

High-Power 770 nm Femtosecond Laser Based on Spectral Pre-Modulated 1540 nm Fiber Laser with Nonlinear Compression

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Abstract

We demonstrate an 80 MHz, 350 mW, 120 fs, 770 nm femtosecond laser based on a nonlinear compressed 1540 nm femtosecond fiber laser. The home-built 1540 nm fiber laser, delivering 80 MHz, 2.69 W, 269 fs laser pulses, was realized by employing spectral pre-modulation and pre-chirp management inside an Er/Yb co-doped fiber power amplifier. The subsequent nonlinear fiber pulse compression stage was utilized to further nonlinearly compress the pulse duration to 128 fs based on the Gaussian assumption. Detailed numerical simulation was also implemented to investigate the optical dynamics of the nonlinear compression process. Finally, a 0.5 mm thick fan-out periodically poled lithium niobate (PPLN) crystal was utilized to generate the frequency-doubled, 350 mW, 770 nm laser pulses with a 120 fs pulse duration based on the Gaussian assumption.

Keywords: 770 nm femtosecond laser; spectral pre-modulation; nonlinear chirped-pulse amplification; nonlinear compression; second-harmonic generation

1. Introduction

Femtosecond lasers operating around 780 nm are widely applied in state-of-the-art research fields, such as multiphoton microscopy (MPM) [1–3], nonlinear micro/nano-fabrication [4–7], terahertz (THz) wave generation [8], and vortex-excited unidirectional luminescence control [9]. In previous decades, titanium-sapphire (Ti:sapphire) lasers played a key role in providing the required ultrafast light source operating around 780 nm, thanks to their perfect characteristics of having high power, hundred-femtosecond pulse duration, and wavelength tunability [1,10,11]. However, the environmental sensitivity induced by free-space construction, the water-cooling requirements, bulky footprints, and high cost seriously restricted the advanced applications of the Ti:sapphire laser [10,11].

Frequency doubling a high-power 1560 nm femtosecond fiber laser to generate a high-power 780 nm femtosecond laser has proved to be an effective approach with high system stability, air cooling, compact footprints, and low cost [12–18]. The large-mode-area (LMA) Er/Yb co-doped double-clad (DC) fiber enables watt-level average power scaling of the 1560 nm fiber laser based on the chirped-pulse amplification (CPA) [12–14]; however, the limited gain bandwidth of this gain fiber induces severe spectral gain narrowing inside the fiber amplifier, making it difficult to achieve compressed 1560 nm laser pulses with



Received: 6 May 2026

Revised: 19 June 2026

Accepted: 23 June 2026

Published: 26 June 2026

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a sub-200 fs pulse duration. Considering the negative dispersion of the fused silica fiber at 1.5 μm , nonlinear self-compression can be employed to deliver nonlinear compressed laser pulses with a hundred-femtosecond pulse duration after carefully managing the conjugation between the self-phase modulation (SPM) and negative dispersion inside the fiber [15–17]. Ref. [17] reported 27 fs, 220 mW, 1560 nm laser generation based on the nonlinear self-compression inside a single-mode fiber (SMF) with negative group velocity dispersion (GVD). Further power scaling can be seriously restricted by the stimulated Raman scattering (SRS) inside the SMF with its small core diameter, which can induce pulse splitting [19]. Ref. [20] reported high-power nonlinear self-compression results with the LMA Er/Yb co-doped DC fiber, delivering a 187 fs, 2.3 W, 1560 nm fiber laser. Due to the significant gain narrowing inside the DC gain fiber, further high-power, hundred-femtosecond 1560 nm laser pulses cannot simply be achieved by managing the SPM and fiber dispersion. Based on the aforementioned approaches, it is difficult to simultaneously realize a 1560 nm fiber laser with high average power and hundred-femtosecond pulse duration. Therefore, in order to generate the 780 nm femtosecond laser with these qualities based on second-harmonic generation (SHG), it is still necessary to conduct investigations into realizing a novel and more practical approach for generating the required high-power 1560 nm femtosecond laser pulses [12–18,20].

Investigations into ultrafast fiber optics over the past decades provide an effective approach for precisely modulating the optical spectrum and managing optical chirp [19–22], making it feasible to generate the required high-power 1560 nm femtosecond fiber laser. The spectral gain-narrowing and optical coherence degradation inside the Er/Yb co-doped fiber amplifier can be significantly inhibited by pre-modulating the spectrum of the 1560 nm signal laser [23]. Through carefully managing the conjugation between the SPM and negative dispersion inside the Er/Yb co-doped fiber amplifier, an optimized high-power 1560 nm femtosecond laser pulse can be achieved after compression [21,22]. A further shorter pulse duration of the high-power 1560 nm signal laser can be realized by employing nonlinear fiber compression, which is achieved by managing the SPM process inside the non-zero dispersion-shifted fiber and compensating for the optical chirp with bulk material. Furthermore, the high-power 780 nm laser with a hundred-femtosecond pulse duration can finally be achieved by utilizing the fan-out PPLN crystal based on the broadband quasi-phase-matched SHG.

In this work, we report on an 80 MHz, 350 mW, 120 fs, 770 nm femtosecond laser, which is based on a spectral pre-modulated 1540 nm femtosecond fiber laser with nonlinear fiber compression. Spectral pre-modulation and pre-chirp management were employed inside a nonlinear chirped-pulse Er/Yb co-doped fiber amplifier, thereby realizing the 80 MHz, 2.69 W, 269 fs, 1540 nm signal laser after compression. Based on the SPM-induced nonlinear spectral broadening, the nonlinear fiber compressor was utilized to further compress the pulse duration of the 1540 nm signal laser to 128 fs, which was based on the Gaussian assumption. The measured optical power stability of the delivered 1.17 W, 128 fs, 1540 nm signal laser was 0.57% at 30 min. A 0.5 mm thick fan-out PPLN crystal was subsequently utilized to generate the 120 fs, 770 nm frequency-doubled laser pulses with an average power of 350 mW. To our knowledge, this is the first time in which the cascaded stages of a nonlinear chirped-pulse amplifier (NCPA), nonlinear fiber compressor, and SHG have been utilized to generate a high-power, hundred-femtosecond signal laser operating around 780 nm, providing an effective illumination laser source for the aforementioned applications.

2. Experimental Setup

The schematic construction of the 770 nm femtosecond laser system is shown in Figure 1, consisting of a mode-locked fiber oscillator, a nonlinear fiber pre-amplifier, a free-space spectral pre-modulator, a fiber stretcher, an Er/Yb co-doped fiber power amplifier, a grating-pair compressor, a nonlinear compressor, and an SHG stage. The home-built 80 MHz Er-doped fiber oscillator was realized with a nonlinear amplifying loop mirror (NALM) delivering the 5.1 mW, mode-locked, 1560 nm signal laser. The nonlinear fiber pre-amplifier was realized with a combination of a fiber pre-chirper, an Er-doped fiber amplifier and a nonlinear fiber compressor. The 5 m PM1550 fiber ($\beta_2 \approx -22.96 \text{ fs}^2/\text{mm}$, Coherent, Saxonburg, PA, USA) was utilized to provide the -0.1148 ps^2 group delay dispersion (GDD) needed to realize the nonlinear amplification process inside the subsequent Er-doped fiber amplifier. The 3.6 m polarization-maintaining (PM) Er-doped fiber (DHB1500, $\beta_2 \approx 30.61 \text{ fs}^2/\text{mm}$, Newport, Irvine, CA, USA) was utilized as the gain medium for the nonlinear fiber pre-amplifier to scale up the average power of the signal laser to 374 mW, pumped with two 950 mW, 976 nm SMLDs. The 1.55 m PM1550 fiber with negative dispersion was further employed to introduce the nonlinear spectral broadening process based on the enhanced SPM [24], ensuring a sufficient broadband spectrum for the subsequent spectral modulator. The cascaded combination of the half-wave plates and the isolator was utilized to prevent potential backward reflection from the spectral modulator.

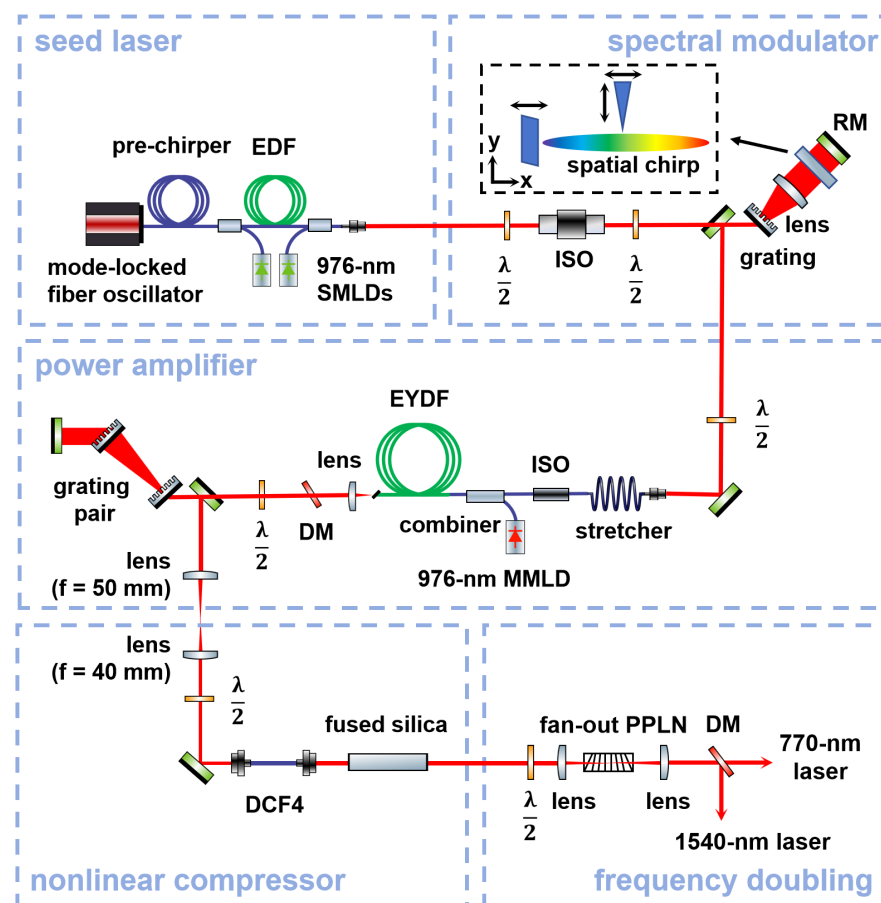


Figure 1. Schematic construction of the high-power, 770 nm femtosecond laser system. EDF: erbium-doped fiber; WDM: wavelength division multiplexer; SMLDs: single-mode laser diodes; MMLD: multi-mode laser diode; EYDF: Er/Yb co-doped fiber; DM: dichroic mirror; ISO: isolator; RM: reflecting mirror; PPLN: periodically poled lithium niobate.

The pre-amplified signal laser was subsequently injected into a spectral modulator based on the 4-f optical system. This modulator consists of a transmission grating (1000 lines/mm, LightSmyth, Eugene, OR, USA), a 40 mm focal length plano-convex lens, a home-built multi-dimensional spectral clipper, and a high-reflection mirror. The injected laser beam was diffracted by the grating, introducing significant spatial chirp in the horizontal (x) direction. The spatially chirped beam was then recollimated by the lens inside the 4-f optical system. A combination of the spectral clipper and the conical mask was utilized as the multi-dimensional spectral clipper to modulate the spatially chirped laser beam, with the specific spectral shaping mechanism illustrated in detail within the black dashed rectangle of Figure 1. The horizontal (x) modulation realized with the clipper was utilized to clip the short-wavelength contents with degraded coherence induced inside the fiber pre-amplifier [23], while the vertical (y) modulation realized with the conical mask was utilized to finely modulate the spectral formation inside the optical fiber, leading to a compensable spectral phase condition [24].

The spectrally modulated signal laser was re-coupled into the length-optimized 17 m PM2000D ($\beta_2 \approx 64 \text{ fs}^2/\text{mm}$, Coherent, Saxonburg, PA, USA) dispersion compensation fiber to realize NCPA inside the subsequent Er/Yb co-doped fiber power amplifier. The pulse duration was increased from 2 ps to approximately 50 ps based on the Gaussian assumption, and the stretched signal laser was further injected into the Er/Yb co-doped fiber power amplifier to scale the average power up to 3.57 W. The fiber power amplifier consisted of the 1.8 m PM Er/Yb co-doped double-clad fiber (PM-EYDF-12/130-HE, Nufern, East Granby, CT, USA) with a core diameter of 12 μm ; a PM fiber combiner; and a 16 W, 976 nm MMLD. The optical power of the amplified signal laser decreased to 2.69 W after being compressed by the transmission-grating-pair compressor (1000 lines/mm, LightSmyth, Eugene, OR, USA), with a compression efficiency of 75%. A home-built telescope consisting of two plano-convex lenses with focal lengths of 50 mm and 40 mm was utilized to optimize the mode-matching condition between the delivered laser beam and the non-zero dispersion-shifted fiber (DCF4, $\beta_2 \approx 5.1 \text{ fs}^2/\text{mm}$, Thorlabs, Newton, NJ, USA) of the nonlinear compressor. A 5 cm DCF4 fiber was utilized to realize the nonlinear spectral broadening of the injected signal laser. A 17 cm long high-purity fused silica block ($\beta_2 \approx -29.1 \text{ fs}^2/\text{mm}$, Casteck, Fuzhou, Fujian, China) was further employed to compensate for the accumulated optical chirp during the nonlinear spectral broadening process. The SHG stage consisted of a half-wave plate, a plano-convex lens with a 15 mm focal length, a 0.5 mm thick fan-out PPLN crystal, and a plano-convex lens with a 25 mm focal length. The fan-out PPLN crystal poling period ranged from 18.0 μm to 20.8 μm , ensuring broadband second harmonic generation of the 1540 nm signal laser. A dichroic mirror was utilized to separate the frequency-doubled 770 nm laser from the residual 1540 nm signal laser.

3. Results and Discussion

Figure 2 illustrates the measured optical characteristics of the signal lasers delivered by the home-built, stretched-pulse, mode-locked oscillator and the nonlinear fiber pre-amplifier. The output spectrum of the 80 MHz, 5.1 mW signal laser delivered by the fiber oscillator was centered at 1555 nm and the corresponding measured spectral bandwidth was 42.6 nm. Based on the designed dispersion compensation inside the fiber pre-amplifier, the nonlinearly amplified 1555 nm signal laser was further compressed inside the subsequent fiber compressor built with the 1.55 m PM1550 fiber. The optical power of the amplified signal laser was significantly transferred to the blue and red sides of the nonlinearly broadened spectrum inside the fiber compressor based on the conjugation between the SPM and the negative GVD of the PM1550 fiber, as shown in Figure 2c. The measured spectral bandwidth of the dual-peak spectrum was broadened to 67 nm and the corresponding

measured pulse duration was 2 ps, based on the Gaussian assumption, as shown in Figure 2d. The condition of the optical pulse train is also shown in Figure 2b, measured with a photodetector (15 GHz bandwidth, EOT) and oscilloscope (1 GHz bandwidth, Tektronix). The measured temporal pulse interval was 12.5 ns, with peak-to-peak intensity fluctuations of 3%.

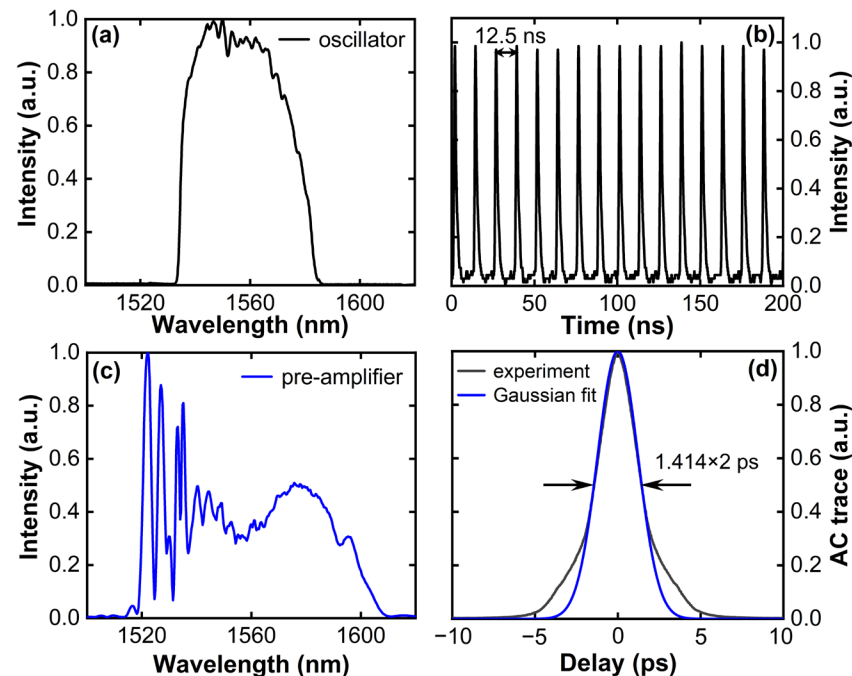


Figure 2. (a) Optical spectrum and (b) pulse train of the mode-locked laser pulses; (c) optical spectrum and (d) auto-correlation trace of the nonlinearly pre-amplified pulses with Gaussian fit (blue curve), indicating a pulse duration of 2 ps.

Figure 3 demonstrates the measured spectra and the corresponding auto-correlation traces delivered by the spectral modulator, the fiber stretcher, and the power amplifier. Detailed investigations regarding spectral pre-modulation were implemented to realize the high-power 1540 nm femtosecond laser with an optimized optical pulse profile, delivered by the NCPA system. The optical chirp accumulated via propagating through the optical fiber can be carefully modified by managing the intensity distribution of the spectral contents [24]. The conical mask illustrated in Figure 1 was employed to carefully modify the optical chirp condition of the signal pulses, ensuring that the accumulated nonlinear phase shift and optical dispersion could be finally compensated by the grating-pair compressor. Furthermore, the mismatch between the gain spectrum of the fiber amplifier and the optical spectrum of the signal laser can lead to the degradation of optical coherence [23], leading to the uncompensated pedestals of the compressed signal pulses. The short-wavelength clipper illustrated in Figure 1 was employed to remove the short-wavelength contents with degraded coherence induced inside the fiber pre-amplifier; therefore, the nonlinearly broadened spectrum delivered by the fiber stretcher can be realized with improved coherence based on the SPM. The coherent stretched signal pulses can sufficiently extract the optical gain provided by the Er/Yb co-doped fiber amplifier, ensuring a favorable optical phase condition. However, due to the mismatch between the spectrum of the signal laser and the gain spectrum of the Er/Yb co-doped gain fiber inside the fiber power amplifier, coherence degradation can still be induced at the short-wavelength region, leading to the uncompensated pedestals.

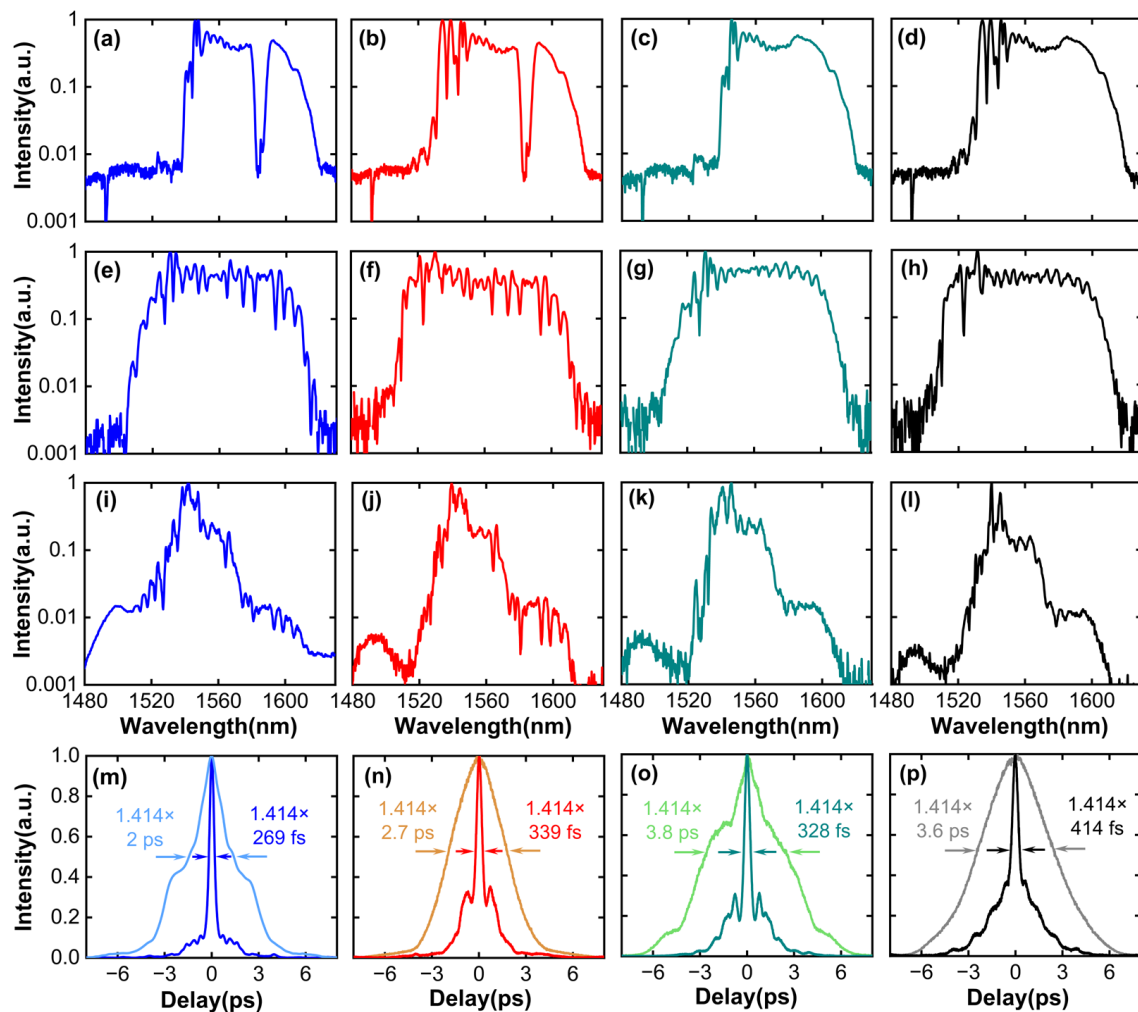


Figure 3. Optical spectra delivered by the spectral modulator, fiber stretcher, and power amplifier under different spectral modulation conditions: (a,e,i) modulated with the spectral clipper and the conical mask; (b,f,j) with the conical mask; (c,g,k) with the spectral clipper; (d,h,l) without modulation. The corresponding auto-correlation traces delivered by the fiber stretcher and the power amplifier under different spectral modulation conditions: (m) modulated with the spectral clipper and the conical mask; (n) with the conical mask; (o) with the spectral clipper; (p) without modulation.

Figure 3a–d illustrate the measured optical spectra obtained by modulating the nonlinearly pre-amplified spectra with or without the spectral clipper and the conical mask. The central wavelength of the conical mask was set at 1583 nm with a full width at half maximum (FWHM) of 9.4 nm, while the short-wavelength components below 1537 nm were truncated by the clipper. Through combined modulation of the conical mask and the clipper, the pulse duration at the spectral modulator output was 2 ps based on the Gaussian assumption. As shown in Figure 3e–h, significant nonlinear spectral broadening processes were induced inside the fiber stretcher by the SPM. The corresponding measured spectral bandwidths were 72 nm, 76 nm, 67 nm, and 76 nm, respectively, indicating the residual coherence-degraded spectral contents, as shown in Figure 3f,h. Figure 3i–l illustrate the measured spectra delivered by the fiber power amplifier. Furthermore, deeper modulation ripples can be observed on the amplified spectra pre-modulated with the conical mask, as shown in Figure 3i,j, indicating a different optical chirp accumulation efficiency compared with the pre-modulation conditions without the conical mask.

Figure 3m–p illustrate the measured auto-correlation traces delivered by the power amplifier, and the optimized compression result is shown in Figure 3m with a pulse

duration of 269 fs, based on the Gaussian assumption. The residual pedestals shown in Figure 3m were caused by the newly generated coherence-degraded spectral contents in the short-wavelength region during the power amplification process. As shown in Figure 3n,p, the coherence-degraded spectral contents consumed the large amounts of optical gain provided by the Er/Yb co-doped fiber, leading to the significant pedestals. Significant improvements were achieved by pre-modulating the spectrum of the signal laser with the spectral clipper and the conical mask, indicating a conjugation condition between the accumulated nonlinear phase shift and the dispersion.

The output average powers delivered by the grating-pair compressor are illustrated in Figure 4 as a function of the coupled 976 nm multi-mode pump power. The corresponding calculated slope efficiencies were approximately 17% and were nearly the same under different spectral modulation conditions. The average power of the signal laser could be scaled up to a maximum of 2.69 W with the optimized spectral pre-modulation after being compressed by the grating-pair compressor. The minor differences in the maximum amplified average power were caused by the signal power differences introduced by the spectral pre-modulation. The linear increasing tendency of the amplification curves indicates a potential power-scaling capability.

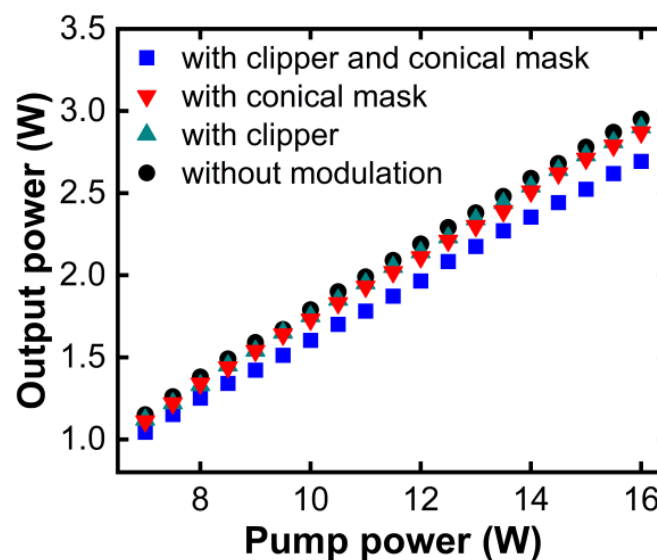


Figure 4. Comparison of the 1540 nm pulse output power from the power amplifier under different spectral modulation conditions.

The output characteristics of the nonlinear compressed signal pulses are illustrated in Figure 5. The compressed 1540 nm signal laser was coupled into the 5 cm DCF4 fiber with significant nonlinear spectral broadening achieved, as shown in Figure 5a. The corresponding spectral bandwidth was broadened to 36 nm, indicating a calculated Fourier transform-limited pulse duration of 87 fs, though after compression with the 17 cm fused silica block this value was 128 fs based on the Gaussian assumption, which is 1.47 times the calculated Fourier transform-limited pulse duration. The measured optical power stability of the nonlinearly compressed 1.17 W, 1540 nm pulses was 0.57% at 30 min, indicating good operating stability for practical applications. A further shorter pulse duration of sub-60 fs can also be achieved by enhancing the nonlinear spectral broadening process.

Numerical simulation was implemented to investigate the nonlinear pulse evolution dynamics inside the DCF4 fiber. A numerical simulation model based on the generalized nonlinear Schrödinger equation (GNLSE), considering the optical loss, optical dispersion, SPM, self-steepening, and SRS, was constructed [25,26]. The simulated spectrum and the

corresponding calculated auto-correlation traces of the nonlinearly compressed pulses are shown in Figure 6. The numerically simulated spectrum is in good agreement with the experimental result, confirming the effective optical chirp management. Figure 6b,c illustrate the calculated auto-correlation traces before and after the fused silica block, which perfectly match the experimental results, indicating that an effective nonlinear compression process was realized with this home-built nonlinear fiber compression stage.

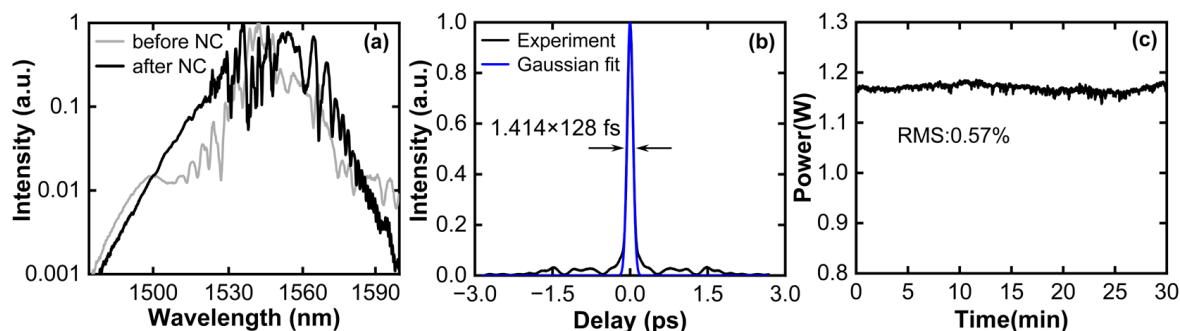


Figure 5. (a) Optical spectra before (light black) and after (dark black) the nonlinear compression (NC) stage; (b) the corresponding auto-correlation trace and the Gaussian fitting curve (blue); (c) power stability delivered by the 17 cm fused silica block.

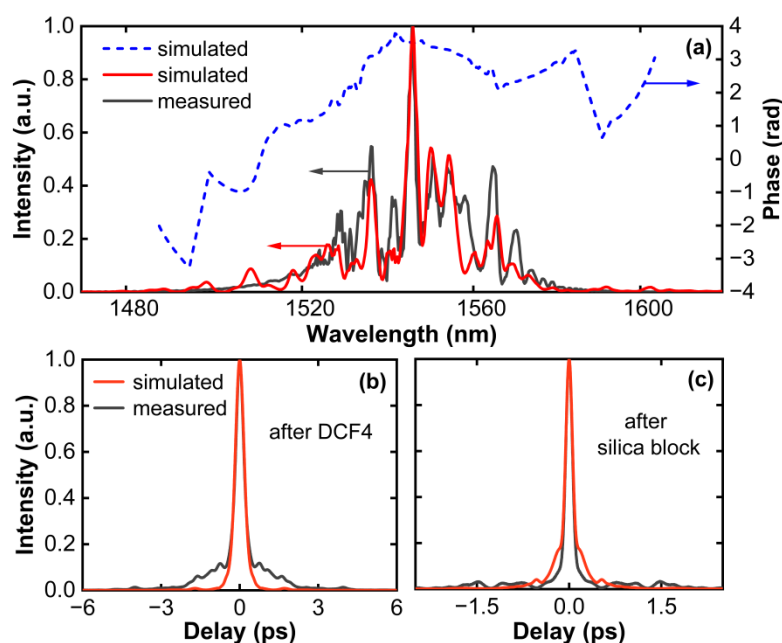


Figure 6. (a) The simulated spectrum (red), the simulated spectral phase (blue), and the measured optical spectrum (black) at the output of the 5 cm DCF4 fiber; (b) the simulated (red) and measured (black) auto-correlation traces at the output of the 5 cm DCF4 fiber; (c) the simulated (red) and measured (black) auto-correlation traces after propagating through the 17 cm fused silica block.

Figure 7 shows the measured spectra and the corresponding auto-correlation traces of the 770 nm pulses delivered by the SHG stage. The nonlinearly compressed 1540 nm pulses were injected into the 0.5 mm thick fan-out PPLN crystal, delivering the 120 fs, 350 mW, 770 nm pulses, with an SHG conversion efficiency of 30%. The fan-out PPLN features the continuously varying poling period ranging from 18.0 μm to 20.8 μm . By carefully adjusting the position of the crystal, a favorable broadband phase-matching condition was achieved. In order to further increase SHG conversion efficiency, a thickness of 0.5 mm for the PPLN crystal was selected to suppress the temporal walk-off effect inside the crystal.

The focal length of the focusing lens was also optimized to generate a sufficient optical power density without inducing severe thermal effects inside the crystal [27]. The measured optical power stability of the 770 nm laser was 1.31% at 30 min.

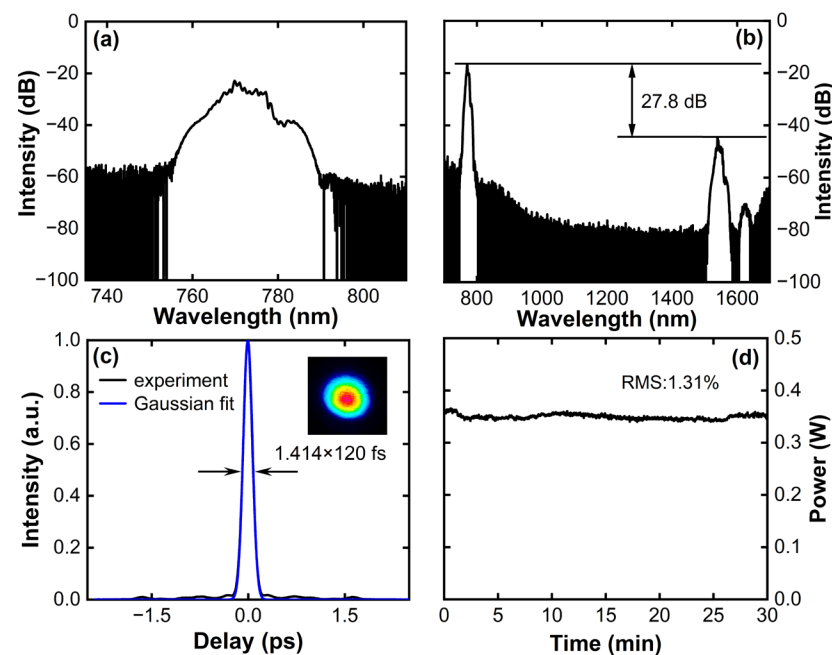


Figure 7. The measured output characteristics of the 770 nm laser after propagating through the dichroic mirror: (a,b) spectra with different scanning ranges; (c) auto-correlation trace with Gaussian fit (blue) and spatial beam profile (inset); (d) power stability.

Table 1 summarizes the comparison between this work and previous reports of femtosecond fiber lasers operating around 780 nm in terms of structure and performance. It can be seen that a high-power, hundred-femtosecond fiber laser operating around 780 nm can be efficiently achieved based on the cascaded stages of the spectral modulated NCPA, nonlinear fiber compressor, and SHG.

Table 1. Comparison of system structure and output parameters for femtosecond fiber lasers operating around 780 nm.

Ref	Structure	Repetition Rate (MHz)	Pulse Duration (fs)	Average Power (mW)
2024-[12]	CPA/NCPA + SHG	1.03	620 (sech ²)	460
2024-[13]		111.5	288 (sech ²)	2220
2015-[14]		85	520 (Gaussian)	880
2019-[16]		40	<50	140
2019-[20]		49	183 (sech ²)	1100
2012-[17]	Nonlinear self-compression + SHG	80	32 (Gaussian)	61
2010-[18]		80	55 (Gaussian)	172
This work	Spectral modulated NCPA + nonlinear compression + SHG	80	120 (Gaussian)	350

4. Conclusions

In conclusion, we report on an 80 MHz, 350 mW, 120 fs, 770 nm femtosecond laser, based on a spectral pre-modulated 1540 nm femtosecond fiber laser with nonlinear fiber compression. Spectral pre-modulation and pre-chirp management were employed in the nonlinear chirped-pulse Er/Yb co-doped fiber amplifier, realizing the 80 MHz, 2.69 W, 269 fs, 1540 nm signal laser after compression. The spectral gain narrowing and optical

coherence degradation inside the fiber amplifier were significantly suppressed by pre-modulating the spectrum of the 1540 nm signal laser. By carefully managing the conjugation between the SPM and negative dispersion inside the Er/Yb co-doped fiber amplifier, the optimized high-power 1540 nm femtosecond laser pulse was achieved after compression. Based on the SPM-induced nonlinear spectral broadening, the nonlinear fiber compressor was utilized to further compress the pulse duration of the 1540 nm signal laser to 128 fs, based on the Gaussian assumption. The measured optical power stability of the delivered 1.17 W, 128 fs, 1540 nm signal laser was 0.57% at 30 min. Detailed numerical simulation was also implemented to investigate the optical dynamics of the nonlinear compression process, indicating effective optical chirp management. A 0.5 mm thick fan-out PPLN crystal was subsequently utilized to generate the 120 fs, 770 nm frequency-doubled laser pulses with the average power of 350 mW. Delivering the hundred-femtosecond pulses operating around 780 nm, the high-power signal laser provides an effective illumination laser source for the aforementioned applications.

Author Contributions: Conceptualization, H.W. and Y.L.; methodology, K.G.; software, H.W.; validation, H.W., H.X., K.G., and X.Z.; investigation, H.W. and K.G.; resources, Y.L.; data curation, H.W.; writing—original draft preparation, H.W.; writing—review and editing, K.G., Z.Y., and Y.L.; visualization, H.W.; supervision, K.G., A.W., and Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 62305186.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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