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Pulse Fidelity Control in a 20-μJ Sub-200-fs Monolithic Yb-Fiber Amplifier[1]

A. Fernández[a, *], L. Zhu[a], A. J. Verhoef[a], D. Sidorov-Biryukov[a, b], A. Pugzlys[a], A. Galvanauskas[c], F. Ö. Ilday[d], and A. Baltuška[a]

[a] *Institut für Photonik, Technische Universität Wien, Gusshausstrasse 27-29/387, 1040 Wien, Austria*
[b] *International Laser Center, Moscow State University, Moscow, 119992 Russia*
[c] *Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099, USA*
[d] *Department of Physics, Bilkent University, Cankaya, Ankara 06800, Turkey*
*e-mail: almadelc@mail.tuwien.ac.at
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Abstract—We discuss nonlinearity management versus energy scalability and compressibility in a three-stage monolithic 100-kHz repetition rate Yb-fiber amplifier designed as a driver source for the generation and tunable parametric amplification of a carrier-envelope phase stable white-light supercontinuum.

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1. INTRODUCTION

Compact and environmentally stable high-energy ultrashort-pulse laser sources have many applications. Examples include biomedical applications (e.g., ophthalmology, biomedical imaging), laser micromachining, index modification in transparent materials (waveguide writing), and frequency conversion. Fiber lasers offer big practical advantages over bulk solid-state laser systems. In terms of flexibility, compactness, reliability, cost effectiveness and turn-key operability, a fiber-based laser system is the preferred laser architecture. Moreover, thermal effects are reduced because fibers have a large surface to volume ratio and the waveguiding properties of fibers ensure good spatial mode quality. With the light guided in a fiber the system is less sensitive to misalignment but this great advantage of fiber laser has not yet been fully exploited and a considerable amount of free standing elements (grating stretcher, in-coupling optics), are commonly used. Parametric amplification is a powerful technique that has been used to achieve wavelength tunability outside the gain bandwidths of optical fiber amplifiers as well as to shorten the pulses generated directly from fiber amplifiers below 10 fs [1, 2]. For many applications in high field physics and attosecond science carrier envelope-phase (CEP) stable pulses are required. Ytterbium doped fiber amplifiers (YDFA) are very attractive scalable sources for seeding and pumping of CEP-stable difference frequency generation (DFG) optical parametric amplifiers (OPAs) [3, 4]. Generation of temporally compressible white light in bulk media for OPA seeding, requires high-fidelity sub-200-fs pulses to minimize the impact of non-instantaneous (e.g., Raman) nonlinearities [5]. Due to a large amount of higher-order linear and nonlinear dispersion [6–8], such pulses are difficult to obtain from YDFA, prompting the use of solid-state lasers for driving OPAs. Yb-doped fibers support broader bandwidths than their crystalline counterparts and using the scheme of chirped-pulse amplification (CPA) in combination with the use of large core specialty fibers YDFA delivering tens and even hundreds of micro-Joules have been demonstrated [9–11]. Realization of these systems requires a considerable amount of free standing components which is detrimental for system stability. Replacing the free-space stretcher optics by a fiber-stretcher is of key importance for achieving a robust turn-key alignment-free design. Compression of up to 100 m of single mode fiber (SMF) using a pair gratings has been demonstrated, in an approach that exploits compensation of self-phase modulation by third-order dispersion and it is known a nonlinear CPA (NLCPA) [9]. In another approach by the same group, better pulse compressibility was achieved by using a grism compressor instead of a grating compressor [12]. Although those systems used a fiber stretcher, the active media of the system were based on specialty fibers therefore such a setup still required a considerable amount of free space in-coupling optics. Recently a monolithic fiber amplifier delivering 170 fs pulses at ~4 μJ of pulse energy was reported. This system is based on the so called NLCPA and although short pulses are obtained, the pulse fidelity is strongly degraded with a considerably portion of the pulse energy in the pulse pedestal [13]. In many applications polarization maintaining (PM) fibers are required and therefore there is a lot of interest not only in having a monolithic fiber architecture but an environmentally stable linearly polarized system as well [14]. We have previously demonstrated a monolithic PM-YDFA that delivers sub-200-fs high fidelity pulses with energies of up to 9 μJ [4]. In this work we followed a differ-

[1] The article is published in the original.

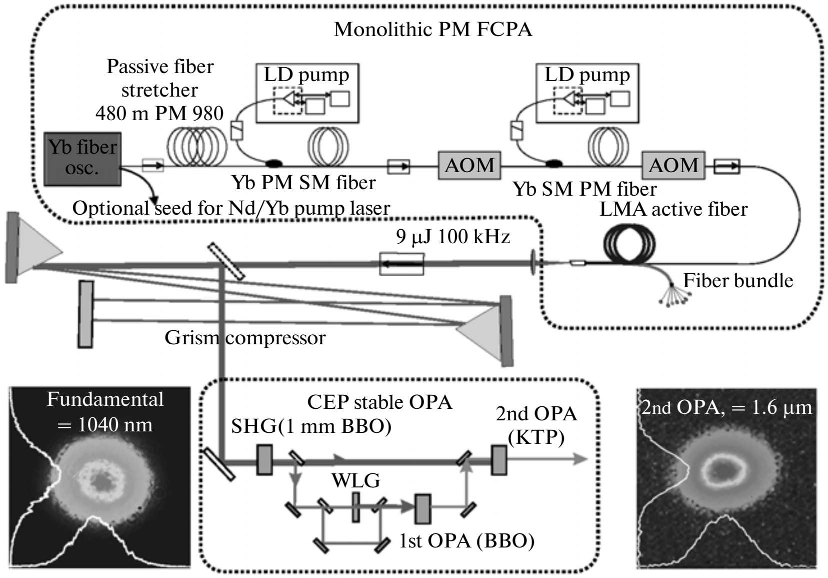

Fig. 1. Experimental layout of the monolithic fiber CPA and DFG OPA (for details see text). In the lower part far-field mode profiles of the FCPA output (left) and CEP-stable output of DFG OPA (right) are presented.

ent approach in which the amount of nonlinearities in the system are kept low. The pulses were stretched in ~480 m of PM SMF and re-compressed with a pair of grisms. Here we discuss in detail key design parameters that have to be taken in consideration for designing a high fidelity sub-200-fs monolithic YDFA and present an improved system that delivers up to 21 μJ with a dechirped pulse duration of ~187 fs.

2. EXPERIMENTAL SETUPS AND DISCUSSION

Two different experimental setups for the YDFA were investigated and will be discussed in detailed in this section. The experimental layout of the first YDFA system is shown in Fig. 1. Note that in the same figure we also show the layout of a type II collinear CEP stable OPA which will be discussed in detailed later on in this section. The YDFA system consists of a fiber oscillator, a stetcher unit consisting of ~480 m of PM SMF, two PM SMF preamplifiers and a PM large mode area (LMA) fiber amplifier. In order to keep nonlinearities low, in both preamplifiers 1.5 m of highly Yb-doped PM SMF from Nufern (PM-YDF-HI) is used as an active medium. After the first amplification stage a fiber pigtailed acousto-optic modulator (AOM) was used to reduce the repetition rate to 100 kHz. Another fiber pigtailed AOM was used after the second amplification stage to suppress amplified spontaneous emission. Via a tapered fiber, the preamplified pulses are launched into the final LMA fiber amplifier. This last amplification stage consists of 3 m of Yb-doped PM LMA double clad fiber (PLMA-YDF-30/250 from Nufern) and a seed-pump combiner (PASA-YD-30/250-7 × 1 from Nufern). The LMA has a core diameter of 30 μm, corresponding to a mode field diameter of ~625 μm^2. The output is taken after a free space isolator with a transmission of ~90%. The far field beam profile of the monolithic fiber CPA output is shown in the left inset of Fig. 1.

In order to find the optimal working conditions for the preamplifier stages the accumulated spectral phase of the pulse after the stretcher, and after each of the first two PM SMF preamplifier stages was measured using second harmonic generation frequency resolved optical gating (SHG FROG). The pulses were compressed in a negative dispersion compressor based on a pair of grisms, each being an assembly of an F2 glass prism and a 1480 lines/mm reflection grating. The compressor efficiency is ~45%. The same measurements were performed for two different oscillator types: an all normal dispersion fiber (ANDi) oscillator as described in [15] and a similariton type fiber oscillator. No significant spectral phase distortion was observed after the stretcher and the first amplification stage. Spectral phase distortions start to be relevant after the second amplification stage.

The measured spectral phases for different output energy levels after the second amplification stage are shown in Figs. 2a and 2b for the ANDi oscillator and the similariton-type oscillator respectively. It can be seen that with increasing intensity the spectral region where the spectral phase remains approximately flat decreases due to bending of the phase at the edges of the spectrum. This effect is more pronounced on the shorter wavelength side of the spectrum, which may be due to enhanced self phase modulation in the presence