Optics and Laser Technology 100 (2018) 282–285

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

High power all-polarization-maintaining photonic crystal fiber monolithic femtosecond nonlinear chirped-pulse amplifier

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ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form 17 September 2017
Accepted 21 October 2017

Keywords:
Photonic crystal fiber
Nonlinear chirped-pulse amplifier
All-fiber

ABSTRACT

We report on an experimental study on fully fusion spliced high power all-polarization-maintaining Yb-doped photonic crystal fiber (PCF) femtosecond nonlinear chirped-pulse amplifier (CPA), which features large values of the positive third-order dispersion (TOD) superposed from the single-mode fiber stretcher (SMFs) and grating-pair compressor. Compensation of the TOD is realized by means of self-phase modulation (SPM) induced nonlinear phase shift during amplification. Up to 9.8 W of compressed average power at 275 kHz repetition rates with 36 μJ pulse energy and 495 fs pulse width has been obtained. To the best of our knowledge, this is the highest output power generated from the strictly all-fiber nonlinear CPA amplifier in femtosecond domain, which provides a possibility for the industrialized promotion and development of the high energy femtosecond fiber laser.

1. Introduction

With the development of the laser science, femtosecond laser sources with high average power and high pulse energy have been rapidly developed and attracted great interests in fundamental science and application areas ranging from strong-field physics [1] and attosecond science [2] to aerospace and automotive fields. In precision manufacturing, ultrashort pulse lasers can break through the constraints and overcome the adverse effects caused by conventional mechanical processing methods, but also provide an effective solution for manufacturing bottlenecks in the fragile materials. To obtain high power and high energy ultrashort pulse laser output, various laser amplification techniques have been proposed in different wavelength regimes (1 μm, 1.5 μm), such as CPA technology [3], divided-pulse amplification technology [4–6], enhancement cavity technology [7], and coherent pulse addition technology [8]. As a mainstream technology, CPA is an effective solution to realize the impressive power and energy output. The core concept is stretching the seed pulse duration to a certain value through diffractive elements before amplification and then compressing the amplified laser pulses via compensation device with opposite dispersion in equal amount. Generally, apart from the matched second-order dispersion, high-order dispersion mismatch between stretcher and compressor should be brought down to zero so as to obtain transform-limited pulse duration. Hence, bulk grating based stretcher with large pulse stretching ratio is frequently-used and contributes to realize the desired fiber laser power output [9,10]. However, the size and alignment sensitivity restrict its use in industrial environment with vibration and dramatically temperature and humidity fluctuation. Consequently, with the increasing requirements for stability and reliability, all-fiber integrated CPA amplifiers are highlighted.

The above mentioned CPA amplifiers belong to the class of lasers based on linear amplification, namely the allowable accumulated nonlinear phase shift is less than π and operating beyond this value will rapidly result in uncompressed distorted pulse duration. In contrast, nonlinear CPA amplification as a new force has been widely studied in the last few years [11–17], which intrinsically differs from the linear CPA and allows large levels of SPM-induced nonlinear phase shift accumulation during amplification, and subsequently compensated by the significant TOD mismatch. The detailed theoretical analysis was presented based on the nonlinear Schrödinger equations by Zhou et al., and experimental study on the expected compensation of the TOD by SPM-induced nonlinear phase shift was also demonstrated [18]. In nonlinear CPA scheme, the SMF stretcher with normal TOD provides a cost-effective solution to construct industrialized integrated fiber laser architecture without compromising the output pulse energy. By 2005, Lawrence Shah et al. had reported a 50 kHz Yb-doped cubicon fiber amplifier, which produced 100 μJ compressed pulse energy with pulse duration of 650 fs [11]. In 2007, Lyuba Kuznetsova et al. obtained a 150 kHz PCF amplifier, which generated 30

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https://doi.org/10.1016/j.optlastec.2017.10.017
0030-3992/

μJ pulses with 240 fs compressible duration [12]. In 2013, Želudevičius reported a Yb-doped chirally-coupled-core (CCC) fiber based 50 μJ high energy laser system in 400 fs duration at a repetition rate of 100 kHz [13]. In 2014, Zeng et al. reported on the generation of up to 80 W average power in Yb-doped PCF laser with pulse duration as short as 38 fs at a repetition rate of 60 MHz [14]. In 2015, Chang et al. demonstrated a rod-type Yb-fiber nonlinear amplifier with 100 W output power at a repetition rate of 75 MHz [15]. Recently, 24 fs, 1 μJ fiber laser has also been demonstrated based on a hybrid amplification scheme at 1 MHz repetition rates [16]. Something in common is that in Ref. [11–16], the principle scheme all adopted free-space coupled large-mode-area double-clad Yb fibers as gain media to realize the high power and high energy output with the shortest pulse duration. However, the introduced bulk optics degrades the performance of the laser system and negates the unique advantages of the fiber amplifier, which restricts its mass industrial applications. An entirely fiber-integrated nonlinear CPA amplifier was demonstrated at 1 MHz repetition rates by H. Kalaycioglu et al., in which the highest 4 μJ energy was obtained with 170-fs-long pulse duration [17]. However, due to the relatively smaller mode-area in 20 μm core diameter double-clad Yb-doped fiber, the larger nonlinear phase accumulation during amplification limited the compressibility of the pulse and scalability of the pulse energy.

In this paper, we report on an all-fiber integrated nonlinear CPA amplifier, in which large-mode-area PCF is fusing spliced other than the previous fiber lasers, which employed free space coupling in the amplifying chain [9–14], and up to 9.8 W of compressed average power and 36 μJ pulse energy with 495 fs pulse duration at a repetition rate of 275 kHz have been realized. Effectively femtosecond pulse compression depends on the compensation between SPM-induced nonlinear phase shift and TOD introduced by SMF stretcher and grating-pair compressor during amplification and further power scaling is severely limited with the occurrence of the stimulated Raman scattering under the state of the current technical parameters.

2. Experiment setup

The fully fusion spliced high power all-polarization-maintaining Yb-doped PCF femtosecond nonlinear CPA amplifier is schematically shown in Fig. 1. The amplifier mainly consists of a polarization-maintaining pigtailed seed source, a fiber stretcher, an AOM, a core-pumped power amplifier, a cladding-pumped energy amplifier and a fusion spliced large-mode-area PCF amplifier as well as a transmission grating-pair compressor. For SMFs used in experiment, the group-velocity dispersion (GVD) is estimated to be ~23 fs^2/mm and the TOD is ~70 fs^3/mm. A SESAM passively mode-locked dispersion management Yb fiber oscillator is used as seed source with 1030.8 nm center wavelength at a repetition rate of 40 MHz with 291 fs compressible pulse duration. Fig. 2 shows the mode-locked output spectrum.

Before reducing the repetition rate to 275 kHz, the stretched pulses are firstly amplified up to 210 mW average power by a single-mode power amplifier. After the AOM, two-stage energy amplifiers are employed to boost the output energy to a desired level. The first-stage cladding-pumped energy amplifier, which has 10 μm gain core diameter and 125 μm cladding diameter, ensures the sufficient seeding power for the second-stage fusion spliced PCF energy amplifier. The fusion spliced PCF energy amplifier mainly consists of a $(2+1)*1$ pump-signal combiner and a single piece of large-mode-area PCF with 40 μm core diameter and 200 μm cladding diameter. The combiner has 20 μm signal core diameter and 130 μm pump cladding diameter for both signal coupling input and output ports. To obtain the high quality splicing between combiner and PCF, the parameters of the fusion splicer need to be carefully optimized, such as discharging current strength, discharging duration, overlap-length and electrode center offset. In experiment, except for the insertion losses of ~50% caused by the fusion spliced connection between combiner and PCF, the other fusion losses are very low (0.01 dB). Although the mode mismatch between combiner and PCF degrades the coupling efficiency, it has no effect on the following amplification process and the strength of the fusion is also very good. The output pulses from the nonlinear CPA amplifier are finally compressed through a

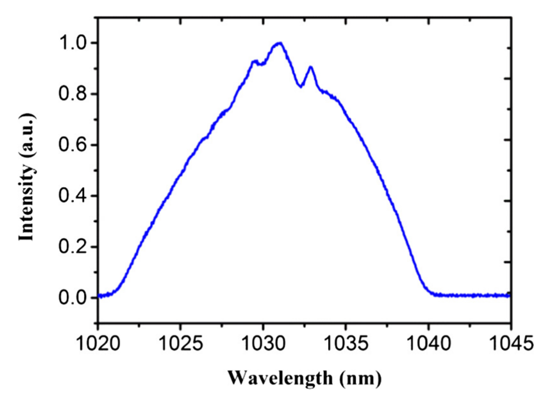

Fig. 2. Mode-locked output spectrum.

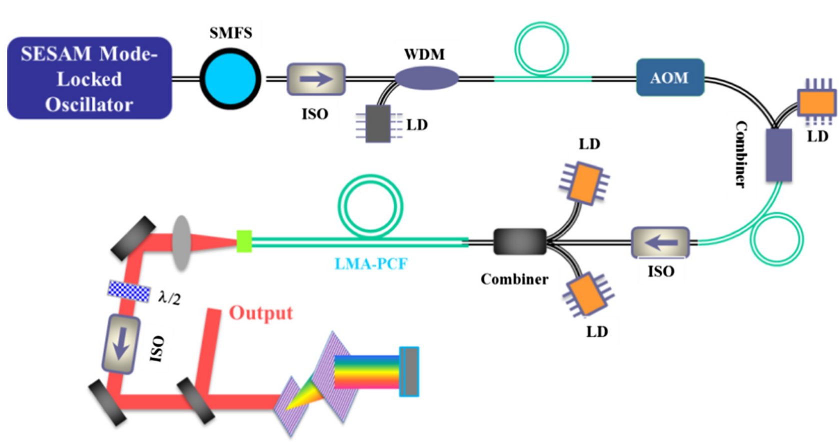

Fig. 1. Schematic of the fully fusion spliced PCF nonlinear CPA amplifier. SMFs: polarization-maintaining single-mode fiber stretcher; ISO: polarization-dependent isolator; WDM: wavelength-division multiplexer; AOM: acousto-optic modulator; LMA-PCF: large-mode-area photonic crystal fiber; λ/2: half-wave plate; LD: laser diode.