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Feng Li
Zhi Yang
Wei Zhao
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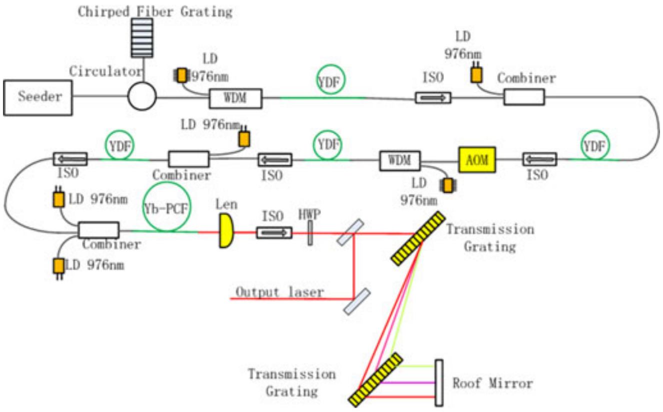
Yishan Wang



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50 μJ Femtosecond Laser System Based on Strictly All-Fiber CPA Structure

Feng Li,[1,2,3] **Zhi Yang,**[1] **Wei Zhao,**[1,3] **Qianglong Li,**[1] **Xin Zhang,**[1,2]
Xiaojun Yang,[1] **Wei Zhang,**[1] **and Yishan Wang**[1,3]

[1]State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and
Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Collaborative Innovation Center of Extreme Optics, Shanxi University,
Taiyuan 030006, China

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Abstract: We demonstrate a strictly all-polarization maintaining, all-fiber chirped pulse amplification of ultrashort pulses. Pulses with the duration of 933 fs and energy as high as 50 μJ are achieved at 200 kHz repetition rate in a compact size. The variations of the spectra and pulse widths as functions of the amplified output power have also been presented. To our best knowledge, this is the highest energy extracted from the strictly all-fiber chirped pulse amplification system. The environmentally stable femtosecond laser source will find various applications in practice.

Index Terms: Fiber amplifier, photonic crystal fiber, femtosecond laser, chirped pulse amplification.

1. Introduction

Fiber lasers have the reputation of being immune to thermo-optical distortions due to the fiber geometry itself and the diffractionless confined propagation of the laser radiation, especially since the strictly all-fiber structure has such advantages as being maintenance free, having no spatial coupling, and so on.

However, it still has challenges in the high energy ultrafast laser amplification due to the nonlinearity accumulated within the tiny fiber core [1]. Hence, the large mode area fibers combined with CPA technology are frequently employed to realize this goal [2]–[7]. The highest energy extracted from the fiber laser is 2.2 mJ with pulse duration of 500 fs and average power of 11 W [8]. In the experiment, the pulse is stretched to 3 ns, and two stages of photonic crystal fiber (PCF) amplifiers are employed to generate final energy output. The first stage is a PCF amplifier with 30 μm mode field diameter, and the second stage is a Ytterbium doped Rod-type Large-Pitch fiber with 85 μm core. Another mJ level CPA system was completed by Röser [9], the pulse is stretched to 2 ns, pulse energy with 1.45 mJ and pulse duration of 800 fs was obtained by employing two stages of PCF, and the last stage is a Rod-type PCF with core diameter of 80 μm. Another high energy CPA system is 0.85 mJ obtained from Yb-doped Rod-type PCF at the repetition rate of 100 kHz with pulse duration of 800 fs [10]. All these high energy fiber CPA systems are based on Rod-type

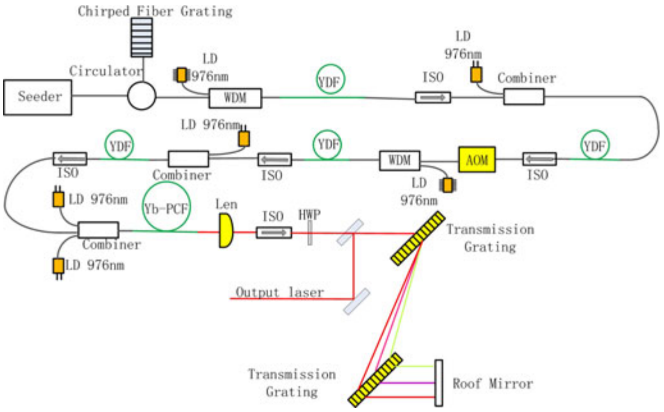


Fig. 1. Schematic diagram of the all-PM fiber-CPA system. WDM: wavelength-division multiplexer; YDF: Yb-doped fiber; ISO: isolator; AOM: acoustic-optic modulator; LD: laser diode; HWP:half-wave plate.

PCF, which is inflexible and has to be spatially coupled for both signal and pump light; it no longer possesses the advantages of the strictly all-fiber system.

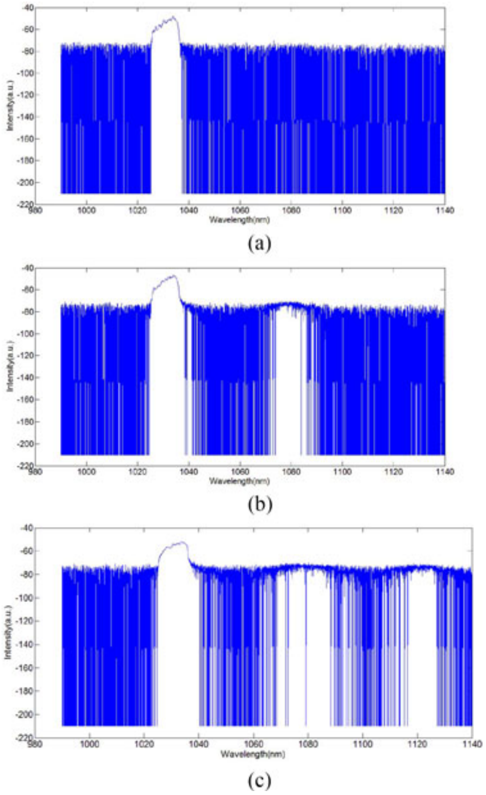
Additionally, without using the Rod-type PCF, some high energy ultrashort pulse amplification systems based on large mode areas flexible PCF have been reported. A pulse energy of 100 μJ with pulse duration of 650 fs was obtained [11], the compressed pulse relies on the compensation of third-order dispersion mismatch between the stretcher and compressor via self-phase modulation of the cubicon pulses in the fiber amplifier, and the main amplifier of PCF was also spatial coupled. Via nonlinear chirped pulse amplification, a pulse energy of 30μJ and pulse duration of 240 fs was obtained through one stage PCF amplifier [12]. Another 50 μJ, 400 fs fiber CPA system was realized by using one stage chirally coupled core (CCC) fiber with spatial coupling [13]. It used the self-phase modulation in a stretcher fiber to broaden the pulse spectrum and dispersion of the fiber to stretch pulses temporally. All these fiber amplification systems need to spatial coupling, which leads to a more complicated structure and system instability.

In this work, a compact and stable all-fiber integrated CPA system with no spatial coupling compared with the similar high energy fiber amplification systems has been realized, which is very promising in industrial processing applications. By rational gain distribution of each amplifier and nonlinearity control in the amplification stages, the optimized pulse of 50 μJ, 933 fs is obtained with one stage strictly all-fiber structured flexible PCF amplifier.

2. Experimental Setup

The schematic diagram of the all-PM fiber-CPA system is shown in Fig. 1. It consists of an oscillator, a pulse stretcher, four stages pre-amplifier, a pulse picker, a main amplifier based on photonic crystal fiber, and a pulse compressor.

The seeder is a mode-locked fiber laser with pulse duration of 15 ps at a repetition rate of 40.7 MHz with power of 20 mW. The pulse stretcher is composed of a circulator and a chirped fiber grating with the chirped parameter of -100ps/nm, which is used to stretch the pulse to nearly 600 ps so as to lower the nonlinearity in the amplification. The pre-amplifier is composed of four stages Yb-doped PM fiber amplifier. The first stage is a single mode fiber amplifier. It amplified the laser power to about 80 mW. A double cladding fiber with a core diameter of 10 μm is employed as the second stage pre-amplifier. In the first two stage amplifier, the pulses are amplified to nearly 2 watts. Then a fiber coupled AOM is employed to reduce the repetition rate to hundreds of kilohertz to increase the pulse energy in the latter amplification. After reducing the repetition rate, the laser power is only a few milliwatts, and therefore, similar amplifiers before AOM were again employed to



(a)

(b)

(c)

Fig. 2. Raman spectrum shift at different power amplification in 10 μm fiber amplifier stage. (a) 700 mW@200 kHz. (b) 800 mW@200 kHz. (c) 2 W@200 kHz.

amplify the low power to 2 W, but in order to lower the nonlinearity and guarantee the compressed pulse quality, the amplified power and gain of each amplifier need to be properly arranged.

The main amplification stage consists of 2 m long Yb-doped large mode area PCF with a core diameter of 40 μm and pump cladding diameter of 200 μm in which the seed energy can be boosted to more than 20 W. After amplification, the output laser pulses are collimated by a plano-convex lens. In order to prevent the feedback from the compressor, an isolator is inserted between the main amplifier and the compressor.

The amplified pulses are compressed using a conventional diffraction grating pair in a double pass configuration. A pair of 1600 groove mm-1 gratings was used in a setup, which is very similar to the Littrow configuration. Considering the polarization dependence of the grating diffraction efficiency, a broadband half wave plate is inserted before the grating pair to improve compression efficiency.

3. Experimental Results and Discussion

In the first two-stage amplification, we find that there is very low nonlinearity due to the high repetition of 40.7 MHz, and the spectrum hardly changes in the amplification process, but after the AOM, the laser repetition rate is reduced to 200 kHz. As shown in Fig. 2, when the laser is amplified no more than 700 mW, the spectrum is only centered at 1030 nm, but as the laser is boosted up to 800 mW, the Stokes components centered at around 1080 nm appear. Further increasing the pump power, the second-order Stokes components centered at 1130 nm also appear when the seed power reaches 2 W. This is because the high energy pulse amplification in the 200 kHz preamplifier stages caused severe nonlinearity. In order to sharpen the SRS threshold, the pulse repetition rate is changed to 543 kHz, and when the amplified output power reaches 1.4 W, the Raman shift just

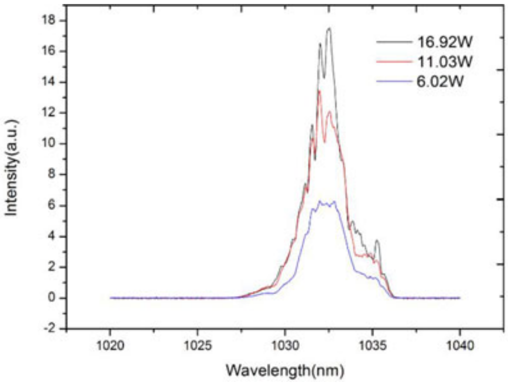


Fig. 3. Spectra at different output power.

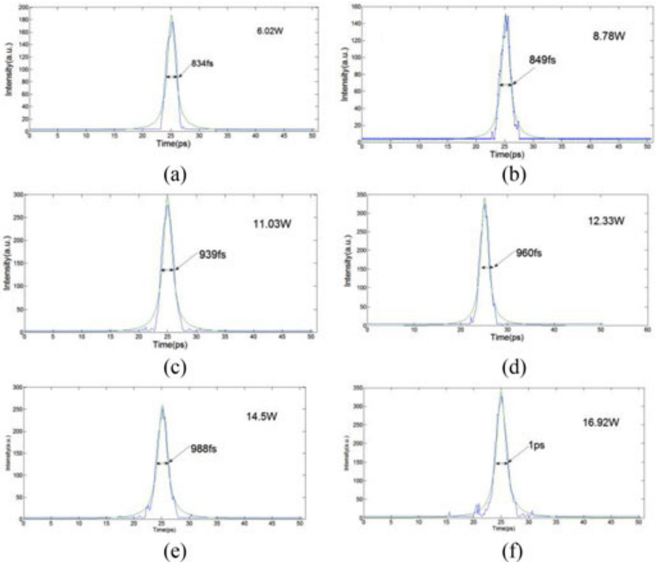
appeared. When the repetition rate is changed to 773 kHz, the Raman shift threshold is about 2 W. Although the higher repetition rate can sharpen the SRS threshold, the pulse energy will decrease. So we need to a proper repetition to balance the pulse energy and the power.

In industrial applications with femtosecond laser, in order to ensure the processing efficiency and lower the thermal effect, lasers with repetition of several hundred kilohertz, pulse energy of several tens of micro joules, pulse width of less than 1 ps is in urgent need. In our laser system, we fixed the repetition rate at 200 KHz, because it can obtain a relatively high pulse energy output and high power, on the other hand, it can guarantee a relatively low nonlinearity to make the laser can be compressed to less than 1 ps. When the pre-amplifier output power is lowered to less than 800 mW as the signal for the main amplifier, the unwanted Raman shift appears when the main amplifier outputs 3 W average power. In order to boost the power of the main amplifier, the pre-amplifier output power is lowered to 300 mW at 200 kHz, the main amplifier can output 19.6 W before the Raman shift appears.

After amplification, a grating pair with 1600 groove mm-1 is used to compress the pulse. By optimizing the distance and the incident angle of the grating pair, the pulse width is less than 1 ps when the grating pair distance is 1.98 m. A series of spectra and the corresponding pulse widths are tracked. As shown in Fig. 3, the amplified power ranges from 6.02 W to 16.92 W. Because of the gain narrowing effect and the increased nonlinearity when the output power increased, the spectrum width is narrowed and the spectrum amplitude is modulated. As shown in Fig. 4, the corresponding pulse width is tracked, the pulse width is gradually widened from 834 fs to 1 ps due to the increased nonlinearity and the narrowing spectrum width.

In order to obtain the shortest pulse duration at high average power, the incident angle of the grating pairs is carefully adjusted, which is slightly deviating from the best diffraction angle. At the same time, the third-order dispersion (TOD) introduced from gratings can compensate the nonlinearity phase accumulation in amplification process to some extend. As shown in Fig. 5, a pulse duration of 933 fs is obtained at 200 kHz, corresponding to the pulse energy of 50 μJ. The autocorrelation traces of the compressed pulse have small fluctuations, this is because the high order dispersion is not totally compensated in high energy amplification.

The output performance versus the pump power is shown in Fig. 6, it reveals that the main amplifier has an excellent performance in amplification. Uncompressed power as high as 20 W, 100 μJ can be obtained, the corresponding slope efficiency and optical-to-optical efficiency is 79.9% and 69.3% respectively. After compression, more than 10 W, 50 μJ output pulse is obtained. The total compression efficiency is $\sim$50%, which mainly limited by the grating-pair diffraction efficiency. The output beam quality is measured by a Spiricon M2–200 laser beam analyzer. As shown in Fig. 7, the measured M2 values are 1.475 in the horizontal and 1.473 in the vertical direction, respectively.



(a) (b) (c) (d) (e) (f)

Fig. 4. Compressed pulse widths at different output power.

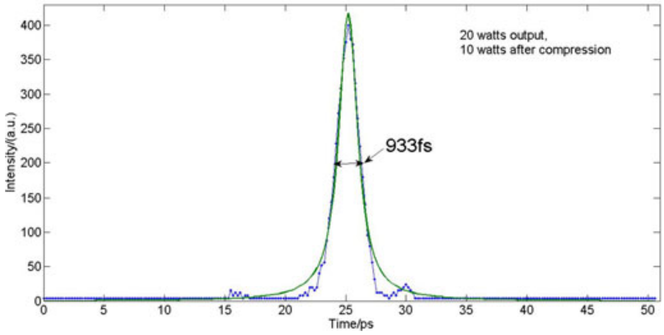


Fig. 5. Auto correlation curves of the pulses with 10 W compressed output power.

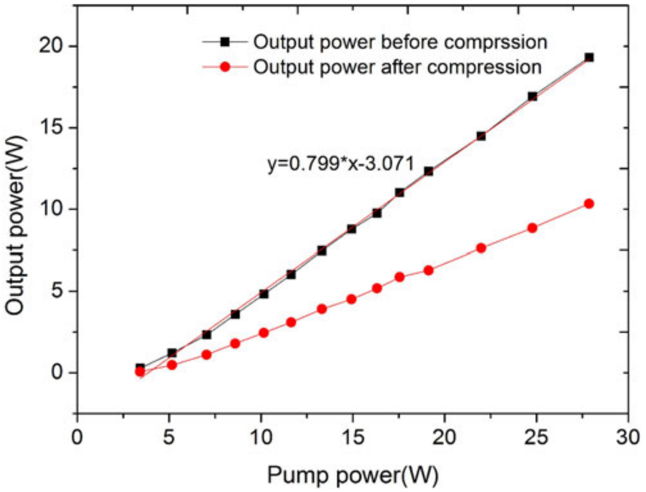


Fig. 6. Output power of the laser system versus incident pump power at 200 kHz.

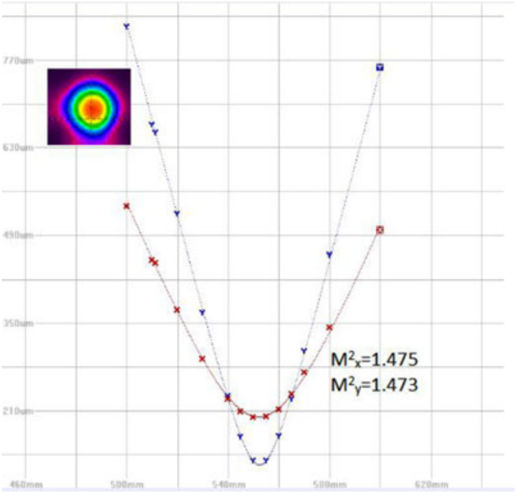


Fig. 7. Measurement of M2.

4. Conclusions

A compact, maintenance-free CPA femtosecond amplifier system with a strictly all-fiber scheme has been demonstrated. In our experiment, in order to suppress the Raman shift that occurred in the main amplification and realize the optimized output laser parameters, the gain of each amplifier is properly distributed so that the nonlinearity and the output power is well balanced, which is mainly characterized by variations of the spectra and pulse widths as functions of the amplified output power. Average power as high as 10 W with compressed pulse duration of 933 fs is achieved at a pulse repetition rate of 200 kHz, which corresponds to an output pulse energy of 50 μJ and peak power of 53.6 MW.

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