CHINESE OPTICS LETTERS

Vol. 19, No. 9 | September 2021

Generation of 601 fs pulse from an 8 kHz Nd:YVO$_4$ picosecond laser by multi-pass-cell spectral broadening

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Received December 7, 2020 | Accepted March 3, 2021 | Posted Online May 24, 2021

We demonstrate nonlinear pulse compression of an 8 kHz Nd:YVO$_4$ picosecond laser using the multi-pass-cell (MPC) technique with fused silica as the nonlinear medium. The pulse duration is compressed from 12.5 ps to 601 fs, corresponding to a pulse shortening factor of 20.8. The output pulse energy is 154 μJ with an efficiency of 74.5%. To the best of our knowledge, this is the highest pulse compression ratio achieved in a single-stage MPC with bulk material as the nonlinear medium. The laser power stability and the beam quality (M^2) before and after the MPC are also experimentally studied. Both the laser power stability and the beam quality are barely deteriorated by the MPC device.

Keywords: multi-pass cell; Nd:YVO$_4$; compression ratio; femtosecond laser.

DOI: 10.3788/COL202119.093201

1. Introduction

Femtosecond laser pulses operated at several kilohertz repetition rate with hundreds of microjoules pulse energy have attracted great interest in the fields of material process[1], spectroscopy[2], mid-infrared generation[3], and so on. So far, the applications mentioned above are employing Ti:sapphire or ytterbium (Yb)-doped femtosecond amplifiers. The femtosecond lasers based on Ti:sapphire or Yb-doped gain media have reached a high level of technological maturity and are commercially available[4–6]. Nevertheless, the price of the Ti:sapphire amplifier and the Yb-doped amplifier is relatively high. Neodymium (Nd)-doped picosecond amplifiers with hundreds of microjoules pulse energy exhibit the advantages of low cost and compact configuration profiting from its chirped pulse amplification (CPA) free structure. So, spectral broadening of the picosecond amplifier and then chirped removal would be an ingenious route to obtain femtosecond laser pulses with around hundreds of microjoules pulse energy. The peak power of the laser pulse with pulse duration of 10 ps and pulse energy mentioned above is several tens of megawatts. In this peak power level, the gas-filled Kagome hollow-core photonic crystal fiber (HC-PCF) has been reported as a feasible compression scheme[7,8]. However, Kagome HC-PCF is sensitive to the beam fluctuation of the input laser, because its core diameter is only tens of microns. In 2016, Schulte *et al.* implemented an innovative scheme for spectral broadening called the multi-pass-cell (MPC), which consists of two concave mirrors (CMs) and nonlinear bulk media[9]. This device is mostly ideal for the spectral broadening of laser pulses with a peak power of tens of megawatts. It can be designed to have an adequate aperture to make the unit insensitive to the fluctuation and beam quality of the coupled laser beam[9]. Both the numerical simulations and experimental results indicate that the homogeneous spectral broadening across the beam spatial profile can be realized if the per pass nonlinear phase is small enough, like 0.1π[10,11]. Therefore, the spectral broadening factor and the pulse duration compression ratio are positively correlated with the number of times the lasers pass through the nonlinear bulk materials. Currently, the maximum round trips of the MPC with bulk media are 29 (57 passes), which result in a pulse compression ratio of 7.5[11]. A higher compression ratio is achievable by cascading the MPC device. For example, Fritsch *et al.* achieved 13.8 times pulse compression by cascading three-stage all-solid-state MPCs[12], and Vicentini *et al.* demonstrated 20.9 times pulse compression by cascading two-stage bulk medium-based MPC devices[13].

Nevertheless, cascaded MPCs suffer from a few complications, such as large footprint, high cost, and intricate configuration. In 2018, Lavenu *et al*. scaled the MPC technology to higher pulse energy with the noble gas as the nonlinear media[14]. The MPC device with noble gas as the nonlinear media has the potential to achieve stable and reliable spectral broadening with higher single-pass B integrals, since the self-focusing thresholds of the gases are about three orders higher than that of bulk media. It means that a higher compression ratio with single-stage gas-filled MPCs could become true. For example, nonlinear pulse compression of a Yb-doped thin disk regenerative amplifier with single-stage gas-filled MPCs and a compression ratio of 31.7 is experimentally achieved by Kaumanns *et al.*[15], and Balla *et al.* demonstrated a compression ratio of 92.3 using a two-stage cascaded gas-filled MPC[16]. Nevertheless, these devices are more suitable for the spectral broadening of high peak power lasers, such as several hundred megawatts to several gigawatts.

In this Letter, an 8 kHz $Nd:YVO_4$ picosecond laser with 12.5 ps pulse duration and 1.65 W average power is coupled into a fused-silica-based MPC device to nonlinearly compress the pulse duration. Fifty-six round trips in our MPC are experimentally achieved by employing 3 inch (1 inch = 2.54 cm). diameter CMs as the MPC mirrors. At the output, the average power and the pulse duration are 1.23 W and 601 fs, corresponding to an overall transmission of 74.5% and a compression ratio of 20.8, respectively. To the best of our knowledge, this is the highest achieved pulse compression ratio in single-stage MPCs with the bulk material as the nonlinear media. The long-term power stability and the beam quality (M^2) of the MPC device are experimentally studied. The root-mean square (RMS) of the laser power drift before and after the MPC unit is 0.61% and 0.66%, respectively, which indicates that the power fluctuation is hardly aggravated by the MPC device. Meanwhile, the beam quality (M^2) is also slightly deteriorated by the MPC device.

2. Experimental Setup

The layout of the experimental setup is shown in Fig. 1. The seed is a passively mode-locked $Nd:YVO_4$ picosecond oscillator, which delivers 2 W average power and 8.2 ps pulse duration at 68 MHz repetition rate. The central wavelength and full width at half-maximum (FWHM) bandwidth of the seed are 1064.12 nm and 0.27 nm, respectively. A thin film polarizer (TFP), Faraday rotator (FR), and half-wave plate ($\lambda/2$) form an optical isolator to prevent the laser pulse from returning to the seed. The structure of the regenerative cavity is the same as that in Ref. [17], which comprises two CMs (M1, M4), two convex mirrors (M2, M3), two TFPs (TFP3, TFP4), two dichroic mirrors (DM1, DM2), and a Pockels cell (PC). The regenerative cavity is operated at 8 kHz repetition rate. Under the pump power of 15 W, 1.65 W amplified seed power is dumped from the regenerative cavity. The bandwidth (FWHM) of the seed narrows to 0.192 nm, as shown in Fig. 2(a). The amplified pulse duration is measured to be 12.5 ps by using an intensity autocorrelator (PulseCheck-50, A. P. E. GmbH). Since the maximal

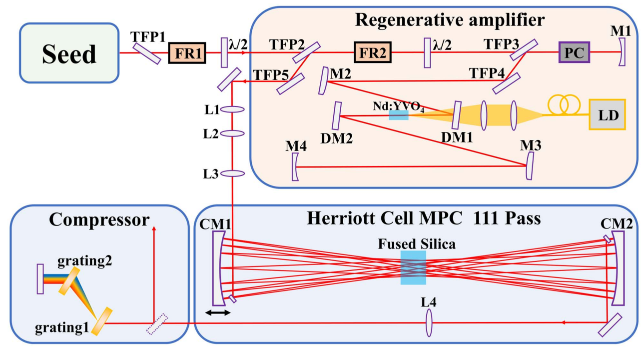

Fig. 1. Experimental setup: $Nd:YVO_4$ regenerative amplifier followed by the MPC and grating compressor. TFP1–TFP5, thin film polarizers; FR1, FR2, Faraday rotators; $\lambda/2$, half-wave plate; PC, Pockels cell; M1–M4, regenerative cavity mirrors; DM1, DM2, dichroic mirrors, with high transmission (HT) at 808 nm and HR at 1064 nm; LD, laser diode at 808 nm; L1–L4, lenses; CM1, CM2, concave mirrors.

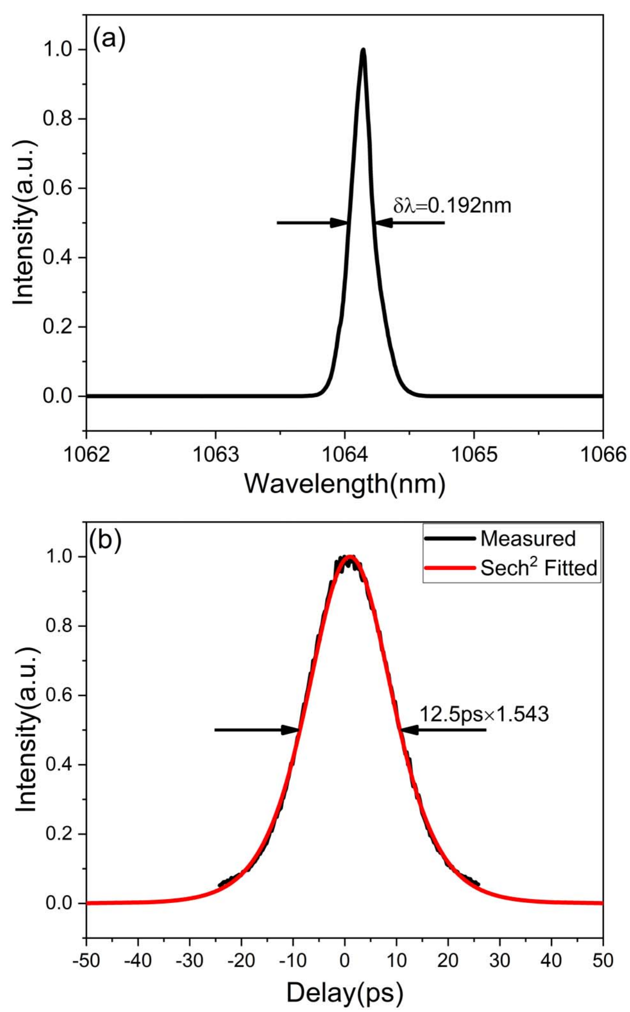

Fig. 2. Characterization of the $Nd:YVO_4$ regenerative amplifier. (a) Spectrum and (b) intensity autocorrelation trace.

delay scale of the intensity autocorrelator is ±25 ps, and the measured intensity value of the delay point ±25 ps is nonzero, a larger sech^2 fitting scale of ±50 ps is executed, as shown in Fig. 2(b). Then, the laser beam is mode matched to the Herriott type MPC with three lenses (L1, L2, L3). The MPC consists of CM1 and CM2 with 76.2 mm diameter and 300 mm radius of curvature. CM1 and CM2 are coated with high-reflection (HR) coating at 1064 nm with a reflectivity greater than 99.9%. The distance between CM1 and CM2 is set to be about 500 mm. So, the eigenmode of the MPC is calculated to be $2w_1 = 0.95$ mm and $2w_0 = 0.39$ mm on the CMs and in the waist, respectively. One piece of fused silica with 25 mm thickness and 50.8 mm diameter is placed on the waist as the nonlinear medium, and both end faces are coated with high transmission ($T > 99.9\%$) at 1064 nm. The laser pulse coupled in and out of the MPC is achieved with two plane mirrors of 3 mm width. In our experiment, 56 round trips are realized by finely tuning the distance of the unit, corresponding to the laser pulse that passes 111 times through the nonlinear media. So, the total propagating distance in the fused silica and in the air is about 2.78 m and 52.73 m, respectively. More round trips are theoretically feasible, but the coupling in/out mirrors will severely clip the laser beam. The laser beam from the MPC is collimated by the lens L4. A Treacy type compressor consisting of two 1000 line/mm transmission gratings (T-1000-1040-31.8 × 12.3-94, Lightsymth) is used for removing the chirp of the spectrally broadened pulses. This is because the required group delay dispersion (GDD) is on the order of the $10^6\ \text{fs}^2$; such a large amount of GDD is difficult to compensate using the chirped mirrors or Gires–Tournois interferometer (GTI) mirrors. The laser is incident on the gratings at a Littrow angle of 32.1°. The distance of the two gratings is set to be 215 mm, and the GDD and third-order dispersion (TOD) of the grating pair are $-1.5 \times 10^6\ \text{fs}^2$ and $4.6 \times 10^6\ \text{fs}^3$, respectively.

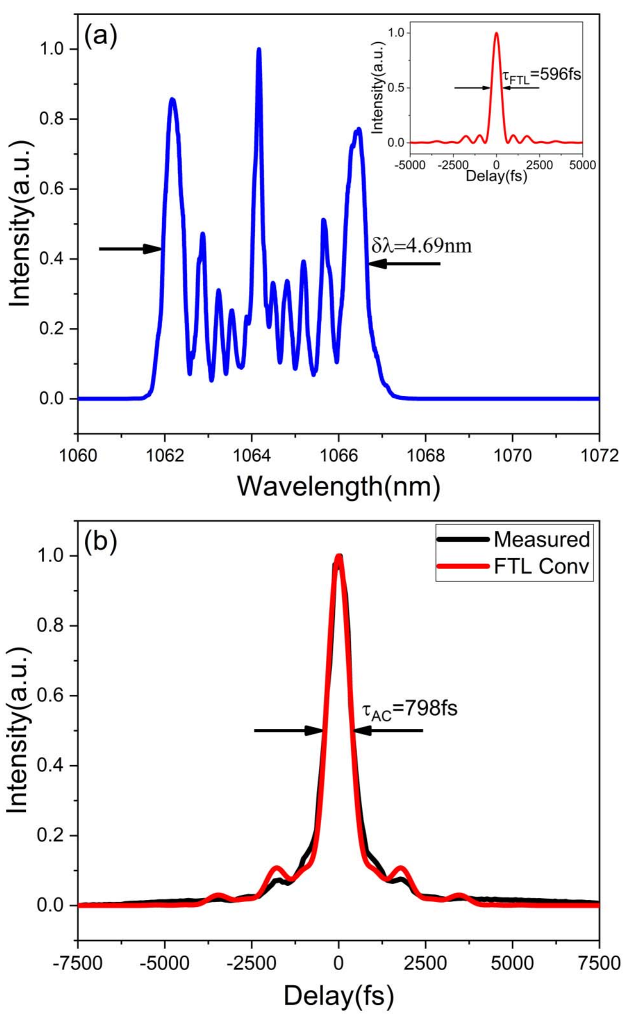

Fig. 3. Characterization of the laser pulses after the compression unit. (a) Spectrum after MPC device; inset: calculated FTL pulse duration. (b) Intensity autocorrelation trace after compressor (black) and convolution of the FTL pulse (red).

3. Experimental Results

The laser power after the lens L4 is 1.37 W when the incident power is 1.65 W, corresponding to a transmission of 83%. The loss mainly comes from the 222 passes through the end faces of the fused silica and 110 times reflection on CM1 and CM2. For example, we assume that the reflectivity of CM1 and CM2 and transmittance of the fused silica are 99.95%, and then

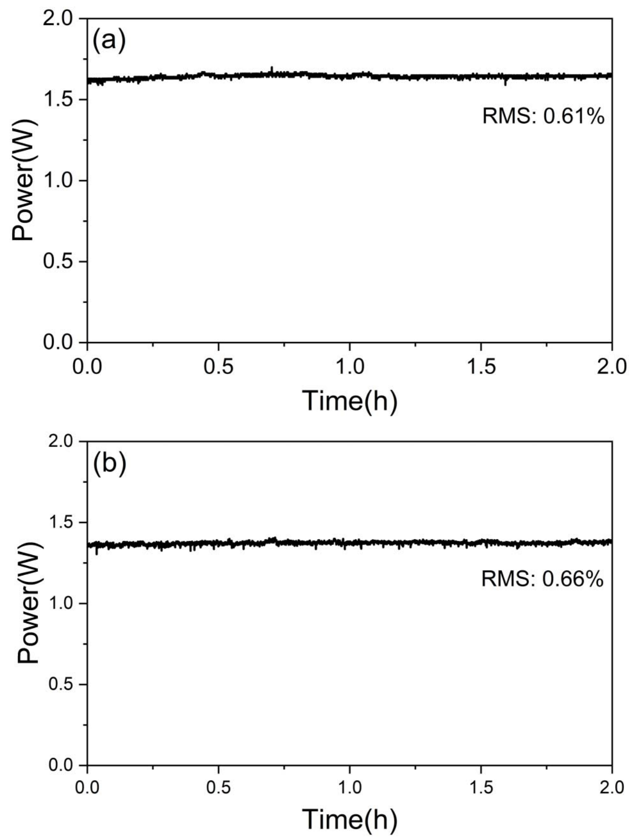

Fig. 4. Long-term power stability of the (a) $Nd:YVO_4$ picosecond laser and (b) MPC.

the transmittance can be estimated to be $0.9995^{332} = 84.7\%$. The other optical elements like lenses and coupling in/out mirrors can also result in a small loss. As the laser power decreases in the MPC device, the per-pass nonlinear phase is also gradually decreasing. The average per-pass and total nonlinear phases are estimated to be 0.1π and 11.1π (beam averaged values), respectively. Spectral broadening to 4.69 nm (half the intensity of the outer spectral maxima) is experimentally achieved, as shown in Fig. 3(a), corresponding to a spectral broadening factor of 24.2. The Fourier transform limited (FTL) pulse duration of the broadened spectrum is calculated to be 596 fs, as shown in the inset of Fig. 3(a). A shortest intensity autocorrelation trace of 798 fs is compressed, as shown in Fig. 3(b). The pulse duration of 601 fs is inferred, assuming that the deconvolution factor of the compressed pulses is the same as the FTL pulses (0.753). So, the pulse duration compressed by a factor of 20.8 is deduced. The laser power after the grating compressor is 1.23 W, corresponding to a transmission of 89.8%. The total transmission of the compression device is calculated to be 74.5%.

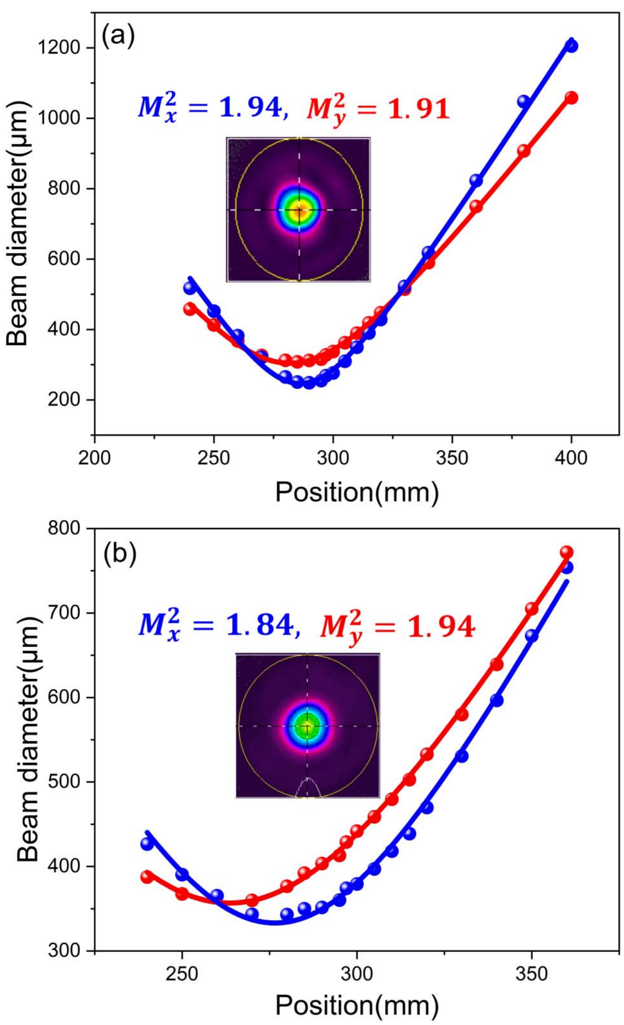

Fig. 5. Beam quality (M^2) (a) before and (b) after the MPC device.

The long-term power stability is measured, as shown in Fig. 4. Within 2 h, one measurement point is recorded per second, and the RMS stability before and after the MPC is 0.61% and 0.66%, respectively, which indicates that the laser power drift is little affected by the spectral broadening process.

The beam quality (M^2) before and after MPC is measured to be 1.94×1.91 and 1.84×1.94, respectively, as shown in Fig. 5. It is observed that the beam quality is hardly deteriorated by the MPC device. At the same time, it is also proved that the MPC device has a lower requirement for the beam quality of the incident laser.

4. Conclusion

In summary, the spectral bandwidth of an 8 kHz $Nd:YVO_4$ picosecond laser is broadened from 0.192 nm to 4.64 nm by using a fused-silica-based MPC device, corresponding to a spectral broadening factor of 24.2. Meanwhile, the pulse duration is compressed from 12.5 ps to 601 fs, corresponding to a pulse shorting factor of 20.8. After the compressor unit, the pulse energy is 154 μJ. Such a laser source has the potential to be applied in many scientific and industrial fields like nonlinear optics and welding processes.

Acknowledgement

This work was supported by the Strategic Priority Research Program of CAS (No. XDB16030200), the National Natural Science Foundation of China (Nos. 91850209 and 11774410), and the Key-Area Research and Development Program of Guangdong Province (No. 2018B090904003).

References

1. B. Le Drogoff, F. Vidal, S. Laville, M. Chaker, T. Johnston, O. Barthelemy, J. Margot, and M. Sabsabi, "Laser-ablated volume and depth as a function of pulse duration in aluminum targets," Appl. Opt. **44**, 278 (2005).
2. M. Liebel, C. Schnedermann, T. Wende, and P. Kukura, "Principles and applications of broadband impulsive vibrational spectroscopy," J. Phys. Chem. A **119**, 9506 (2015).
3. I. B. Mukhin, M. R. Volkov, I. A. Vikulov, E. A. Perevezentsev, and O. V. Palashov, "Ytterbium laser system for studying parametric amplification of femtosecond pulses with a centre wavelength of similar to 2 μm," Quantum Electron. **50**, 321 (2020).
4. D. Yan, B. Liu, Y. Chu, H. Song, L. Chai, M. Hu, and C. Wang, "Hybrid femtosecond laser system based on a Yb:KGW regenerative amplifier for NP polarization," Chin. Opt. Lett. **17**, 041404 (2019).
5. H. Liu, G. Wang, J. Jiang, W. Tian, D. Zhang, H. Han, S. Fang, J. Zhu, and Z. Wei, "Sub-10-fs pulse generation from a blue laser-diode-pumped Ti:sapphire oscillator," Chin. Opt. Lett. **18**, 071402 (2020).
6. Y. M. Ma, F. Meng, Y. Wang, A. Wang, and Z. Zhang, "High contrast linking six lasers to a 1 GHz Yb:fiber laser frequency comb," Chin. Opt. Lett. **17**, 041402 (2019).
7. F. Emaury, C. J. Saraceno, B. Debord, D. Ghosh, A. Diebold, F. Gerome, T. Sudmeyer, F. Benabid, and U. Keller, "Efficient spectral broadening in the 100-W average power regime using gas-filled kagome HC-PCF and pulse compression," Opt. Lett. **39**, 6843 (2014).
8. S. Hadrich, M. Krebs, A. Hoffmann, A. Klenke, J. Rothhardt, J. Limpert, and A. Tunnermann, "Exploring new avenues in high repetition rate table-top coherent extreme ultraviolet sources," Light-Sci. Appl. **4**, e320 (2015).

9. J. Schulte, T. Sartorius, J. Weitenberg, A. Vernaleken, and P. Russbueldt, "Nonlinear pulse compression in a multi-pass cell," Opt. Lett. **41**, 4511 (2016).
10. M. Hanna, X. Delen, L. Lavenu, F. Guichard, Y. Zaouter, F. Druon, and P. Georges, "Nonlinear temporal compression in multipass cells: theory," J. Opt. Soc. Am. B **34**, 1340 (2017).
11. J. Weitenberg, A. Vernaleken, J. Schulte, A. Ozawa, T. Sartorius, V. Pervak, H. D. Hoffmann, T. Udem, P. Russbuldt, and T. W. Hansch, "Multi-pass-cell-based nonlinear pulse compression to 115 fs at 7.5 μJ pulse energy and 300 W average power," Opt. Express **25**, 20502 (2017).
12. K. Fritsch, M. Poetzlberger, V. Pervak, J. Brons, and O. Pronin, "All-solid-state multipass spectral broadening to sub-20 fs," Opt. Lett. **43**, 4643 (2018).
13. E. Vicentini, Y. C. Wang, D. Gatti, A. Gambetta, P. Laporta, G. Galzerano, K. Curtis, K. McEwan, C. R. Howle, and N. Coluccelli, "Nonlinear pulse compression to 22 fs at 15.6 μJ by an all-solid-state multipass approach," Opt. Express **28**, 4541 (2020).
14. L. Lavenu, M. Natile, F. Guichard, Y. Zaouter, X. Delen, M. Hanna, E. Mottay, and P. Georges, "Nonlinear pulse compression based on a gas-filled multipass cell," Opt. Lett. **43**, 2252 (2018).
15. M. Kaumanns, V. Pervak, D. Kormin, V. Leshchenko, A. Kessel, M. Ueffing, Y. Chen, and T. Nubbemeyer, "Multipass spectral broadening of 18 mJ pulses compressible from 1.3 ps to 41 fs," Opt. Lett. **43**, 5877 (2018).
16. P. Balla, A. B. Wahid, I. Sytcevich, C. Guo, A. L. Viotti, L. Silletti, A. Cartella, S. Alisauskas, H. Tavakol, U. Grosse-Wortmann, A. Schonberg, M. Seidel, A. Trabattoni, B. Manschwetus, T. Lang, F. Calegari, A. Couairon, A. L'Huillier, C. L. Arnold, I. Hartl, and C. M. Heyl, "Postcompression of picosecond pulses into the few-cycle regime," Opt. Lett. **45**, 2572 (2020).
17. J. X. Liu, W. Wang, Z. H. Wang, Z. G. Lv, Z. Y. Zhang, and Z. Y. Wei, "Diode-pumped high energy and high average power all-solid-state picosecond amplifier systems," Appl. Sci. Basel **5**, 1590 (2015).