). The hollow star at the top predicts 40 fs pulses for 6 plates if mode-matching accounts for self-focusing. The semi-filled star shows the experimental transform-limit achieved with this method. **b.** Experimental setup. **c.** Retrieved FROG spectrum in comparison to grating spectrometer spectrum after 31 roundtrips in a 350 mm long cavity. **d.** Corresponding retrieved pulse in comparison to the Fourier transformed spectrum.

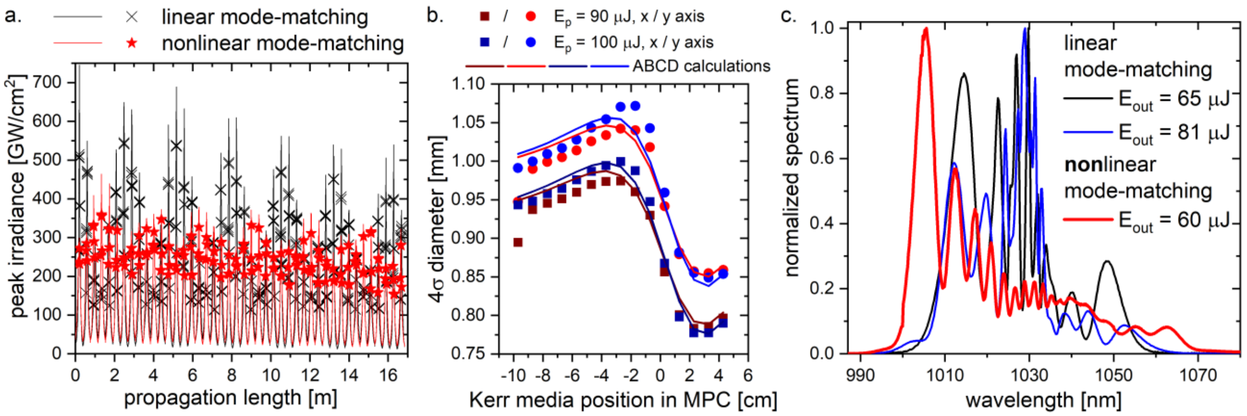

Fig. 2 a. Simulation of peak irradiances inside the experimental 350 mm long MPC with 3 thin Kerr media with linear (black) and nonlinear (red) mode-matching. The crosses and stars, resp., indicate the locations of the silica plates. **b.** Z-scan-type measurement of Kerr-lensing inside a 375 mm long MPC with three 1 mm thick silica plates inside. The dots show measured beam diameters, the lines the ABCD matrix fit with $n_2 = 2.25 \times 10^{-16}$ cm²/W for all curves. Position 0 denotes the center of the MPC. **c.** Comparison of spectral broadening in a 375 mm long MPC between linear mode-matching at two different output pulse energies with 3 plates inside the MPC and nonlinear mode-matching with 6 plates inside the MPC.

Fourier transform-limit for the single thicker sample, we measured 100 µJ output energy and a transform-limit of 57 fs for the 3 thin plates with 3 cm mutual distance for the same input. Fig. 1c and d show results of a FROG measurement after pulse compression with a grating pair. The retrieved spectrum is in good agreement with the spectrum recorded with a grating spectrometer. The retrieved pulses exhibit sub-60 fs duration and are nearly transform-limited. The pedestal amplitude is about 10 % of the main peak. It is mainly resulting from the modulations of the broadened spectrum as the transform-limited pulse shows. Although the beam passes 372 AR-coated interfaces in the MPC, 80 % of the input energy was transmitted. We measured M^2-factors < 1.2 for x- and y-direction after the MPC and a standard deviation of the transform-limit of only 0.6 fs over a 50-hour measurement with 10 s recording period.

A further increase of compression factor is possible by considering the Kerr-lensing effect of the thin silica plates. Fig. 2a shows simulations with the SISYFOS code [3] of peak irradiances inside the 350 mm long MPC. The black curve results from perfect mode-matching at low input power, i.e. when self-focusing is suppressed. Whereas in an empty MPC, the peak irradiance would not exceed 300 GW/cm², the MPC with 3 silica plates inside exhibits peak irradiances of more than 700 GW/cm². This high-power mode-mismatch limits the average intensities inside the Kerr media which eventually determine the broadening factor. To account for self-focusing, we incorporated Kerr-lens ABCD matrices in our mode-matching calculations. Fig. 2a shows that this lowers the maximal peak irradiance in the MPC for the same geometry to 450 GW/cm² in simulation. This allows for setting-up MPCs with more Kerr media and tighter focusing by going closer to the stability edge of the cell. Fig. 1a displays a simulation result of a 380 mm long cell and 6 instead of 3 plates. Compression to sub-40 fs was computed. To experimentally validate this prediction, we measured the Kerr effect directly in a 375 mm long MPC with 3 plates by monitoring the beam sizes at the second cavity mirror position after a single pass. Fig. 2b shows characteristic Z-scan curves which have been fitted by means of the Kerr-lens ABCD matrices and n_2 as free parameter. We then compared spectral broadening in the 375 mm long MPC for first linear mode-matching and 3 silica plates and second nonlinear mode-matching and 6 silica plates (Fig. 2c). Whereas in the linear matching case spectral broadening saturated at a certain energy level and optical power was mainly transferred to the central part of the spectrum, indicating mode-mismatch, the nonlinear matching case resulted in a significantly broader spectrum with 38 fs transform-limit and no distinct peaks near the 1030 nm input wavelength. This suggests that even tighter focusing and more spectral broadening towards the about 30 fs bandwidth limit of cavity mirrors is possible and will be investigated next before compressibility is demonstrated.

In conclusion, we have shown that hybridizing multi-plate and multi-pass bulk broadening techniques results in a significant boost of spectral broadening and pulse compression factors in an all-bulk spectral broadening. We generated clean, nearly transform-limited sub-60 fs pulses with excellent long-term stability, good efficiency and low M^2-factor. Moreover, we have demonstrated spectral broadening factors of more than 20 in a single bulk stage by considering nonlinear lensing in mode-matching. The scalable, simple-to-implement and robust bulk broadening method is therefore an excellent technique for post-compression of high-power ps-level pulses and moreover becomes increasingly competitive to gas-filled MPCs [8-10].

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