Nonlinear Pulse Compression to Sub-40 fs at 4.5 μJ Pulse Energy by Multi-Pass-Cell Spectral Broadening

Johannes Weitenberg, Tobias Saule, Jan Schulte, and Peter Rußbüldt

***Abstract*— We report on the pulse compression of an 18.5 MHz repetition rate pulse train from 230 fs to sub-40 fs by nonlinear spectral broadening in a multi-pass cell and subsequent chirp removal. The compressed pulse energy is 4.5 μJ, which corresponds to 84 W of average power, with a compression efficiency of 88%. This recently introduced compression scheme is suitable for a large pulse energy range and for high average power. In this paper, we show that it can achieve three times shorter pulses than previously demonstrated.**

***Index Terms*— Nonlinear optics, optical pulse compression, ultrafast optics.**

I. Introduction

EXTERNAL nonlinear pulse compression enables combining the high average power of Yb-based laser systems (100 W level and above) with short pulse durations (100 fs level and below), which are not supported by the gain bandwidth of the employed Yb-doped active medium. It relies on nonlinear spectral broadening by self-phase modulation (SPM) in a nonlinear medium and subsequent chirp removal [1]. Many scientific applications, such as single-pass [2] or resonator-enhanced [3] high-harmonic generation, rely on a short pulse duration and benefit from a larger power and higher repetition rate, enabled by the use of Yb-based laser systems. These highly nonlinear applications profit from a pulse duration well below 100 fs.

Established external pulse compression schemes (Fig. 1) rely on spectral broadening in a waveguide. This technique maintains a high intensity over a long interaction length, which produces a large nonlinear phase for pulses with peak power below the threshold for catastrophic self-focusing (the material-dependent critical power). The waveguide also mitigates the effects of Kerr lensing, which inevitably goes along with SPM. These schemes are limited to certain energy ranges; broadening in a solid-core fiber is limited to peak powers below the critical power of fused-silica of 4 MW, which corresponds to a few μJ at several 100 fs pulse duration [4]. For higher peak power, spectral broadening in a gas-filled capillary can be employed [5]. The critical power is about three orders of magnitude larger than for dielectric media and can be adjusted via gas type and pressure. However, this scheme is limited to sufficiently large peak powers, i.e. pulse energy. It can only be applied to pulses with energy below $\sim$100 μJ when using impractical gas pressures ($\gg$1 bar) due to the small gas nonlinearity and limitations in diameter and length of the capillary.

Different schemes have been demonstrated in the last years that aim to address this gap in pulse energy range. A Kagome-type gas-filled hollow-core fiber allows spectral broadening of pulses with smaller pulse energy than in a capillary because a smaller core diameter and larger fiber length can be implemented without considerable propagation loss. Compression to 31 fs pulse duration at 7.1 μJ pulse energy and 10.7 MHz repetition rate (76 W average power) has been reported [2]. Scalability of the scheme to even higher average power can be expected from the demonstration of coupling 900 W of cw radiation through a Kagome fiber [6].

Spectral broadening in a dielectric can be scaled to higher pulse energies by employing a divided-pulse compression scheme (DPC), which reduces the peak power by dividing the pulse into multiple replica inside the nonlinear medium [7]. Also, operation above the critical power is possible with no waveguide employed – spectral broadening can be achieved in a single pass through a bulk nonlinear medium [8], [9], or by passing through several nonlinear elements [10]. Catastrophic self-focusing is avoided for a restricted nonlinear phase shift and carefully adjusted beam parameters. However, spectral broadening for a beam passing through a single bulk nonlinear medium is inhomogeneous across the beam profile. This reduces the beam quality and pulse compressibility or leads to high loss at spatial filtering [8].

We recently demonstrated a compression scheme for peak powers above the critical power that avoids a waveguide and mitigates the disadvantage of spatially inhomogeneous broadening by splitting the nonlinear phase shift into many steps with propagation without nonlinearity in-between [11]. This can be achieved in a compact way with a multi-pass cell and is called multi-pass-cell spectral broadening (MPCSB). The scheme is efficient and insensitive to fluctuations of the

Manuscript received July 12, 2017; revised September 25, 2017; accepted October 5, 2017. Date of publication October 16, 2017; date of current version November 2, 2017. This work was supported in part by the Max-Planck Fraunhofer Cooperation Project MEGAS, in part by the Deutsche Forschungsgemeinschaft (Cluster of Excellence 158, Munich-Centre for Advanced Photonics, MAP), and in part by the European Union's Horizon 2020 Research and Innovation Programme under Grant 664732 nuClock. *(Corresponding author: Johannes Weitenberg.)*

J. Weitenberg is with the Fraunhofer Institute for Laser Technology ILT, 52074 Aachen, Germany, and with the Max-Planck Institute of Quantum Optics MPQ, 85748 Garching, Germany (e-mail: johannes.weitenberg@ilt.fraunhofer.de).

T. Saule is with the Ludwig-Maximilian University of Munich, 85748 Garching, Germany (e-mail: tobias.saule@physik.uni-muenchen.de).

J. Schulte and P. Rußbüldt are with the Fraunhofer Institute for Laser Technology ILT, 52074 Aachen, Germany (e-mail: jan.schulte@ilt.fraunhofer.de; peter.russbueldt@ilt.fraunhofer.de).

Digital Object Identifier 10.1109/JQE.2017.2761883

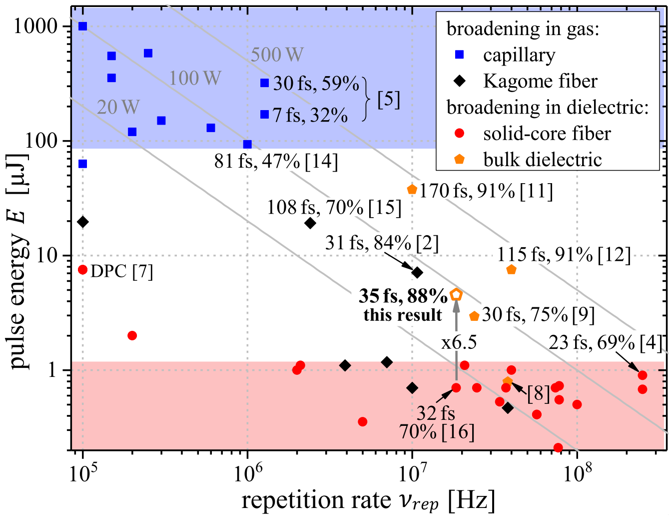

Fig. 1. Overview of laser systems with external nonlinear pulse com-pression. The shaded areas mark pulse energy ranges for which established compression schemes are applicable at high average power. Blue: pulse energies $\gtrsim$100 μJ for spectral broadening in a gas-filled capillary. Red: pulse energies $\lesssim$1 μJ for spectral broadening in a solid-core silica fiber. Diagonal gray lines connect points with the indicated average powers. Selected data points are labeled with compressed pulse duration and compression efficiency. The gray arrow marks the pulse power increase of the reported system compared to the previous fiber-based compression of the same laser system. DPC: divided pulse compression. There is no claim of completeness for results below 20 W average power.

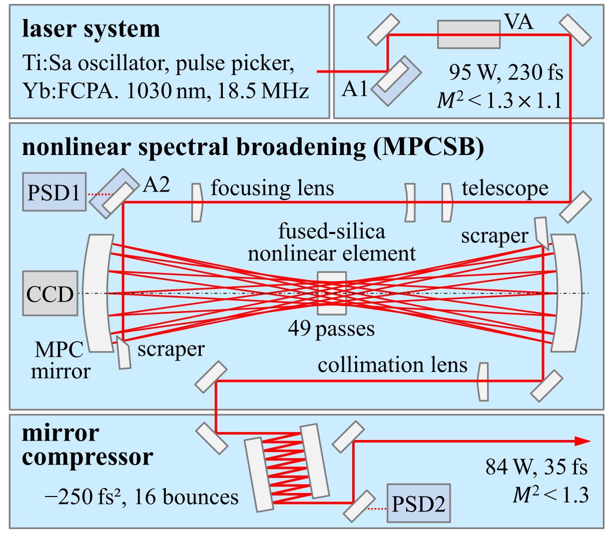

Fig. 2. Sketch of nonlinear pulse compression setup by multi-pass cell spectral broadening (MPCSB). FCPA: fiber chirped-pulse amplifier; VA: variable attenuator; A1, A2: actuators for beam pointing stabilization; PSD1, PSD2: position-sensitive detectors; CCD: camera for evaluation of mode-matching.

impinging beam pointing or profile, which makes it especially suited for high-power operation and even for pulses with imperfect beam quality [11]. So far, compression from 850 fs to 170 fs at 37.5 μJ pulse energy and 10 MHz repetition rate (375 W average power) [11], and compression from 860 fs to 115 fs at 7.5 μJ and 40 MHz repetition rate (300 W average power) [12] has been achieved. The effectiveness of the MPCSB approach in mitigating space-time coupling due to the temporally varying Kerr lens and spatially inhomogeneous broadening has recently been studied and verified by numerical simulation [13]. Good homogeneity of the spectral broadening across the beam profile and of the beam parameters across the broadened spectrum has been experimentally verified [12].

These prior implementations of the MPCSB scheme used laser systems with Yb:Innoslab amplifiers and pulse durations of more than 800 fs which were compressed to pulse durations between 100 fs and 200 fs. Here, we demonstrate the applicability by adopting the MPCSB compression scheme to pulses from an Yb-doped fiber amplifier with more than three times shorter pulses than the Yb:Innoslab amplifiers. We achieve a similar compression factor and three times shorter pulses. The pulses are well compressible, although the pulses from the fiber amplifier are not Fourier transform limited and possess a pre- or post-pulse.

Fig. 1 shows an overview of reported systems with external nonlinear pulse compression, showing the gap in pulse energy range that is not covered by the established compression schemes and that can be accessed by spectral broadening in a gas-filled Kagome fiber or by the MPCSB scheme (employing a bulk dielectric). The pulses from the same fiber amplifier used in the reported experiment have been previously compressed by spectral broadening in a solid-core fiber [16]. However, in that case only a fraction of the available pulse energy could be sent to the compression stage due to the self-focusing limit. With the MPCSB scheme we could increase the compressed pulse energy by a factor 6.5 with respect to the fiber-based compression.

II. Experimental Setup

The setup comprises the following elements (Fig. 2). The laser system is described in detail in [16]. It consists of a Ti:sapphire oscillator at 74 MHz repetition rate, which is reduced with a pulse picker by a factor of four. The subsequent chirped-pulse fiber amplifier delivers up to 120 W of average power. In this experiment, up to 95 W are sent to the compression stage. The spectrum is centered at 1030 nm and has a bandwidth of 8.2 nm (FWHM), as shown in Fig 3(a). Fig. 3(b) shows an autocorrelation trace of the pulses from the amplifier, revealing a pre- or post-pulse. We estimate a pulse duration of 230 fs (assuming a Gaussian pulse shape) and a fraction of 85% of the pulse energy in the main pulse. This corresponds to a peak power of 18 MW at 95 W. The Fourier transform-limited pulse duration is 150 fs (FWHM). The beam quality factor is $M^2 = 1.24\times1.07$. A variable attenuator (wave-plate and thin-film polarizer) adjusts the power sent to the compression setup.

The multi-pass cell (MPC) for nonlinear spectral broadening is formed by two concave-convex mirrors with 300 mm radius of curvature and 50.8 mm diameter. The concave surfaces are facing each other and are coated with a dispersive HR coating with $GDD = (-250\pm50)$ fs^2. This is designed to compensate for the material dispersion of the 13 mm thick AR-coated fused-silica plate, which serves as the nonlinear element and is placed half way between the mirrors. The distance of the MPC mirrors is 583 mm. Coupling to and from the MPC is achieved with scraper mirrors with a width of 5 mm. The beam passing through the MPC forms a circle of 25 evenly spaced reflections on each mirror (one of which is screened

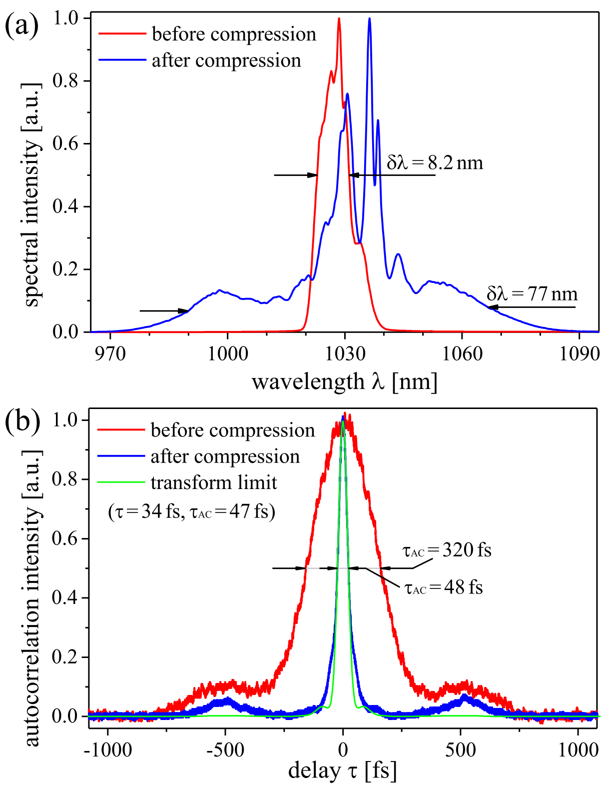

Fig. 3. Characterization of the compressed pulses. (a) Spectrum before (red) and after (blue) pulse compression unit; (b) autocorrelation trace before (red) and after (blue) the pulse compression together with the autocorrelation of the Fourier transform-limited pulse for the measured spectrum (green).

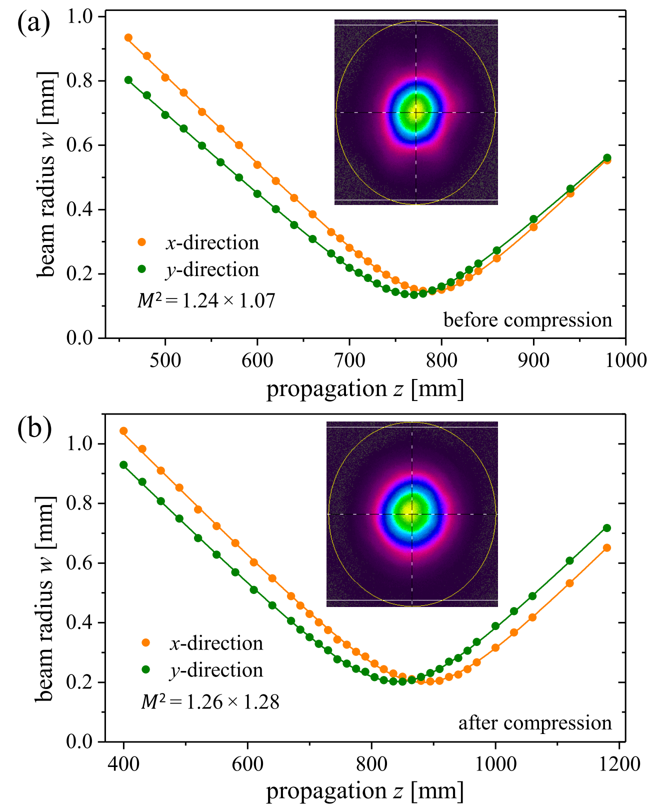

Fig. 4. Beam quality measurement and beam profile of the collimated beam before (a) and after (b) the pulse compression setup. The solid lines show the hyperbolic fits to the measured beam caustics. (The x direction corresponds to the horizontal direction before compression and to vertical direction after compression, because the profile is rotated at a periscope.)

by the scraper) and advances by 22 positions along this circle every time it hits the mirror. This yields 49 passes through the nonlinear element. The total distance propagated in glass and air is 0.64 m and 28 m, respectively. The beam diameter of a Gaussian beam with the eigen-q-parameter of the MPC is $2w_1 = 1.44$ mm and $2w_0 = 0.27$ mm on the mirrors and in the nonlinear element, respectively. Mode-matching is achieved with a spherical telescope and a focusing lens. The beam after the MPC is collimated with a single spherical lens. The spectrally broadened pulses are compressed by 16 reflections on dispersive mirrors with $GDD = -250$ fs^2, yielding a total GDD of -4000 fs^2.

The setup includes beam pointing stabilization, consisting of two piezo-actuated mirrors and two corresponding position sensitive detectors at different positions in the setup (see Fig. 2). The pointing fluctuations stem mainly from the laser system; additional fluctuations are imprinted at the long path through the MPC. Inspection with a thermal camera shows that the MPC mirrors are hardly heating at full power and that they are ~1 K hotter at the position of the reflections. We estimate the thermal lens from the thermally induced mirror deformation to be negligible. The pointing (*rms* deviation of the beam centroid Δr_{rms} referred to the beam radius w) after the compression unit is measured to be $\Delta r_{\mathrm{rms}}/w = 3.6\%$ without stabilization and 1.4% with stabilization.

III. Nonlinear Compression Results

Spectral broadening to a bandwidth of 77 nm (taken at half the intensity of the outer spectral maxima) is achieved at 95 W incident power. The broadened spectrum is shown in Fig. 3(a). The compressed power is 84 W, corresponding to a transmission of the compression unit of 88%. The pulses corresponding to the Fourier transform limit of the broadened spectrum have a pulse duration of 34 fs (FWHM), an autocorrelation width of 47 fs (FWHM), and a peak power of 120 MW. The measured autocorrelation width of the compressed pulses is 48 fs (FWHM), as shown in Fig. 3(b). Assuming the same deconvolution factor as for the Fourier transform-limited pulse (0.72), yields an estimated compressed pulse duration of 35 fs (FWHM). The autocorrelation shows side maxima at the same delay (505 fs) as for the pulse before compression. This probably stems from the pre- or post-pulse which is weakly affected by SPM. The compressed peak power is smaller than the value for the Fourier transform-limited pulse, which does not exhibit significant pre-/post-pulses. Spectral broadening by a factor 9 and pulse shortening by a factor 6.5 is achieved. Fig. 4(a) and (b) show the beam quality measurements before and after the pulse compression setup. The beam quality is almost preserved with $M^2 = 1.26 \times 1.28$.

The shape of the broadened spectrum (Fig. 3(a)) differs from a spectrum typical for SPM, which would be strongly modulated and symmetrical. We attribute this to the fact that the start pulse is not Fourier transform limited and that the dispersion of the nonlinear element is not completely compensated by the dispersive MPC mirrors. This leads to an elongation of the pulse as it propagates through the MPC, with a measured duration of 430 fs after the MPC. Due to the increasing pulse duration the nonlinear phase per pass through the nonlinear element decreases. We estimate an average nonlinear phase of 0.09π per pass (4.4π after a complete pass through the MPC), derived from the beam diameter in the middle of the MPC (including the Kerr lens and M^2 factor) and an average peak power in the MPC of 13 MW.

The spectral broadening factor in this experiment is limited by damage of the nonlinear element, which was observed for higher power sent to the MPC. We do not know the reason for this damage. According to the layout of the setup the fluence on the surfaces of the nonlinear element should be an order of magnitude below the damage threshold and the self-focusing length should be much longer than the nonlinear element. Alignment-free operation over several months has been observed with the reported parameters.

IV. Scaling

The MPCSB compression scheme can be applied to pulse energies in the range of a few μJ up to a few 100 μJ, limited by the damage threshold of the optics and the dimensions of the setup [12]. The scheme has proven average power scalability to the multi-100 W range [11], [12]; powers exceeding 1 kW seem feasible. While a somewhat larger compression factor than the demonstrated value of 6.5 seems possible, for a much larger factor, two (or more) compression stages are advantageous. For each compression stage the achievable pulse duration is limited by the bandwidth of the MPC optics. In addition to the reflectivity of HR and AR coatings, this especially refers to the spectral phase of the MPC mirrors, which should compensate the material dispersion of the nonlinear element across the full bandwidth, in order to achieve a spectrally compressible pulse. Even shorter pulses than 35 fs should be feasible with suitable MPC mirrors.

Acknowledgment

The authors thank Vladimir Pervak for providing dispersive mirrors, Christina Hofer for help with pulse characterization, and Ioachim Pupeza and Akira Ozawa for fruitful discussions.

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Johannes Weitenberg was born in Rhede, Germany, in 1981. He received the degree in physics from RWTH Aachen University, Germany, in 2007.

From 2008 to 2015, he has been with the Chair for Laser Technology at RWTH Aachen University. Since 2015, he has been with the Fraunhofer Institute for Laser Technology, Aachen. Since 2015, he has been with the Max-Planck Institute of Quantum Optics, Garching. His current research interests include development of solid-state lasers, high-harmonic generation, enhancement resonators, nonlinear pulse compression, and frequency comb spectroscopy.

Mr. Weitenberg is a member of Deutsche Physikalische Gesellschaft and the Optical Society of America. He was a recipient of the Stifterverband Science Prize (Stifterverband für die Deutsche Wissenschaft) and Berthold Leibinger Innovationspreis (second price, Berthold Leibinger Stiftung).

Tobias Saule was born in Augsburg, Germany, in 1989. He received the M.Sc. degree in physics from the Technical University, Munich, Germany, in 2013. He is currently pursuing the Ph.D. degree with the Max-Planck Institute of Quantum Optics, Garching and the Ludwig-Maximilians University of Munich. His research areas include fiber amplifiers, pulse broadening and compression, enhancement cavities and intra-cavity high harmonic generation and its application.

Jan Schulte was born in Aachen, Germany, in 1989. He received the B.Sc. and M.Sc. degrees in physics from RWTH Aachen University, Germany, in 2010 and 2013, respectively.

From 2014 to 2015, he has been with the Center for Free Electron Laser Science, DESY, Hamburg, Germany and since 2015, he was with the Fraunhofer Institute for Laser Technology, Aachen, Germany. His current research interests include development of high-power ultrafast lasers, nonlinear pulse compression, and high-harmonic generation.

Mr. Schulte is a member of Deutsche Physikalische Gesellschaft and the Optical Society of America.

Peter Rußbüldt was born in Jülich, Germany, in 1970. He received the Ph.D. degree in physics from RWTH Aachen University, Germany, in 2004.

Since 1995, he has been with the Chair for Laser Technology at RWTH Aachen University and also with the Fraunhofer Institute for Laser Technolgy (ILT), Aachen. He is currently managing the Ultrafast Lasers Group, ILT. His main research interests include development of femtosecond oscillators and amplifiers based on various laser materials, involving its metrology, and application.

Mr. Rußbüldt is a Member of the Optical Society of America. He was a recipient of the Borchers badge, RWTH Aachen University, Stifterverband Science Prize (Stifterverband für die Deutsche Wissenschaft), and Berthold Leibinger Innovationspreis (second price, Berthold Leibinger Stiftung).