High average power nonlinear self-compression to few-cycle pulses at 2 µm wavelength in antiresonant hollow-core fiber

Martin Gebhardt,[1,2*] Christian Gaida,[1] Fabian Stutzki,[1+] Cesar Jauregui,[1] Jose Antonio-Lopez,[4] Axel Schulzgen,[4] Rodrigo Amezcua-Correa,[4] Jens Limpert,[1,2,3] and Andreas Tünnermann[1,2,3]

1 Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany
2 Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
3 Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany
4. CREOL, College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA
**martin.gebhardt@uni-jena.de*
+ Now Fraunhofer Institute for Applied Optics and Precision Engineering

Abstract: We present the nonlinear self-compression of pulses from a high repetition rate thulium-doped fiber laser system using a gas-filled antiresonant hollow-core fiber. Sub-3-cycle pulses with several GW peak power at 21.4 W of average power have been generated.
OCIS codes: (140.3070) IR and far-IR lasers; (320.5520) Pulse compression; (340.7480) X-rays, soft x-rays, (EUV)

1. Introduction

Ultrafast laser sources emitting at around 2 µm wavelength have become important tools for scientific research in various fields including spectroscopy, materials processing or the investigation of strong-field light matter interactions [1]. Pushing such laser systems to shorter and shorter pulse durations as well as scaling their output power is especially interesting regarding their potential for nonlinear frequency conversion into spectral regions that are not easily accessible with direct laser emission. One of the most popular examples is the efficient generation of phase-matched high-order harmonics [2] providing high photon flux within and beyond the water-window (280 eV – 530 eV). A significant increase of the available brightness from coherent sources within this spectral region is of paramount interest for subsequent applications like nanometer-scale imaging and/or X-ray spectroscopy. With respect to an optimized conversion efficiency and photon-energy cut-off it is particularly important to drive the HHG-process with few-cycle pulses, which allows for high intensities in the interaction region without spoiling the phase-matching by ionization. Additionally, a few-cycle driver directly enables the generation of isolated attosecond pulses [3] opening up numerous applications with extreme temporal resolution. Hence, there is a strong application-driven demand for 2 µm laser systems delivering intense few-cycle pulses at high average power.

Few-cycle 2 µm laser sources are also extremely interesting for other research activities such as covering the molecular-fingerprint region with ultra-broadband frequency combs via intra-pulse frequency down-conversion. High power, phase stable pulses in the mid-infrared find important applications in the spectroscopy of trace gases and enable ultra-high sensitivity [4]. Starting from the 2 µm wavelength region is very beneficial for generating these pulses as most nonlinear crystals with high nonlinearity and broad mid-IR transmission absorb in the near-IR.

Thulium-doped fiber laser systems represent a promising concept for the generation of high average power ultrashort pulses around 2 µm wavelength. Thulium-doped silica offers a broad amplification bandwidth within 1700-2000 nm and it can be pumped by commercially available high power diode lasers. As a result, today's thulium-doped fiber laser systems deliver average powers beyond 100 W in ultrafast operation and the peak power record is about 2 GW with 200 fs pulses and substantial power scaling prospects [5, 6]. Furthermore, it has recently been demonstrated that nonlinear pulse compression in gas-filled waveguides is a promising approach to further decrease the pulse durations and push the pulse peak powers, which are achieved with such laser systems [7]. However, the few-cycle regime at 2 µm wavelength has so far only been reached by nonlinear pulse compression starting from optical parametric amplifiers with watt-level average power [8, 9] or with energies limited to about 1 µJ due to self-focusing in a solid-core fiber [10].

In this contribution we demonstrate pulse shortening of an ultrafast thulium-doped fiber laser down to the few-cycle regime using a single stage nonlinear compressor. This way, GW-class pulses with only 14.6 fs (FWHM) duration at unpreceded average power have been achieved. The key features of the experiment presented herein are the broad gain bandwidth offered by the active medium in the first place, allowing for 110 fs pulses directly from the laser, and a gas-filled antiresonant hollow-core fiber (ARHCF) with excellent transmission and weak anomalous dispersion, leading to self-compression of the pulses.

2. Experimental Setup and Results

The experimental setup can be seen in Fig. 1a. The nonlinear pulse compression stage was driven by a thulium-doped fiber chirped-pulse amplification system (Tm:FCPA) with about 140 nm bandwidth around 1920 nm. The system architecture was similar to the one described in Ref. [6]. For the experiments presented herein, the laser delivered 110 fs (FWHM) pulses with up to 28 W of average power at a repetition rate of 392 kHz. Fig. 2 depicts the pulse spectrum (a) and intensity-autocorrelation (b) at this performance level prior the ARHCF as represented by the red line. The ultrashort pulses from the Tm:FCPA were coupled into a 42 cm long ARHCF (53 µm inner diameter), which was differentially pumped using about 3 bars of argon gas. A cross-section of the hollow-fiber is depicted in Fig. 1b. It was optimized for operation in the 2 µm wavelength region allowing for >90% transmission.

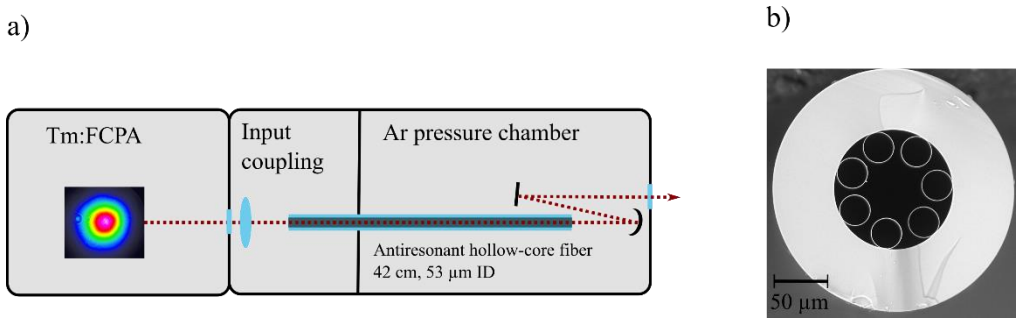

Fig. 1: Schematic of the nonlinear pulse compression setup (a) and cross-section of the antiresonant hollow-core fiber (b).

The pulse propagation along the fiber was governed by significant self-phase modulation (SPM) and spectral broadening. At the same time the pulse duration was shortened resulting from the anomalous waveguide dispersion in the 2 µm wavelength regime, which compensated for the SPM-induced temporal chirp. Clearly, since the pulse peak power increased along the fiber the effect of spectral broadening could be significantly enhanced leading to more than 800 nm bandwidth (at -20 dB) at the fiber output. The broadened pulse spectrum is depicted in Fig. 2a (green line). We have chosen the experimental conditions in a way such that the shortest pulses were obtained after propagation through the 1 mm thick fused silica window at the exit of the pressure chamber. The measured intensity-autocorrelation at this point can be seen in Fig. 2b. It had a FWHM duration of 20 fs. Comparing this measurement to the autocorrelation of the input pulses reveals the strong temporal compression achieved in this experiment. The central wavelength of the broadened spectrum was around 1810 nm. Assuming a deconvolution factor of 1.37 as derived from the transform limit of the pulse spectrum the pulse duration was estimated to 14.6 fs, which corresponds to less than 2.5 optical cycles.

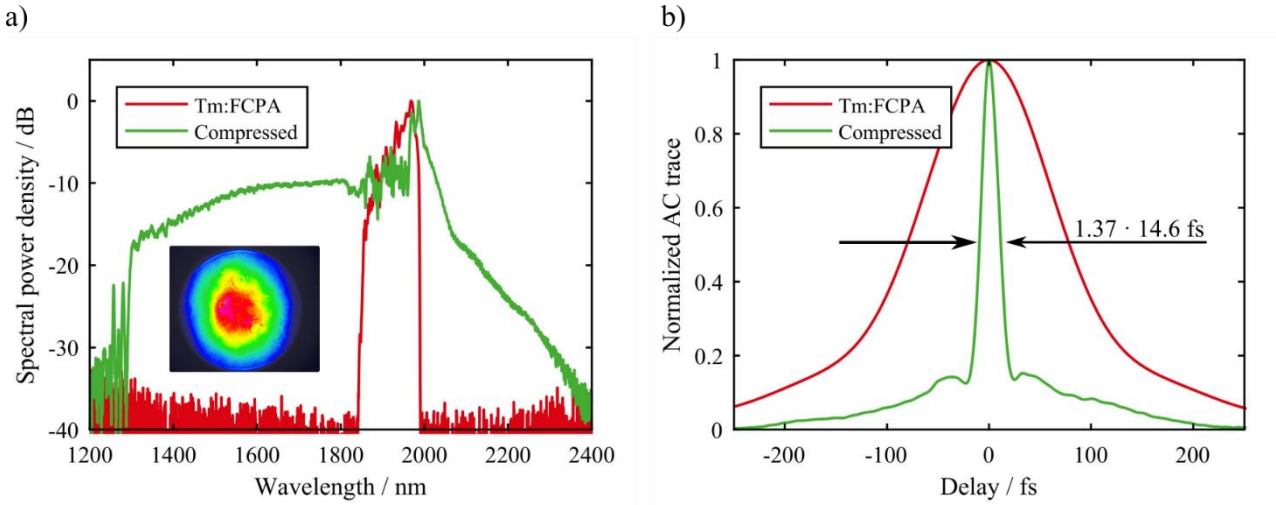

Fig. 2: a) Measured pulse spectra before (red line) and after (green line) the nonlinear compression stage. Inset: Measured intensity profile of the collimated beam. b) Measured autocorrelation of the input and of the compressed pulses.

The compressed average power was measured to 21.4 W, hence the compressed pulse energy was 55 µJ at 392 kHz repetition rate. The transmission through the nonlinear compressor slightly degraded at this energy level due to the onset of ionization effects. As supported by a numerical simulation of the pulse evolution along the ARHCF we estimated the pulse peak power to >2 GW, making the laser system presented herein an attractive and simple source for driving strong-field experiments at high repetition rate. When looking at the short wavelength edge of the broadened output spectrum a sharp drop in spectral power density becomes apparent at around 1300 nm. This behavior is associated with the end of the fiber transmission window, meaning that optimized fiber parameter will readily enable even shorter pulses with the potential to address the single-cycle regime [9] at record average power.

3. Conclusion and Outlook

To the best of our knowledge, we have presented the first 2 µm laser source delivering intense, GW-class few-cycle pulses at an average power beyond the 20 W-level. This performance was enabled by nonlinear compression of pulses from a high-repetition rate ultrafast thulium-doped fiber laser system, i.e. an average power scalable laser concept. The laser system used in this experiment delivered 110 fs pulses. In fact, it can be expected that these pulse durations will further decrease as the spectral bandwidth of our laser system was only limited by the transmission of optical elements. This potential as well as an optimization of the ARHCF transmission window will lead to the generation of high-contrast sub-2-cycle pulses with several GW of peak power.

In the experiment presented herein, we used an antiresonant hollow-core fiber for nonlinear compression in the 2 µm wavelength region for the first time. We have shown that these fibers are well-suited for nonlinear pulse compression around 2 µm wavelength and that this concept features excellent average power handling capabilities. In order to fully exploit the pulse energy and average power levels, which are available from today's thulium-doped fiber laser systems, our future work will concentrate on optimizing the ARHCF parameter as well as the gas filling concepts. This way, a 100 W-class laser source with intense few-cycle pulses and mJ-level energies at 2 µm wavelength is feasible in the near future. Such a laser system is extremely interesting for increasing the available photon-flux within the water-window via HHG or generating high power mid-IR frequency combs.

We acknowledge funding by the BMBF (13N13973), the ARO (W911NF-12-1-0450) and the AFOSR (FA9550- 15-10041).

4. References

[1] H. Pires, M. Baudisch, D. Sanchez, M. Hemmer, J. Biegert, Progress in Quantum Electronics, 43 (2015) 1–30
[2] S. L. Cousin, F. Silva, S. Teichmann, M. Hemmer, B. Buades, and J. Biegert, Opt. Lett. 39, 5383-5386 (2014)
[3] F. Silva, S. M. Teichmann, S. L. Cousin, M. Hemmer, and J. Biegert, Nature Photonics 6.11 6611 (2015)
[4] I. Pupeza et al. Nature Photonics 9.11 (2015): 721-724
[5] F. Stutzki, C. Gaida, M. Gebhardt, F. Jansen, A. Wienke, U. Zeitner, F. Fuchs, C. Jauregui, D. Wandt, D. Kracht, J. Limpert, and A. Tünnermann, Opt. Lett. 39, 4671-4674 (2014)
[6] C. Gaida, M. Gebhardt, F. Stutzki, C. Jauregui, J. Limpert, and A. Tünnermann, Opt. Lett. 41, 4130-4133 (2016)
[7] M. Gebhardt, C. Gaida, F. Stutzki, S. Hädrich, C. Jauregui, J. Limpert, and A. Tünnermann, Opt. Lett. 42, 747-750 (2017)
[8] V. Cardin, N. Thiré, S. Beaulieu, V. Wanie, F. Légaré, B. E. Schmidt, Applied Physics Letters 107, 181101 (2015)
[9] T. Balciunas, C. Fourcade-Dutin, G. Fan, T. Witting, A. A. Voronin, A. M. Zheltikov, F. Gerome, G. G. Paulus, A. Baltuska, and F. Benabid, Nat. Commun. 6, 6117 (2015).
[10] C. Gaida, M. Gebhardt, F. Stutzki, C. Jauregui, J. Limpert, and A. Tünnermann, Opt. Lett. 40, 5160-5163 (2015)