Article

Nonlinearity and Dispersion Controlled All-Fiber High-Energy Femtosecond Chirped Pulse Amplification System with Peak Power More than 0.5 GW

Feng Li *, Qianglong Li, Jixin Xing, Xue Cao, Wenlong Wen, Lei Wang, Yufeng Wei, Hualong Zhao, Yishan Wang, Yuxi Fu, Wei Zhao *

Posted Date: 25 November 2025

doi: 10.20944/preprints202511.1889.v1

Keywords: monolithic fiber femtosecond laser; high peak power; large dispersion; high-order dispersion compensation doi:10.20944/preprints202511.1889.v1

Article

Nonlinearity and Dispersion Controlled All-Fiber High-Energy Femtosecond Chirped Pulse Amplification System with Peak Power More than 0.5 GW

Feng Li *, Qianglong Li, Jixin Xing, Xue Cao, Wenlong Wen, Lei Wang, Yufeng Wei, Hualong Zhao, Yishan Wang, Yuxi Fu and Wei Zhao *

State Key Laboratory of Ultrafast Optical Science and Technology, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China

* Correspondence: lifeng@opt.ac.cn (F.L.); weiz@opt.ac.cn (W.Z.)

Abstract

A monolithic all-fiber high-energy chirped pulse amplification (CPA) system with a managed large dispersion is demonstrated. To lower the system's nonlinearity, two temperature-tuning cascaded chirped fiber Bragg gratings (CFBGs) with a large dispersion of 200 ps/nm are used as the stretcher to stretch the pulse duration to more than 2 ns in the time domain. The main amplifier, a short-length silicate glass fiber with a large mode area and a high gain, increases the energy to 293 μJ at 100 kHz. To compress the large-dispersion chirped pulse into a compact structure, a reflective grating pair with a high density of 1740 lines/mm is used as the compressor. Owing to the high-order dispersion pre-compensation by the CFBGs and the large-sized grating with high diffraction efficiency, a compressed pulse duration of 466 fs with a pulse energy of 250 μJ is obtained, corresponding to a compression efficiency of more than 85%. The well-preserved beam quality with measured M^2 value is better than 1.3. To best of our knowledge, this is the highest pulse energy ever achieved in a monolithic fiber femtosecond laser system.

Keywords: monolithic fiber femtosecond laser; high peak power; large dispersion; high-order dispersion compensation

Femtosecond lasers are favorable for a variety of applications, such as drilling of microholes, micro/nanofabrication, welding of glass [1–3] and scientific research [4,5]. Many amplification methods have been developed to achieve this target, such as the use of thin disk amplifiers [6,7], Innoslab laser amplifiers [8,9], traditional bulk crystal amplifiers [10] and fiber amplifiers [11–14]. Out of all the amplifiers, monolithic all-fiber femtosecond lasers have drawn attention due to their ease of integration and maintenance, good beam quality, and ease of heat dissipation. However, intense nonlinear effects, such as self-phase modulation (SPM) and stimulated Raman scattering (SRS), limit the energy enhancement of fiber lasers because of the high peak power confined in the fiber core.

In order to obtain high pulse energy ultrafast laser output in fiber, sufficient pulse stretching and the use of low-nonlinearity fibers (short length and large mode area) are vital. All kinds of large-mode-area fibers are employed in chirped pulse amplification system to achieve high energy output. A stretched pulse duration of ~600 ps and a flexible photonic crystal fiber (PCF) with a core diameter of 40 μm is used to achieve high energy output in a monolithic setup [15], and a pulse energy of 50 μJ and a pulse duration of 933 fs are obtained. Researchers have presented a new optical fiber structure termed a chirally coupled core (CCC) fiber to achieve single-mode output where the core size is larger than 30 μm. During the amplification, the pulse is stretched to 450 ps with 1 km polarization maintained single-mode fiber. A pulse energy of 50 μJ and a pulse duration of 400 fs are attained with a CCC fiber with a core diameter of 33 μm [16]. In recent years, taped fibers have been used to achieve high energy output. Even with a core diameter of 56 μm, the beam quality can be conserved in a single mode and can be better than 1.2 due to their multiclad structure and tapered design along the fiber length. A stretched pulse with a pulse width of about 1 ns was amplified in a tapered fiber, and a laser output with a repetition frequency of 2 MHz, a pulse energy of 35 μJ and a pulse width of 266 fs was obtained [17]. Another chirped pulse amplification system used a similar tapered fiber with a stretched pulse width of about 1.7 ns, resulting in a laser output with a repetition rate of 504 kHz, a pulse energy of 126.3 μJ, and a pulse width of 401 fs [18]. Among the high-gain medium (HGM) monolithic fiber amplifiers, by heavily doping and shortening the gain fiber length to ~20 cm, the accumulation of nonlinearity in chirped pulse amplification (CPA) systems is greatly reduced. The seed pulse at a wavelength of 1.55 μm was stretched to 1.4 ns before amplification and amplified to 144 μJ at 100 kHz. After compression, a pulse energy of 102 μJ and a pulse duration of 636 fs were obtained in 2013 [19]. In the CPA system with a wavelength of 1.03 μm, the seed pulse was stretched to 1 ns before amplification and amplified to 80 μJ at 400 kHz. After compression, a pulse energy of 62 μJ and a pulse duration of 380 fs were obtained in 2015 [20]. In our previous work, the energy was increased to 170 μJ, with a pulse duration of 781 fs. However, the pulse duration of the main amplifier was restricted to approximately 1 ns after spectrum filtering [21]. In the high-energy fiber laser system, the rod-type PCF plays an important role and has the largest mode area of all fibers. By using a one-stage flexible PCF and a one-stage rod PCF, a pulse energy of 100 μJ with a pulse duration of 270 fs and an average power of 100 W was obtained in 2016 [22]. By using a two-stage rod PCF, a pulse duration of 357 fs, an average power of 175 W, and a pulse energy of 233 μJ were obtained in 2022 [23], and a pulse energy of 212 μJ and a pulse duration of 460 fs at a repetition rate of 0.5 MHz were obtained in 2024 [24]. Recently, a laser with an average power of 273 W, a pulse energy of 273 μJ, and a pulse duration of 264 fs was achieved in a rod-type PCF fiber [25]. Although the average power and pulse energy of the femtosecond laser achieved with a rod-type PCF are satisfactory, spatial coupling, the nonbendable long rod structure (~1 m) and the high cost of the PCF itself pose significant challenges in large-scale applications. A hybrid fiber–single-crystal fiber CPA system was also developed to increase the pulse energy, and a pulse energy of 540 μJ with a pulse width of 358 fs at 100 kHz [13] and an amplified pulse energy of 240 μJ at 1 MHz with a compressed pulse duration of 744 fs were reported [26]. With coherent combination, the femtosecond fiber laser achieved a recorded pulse energy of 32 mJ and a pulse duration of 158 fs at 20 kHz [27], and a 1 kW, 10 mJ, 120 fs pulse [28] was achieved through 16 parallel ytterbium-doped rod-type amplifiers. Figure 1 summarizes the high-energy fiber femtosecond research results from [15–25] and this work, which demonstrates that the energy obtained in this work is the highest pulse energy obtained from monolithic all-fiber femtosecond CPA laser systems and has the highest peak power; additionally, this energy level is equivalent to that of the rod-type PCF obtained via spatial coupling.

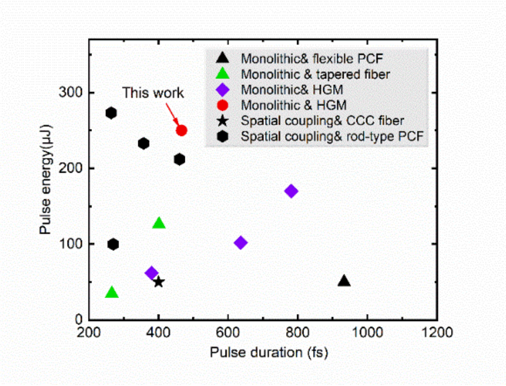

Figure 1. Pulse energy obtained from fiber femtosecond CPA laser systems.

In this work, we demonstrate a monolithic all-fiber femtosecond laser system with a large stretch–compression ratio. The pulse is stretched to ~2 ns during the amplification stage with two large-dispersion CFBGs to reduce the nonlinearity accumulated in the amplification stage. The main amplifier is a heavily Yb-doped silicate glass fiber with a large mode area and a high gain within an only 20 cm length. A maximum pulse energy of 293 μJ is obtained at 100 kHz. To compress the enormous-dispersion chirped pulse into a compact structure, a high-density 1740 lines/mm reflective grating pair is used. Optimization of high-order dispersion with temperature-tuning CFBGs results in a compressed pulse duration of 466 fs, a pulse energy of 250 μJ, and a beam quality better than 1.3. This monolithic all-fiber high-energy laser system has a wide range of applications in industry and scientific research.

Figure 2 shows the experimental setup for this high-energy monolithic all-fiber femtosecond laser. The CPA system includes a semiconductor saturable absorber mirror (SESAM) mode-locked oscillator, a large-dispersion stretcher, a one-stage single-mode fiber amplifier, a two-stage double cladding fiber amplifier, and a pulse picker. The main amplifier is a high-gain silicate glass fiber amplifier. After amplification, a large-aperture reflective grating pair with a high density serves as the compressor.

The oscillator is a self-made SESAM mode-locked fiber laser that delivers pulses with a 34 MHz repetition rate and a power of 6 mW. The center wavelength is approximately 1030 nm, with a spectral width of 12 nm. A four-port circulator connects two temperature-tuning chirped fiber Bragg gratings (CFBGs), which are commercially available from Teraxion Co. Ltd., to form the stretcher. The CFBGs have a reflection band of approximately 12 nm, allowing full use of the oscillator spectrum. Additionally, the two CFBGs provide an ultralarge dispersion of 112.63 ps^2 with a reflectivity of 49% over the operation bandwidth and can stretch the pulse duration to more than 2 ns to reduce the nonlinearity in the cascaded fiber amplifiers. Considering the insertion loss of the circulator and the CFBG reflectivity, the power after the stretcher is ~1 mW. A core-pumped single-mode fiber amplifier with a gain fiber (Nufern, PM-YSF-HI-HP) length of 0.6 m is then used to increase the power to approximately 10 mW. The following stage involves a double cladding (DC) power amplifier with a 10 μm core diameter and a 125 μm cladding diameter (Nufern, PLMA-YDF-10/125-M). A fiber-coupled multimode semiconductor laser with a maximum power of 9 W amplifies the power to approximately 700 mW. A polarization-maintaining (PM) DC fiber-coupled acousto-optic modulator (AOM) is subsequently used as the pulse picker to reduce the repetition rate from 34 MHz to 100 kHz, with an average power of ~ 1 mW. Then, another stage 10/125 DC amplifier is used to increase the power to 160 mW, which can satisfy the power needs of the main amplifier. The last stage of the monolithic fiber amplifier is a heavily ytterbium-doped silicate glass fiber amplifier with a mode field diameter of 40 μm and a length of only 20 cm. The amplifier module, commercial available from Advalue Photonics, is conductively cooled, and in order to maintain its high power stability, the module is placed on a water-cooled plate. The large mode area silicate glass fiber can be spliced with the 10/125 double-cladding fiber (inner core of 10 μm, cladding diameter of 125 μm) directly, and this will constitute a monolithic all-fiber system. This high-efficiency medium (HEM) is pumped by a 100 W fiber-coupled laser diode (LD) from BWT Beijing Ltd. with a locked wavelength of 976 nm through a high-power (2+1) ×1 combiner. The main amplifier increases the power to ~30 W with pumped power close to 60 W. Due to the pump laser's relatively wide beam divergence, a 5 mm aperture diaphragm was placed 15 mm from the fiber end face to filter out residual pump light. This simple pump power management scheme proves highly effective even at elevated pump powers of 154 W, ensuring exceptional output power stability of 0.105%[29]. The amplified laser is collimated by a planoconvex lens with focal length of 50.8 mm. Then, a half-wave plate is used to change the linear polarization direction to obtain the optimal diffraction efficiency because of the polarization dependence of the reflective gratings. The compressor uses a large-aperture reflective grating pair (commercial available from Plymouth Grating Laboratory) with a groove density of 1740 lines/mm to compensate for the large dispersion employed in amplification, whose diffraction efficency is more than 97% . The grating apertures are 110 mm × 110 mm and 210 mm × 110 mm, which is large enough to fully capture the diffracted spectrum without any loss of spectrum.

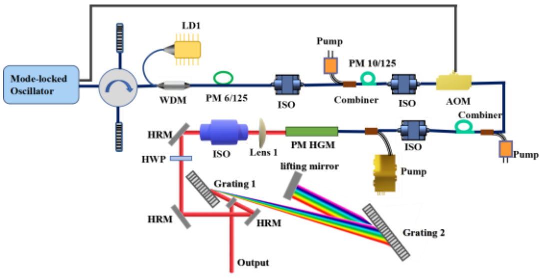

Figure 2. Experimental setup. LD: laser diode; WDM: Wavelength Division Multiplexing; PM: polarization maintaining; ISO: isolator; AOM: acoustic-optic modulator; HRM:high reflective mirror; HWP: half-wave plate.

To obtain high-energy femtosecond laser output from this monolithic all-fiber setup CPA system, the homemade linear cavity SESAM mode-locked laser has a wide spectrum of 12 nm (full width at half maximum, FWHM), which matches the bandwidth of the stretcher reflection band of ~12 nm. To reduce the nonlinearity in the CPA system, the stretcher, which is composed of two large-dispersion CFBGs and a four-port circulator, provides a large dispersion of 112.63 ps^2. To compensate for the high-order dispersion of the system, which is caused primarily by the high-density grating pair compressor, the third-order dispersion of -1.89 ps^3 is pre-engraved into the stretcher of chirped fiber gratings; additionally, the gratings can offer second-order dispersion and third-order dispersion tuning capabilities of 4.5 ps^2 and 0.5 ps^3 by applying a temperature gradient along the CFBGs, which can achieve precise dispersion compensation matching with the compressor. After the stretcher, the mode-locked pulse is stretched and measured by an oscilloscope (LECROY) with a bandwidth of 36 GHz and a sampling frequency of 80 GS/s, which is shown in Figure 3. The pulse width (FWHM) is greater than 2 ns, and such a large pulse width is more conducive to increasing the pulse energy in the subsequent amplification process.

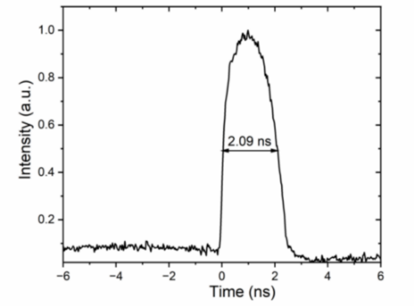

Figure 3. Pulse duration measurement after the stretcher.

The nonlinearities experienced by the laser pulse during amplification directly affect the spectral and temporal performance and should be minimized [30,31]. Essentially, they can be quantified by the accumulated nonlinear phase shift in terms of the B integral and can be calculated as follows:

$$\mathrm{B}=\frac{\lambda}{2\pi\,\mathrm{A_{eff}}}\int_0^{\mathrm{L}}\mathrm{n_2P_{AF}}(z)dz+\frac{\lambda\mathrm{n_2}}{2\pi\,\mathrm{A_{eff}}}\mathrm{P_{PF}}L_{\mathrm{PF}} \quad (1)$$

where λ is the laser wavelength, n_2 is the nonlinear refractive index coefficient, $P_{AF}(z)$ is the pulse peak power in the active gain fiber, L is the total fiber length of the active fiber, PPF is the pulse peak power in the passive fiber, which can be assumed to be a constant value, L_{PF} is the length of the passive fiber for transmitting the laser, and Aeff is the fiber effective mode area. For numerical calculations, we can assume that this process corresponds to a small signal amplification process in the active fiber and is constant in the passive fiber. In the fiber CPA system, the highest peak power is confined in the main amplifier. To compare the B integral in our main amplifier with the similar pulse energy obtained using a rod PCF with a large mode area reported in reference [23], the related calculation parameters and results are listed in Table 1. During amplification, the spectrum narrows due to the gain narrowing effect. In the main amplifier of an HGM, the spectrum narrows to approximately 6 nm, resulting in a pulse duration of ~1.2 ns. According to the comparison, the B integral of the silicate glass fiber amplifier is only 1.38, which is significantly lower than that of the rod PCF of 4.38, making the silicate glass fiber amplifier more suitable for producing high-energy femtosecond laser outputs.

Table 1. B integral calculation comparison of a Rod PCF and a silicate glass fiber.

	Fiber Type	**In&out energy (μJ)**	**Length(mm)**	**MFD (μm)**	**τ (ns)**	**B (rad)**
Ref. [23]	Rod PCF	33 &333	800	60	1.5	4.38
This work	Silicate glass fiber	1.6 & 293	200	40	1.2	1.38

MFD, mode field diameter; τ, pulse duration.

Figure 4 depicts the amplification and compression performance vs. the pump power. The power output of the amplifier is tested at various pump power levels, and through linear fitting, a high slope efficiency of 59% is attained. The main amplifier exhibits such high pump energy absorption capability and amplification efficiency because it is a heavily Yb-doped silicate glass fiber amplifier. As we know, to enhance the amplifier gain per unit length, it is necessary to increase the active ion concentration in the fiber through doping. However, higher doping concentrations lead to a reduction in the optimal fiber length. In silica-based large-mode-area (LMA) fibers, doping concentrations are constrained by strong ion clustering effects [32]. These effects arise from the close proximity of ions, which promotes cooperative energy coupling into parasitic transitions that compete with the desired laser transition. As a result, at high concentrations, ion-ion interactions reduce the upper laser level lifetime under increasing pump power, further diminishing amplifier efficiency.Unlike silica fibers, silicate or phosphate glass fibers can mitigate the detrimental effects of high rare-earth ion concentrations. By employing heavily doped silicate glass fibers, sufficient pump absorption is achieved while maintaining relatively high slope efficiency and pump-to-signal conversion efficiency.

Notably, the signal injected into the main amplifier is only 160 mW, whereas the maximum output power reaches 29.3 W at 100 kHz, corresponding to a high gain of 1.13 dB/cm and a pulse energy of 293 μJ. By using a large-aperture reflective grating pair with a high groove density of 1740 lines/mm to compress a laser pulse with large dispersion, a maximum compressed power of 250 μJ is obtained, corresponding to a total compression efficiency of 85.3%. The diffraction efficiency of the grating is better than 97%, considering the losses of the reflective mirror and the lifting mirror, and the total efficiency is close to the optimal efficiency. The spectrum of the compressed pulse is also measured by the optical spectrum analyzer Yokogawa AQ6370D , as shown in Figure 5(b), and it has a spectrum width of approximately 6 nm (FWHM), which supports a short pulse duration output. The spectrum has some modulations, which are caused primarily by the nonlinear effect of SPM. There is no spectrum filtering, indicating that the aperture of the reflective grating is large enough to receive the entire spectrum. The seeder oscillator spectrum is also measured, as shown in Figure 5(a) ,which has a spectrum width of 12 nm. It should be noted that Yb-doped fibers exhibit a relatively weaker gain narrowing effect compared to Yb:YAG solid-state laser media, owing to their significantly broader emission bandwidth, as a result, at the maximum output power, the spectrum width of 6nm is obtained, as showed in Figure 5 (b). The logarithmic-scale spectrum of the amplified laser output is presented in the inset of Figure 5(b), demonstrating negligible amplified spontaneous emission (ASE) components within the measurement sensitivity. Although high-energy Yb-doped solid-state lasers, such as the Yb:YAG laser, have lower nonlinearity and higher pulse energy output, they suffer from significant gain narrowing during high-gain amplification, resulting in a narrow spectrum width of typically less than 3 nm and pulse widths greater than 700 fs [33,34]. To assess the pulse evolution during the amplification process, the pulse widths are measured by the oscilloscope, as shown in Figure 6, With increasing amplification power, the gain narrowing effect becomes progressively more pronounced. This phenomenon manifests as a continuous spectral narrowing, while the pulse duration simultaneously decreases due to the chirped nature of the pulses. As illustrated in Figure 6, the pulse duration decreases from approximately 1.55 ns at an amplified power of 10 W to about 1.2 ns at maximum output power.

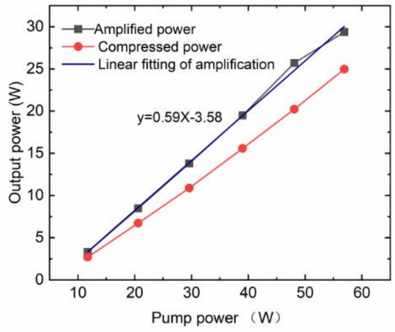

Figure 4. Output power performance vs. pump power.

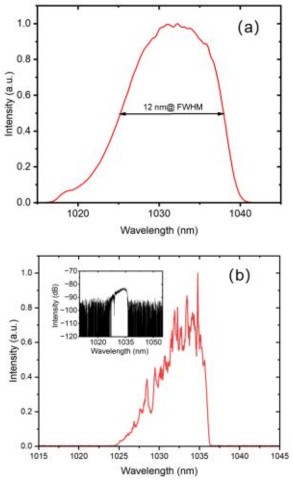

Figure 5. Spectrum of the laser. (a) Spectrum of the seeder oscillator; (b)Spectrum of the compressed laser. Inset: the spectrum of amplified laser in logarithmic.

To obtain a short pulse duration output, the distance of the grating pair and the input angle of the grating are carefully adjusted. The autocorrelator produces the shortest pulse duration at a linear distance of approximately 2.1 m for the grating pair, which results in a second-order dispersion of 112.5 ps^2. To achieve the optimal short pulse duration, we use temperature tuning of the CFBGs to achieve more precise dispersion matching. The third-order dispersion of -1.89 ps^3 is pre-engraved into the stretcher of CFBGs, which can compensate for the third-order dispersion of the grating pair. The optimal distance of 2.1 m results in a third-order dispersion of ~1.5 ps^3 for the compressor. This value is estimated using an input angle of 65.4°and a diffraction angle of 61.9°, which differs from the Littrow angle for beam splitting. The third-order dispersion still has a slight mismatch with the stretcher. As a result, the compressed pulse duration cannot reach the transform-limited pulse duration. The compressed pulse duration is measured by the APE pulsecheck autocorrelator, as shown in Figure 7, the pulse duration is 466 fs with Lorentz fitting in a 15 ps scanning range. Different pulse fittting of Gaussian, Sech^2 and Lorentz fitting are used, we find that the Lorentz fitting method is the closest to the actual pulse shape. To evaluate the energy distribution, we also scan the pulse in a 150 ps range, and we can observe that the pulse has a small pedestal. For most applications, beam quality is crucial. As a monolithic all-fiber CPA system, the silicate glass fiber has a good beam quality. By carefully adjusting the grating pair, the beam quality after compression is still conserved in single mode, with a beam quality better than 1.3, which is measured by the beam quality analyzer of Ophir beam squared SP920, as shown in Figure 8.

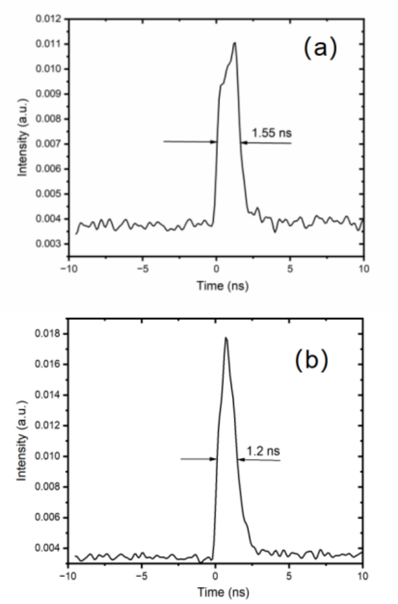

Figure 6. Oscilloscope trace of amplified pulses. (a) Oscilloscope trace of amplified pulse traces at 10 W; (b) Oscilloscope trace of amplified pulse at maximum power.

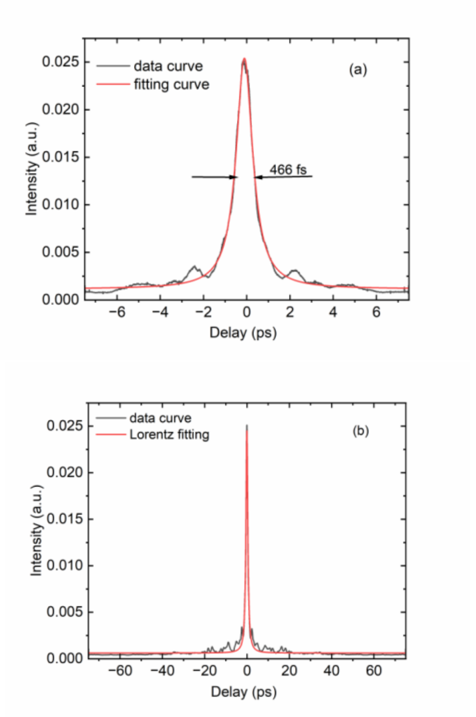

Figure 7. Pulse duration measurement. (a) Autocorrelation curve in the 15 ps scanning range; (b) Autocorrelation curve in the 150 ps scanning range.

In this work, a monolithic all-fiber high-energy femtosecond fiber laser is demonstrated. By using the large dispersion of the stretcher, the pulse is stretched to ~2 ns for the subsequent fiber amplification to reduce the nonlinearity. The main amplifier, a short-length silicate glass fiber with a large mode area and a high gain, increases the energy to 293 μJ at 100 kHz, with an amplification gain of 29.6 dB. To construct a compact compressor, a large-aperture reflective grating pair with a density of 1740 lines/mm is used as the compressor. Due to the temperature tuning of the stretcher, the second-order dispersion and high-order dispersion are simultaneously compensated, a short pulse duration of 466 fs is obtained, corresponding to a peak power of 536 MW, and the beam quality is better than 1.3. This monolithic all-fiber femtosecond laser will be a useful tool in various scientific research and industrial applications.

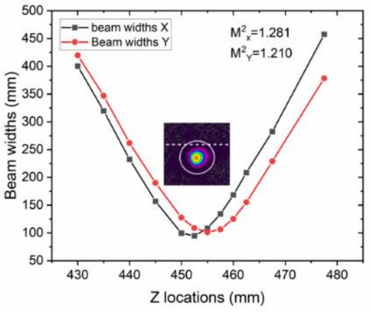

Figure 8. Beam quality measurement.

Author Contributions: Feng Li: Investigation, Methodology, Conceptualization, Validation, Writing–original draft. Qianglong Li: Investigation. Jixin Xing: Investigation. Xue Cao: Investigation. Wenlong Wen: Investigation. Lei Wang: Investigation. Yufeng Wei: Investigation; Hualong Zhao: Resources, Supervision. Yishan Wang: Resources,Project administration. Yuxi Fu: Conceptualization,Resources.Wei Zhao: Validation, Project administration.

Funding: This work was supported by National key research and development program of China, No. 2024YFB3613500; The Chinese academy of science "light of west China" program (XAB2021YN12); The independent research project of State Key Laboratory of Ultrafast Optical Science and Technology.

Data Availability Statement: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Conflicts of Interest: The authors have no conflicts to disclose.

References

1. L. Jiang, A.D. Wang, B. Li, T.H. Cui, Y.F. Lu, Electrons dynamics control by shaping femtosecond laser pulses in micro/nanofabrication: modeling, method, measurement and application, Light, science & applications 7 (2018) 17134.
2. L. Jiang, J. Fang, Q. Cao, K. Zhang, P. Wang, Y. Yu, Q. Huang, Y. Lu, Femtosecond laser high-efficiency drilling of high-aspect-ratio microholes based on free-electron-density adjustments, Appl. Opt. 53(31) (2014) 7290-7295.
3. C. Wang, S. Zhang, Z. Luo, K. Ding, B. Liu, J.a. Duan, High-quality welding of glass by a femtosecond laser assisted with silver nanofilm, Appl. Opt. 60(18) (2021) 5360-5364.
4. G. Chang, C.J. Divin, C.-H. Liu, S.L. Williamson, A. Galvanauskas, T.B. Norris, Power scalable compact THz system based on an ultrafast Yb-doped fiber amplifier, Optics Express 14(17) (2006) 7909-7913.
5. J. Ferri, V. Horny, T. Fulop, Generation of attosecond electron bunches and x-ray pulses from few-cycle femtosecond laser pulses, Plasma Physics and Controlled Fusion 63(4) (2021).
6. Z. Yao, J. Yu, Y. Chen, J. Sun, Y. Zhang, J. Fan, R. Han, X. Zhang, F. Chen, Compact high-repetition-rate Yb:YAG thin-disk regenerative amplifier with fundamental transverse mode laser output, Optics Express 32(26) (2024) 47041-47056.
7. J.-P. Negel, A. Voss, M.A. Ahmed, D. Bauer, D. Sutter, A. Killi, T. Graf, 1.1 kW average output power from a thin-disk multipass amplifier for ultrashort laser pulses, Optics Letters 38(24) (2013) 5442-5445.

8. Y. Gao, J. Guo, Y. Huang, Z. Gao, Z. Gan, Z. Tu, X. Liang, R. Li, 417 W, 2.38 mJ Innoslab amplifier compressible to a high pulse quality of 406 fs, Optics Letters 48(20) (2023) 5328-5331.
9. P. Russbueldt, T. Mans, J. Weitenberg, H.D. Hoffmann, R. Poprawe, Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier, Optics Letters 35(24) (2010) 4169-4171.
10. Huijun He, Jun Yu,Wentao Zhu, Xiaoyang Guo, Cangtao Zhou, and Shuangchen Ruan, A Yb:KGW dual-crystal regenerative amplifier, High Power Laser Science and Engineering 8(4) (2020).
11. Q. Zhao, G. Gao, Z. Cong, Z. Zhang, G. Liu, Z. Liu, X. Zhang, Z. Zhao, High-repetition-rate, 50-μJ-level, 1064-nm, CPA laser system based on a single-stage double-pass Yb-doped rod-type fiber amplifier, Optics Express 30(3) (2022) 3611-3619.
12. P. Wan, L.-M. Yang, J. Liu, All fiber-based Yb-doped high energy, high power femtosecond fiber lasers, Optics Express 21(24) (2013) 29854-29859.
13. F. Li, W. Zhao, Q. Li, H. Zhao, Y. Wang, Y. Yang, W. Wen, X. Cao, Hybrid fiber-single crystal fiber chirped-pulse amplification system emitting more than 1.5 GW peak power with beam quality better than 1.3, Journal of Lightwave Technology (2023) 1-6.
14. X. Cao, F. Li, Y. Wang, H. Zhao, W. Zhao, Q. Li, J. Xing, W. Wen, J. Si, 2.6 GW, mJ-class high-energy femtosecond laser system based on Yb:YAG single-crystal fiber amplifier, Infrared Physics & Technology 144 (2025) 105643.
15. F. Li, Z. Yang, W. Zhao, Q. Li, X. Zhang, X. Yang, W. Zhang, Y. Wang, 50 mu J Femtosecond Laser System Based on Strictly All-Fiber CPA Structure, Ieee Photonics Journal 8(5) (2016).
16. J. Želudevičius, R. Danilevičius, K. Viskontas, N. Rusteika, K. Regelskis, Femtosecond fiber CPA system based on picosecond master oscillator and power amplifier with CCC fiber, Optics Express 21(5) (2013) 5338-5345.
17. X. Cao, Q. Li, F. Li, H. Zhao, W. Zhao, Y. Wang, D. Li, Y. Yang, W. Wen, J. Si, Femtosecond Yb-doped tapered fiber pulse amplifiers with peak power of over hundred megawatts, Optics Express 31(4) (2023) 5507-5518.
18. T. Wang, B. Ren, C. Li, K. Guo, J. Leng, P. Zhou, Monolithic tapered Yb-doped fiber chirped pulse amplifier delivering 126 μJ and 207 MW femtosecond laser with near diffraction-limited beam quality, Frontiers of Optoelectronics 16(1) (2023) 30.
19. X. Peng, K. Kim, M. Mielke, S. Jennings, G. Masor, D. Stohl, A. Chavez-Pirson, D.T. Nguyen, D. Rhonehouse, J. Zong, D. Churin, N. Peyghambarian, High efficiency, monolithic fiber chirped pulse amplification system for high energy femtosecond pulse generation, Optics Express 21(21) (2013) 25440-25451.
20. K. Kim, X. Peng, W. Lee, S. Gee, M. Mielke, T. Luo, L. Pan, Q. Wang, S. Jiang, Monolithic polarization maintaining fiber chirped pulse amplification (CPA) System for high energy femtosecond pulse generation at 1.03 mu m, Optics Express 23(4) (2015) 4766-4770.
21. F. Li, W. Zhao, Y. Wang, N. Wang, Q. Li, Y. Yang, W. Wen, A large dispersion-managed monolithic all-fiber chirped pulse amplification system for high-energy femtosecond laser generation, Optics & Laser Technology 147 (2022) 107684.
22. Z. Zhao, Y. Kobayashi, Ytterbium fiber-based, 270 fs, 100 W chirped pulse amplification laser system with 1 MHz repetition rate, Applied Physics Express 9(1) (2016).
23. M.E.V. Pedersen, M.M. Johansen, A.S. Olesen, M. Michieletto, M. Gaponenko, M.D. Maack, 175 W average power from a single-core rod fiber-based chirped-pulse-amplification system, Optics Letters 47(19) (2022) 5172-5175.
24. S. Wang, Q. Zhao, G. Gao, Z. Cong, Z. Liu, Z. Zhao, Old Wavelength, New Performance: Hectowatt 200-μJ-Level Femtosecond Fiber CPA System at 1064 Nm, Journal of Lightwave Technology 42(5) (2024) 1659-1666.
25. D.-L. Wang, Z. Shi, J.-S. Wang, H.-Y. Wu, X.-H. Zhang, G.-Q. Chang, 1 MHz, 273 W average power Ytterbium-doped rod-type fiber chirped pulse amplification system, Acta Physica Sinica 73(13) (2024) 134204-1-134204-6.
26. S. Wang, Z. Cong, J. Liu, X. Zhang, Z. Zhao, Z. Liu, High-efficiency 940-and 969-nm brightness-maintaining wavelength-multiplexed LD-pumped 240-W thin-rod Yb:YAG amplifier, Optics Letters 47(8) (2022) 2113-2116.
27. H. Stark, M. Benner, J. Buldt, A. Klenke, J. Limpert, Pulses of 32 mJ and 158 fs at 20-kHz repetition rate from a spatiotemporally combined fiber laser system, Optics Letters 48(11) (2023) 3007-3010.

28. H. Stark, J. Buldt, M. Müller, A. Klenke, J. Limpert, 1 kW, 10 mJ, 120 fs coherently combined fiber CPA laser system, Optics Letters 46(5) (2021) 969-972.
29. Q. Li, F. Li, W. Zhao, Y. Wang, W. Wen, Y. Yang, H. Zhao, X. Cao, J. Si, Hundred watt level and high energy compact hybrid fiber femtosecond laser with good beam quality, Laser Physics Letters 20(5) (2023) 055104
30. J. Limpert, F. Roeser, D.N. Schimpf, E. Seise, T. Eidam, S. Haedrich, J. Rothhardt, C.J. Misas, A. Tuennermann, High Repetition Rate Gigawatt Peak Power Fiber Laser-Systems: Challenges, Design, and Experiment, IEEE J. Sel. Top. Quantum Electron. 15(1) (2009) 159-169.
31. M.D. Perry, T. Ditmire, B.C. Stuart, Self-phase modulation in chirped-pulse amplification, Optics Letters 19(24) (1994) 2149-2151.
32. B.-C. Hwang, S. Jiang, T. Luo, J. Watson, G. Sorbello, N. Peyghambarian, Cooperative upconversion and energy transfer of new high Er3+- and Yb3+–Er3+-doped phosphate glasses, J. Opt. Soc. Am. B 17(5) (2000) 833-839.
33. C.G. Leburn, C.Y. Ramírez-Corral, I.J. Thomson, D.R. Hall, H.J. Baker, D.T. Reid, Femtosecond pulses at 50-W average power from an Yb:YAG planar waveguide amplifier seeded by an Yb:KYW oscillator, Optics Express 20(16) (2012) 17367-17373.
34. W. Schneider, A. Ryabov, C. Lombosi, T. Metzger, Z. Major, J.A. Fülöp, P. Baum, 800-fs, 330-μJ pulses from a 100-W regenerative Yb:YAG thin-disk amplifier at 300 kHz and THz generation in $LiNbO_3$, Optics Letters 39(23) (2014) 6604-6607.