Bulk Post-Compression of Multi-10 mJ, Few-ps Pulses at 2 µm – Gaussian- vs Needle-Beam Profiles

U G Griebner[1], M B Bock[1], F F Furch[2,3], and D U Ueberschaer[1]

[1] *C2, Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2a, 12489 Berlin, Berlin, Germany. Contact Phone: +4963921457*
[2] *A3, Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2a, 12489 Berlin, Berlin, Germany. Contact Phone: +4963921457*
[3] *Ruhr-University Bochum, Universitätsstraße 150, 44801 Bochum, Regensburg, Germany. Contact Phone: +4963921457*
Contact Email: griebner@mbi-berlin.de

Major attention is dedicated on the generation of high-intensity pulses in the 2-µm spectral range [1]. A popular way is based on OPCPA systems. Commercially available kW-class 1-µm lasers as pump enables the generation of sub-30 fs pulses at 2.1 µm with energies of 2.7 mJ at 10 kHz repetition rate [2]. However, further energy scaling of 2 µm OPCPAs at a few kHz repetition rate appears to be challenging. Another approach for few-kHz laser systems with multi-mJ pulse energies is direct, laser-based amplification using the CPA technique. Around 2-µm, the amplification systems are typically based on Tm- or Ho-doped gain media [1,3]. Up to date, pulses with multi-10 mJ energies at 2-µm are exclusively provided by Ho:YLF laser sources. However, due to their limited gain bandwidth the duration is in the few-ps range [1]. Compression of these ps pulses into the few-10 fs range applying spectral broadening methods would enable the generation of higher harmonics in the water window with high flux.

Methods for post-compression comprise hollow-core fibers (HCF) [4], thin plates or multi-pass cells (MPC) [5]. Recently, we generated 90 fs pulses with 22 mJ energy at 2.05 µm by compressing 40 mJ pulses with a duration of 2.8 ps in a two-stage arrangement [4]. In this system, the 1 kHz input pulses were SPM broadened in the first stage in air. This produced 1.5 ps pulses for the second stage, a stretched-flexible HCF. The duration of the nearly 3 ps input pulses proved to be too long to reach the sub-50 fs range. Therefore, a significantly larger compression ratio in the first stage must be realized. The compression of high-energy ps pulses has been impressively demonstrated using MPCs in the near-infrared range. MPCs have also been successfully applied around 2-µm, however, not yet for pulse energies in the multi-10 mJ range [5]. MPC mirror damage and gas ionization denote the main challenges.

Here we present nonlinear bulk compression for generating multi-10-mJ femtosecond pulses at 2.05 µm. For this purpose 2.0 ps pulses at 2.05 µm, from a 1 kHz Ho:YLF CPA, are spectrally broadened due to SPM in fluoride materials. In doing so, we compare the SPM broadening of the Gaussian-beam provided directly by the laser system with that of a Needle-beam generated by beam shaping using axicons. Particular attention is paid to the spatio-temporal homogeneity of the post-compressed fs pulses.

The output of a Ho:YLF CPA operating at 1 kHz repetition rate provides the input pulses [1]. The pulses with a Gaussian profile, i.e. the unshaped beam, contain 52 mJ energy. The beam with a diameter of 14 mm is sent through two 180 mm long CaF_2 plates. SPM broadening takes place below the onset of filamentation. Subsequent compression employing a pair of transmission gratings delivers 770-fs pulses with an energy of 41 mJ. The almost undisturbed beam profile results in a M^2 of 1.1. The post-compression is associated with a loss of 25%, mainly due to the compression gratings. Despite this, the resulting peak power is remarkable 46 GW, the highest for 2-µm sub-ps sources. The homogeneity of spectral broadening within the beam profile is analyzed after the compressor gratings by calculating the V-parameter. The latter drops to ~70% at the $1/e^2$ intensity level of the beam profile and its weighting with intensity gives an averaged overlap of 93%, typical values, but rather good for bulk compression.

For the axicon-based post-compression, the initial Gaussian beam diameter is reduced from 10.0 mm to 5.8 mm to adapt the beam size for an optimal transformation to a Needle-beam [6] by using an axicon with a very high apex angle of 179.85°. The needle beam generated in the extended Bessel zone consists solely of the central maximum and the first ring of the Bessel distribution. Five pairs of fluoride plates

(MgF_2 and CaF_2) with total thickness of 95 mm represent the medium for SPM. A second axicon with the same apex angle at the end of the Bessel zone transform the Needle-beam back in a Gaussian-beam. For compression the same transmission grating pair is used.

With the applied 23 mJ input pulse energy no signs of filamentation are observed. The 2.05 µm input pulses with a bandwidth of 3 nm are broadened to 9.5 nm (FWHM). A pulse duration of 520 fs (spatially averaged, sech^2-pulse shape) is measured after the compressor gratings which is close to the FTL duration. The compressed pulse duration amounts to 15 mJ. The slight increase of the loss is attributed to uncoated optical elements in the beam path (axicons). The re-transformed Gaussian intensity distribution shows almost no astigmatism and the measurement of the M^2 gives a value of 1.3. The characteristic V-parameter for the axicon-based post-compression remains larger than 92% within the $1/e^2$ intensity range of the beam profile and the averaged overlap gives 98%. The exceptional high spatio-temporal homogeneity is related to the interference properties of a Bessel beam. Of particular note is the excellent beam pointing of our axicon-based approach, which measures 20 µrad. Even after more than 10 m of propagation, the beam remains geometrically self-stabilizing.

In conclusion, nonlinear bulk compression of 2.0 ps, multi-10 mJ pulses at 2.05 µm was demonstrated using fluoride plates. Two approaches were pursued in this context; propagation of a Gaussian-beam and propagation of a Needle beam through fluoride blocks where spectral broadening occurs via SPM. Both regimes operated below the onset of filamentation, resulting in undisturbed beam profiles.

In the case of the Gaussian-beam 52 mJ input pulses were compressed to 770 fs with 41 mJ energy. The resulting peak power in the 1-kHz pulse train is remarkable 46 GW, the highest for 2-µm sub-ps sources. The analyzed spatio-temporal homogeneity yielded an average V-parameter of 92%, which is a typical value for bulk compression. Using the needle-beam approach, 23 mJ input pulses were compressed to 520 fs with 15 mJ energy. The axicon-based compression scheme exhibits an outstanding spatio-temporal homogeneity over the entire beam profile with an averaged V-parameter of 98%, which distinguishes them from other bulk compression schemes. This opens a new approach to re-design the first stage of our cascaded high-energy pulse compression scheme at 2 µm in order to achieve the targeted sub-50 fs pulse duration [4].

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