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High power Yb-fiber laser amplifier based on nonlinear chirped-pulse amplification at a repetition rate of 1 MHz

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We report a high power fiber amplifier based on nonlinear chirped-pulse amplification (NCPA). To manage the nonlinearity, pulse shaping is introduced by self-phase modulation in the fiber stretcher with the help of spectral filtering. The third-order dispersion is compensated for by the nonlinear phase shift in the NCPA. With optimization, the system can output 382 fs pulse duration with 20 W average power at 1 MHz repetition rate. The long-term average power fluctuation is measured to be 0.5% in 24 h, and the beam quality factor (M^2) is 1.25.

Keywords: nonlinear chirped-pulse amplification; spectral shaping; fiber amplifier.

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1. Introduction

The high power Yb-doped femtosecond fiber laser has received great attention in industrial applications[1] and scientific researches[2]. To obtain the ultrashort laser pulses with high power and high energy, versatile laser pulse amplification schemes have been proposed, such as chirped-pulse amplification (CPA)[3–5], coherent beam combination[6], divided-pulse amplification[7], and coherent pulse stacking amplification[8]. Among all of the above-mentioned techniques, the CPA has become a powerful scheme to generate ultrashort laser pulses with high power and high intensity. However, extensive stretching to several nanoseconds (ns) to realize linear amplification of the laser pulses requires highly dispersive prisms, grating components, or well-designed chirped fiber Bragg gratings (CFBGs)[4,9]. Large high-order dispersion from the fiber amplifier in CPA needs intricate adaptive dispersion management schemes for proper recompression to yield Fourier-transform-limited (FTL) pulses with high contrast ratio. Moreover, the CPA device dramatically increases the complexity and cost of the system. In contrast to the linear amplification in the CPA system, the nonlinear effect in Yb-doped fiber amplifiers is under extensive investigation[10]; this method has been extended to bulk regenerative amplifiers[11]. Intrinsically differing from the linear amplification of the CPA, accumulated nonlinear effects in the fiber amplifier can overcome the gain-bandwidth limit to obtain a broadband spectrum and realize good compensation of third-order dispersion (TOD)[12–16]. Significant analysis and discussion were presented by Zhou *et al.*[17], theoretical analysis based on the nonlinear Schrödinger equations was proposed, and an experimental result was demonstrated, which was called a "cubicon" pulse. In the same year, Kalaycioglu *et al.* demonstrated a high energy cubicon fiber amplifier, in which the compressed pulse energy was 100 μJ[18], whereas its pulse duration was 650 fs. Much shorter cubicon pulses of 140 fs at 3 μJ pulse energy were achieved in an all-fiber system[13].

Compared with the cubicon pulse, the parabolic pulse can introduce the linear chirp and increase the nonlinearity tolerance, which is more suitable for the nonlinear CPA (NCPA). The advantages of the parabolic pulse are as follows: (1) the amplified pulses with linear chirp can be dechirped by a standard grating-pair compressor or chirped mirrors, and (2) large nonlinearity tolerance of the parabolic pulse can be obtained as compared to the Gaussian pulse. Several techniques have been developed to obtain parabolic pulses[19–21]. When a pre-shaper was employed, pulses with 24 fs pulse duration and 1 μJ pulse energy were obtained[22]. Recently, the passive parabolic pulse shaping using the CFBG was achieved with the compressed pulse duration of 172 fs[23], and this passive method provided significant benefits in nonlinearity tolerance up to 12 rad. The studies presented thus far provide evidence that passive parabolic shaping combined with the TOD compensation technique is a proven method to obtain much shorter pulses with high peak power in the NCPA system.

In this Letter, a modified all-fiber laser amplifier based on NCPA is demonstrated. A bandpass filter is employed to select the appropriate spectrum, and the parabolic pulse is obtained by controlling the pulse energy injected into the stretcher. Moreover, the TOD is compensated with the nonlinear phase shift introduced by the self-phase modulation (SPM) in the amplifier, which accomplishes twofold tasks in one set-up. Pulses as short as 382 fs with the energy of 20 μJ at 1 MHz repetition rate are obtained. The long-term average power fluctuation (root mean square, RMS) is measured to be 0.5% in 24 h with an average power of 20 W, which shows good power stability.

2. Experiments

The experimental schematic of the high power NCPA laser system is depicted in Fig. 1, which is composed of four parts: a nonlinear polarization evolution (NPE) mode-locked oscillator, a spectral shaper, cascaded fiber amplifiers, and a compressor constituted by a transmission grating pair. All of the elements used in the laser amplifier system are polarization-maintaining, and the linear polarization of the amplifier and high power stability are realized.

The all-normal-dispersion (AND) oscillator delivers an average output power of ~50 mW at a repetition rate of 41.3 MHz.

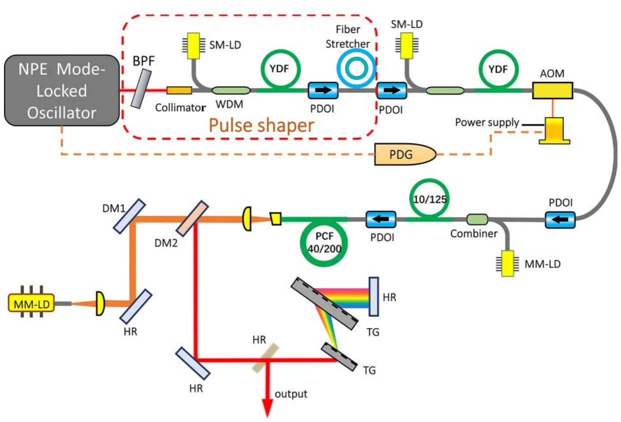

Fig. 1. Schematic of the NCPA system. BPF, bandpass filter; WDM, wavelength division multiplex; SM-LD, single-mode laser diode; YDF, Yb-doped gain fiber; PDG, pulse delay generator; AOM, acoustic optical modulator; PDOI, polarization dependent optical isolator; MM-LD, multi-mode laser diode; DM, dichromic mirror; TG, transmission grating; HR, high reflecting mirror; PCF, photonic crystal fiber.

A polarization beam splitter (PBS) is employed to improve the linear polarization of the pulses from the oscillator. Subsequently, the laser is coupled into a single-mode fiber using a collimator. A bandpass filter with 15 nm bandwidth centered at 1050 nm is located before the collimator to adjust the transmission spectrum to get the shortest compressed pulses. The seeding laser pulses are then amplified to critical power and coupled into a 500-m-long single-mode fiber stretcher. The bandpass filter, the single-mode fiber amplifier, and the fiber stretcher form a pulse shaper. By tuning the transmission spectrum and controlling the pulse energy into the fiber stretcher, the spectrum is reshaped, and parabolic pulses are obtained. After the spectral shaper, the average power is gradually increased in the cascaded fiber amplifiers. Between the first two amplification stages, a fiber-coupled acoustic optical modulator (AOM) is implemented to reduce the repetition rate of the laser pulses to 1 MHz. The first stage of the single-mode fiber pre-amplifier is located before the AOM. Pumped by a 976 nm wavelength stabilized diode laser, the signal power is amplified to compensate for the loss of the AOM. The gain fiber is a 2 m Yb-doped double-clad fiber in the second-stage pre-amplifier, where it is coiled with a diameter of 15 cm to suppress the high-order mode. The main amplifier is equipped with a 1.8 m Yb-doped large mode area photonic crystal fiber (PCF) with a mode field diameter of 31 μm and a pump cladding diameter of 200 μm. The core NA of the PCF is 0.03, and the PCF is single mode for wavelength around 1040 nm. The gain fiber is end-pumped by a fiber-coupled laser diode with more than 150 W output power from a 105 μm core diameter delivery fiber. Two aspheric focusing lenses with high NA are used to couple the output from the delivery fiber into the PCF. To filter the signal output from the pump light, a dichroic mirror is used to transmit the pump light and reflect the signal output. The extracted signal pulses are eventually compressed by a transmission grating pair of 1600 lines/mm, with a total compression efficiency of ~71% at a Littrow angle of 56°.

3. Results and Discussion

The repetition rate and the autocorrelation (AC) trace of the pulse train from the oscillator are shown in Figs. 2(a) and 2(b), respectively. In the RF spectrum, as shown in Fig. 2(a), the signal-to-noise ratio of the fundamental beat note at 41.3 MHz is as high as 79 dB when measured with a resolution bandwidth (RBW) of 300 Hz. It shows an excellent mode-locking property. The oscillator produces seed pulses with a duration of 2.4 ps, as shown in Fig. 2(b), due to no dispersion compensation.

According to the dispersion-induced frequency-to-time mapping, when the spectral distribution is formed into a parabolic profile, a temporally stretched parabolic pulse is obtained. The evolution of the pulse profiles, in both the temporal and spectral domains, is principally determined by the pulse energy and pulse duration. In the experiment, a fiber amplifier and a single-mode fiber stretcher are used to control the two parameters mentioned above. The central wavelength of the oscillator

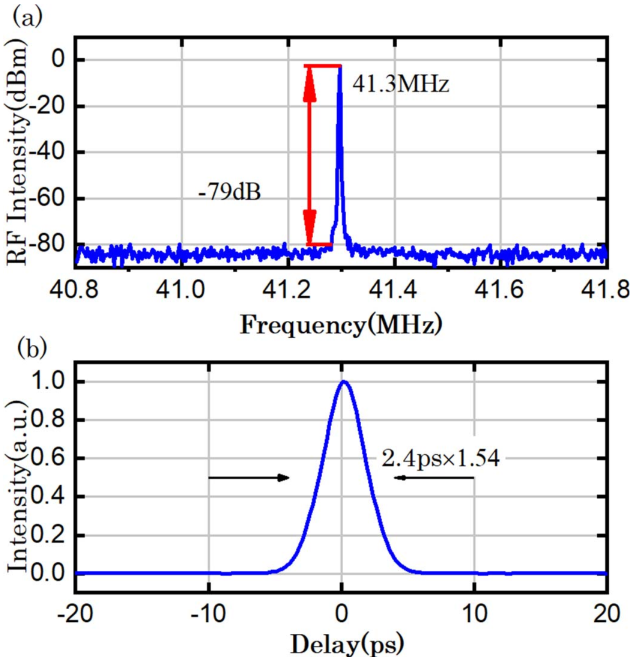

Fig. 2. (a) RF spectrum of the oscillator. (b) The AC trace of the laser pulses from the oscillator.

is at 1040 nm, and the spectral bandwidth is 23 nm. The laser from the oscillator is spectrally filtered and pre-amplified. By tuning the angle of the BPF, the spectra of the seed pulses centered at 1038 nm with 15 nm bandwidth are selected for injection into the amplifier, as shown in Fig. 3. In comparison to the spectrum of the oscillator, the narrower spectrum centered at a longer wavelength is selected. Spectral shaping is achieved by controlling the pulse energy into the fiber stretcher.

With an input average power of 250 mW from the second-stage amplifier, the average power is further boosted to 26 W in the main amplifier, corresponding to a pulse energy of 26 μJ. The spectrum from the boost amplifier is shown in Fig. 4(a), where the 3 dB spectral bandwidth is around 7.5 nm,

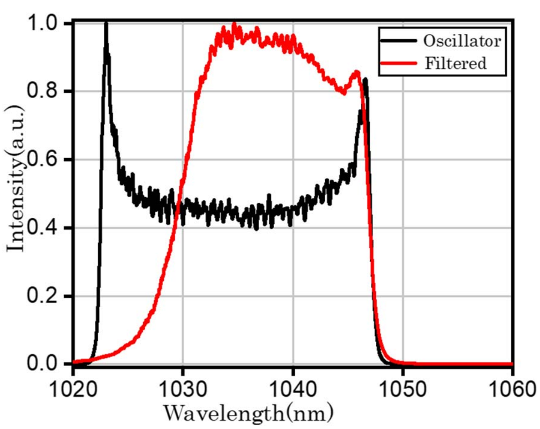

Fig. 3. Comparison of the transmission spectra after the BPF and the oscillator.

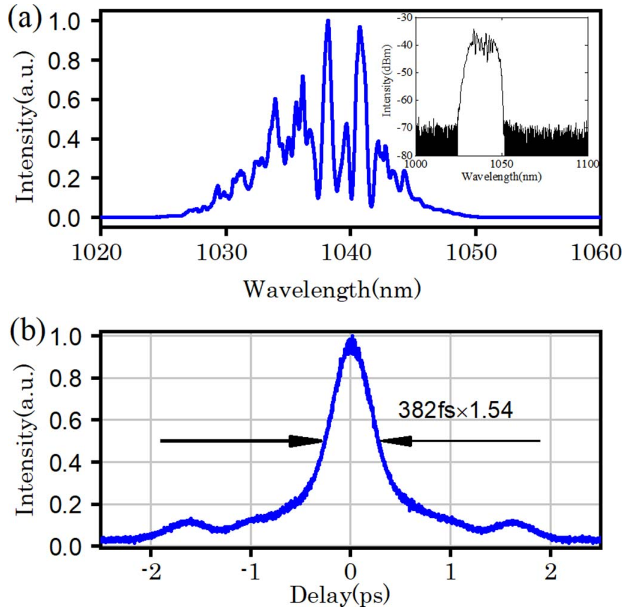

Fig. 4. (a) Spectral distribution from amplified pulses on linear and logarithmic (inset) scale; (b) AC trace of compressed pulses.

which supports an FTL pulse duration of 210 fs. The spectral distribution with multiple peaks exhibits strong modulation resulting from the accumulated nonlinearity. Further power scaling would be limited by the enhanced SPM and stimulated Raman scattering (SRS)[24], the nonlinearity would aggravate spectral modulation, and a portion of the energy will flow into the side lobes of the pulse. The inset in Fig. 4(a) shows the output spectrum on a logarithmic scale, which shows very low contributions of SRS and amplified spontaneous emission (ASE).

Controlling the dispersion and nonlinearity plays an important role in the optimization of the nonlinear amplification. By tuning the transmission spectrum and the pulse energy injected into the fiber stretcher, complex nonlinearity management is effectively simplified. When the grating pair has an optimized distance of 192 mm, pulses with a 382 fs pulse duration at a 20 μJ pulse energy are obtained, as shown in Fig. 4(b). According to the AC trace, the peak power is estimated to be ~40 MW. The existing differences between the compressed pulse and the FTL pulse are primarily due to the residual TOD and nonlinearity. Precise control of dispersion and nonlinearity is needed to improve the quality of the compressed pulse, for example, the pre-chirp management amplification (PCMA) or the prism compressor can be used to get much shorter and high quality pulses[25].

Considering the grating-pair compressor, the overall optical-to-optical conversion efficiency is 40.4 % for the main amplifier, as shown in Fig. 5(a). In many applications, long-term power stability is a crucial parameter. The output power is maintained at 20 W over a 24 h period and varies only by about 0.5% power fluctuation (RMS), as depicted in Fig. 5(b). The pulse train is also shown to indicate the pulse stability. The measured polarization extinction ratio for the amplifier is above 16 dB. Figure 5(c)

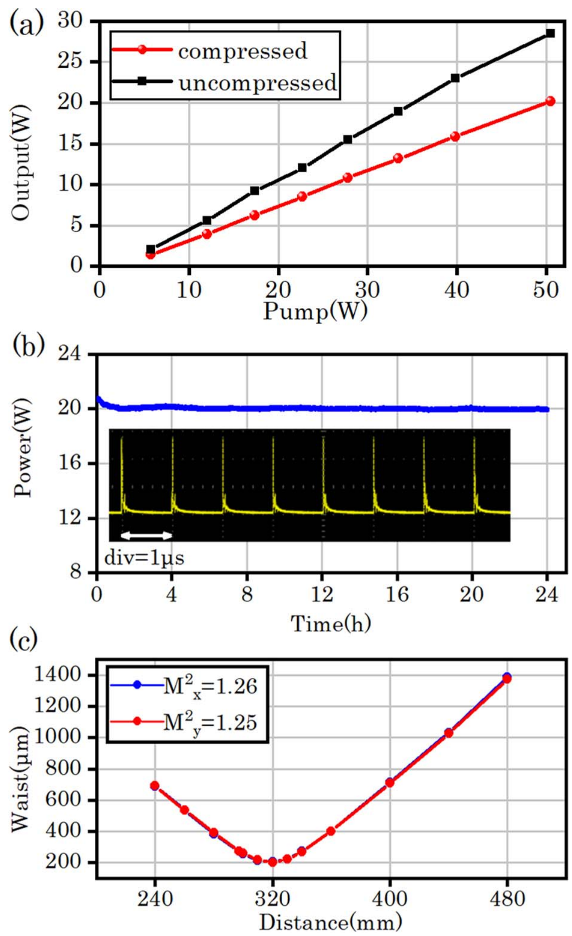

Fig. 5. (a) Dependence of output power versus the pump power for the main amplifier; (b) measured power stability and pulse train; (c) M^2 value of this NCPA system.

shows the measured beam profile factor (M^2) value of the output beam at 20 W, where it is around 1.26 in both axes, which shows a good beam quality.

The AC traces of the compressed pulses with different output power are measured to identify the effect of the spectrum shaping, as shown in Fig. 6. The measured AC traces are significantly different for the same output power with and without a bandpass filter. Without spectrum filtering and pulse shaping, the compressed pulse profile exhibits a larger pedestal, and the pulse energy contained in the central peak decreases as the energy increases. This result indicates that a large nonlinear phase accumulated in the fiber amplifier cannot be properly compensated, which will greatly distort the compressed pulse. The mismatch between the nonlinear chirp and TOD, the imperfect parabolic shaping, and the gain shaping effect contribute to the deterioration of pulse quality. On the contrary, the spectral shaping pulses show approximately similar AC traces despite an increase of pulse energy up to 20 μJ. A possible explanation for these results is that the TOD of the fiber and grating-pair compressor is well compensated by the SPM-induced nonlinear chirp.

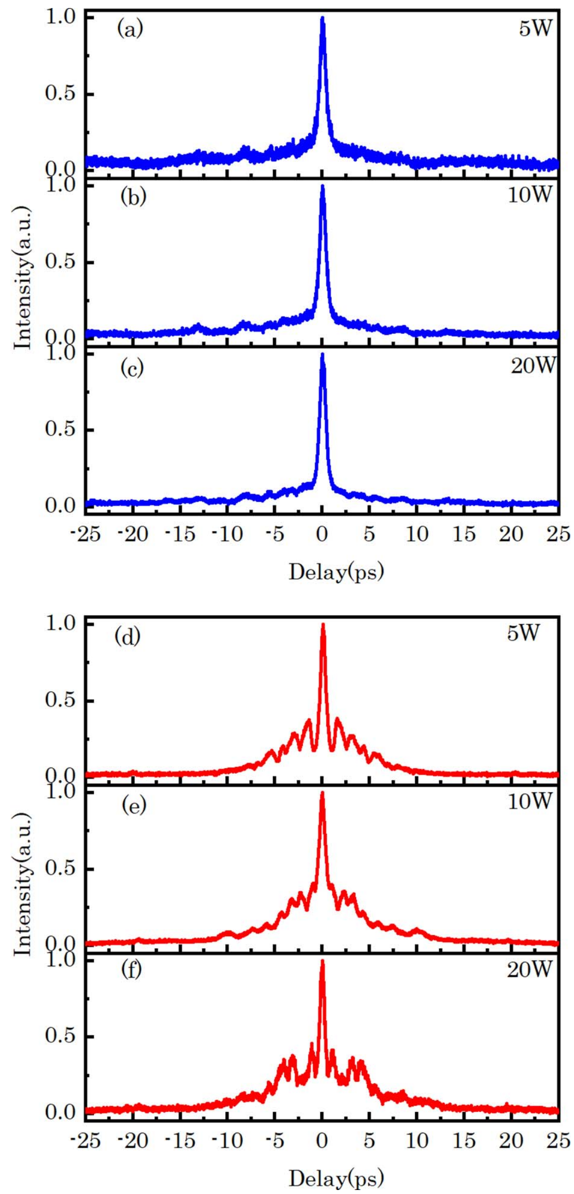

Fig. 6. AC traces at different pulse energies (a)–(c) with BPF and (d)–(f) without BPF.

4. Conclusion

In conclusion, the ultra stable compressed pulses with a 20 μJ pulse energy and a 382 fs pulse duration at a repetition rate of 1 MHz based on the NCPA are demonstrated. The pulses are optimized by compressive consideration of the length of the stretcher single-mode fiber, the amplified spectral distribution, and the amplified energy to achieve the gain-shaped parabolic pulse and good compensation of TOD induced by SPM in the NCPA. The maximal power of 20 W is limited by the mode field diameter of the gain fiber. The near FTL compressed pulses with scalable output power up to hundreds of watts can be achieved by employing the larger mode field diameter fibers in the NCPA. The results will pave the way to develop all-fiber high power femtosecond laser pulses with near FTL pulse duration and high temporal contrast ratio.

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References

1. A. Ancona, S. Döring, C. Jauregui, F. Röser, J. Limpert, S. Nolte, and A. Tünnermann, "Femtosecond and picosecond laser drilling of metals at high repetition rates and average powers," Opt. Lett. **34**, 3304 (2009).
2. J. Rothhardt, S. Hädrich, Y. Shamir, M. Tschnernajew, R. Klas, A. Hoffmann, G. K. Tadesse, A. Klenke, T. Gottschall, and T. Eidam, "High-repetition-rate and high-photon-flux 70 eV high-harmonic source for coincidence ion imaging of gas-phase molecules," Opt. Express **24**, 18133 (2016).
3. F. Röser, T. Eidam, J. Rothhardt, O. Schmidt, D. Schimpf, J. Limpert, and A. Tünnermann, "Millijoule pulse energy high repetition rate femtosecond fiber chirped-pulse amplification system," Opt. Lett. **32**, 3495 (2007).
4. T. Eidam, J. Rothhardt, F. Stutzki, F. Jansen, S. Hädrich, H. Carstens, C. Jauregui, J. Limpert, and A. Tünnermann, "Fiber chirped-pulse amplification system emitting 3.8 GW peak power," Opt. Express **19**, 255 (2011).
5. C. Zhou, "Chirped pulse amplification: review and prospective from diffractive optics," Chin. Opt. Lett. **18**, 110502 (2020).
6. A. Klenke, S. Breitkopf, M. Kienel, T. Gottschall, T. Eidam, S. Hädrich, J. Rothhardt, J. Limpert, and A. Tünnermann, "530 W, 1.3 mJ, four-channel coherently combined femtosecond fiber chirped-pulse amplification system," Opt. Lett. **38**, 2283 (2013).
7. S. Zhou, F. W. Wise, and D. G. Ouzounov, "Divided-pulse amplification of ultrashort pulses," Opt. Lett. **32**, 871 (2007).
8. T. Zhou, J. Ruppe, C. Zhu, I.-N. Hu, J. Nees, and A. Galvanauskas, "Coherent pulse stacking amplification using low-finesse Gires–Tournois interferometers," Opt. Express **23**, 7442 (2015).
9. P. Yang, T. Hao, Z. Hu, S. Fang, J. Wang, J. Zhu, and Z. Wei, "Highly stable Yb-fiber laser amplifier of delivering 32-μJ, 153-fs pulses at 1-MHz repetition rate," Appl. Phys. B **124**, 169 (2018).
10. Z. Zhang, J. Tian, C. Xu, R. Xu, Y. Cui, B. Zhuang, and Y. Song, "Noise-like pulse with a 690 fs pedestal generated from a nonlinear Yb-doped fiber amplification system," Chin. Opt. Lett. **18**, 121403 (2020).
11. D. Yan, B. Liu, Y. Chu, H. Song, L. Chai, M. Hu, and C. Wang, "Hybrid femtosecond laser system based on a Yb: KGW regenerative amplifier for NP polarization," Chin. Opt. Lett. **17**, 041404 (2019).
12. L. Kuznetsova and F. W. Wise, "Scaling of femtosecond Yb-doped fiber amplifiers to tens of microjoule pulse energy via nonlinear chirped pulse amplification," Opt. Lett. **32**, 2671 (2007).
13. L. Shah, Z. Liu, I. Hartl, G. Imeshev, G. C. Cho, and M. E. Fermann, "High energy femtosecond Yb cubicon fiber amplifier," Opt. Express **13**, 4717 (2005).
14. J. Želudevičius, R. Danilevičius, K. Viskontas, N. Rusteika, and K. Regelskis, "Femtosecond fiber CPA system based on picosecond master oscillator and power amplifier with CCC fiber," Opt. Express **21**, 5338 (2013).
15. J. Zhao, W. Li, C. Wang, Y. Liu, and H. Zeng, "Pre-chirping management of a self-similar Yb-fiber amplifier towards 80 W average power with sub-40 fs pulse generation," Opt. Express **22**, 32214 (2014).
16. W. Liu, D. N. Schimpf, T. Eidam, J. Limpert, A. Tünnermann, F. X. Kärtner, and G. Chang, "Pre-chirp managed nonlinear amplification in fibers delivering 100 W, 60 fs pulses," Opt. Lett. **40**, 151 (2015).
17. S. Zhou, L. Kuznetsova, A. Chong, and F. W. Wise, "Compensation of nonlinear phase shifts with third-order dispersion in short-pulse fiber amplifiers," Opt. Express **13**, 4869 (2005).
18. H. Kalaycioglu, B. Oktem, Ç. Şenel, P. Paltani, and F. Ilday, "Microjoule-energy, 1 MHz repetition rate pulses from all-fiber-integrated nonlinear chirped-pulse amplifier," Opt. Lett. **35**, 959 (2010).
19. M. Fermann, V. Kruglov, B. Thomsen, J. Dudley, and J. Harvey, "Self-similar propagation and amplification of parabolic pulses in optical fibers," Phys. Rev. Lett. **84**, 6010 (2000).
20. S. Wang, B. Liu, C. Gu, Y. Song, C. Qian, M. Hu, L. Chai, and C. Wang, "Self-similar evolution in a short fiber amplifier through nonlinear pulse preshaping," Opt. Lett. **38**, 296 (2013).
21. J. Huh and J. Azaña, "Generation of high-quality parabolic pulses with optimized duration and energy by use of dispersive frequency-to-time mapping," Opt. Express **23**, 27751 (2015).
22. H. Song, B. Liu, Y. Li, Y. Song, H. He, L. Chai, M. Hu, and C. Wang, "Practical 24-fs, 1-μJ, 1-MHz Yb-fiber laser amplification system," Opt. Express **25**, 7559 (2017).
23. H. Chang, Z. Cheng, R. Sun, Z. Peng, M. Yu, Y. You, M. Wang, and P. Wang, "172-fs, 27-μJ, Yb-doped all-fiber-integrated chirped pulse amplification system based on parabolic evolution by passive spectral amplitude shaping," Opt. Express **27**, 34103 (2019).
24. W. Fu, Y. Tang, T. S. McComb, T. L. Lowder, and F. W. Wise, "Limits of femtosecond fiber amplification by parabolic pre-shaping," J. Opt. Soc. Am. B **34**, A37 (2017).
25. D. Luo, Y. Liu, C. Gu, Z. Zhu, Z. Deng, L. Zhou, Y. Di, G. Xie, and W. Li, "130 W, 180 fs ultrafast Yb-doped fiber frequency comb based on chirped-pulse fiber amplification," Opt. Express **28**, 4817 (2020).