JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 42, NO. 1, JANUARY 1, 2024

Hybrid Fiber-Single Crystal Fiber Chirped-Pulse Amplification System Emitting More Than 1.5 GW Peak Power With Beam Quality Better Than 1.3

Feng Li, Wei Zhao, Qianglong Li, Hualong Zhao, Yishan Wang, Yang Yang, Wenlong Wen,
and Xue Cao

***Abstract*—A hybrid chirped pulse amplification system composed by the monolithic fiber pre-amplifier and a two-stage single-pass single crystal fiber amplifier was demonstrated. A maximum power of 68 W at the repetition rate of 100 kHz was obtained. The laser pulses were amplified and then compressed using a 1600 line/mm grating pair compressor. A short pulse duration of 358 fs and a power of 54 W were obtained at 100 kHz, corresponding to a peak power of 1.508 GW, to the best of our knowledge, this is the highest peak power ever obtained from single crystal fiber at repetition rate above 100 kHz due to the consideration of the third order dispersion which was engraved in the stretcher and the tuning capacity of higher-order dispersion compensation of chirped fiber Bragg grating. Additionally, the beam quality better than 1.3 was obtained. This high peak power CPA system with excellent comprehensive parameters will find various applications in scientific research and industrial applications.**

***Index Terms*—Chirped pulse amplification, high peak power, high-order dispersion compensation, single crystal fiber.**

TABLE I
ULTRAFAST LASER AMPLIFICATION RESULTS BASED ON SINGLE CRYSTAL FIBER AMPLIFIER

Ref.	Pulse Energy (μJ)	Pulse Duration (fs)	Peak Power (MW)	M^2	Repetition Rate (kHz)
[16]	339	2500	135.6	~1.52	200
[17]	90	660	136	-	1000
[18]	~200	744	~268	~1.42	1000
[19]	80.6	580	~139	~1.72	1000
[20]	105	2400	43.7	1.3	200
[21]	1.918	800	2.39	1.9	83400
[22]	5	750	6.67	-	20000
[23]	148	278	532	1.22	200
This work	540	358	1500	1.27	100

IN THE last decade, ultrafast lasers have found various applications in science and industry, e.g., attosecond generation [1], THz generation [2], ultrafast pump-probe spectroscopy [3], angle resolved photoemission spectroscopy [4], and material precision machining [5], [6], [7], [8]. Most of these femtosecond lasers are configured in chirped pulse amplification architectures. Notable results with kilowatts average power have been reported by different Yb-doped gain mediums, such as the thin-disk amplifier [9], the innoslab amplifier [10] and Yb-doped fibers [11]. The thin-disk and innoslab lasers' inherent complexity and multiple passes of the laser beam with no optical wave guide pose a challenge for its stability and wider industrial applications.The Yb-doped gain fibers has many advantages in laser amplification, including compact design, effective pump conversion, free from thermal effects, and diffraction-limited beam quality. However, the nonlinearity in the fiber amplification pose a challenge in obtaining high-energy ultrashort pulses. Despite the use of techniques such as CPA and various large mode area fibers, including rod-type photonic crystal fiber [12], chirally-coupled core fiber [13], heavily doped glass fiber [14] and tapered fiber [15], pulse energy remains constrained, typically ranging from tens to hundreds of microjoules.

In recent years, the Yb:YAG single crystal fiber, which has the advantages of solid-state amplifier in high energy regime and fiber amplifier in high power regime, has been used to scale the ultrafast laser power to hundred-watt level and energy level ranging from microjoules to millijoules in a compact and simple structure, making them well-suited for a wide range of precision machining applications. As the Table I showed, the ultrafast laser amplification results based on single crystal fiber [16], [17], [18], [19], [20], [21], [22], [23] above 100 kHz are demonstrated, the highest reported amplification power was approximately 240 W, using a three-stage single crystal fiber amplifier [18], which was partially compressed by chirped volume bragg grating(CVBG)

Manuscript received 21 November 2022; revised 10 July 2023; accepted 1 September 2023. Date of publication 6 September 2023; date of current version 2 January 2024. This work was supported by the Chinese Academy of Science "Light of West China" Program under Grant XAB2021YN12, in part by Shaanxi Young Science and Technology Star under Grant 2022KJXX-98, in part by the Key Project of "Double Chain" Integration of Shaanxi Province, in part by the National Natural Science Foundation of China under Grant 61690222, and in part by The Youth Innovation Promotion Association XIOPM-CAS under Grant XIOPMQCH2021007. *(Corresponding author: Feng Li.)*

The authors are with the State Key Laboratory of Transient Optics and Photonics, Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an 710119, China (e-mail: laser_lifeng@opt.cn; zwei@opt.ac.cn; laser_liqianglong@opt.cn; zhaohualong@opt.ac.cn; yshwang@opt.ac.cn; yangyang@opt.ac.cn; romber@opt.ac.cn; caoxue0115@163.com).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/JLT.2023.3312399.

Digital Object Identifier 10.1109/JLT.2023.3312399

with efficiency of 83.1%, and the estimated compressed power and energy was ∼200 W and ∼200 μJ, respectively, with a compressed pulse duration of 744 fs. The highest compressed pulse energy of 339 μJ [16] was obtained at 200 kHz using a three-stage single crystal amplifier and a CVBG compressor. However, the pulse duration was approximately 2.5 ps due to the gain narrowing effect and imperfect dispersion match. Among these single crystal based amplification systems, the obtained pulse duration is relatively wide due to the spectrum gain narrowing effect and some ignorance of higher order dispersion compensation. Furthermore, some explorations of high energy femtosecond laser based on single crystal fiber amplification are also experimentally studied. Fabien Lesparre [24] et al. used the master-oscillator power-amplifier (MOPA) system to generate high peak power laser, by using two-stage single crystal fiber amplifier and divided pulse amplification technique, ultrashort laser with pulse energy of 2 mJ, pulse duration of 6 ps at 12.5 kHz is obtained, corresponding to a peak power of 0.33 GW. By using double-pass configuration of two-channel single crystal amplifier and coherent beam combination based on Michelson-interferometer-type combining implementation in a chirped pulse amplification system, Marco Kienel [25] et al. obtained a pulse energy of 3 mJ and pulse duration of 695 fs at 6 kHz, corresponding to a peak power of 4.3 GW. These two coherent combining experimental results proves the capability of single crystal amplifier in obtaining high pulse energy.

In this work, a hybrid chirped pulse amplification system composed by the monolithic fiber pre-amplifier and a two-stage single-pass single crystal fiber amplifier was constructed. Due to the large dispersion managed amplification (stretched pulse duration more than 1 ns) and high gain, low nonlinearity large mode area silicate glass fiber amplifier, we offered a monolithic fiber pre-amplifier with high pulse energy of >95 μJ, the gain of ∼7 is achieved in the cascaded single crystal fiber amplification. A maximum power of 68 W at the repetition rate of 100 kHz was obtained with high beam quality of 1.268 and 1.243 in the horizontal direction and vertical direction, respectively. The spectrum gain narrowing effect is not so severe, which is beneficial to obtain a short pulse duration. Meanwhile, the higher order dispersion has been taken into consideration, the fiber system's high-order dispersion and the grating compressor's high order dispersion was compensated in the chirped fiber Bragg grating in the process of fiber Bragg grating engraving, and the chirped fiber grating also has the temperature based dispersion tuning capacity, which offered the system a precision dispersion match. Therefore, a short pulse duraion of 358 fs and power of 54 W were obtained after a grating pair compressor with groove density of 1600 line/mm, the corresponding pulse energy and peak power of 540 μJ and 1.5 GW are obtained in this system. The beam quality is also conserved better than 1.3 after single crystal amplification and grating-pair compression.

I. EXPERIMENTAL SETUP

The experimental setup of this high peak power fiber CPA system is schematically shown in Fig. 1. This CPA system consists of a SESAM mode-locked oscillator, a large dispersion stretcher, one stage single mode fiber amplifier, two-stage 10/125 double cladding fiber amplifier, an acoustic-optic modulator, a silicate glass fiber amplifier, which composed a monolithic fiber pre-amplifier, a two-stage single-pass single crystal fiber amplifier as the main amplifier, as well as a grating pair compressor.

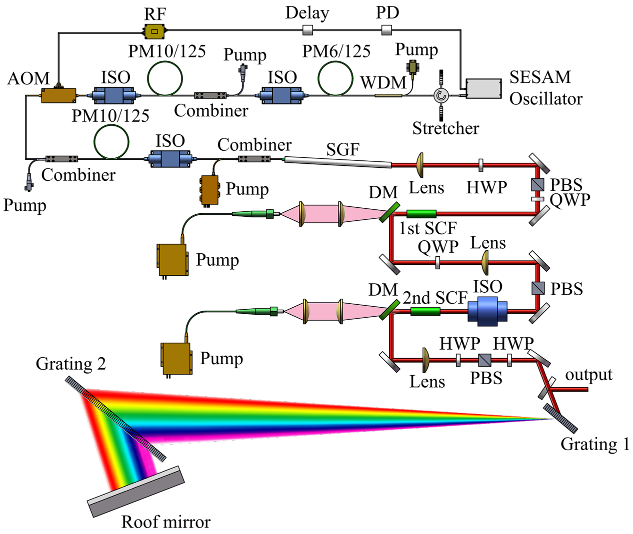

Fig. 1. Schematic of the hybrid fiber-single crystal fiber CPA laser system. SESAM, semiconductor msaturable absorption mirror; PD, photodiode; WDM, wavelength division multiplexing; ISO, isolator; SGF, silicate glass fiber; HWP, half wave plate; PBS, polarization beam splitter; QWP, quarter wave plate; SCF, single crystal fiber; DM, dichroic mirror.

The oscillator is a home-made SESAM mode locked fiber laser, which delivers pulses with 36.4 MHz repetition rates and power around 5 mW. The central wavelength is about 1030 nm with a spectral width of 15 nm. The stretcher consists of two temperature-tuning chirped fiber Bragg gratings (CFBGs) coupled by a four-port circulator, and the reflection band of the chirped fiber Bragg grating is 20 nm, allowing it to utilize the oscillator's whole spectrum with no spectrum filtration. Additionally, the two CFBGs provide a large dispersion of 87 ps/nm to stretch the laser pulse duration to more than 1 ns. The average power of the laser pulse after stretching is less than 1 mW. The first amplifier is a core-pumped single mode fiber amplifier, pumped by a single mode laser diode. The 0.6-meter-long Yb-doped gain fiber (Nufern, PM-YSF-HI-HP) amplified the power to roughly 10 mW. The next stage is a power amplifier using double cladding (DC) fiber with a core diameter of 10 μm and cladding diameter of 125 μm (Nufern, PLMA-YDF-10/125-M), pumped by a fiber coupled multimode semiconductor laser with maximum power of 9 W, which amplified the power to approximately 700 mW. Then the fiber coupled acousto-optic modulator (AOM) is used to reduce the pulse repetition rate to 100 kHz and an average power of 0.7 mW. Then one more stage 10/125 DC amplifier is used to boost the power to 70 mW. The last stage of the monolithic fiber pre-amplifier is a Yb heavily doped silicate glass fiber amplifier with a mode field diameter of 40 μm and length of merely 20 cm, which is used to boost the power to 9.55 W. This high efficiency medium was pumped by a 100 W LD with locked wavelength of 976 nm through the high power $(2 + 1) \times 1$ combiner.

The laser output from this monolithic fiber pre-amplifier and collimated by a plano-convex lens, and injected into the first stage Yb-doped single crystal fiber amplifier with a focused laser spot size of ∼400 μm. A half wave plate, a PBS and a quarter wave plate are used as the attenuator to lower the power when we do the precised laser coupling of SCF, meanwhile, these components also act as the isolator of the reflected beam from the end face of the SCF. The two-stage single crystal fiber amplifier is used to boost the power. In this article, the single-pass structure made this system a simple and compact system. The parameters of the SCF are 30 mm long, 1 mm diameter with a 1 at.% doping rate and water cooled at the temperature of 23 °C. The SCF is end pumped by a fiber coupled multi-mode 940 nm laser diode with a core diameter of 135 μm and NA of 0.22. To have a good beam quality and acceptable thermal lensing effect, the power of the first stage SCF amplifier is set at 27.35 W at the pump power of 96.5 W. After the first stage SCF amplification, the output laser polarization is changed into the linear polarization by the second quarter wave plate. By inserting a lens with a focal length of 175 mm to change the amplified laser's divergence and beam spot size, the amplified laser is injected into the SCF with a beam size of ∼400 μm. The second stage is the same structured amplifier, at the maximum pump power of 147.9 W, a maximum power of 68 W is obtained at the repetition rate of 100 kHz. The laser is collimated after being amplified. The half wave plate and the PBS are used as the attenuator to lower the power injected into the compressor when we do the precised adjusting of the grating compressor, the next half wave plate is used to change the linear polarization direction to obtain the optimal diffraction efficiency due to the polarization dependence of the gratings. The compressor is a grating pair with a groove density of 1600 line/mm. Due to the large dispersion employed in the amplification, two large aperture grating with sizes of 30 mm× 20 mm × 6.35 mm and 135 mm × 20 mm × 6.35 mm are employed.

II. Results and Discussion

To obtain the high peak power femtosecond laser output from this system, the nonlinearity of the monolithic pre-amplifier is strictly controlled. After the AOM, the repetition rate is reduced to 100 kHz, so when the average power is scaled, the pulse energy and corresponding peak power is very high in the limited mode field area. So the largest nonlinear phase shift in the system is accumulated in the 10/125 fiber amplifier after the AOM and silicate glass fiber amplifier. Even the 10/125 amplifier has the ability to boost the power to more than 1 W, we limit the output power to 70 mW, which is enough for the high efficiency silicate glass fiber amplifier with amplification gain more than 23 dB. This high gain efficiency medium is preferable for ultrafast laser amplification due to its large mode area of 40 μm, short gain fiber length of 20 cm, high efficiency of more than 23 dB and high beam quality of single mode output. The laser is amplified to 9.55 W in this stage, corresponding to a pulse energy of 95.5 μJ, this energy level is relatively high in a monolithic fiber laser system. This powerful seeder will facilitate the whole system to build a high energy system in a compact and simple structure.

The main amplifier is a two-stage single crystal fiber amplifier with a simple single pass amplification structure. The output power of the first stage SCF amplifier is set at 27.35 W at the pump power of 96.5 W, the amplifier cannot fully give its power potential. It is under the consideration that the first SCF amplifier needs to keep a high beam quality output and an acceptable thermal lensing effect under the pump power level. The thermal lensing effect is crucial in this cascaded single-crystal fiber amplification, if the thermal lensing effect is severe, the beam spot size can be bigger than the aperture of the SCF2 during the process when we turn on the pump of the SCF1 to the set power level, which may cause the instability of the system and even damage the end face of the SCF2. In this first SCF amplification stage, to compensate for the SCF1's thermal lensing effect and ensure that the beam spot size change is not severe under different pump powers, a detailed beam divergence control is employed. The laser has a slight divergence with a beam spot of ∼370 μm on the first end face of the SCF1 and ∼420 μm on the second output end face, which guaranteed that under different pump power level of SCF1, the beam diameter is less than 600 μm on the second SCF2, during increasing the pump power, the beam diameter is reduced from 600 μm to 400 μm when the pump power of SCF1 is increased to the set power of 96.5 W. The second-stage SCF amplification used the similar setup, and the amplification performance is showed in Fig. 2, at the injected laser power of 27.35 W, the amplified power reached 68 W at the pump power of 147.9 W. The slope efficiency of 33% is obtained, and it indicates no sign of saturation, which still has the capacity to output higher power when more pump power is injected.

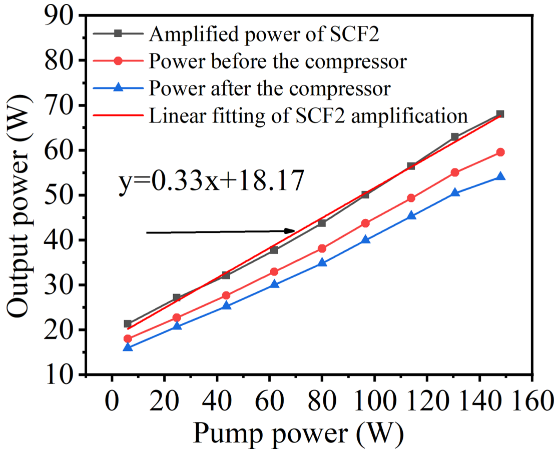

Fig. 2. Output power versus the launched pump power.

After the amplification, the laser is collimated by the plano-convex lens, and injected into the HWP and the PBS to improve the polarization extinction ratio, as showed in Fig. 2, there has some power is reflected from the PBS even we change the polarization by the HWP, which showed that there exists depolarization in the amplification, the main reason is that in high power amplification, there has an ignorant thermal depolarization. When 68 W is injected into the PBS, the maximum transmitted power is 59.5 W, there is a reflection from the PBS of about 8.5 W. After the PBS, one more half wave-plate is used to change the polarization direction to obtain an optimal

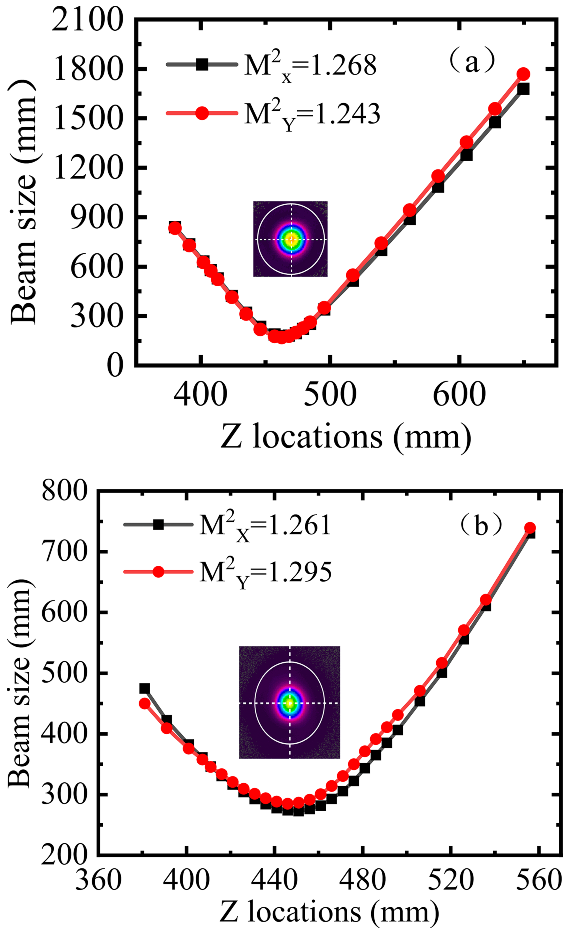

Fig. 3. Beam quality of laser: (a) The beam quality of amplified laser from SCF2; (b) the beam quality of compressed output laser.

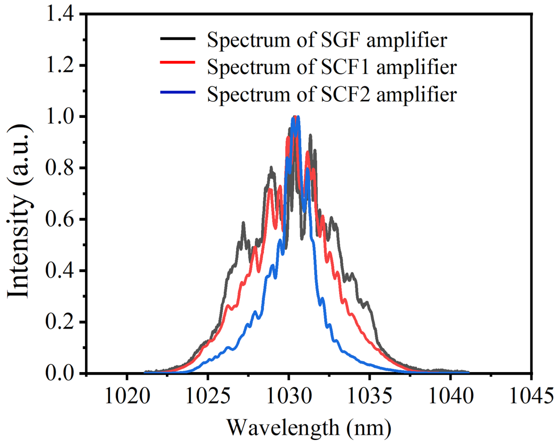

Fig. 4. Evolution of spectrum from different amplification stage.

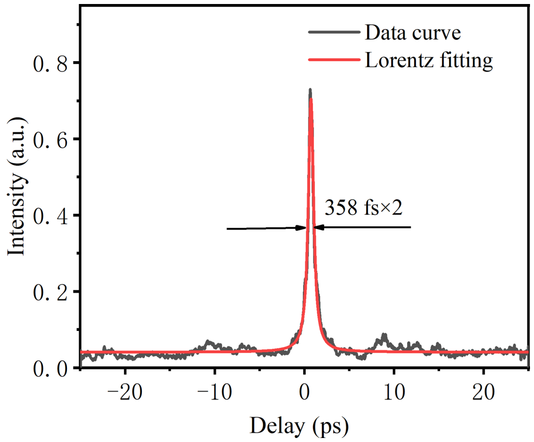

Fig. 5. Pulse autocorrelation trace after compression.

efficiency of the diffraction grating. We can find that the compression efficiency is high in this system, the maximum power after compression is 54 W, the corresponding pulse energy and efficiency is as high as 540 μJ and 90.7%, respectively. The beam qualities at this high power and high energy level are measured after amplification and after compression, as shown in Fig. 3(a) and (b), respectively. The beam has a very good beam profile and the beam quality can be controlled better than 1.3, and there is no discernible deterioration of the beam quality during the compression stage.

The spectrum evolution at different stage is measured as showed in Fig. 4, this is a large dispersion managed system, the stretcher has a reflection band of 20 nm, so there has no spectrum filtration in the stretcher, and the spectrum change is mainly caused by the gain narrowing effect and the nonlinearity accumulated in this high energy CPA system. Due to the Yb-doped fiber's wider emission band, the spectrum after the SGF amplification is relatively wide; it has a spectrum width of more than 7 nm (FWHM). The output spectrum exhibits some modulation, which is primarily caused by the self-phase modulation in the fiber amplifier. After the amplification of SCF, the spectrum is narrowed to about 6 nm in the first-stage SCF amplifier and 4 nm in the second-stage SCF amplifier, this is caused by the spectrum gain narrowing effect of Yb:YAG single crystal fiber. Even after two stage SCF amplification, the spectrum width can be still about 4 nm, which is very useful to obtain a short pulse duration. In this CPA system, the stretcher is composed by two temperature tuning CFBGs, whose reflection band of 20 nm and second order dispersion of ∼48.73 ps^2, this broadband large dispersion stretcher can stretch the pulse duration to more than 1 ns in the amplification, so it lowered the system's nonlinearity and offered the system a wide spectrum which is favorable in obtain short pulse duration. Furthermore, the third order dispersion is also considered in designing the CFBG. The compressor is the grating pair compressor with groove density of 1600 line/mm, and the distance of the grating pair is about 1.67 m, to make a rough calculation, the third order dispersion is 0.209 ps^3, the fiber itself in the CPA system can also introduce the positive third order dispersion, so a calculated third order dispersion of -0.422 ps^3 is engraved in the CFBG to compensate the system's third order dispersion, and through adding temperature gradient along the CFBGs, a range of more than 0.07 ps^3 can be tuned in the system. With this compensation of third order dispersion, the compressed pulse autocorrelation trace is showed in Fig. 5, the pulse duration is 358 fs, the compressed pulse energy is as high as 540 μJ, the corresponding peak power is 1.508 GW. This laser source will be a powerful tool in ultrafast laser micromachining field.

III. CONCLUSION

In conclusion, a high peak power CPA system is demonstrated based on a monolithic fiber pre-amplifier and two cascaded single crystal fiber amplifier, the compressed output power is as high as 54 W at 100 kHz. Benefited from the large dispersion managed system and precised high order dispersion compensation, the short pulse duration of 358 fs at the high pulse energy of 540 μJ is obtained, corresponding to a peak power of more than 1.5 GW. This high power and high energy femtosecond laser system also has a high beam quality better than 1.3. The comprehensive parameters make the laser a useful tool in various applications of scientific research and industrial applications.

REFERENCES

[1] J. Ferri, V. Horny, and T. Fulop, "Generation of attosecond electron bunches and X-ray pulses from few-cycle femtosecond laser pulses," *Plasma Phys. Controlled Fusion*, vol. 63, no. 4, Apr. 2021, Art. no. 045019.

[2] F. Meyer et al., "Milliwatt-class broadband THz source driven by a 112 W, sub-100 fs thin-disk laser," *Opt. Exp.*, vol. 27, no. 21, pp. 30340–30349, Oct. 2019.

[3] F. Köttig et al., "High average-power and energy deep-ultraviolet femtosecond pulse source driven by 10 MHz fibre-laser," in *Proc. Eur. Conf. Lasers Electro-Opt.*, 2015, Paper PD_A_7.

[4] C. M. Cacho et al., "Ultrafast Tr-ARPES with Artemis XUV Beamline," in *Proc. Int. Conf. Ultrafast Struct. Dyn.*, 2012, Paper JT2A.43.

[5] L. Jiang et al., "Femtosecond laser high-efficiency drilling of high-aspect-ratio microholes based on free-electron-density adjustments," *Appl. Opt.*, vol. 53, no. 31, pp. 7290–7295, Nov. 2014.

[6] S. Bag and M. R. Amin, "Investigation on ultrashort pulse laser welding of dissimilar metallic materials expending phase-lag influence," *J. Thermal Sci. Eng. Appl.*, vol. 12, no. 5, Oct. 2020, Art. no. 051014.

[7] C. Wang et al., "High-quality welding of glass by a femtosecond laser assisted with silver nanofilm," *Appl. Opt.*, vol. 60, no. 18, pp. 5360–5364, Jun. 2021.

[8] G. Mincuzzi et al., "Pulse to pulse control for highly precise and efficient micromachining with femtosecond lasers," *Opt. Exp.*, vol. 28, no. 12, pp. 17209–17218, Jun. 2020.

[9] J.-P. Negel et al., "1.1kW average output power from a thin-disk multipass amplifier for ultrashort laser pulses," *Opt. Lett.*, vol. 38, no. 24, pp. 5442–5445, Dec. 2013.

[10] P. Russbueldt et al., "Compact diode-pumped 1.1 kW Yb:YAG Innoslab femtosecond amplifier," *Opt. Lett.*, vol. 35, no. 24, pp. 4169–4171, Dec. 2010.

[11] H. Stark et al., "1 kW, 10 mJ, 120 fs coherently combined fiber CPA laser system," *Opt. Lett.*, vol. 46, no. 5, pp. 969–972, Mar. 2021.

[12] Z. Lv et al., "Photonic crystal rod-based high-performance ultrafast fiber laser system," *High Power Laser Sci. Eng.*, vol. 8, Dec. 2020, Art. no. e40.

[13] J. Zeludevicius et al., "Femtosecond fiber CPA system based on picosecond master oscillator and power amplifier with CCC fiber," *Opt. Exp.*, vol. 21, no. 5, pp. 5338–5345, Mar. 2013.

[14] F. Li et al., "A large dispersion-managed monolithic all-fiber chirped pulse amplification system for high-energy femtosecond laser generation," *Opt. Laser Technol.*, vol. 147, Mar. 2022, Art. no. 107684.

[15] K. Bobkov et al., "Sub-MW peak power diffraction-limited chirped-pulse monolithic Yb-doped tapered fiber amplifier," *Opt. Exp.*, vol. 25, no. 22, pp. 26958–26972, Oct. 2017.

[16] N. N. Wang et al., "Development of a 67.8 W, 2.5 ps ultrafast chirped-pulse amplification system based on single-crystal fiber amplifiers," *Appl. Opt.*, vol. 59, no. 27, pp. 8106–8110, Sep. 2020.

[17] F. Li et al., "Hybrid CPA system comprised by fiber-silicate glass fiber-single crystal fiber with femtosecond laser power more than 90 W at 1 MHz," *Opt. Laser Technol.*, vol. 129, Sep. 2020, Art. no. 106291.

[18] S. Wang et al., "High-efficiency 940-and 969-nm brightness-maintaining wavelength-multiplexed LD-pumped 240-W thin-rod Yb:YAG amplifier," *Opt. Lett.*, vol. 47, no. 8, pp. 2113–2116, Apr. 2022.

[19] Y. Xu, Z. Peng, Y. Shi, B. Wang, Z. Cheng, and P. Wang, "Compact 80 W, 1 MHz femtosecond chirped pulse amplification laser system based on a Yb-doped fiber and a Yb:YAG thin rod," *IEEE Photon. J.*, vol. 14, no. 2, Apr. 2022, Art. no. 1518506.

[20] Z. Peng et al., "21 W, 105 μJ regenerative amplifier based on Yb:YAG SCF and NALM fiber oscillator," *IEEE Photon. Technol. Lett.*, vol. 32, no. 6, pp. 333–336, Mar. 2020.

[21] V. Markovic et al., "160 W 800 fs Yb:YAG single crystal fiber amplifier without CPA," *Opt. Exp.*, vol. 23, no. 20, pp. 25883–25888, Oct. 2015.

[22] F. Lesparre et al., "High-power Yb:YAG single-crystal fiber amplifiers for femtosecond lasers in cylindrical polarization," *Opt. Lett.*, vol. 40, no. 11, pp. 2517–2520, Jun. 2015.

[23] F. Li et al., "Large dispersion-managed broadband high-energy fiber femtosecond laser system with sub 300 fs pulses and high beam quality output," *Opt. Laser Technol.*, vol. 157, Oct. 2023, Art. no. 108653.

[24] F. Lesparre et al., "Yb:YAG single-crystal fiber amplifiers for picosecond lasers using the divided pulse amplification technique," *Opt. Lett.*, vol. 41, no. 7, pp. 1628–1631, Apr. 2016.

[25] M. Kienel et al., "Coherent beam combination of Yb:YAG single-crystal rod amplifiers," *Opt. Lett.*, vol. 39, no. 11, pp. 3278–3281, Jun. 2014.

Feng Li received the Ph.D. degree in optics from the University of Chinese Academy of Sciences, Beijing, China, in 2019. He is currently an Associate Researcher with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. His research focuses on the amplification of ultrashort pulse fiber laser.

Wei Zhao received the Ph.D. degree in optics from the University of Chinese Academy of Sciences, Beijing, China, in 1994. He is currently a Researcher with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. His research interests include the ultrafast optics, laser technology, and optoelectronics.

Qianglong Li received the M.S. degree in optics from Northwest University, Xi'an, China, in 2012. He is currently an Engineer with the Xi'an Institute of Optics and Precision Mechanics of Chinese Academy of Sciences, Xi'an, China. His research focuses include amplification of ultrashort pulse fiber laser.

Hualong Zhao received the Ph.D. degree in optics from the University of Chinese Academy of Sciences, Beijing, China, in 2015, He is currently an Associate Researcher with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. His research focuses on the ultrafast precision machining.

Yishan Wang received the Ph.D. degree in optics from the University of Chinese Academy of Sciences, Beijing, China, in 1999. He is currently a Researcher with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. His research focuses on the ultrafast optics and devices.

Yang Yang received the M.S. degree in optical engineering from the Beijing University of Technology, Beijing, China, in 2013. She is currently an Engineer with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. Her research focuses on the control of ultrafast fiber laser.

Wenlong Wen received the M.S. degree in circuits and systems from Northwest University, Xi'an, China, in 2005. He is currently an Associate Researcher with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. His research focuses on the high-speed circuits design.

Xue Cao received the M.S. degree in optics from Jiangsu Normal University, Xuzhou, China, in 2022. She is currently working toward the Doctorate degree with the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, Xi'an, China. Her research focuses on the high energy ultrafast laser generation.