Self-similar evolution in a short fiber amplifier through nonlinear pulse preshaping

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We report on a nonlinear preshaper that optimizes initial pulses for self-similar evolution in a next fiber amplifier. It consists of a pair of gratings and a segment of single-mode fiber (SMF). The grating pair provides negative chirp to make the pulses preshaped temporally and spectrally in the SMF. With this optimization, the self-similar amplification can be realized in a 2.2 m Yb-doped fiber in a large range of pump power. After amplification, the pulse can be dechirped to transform-limited pulses with ~60 fs pulse duration.

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Femtosecond lasers are playing a more and more important role in both fundamental science and industrial applications. Apart from high peak power, femtosecond fiber lasers show many advantages over bulk solid-state lasers, including high average power, compactness, and low cost [1]. To improve the performance of femtosecond fiber laser systems, there are two kinds of amplification structures: chirped-pulse amplification (CPA) and nonlinear amplification [2]. To scale up pulse energy, the CPA technique is always applied. However, due to the bandwidth limitation of gain fibers, the pulse is hardly shorter than 100 fs, which limits their applications. To obtain a sub-100 fs pulse, nonlinear amplification is demonstrated. With this scheme, the bandwidth of pulses can be expanded to nearly 50 nm to support ~50 fs pulses by self-phase modulation (SPM) during amplification [3,4]. But it always evokes nonlinear pulse distortions. To overcome this drawback, cubicons and self-similaritions are exploited in nonlinear amplification. The cubicon amplification applies third-order dispersion accumulated in a stretcher and compressor to compensate nonlinear chirp produced in the amplification stage [5,6]. Unfortunately, it is difficult to realize perfect match to promise linear chirp, so output pulses are scarcely dechirped to transform-limited (TL) ones [7].

Contrary to the cubicon amplification, the self-similarition in a normal-dispersion fiber amplifier can supply linear chirp, which leads to highly efficient pulse compression for nearly sub-100 fs TL pulses. According to the similarity theory [8], the asymptotic behavior for a given amplifier is only determined by the initial pulse energy, and the rate of evolution depends strongly on the input pulse duration and temporal shape [9]. In previous research, a long rare earth doped fiber was always required to complete the parabolic evolution. But the long gain fiber length might induce stimulated Raman scattering in amplification, which limits the output energy, disturbs the linear chirp, and degrades the quality [10]. So it is better to achieve self-similar amplification in a short gain fiber. Moreover, the evolution is also in relationship with the spectral bandwidth and the shape of initial pulses. So how to optimize initial pulses to accelerate the evolution and obtain high-quality dechirped pulses after compression is an important problem to solve [11,12]. Furthermore, as the parameters of seed pulses from the oscillator are almost fixed, there is only one optimal pump power for self-similar evolution due to the inversion-ratio-determined gain spectral profile [13]. The deviation from it will degrade the dechirped pulse quality [4].

To reduce the length of the gain fiber avoiding Raman scattering and to relieve the sensitivity of pulse quality to pump power, we report a passive nonlinear pulse preshaping method in this Letter. With this method, the initial pulses are optimized before amplification temporally and spectrally for a fast self-similar evolution in the next amplifier and TL pulses after compression over a large range of pump power. This nonlinear preshaper includes a pair of gratings and a segment of single-mode fiber (SMF). A similar structure has been demonstrated to produce ps TL pulses directly without compression after the amplifier [14]. The gratings supply negative prechirp for pulses from the oscillator, and then they are compressed and preshaped in the temporal and spectral domains when propagating in the SMF [15]. By adjusting the amount of prechirp imposed by the gratings, the pulse duration, bandwidth, and spectral shape of the output pulse from SMF are optimized via the interplay between SPM and group-velocity dispersion (GVD) for the next self-similar amplification. With this method, the self-similar evolution was completed in only ~2 m Yb-doped fiber and the adjustable nonlinear preshaping made sure of optimal parameters over a large range of pump power in the experiment. Meanwhile, the preshaper can lower the restriction to pulse profile of seed pulses from the oscillator for self-similar evolution [12]. Although an ANDi mode-locked fiber laser outputs pulses with a typical asymmetric, highly structured, and steep-edge spectrum, it can be used as a seed source for self-similar amplification after preshaping by this scheme. Above all, the nonlinear preshaper promises the linear chirp in self-similar amplification and TL-dechirped pulses with ~60 fs pulse duration.

A schematic of the experimental setup is shown in Fig. 1. The oscillator is an ANDi mode-locked Yb-doped

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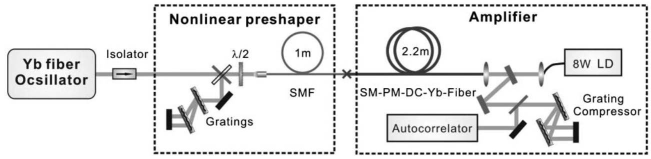

Fig. 1. Schematic of the experimental setup. LD, laser diode and DM, dichroic mirror.

fiber laser, which outputs 1 ps pulses with 15 nm bandwidth around 1040 nm at 48 MHz repetition rate. The pulses can be compressed to 140 fs [the autocorrelation (AC) trace and spectrum are shown in Fig. 2(a)]. The nonlinear preshaper is composed of a 1200 lines/mm transmission grating pair and a 1 m long SMF. The average power is ~60 mW before coupled into the amplifier. The amplifier consists of a 2.2 m single-mode polarization-maintaining double-cladding ytterbium fiber (SM-PM-DC-Yb-fiber), whose core diameter is 11 μm. Its bow-tie configured stress elements promise a 17 dB polarization extinction ratio. One end of the gain fiber is spliced to the SMF pigtail (1% fusion loss). The other end is fused and polished at 8° to suppress parasitic lasing. The amplifier is counterdirectionally end-pumped by an 8 W pump laser diode emitting at 976 nm. The output pulses were compressed by a 600 lines/mm grating pair with 4 bounce configuration (64% efficiency).

In the nonlinear preshaper, the negative prechirped pulses are not only compressed temporally due to the positive GVD of the SMF, but also narrowed and tailed spectrally by interplaying with SPM. The initial pulse duration is the most important and sensitive parameter to accelerate the self-similar evolution [9], which can be optimized by the preshaper precisely. Meanwhile, the spectrum is compressed, which makes a narrower bandwidth to avoid spectrally expanding over gain bandwidth in evolution [10]. Furthermore, the spectral ripple, which is harmful to self-similar evolution, is effectively suppressed. These two spectral optimizations mainly promise the linear chirp after self-similar amplification and high-quality dechirped pulses after compression. In the experiment, appropriate preshaping was judged by the pulse duration and the quality of the AC trace of the dechirped pulse out of the amplifier.

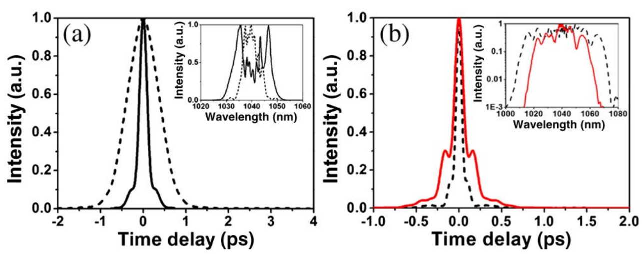

Fig. 2. (Color online) Experimental results of the oscillator and numerical simulation results. (a) The black solid curves are the AC trace and the spectrum of the dechirped pulse output from the oscillator in experiment. The black dashed curves, the simulation results, are the AC trace and the spectrum of the pulse output from SMF. (b) The simulation results of spectra and AC traces after compression are presented. The black dashed curves are the AC and the spectrum of the dechirped pulse with optimization of the preshaper. The red solid curves are for pulses without optimization.

We first simulate pulse evolutions in the nonlinear preshaper and amplifier employing the measured pulse spectrum [solid curve in the inset of Fig. 2(a)] of the ANDi fiber laser as an input. And the prechirp was the same as in experiment; the pulse was simulated to stretching to ~1 ps with a negative chirp. After that, the split-step Fourier algorithm was applied to solve the extended nonlinear Schrödinger equation. The AC trace and the spectrum of pulses out of the nonlinear preshaper are shown in Fig. 2a. It is obvious that the spectrum is narrowed and reshaped after the SMF. In the simulation of the amplifier, the gain is described by homogeneously broadened two-level rate equations and the power propagation equations model. The emission cross section $\sigma_{21}(\nu)$ and absorption cross section $\sigma_{12}(\nu)$ in the model are derived from the data in [13]. After amplification, the pulses were dechirped by the grating pair in the simulation, with the AC trace and spectrum shown in Fig. 2b. To confirm the benefit of nonlinear preshaping for the self-similar evolution, the same amplification without nonlinear preshaping was simulated for comparison. The pulse from the oscillator was firstly positively chirped to the same temporal shape with the pulse out of the nonlinear preshaper (dashed curve in Fig. 2a), and then was directly coupled into the amplifier in the absence of SMF. Under the same pump power, the AC trace and spectrum of the dechirped pulse are shown in Fig. 2b (red curves). From comparison, pulses optimized by the nonlinear preshaper show shorter pulse duration, less pedestal, and broader spectrum after amplification and compensation. So it is demonstrated that the nonlinear preshaping can benefit the self-similar evolution in the following amplifier.

We conducted the experiment based on the simulation results. The rapid parabolic pulse evolution can be realized under various pump power levels by optimizing the seed pulse parameters in the preshaper stage. In the experiment, the negative chirp provided by the grating pair before the SMF is optimized under different pump power to get high-quality compressed pulses. The optimal pulse duration and spectrum of pulses out from the SMF make the amplification of pulses quickly evolve into the parabolic pulse regime, although the pump power is changed. As seen in Fig. 3, the PICASO-retrieved dechirped pulse profiles are almost the same as the TL pulse profile assuming a flat spectral phase, when the pump power changes from 2.9 to 7.2 W. This reveals the high linearity

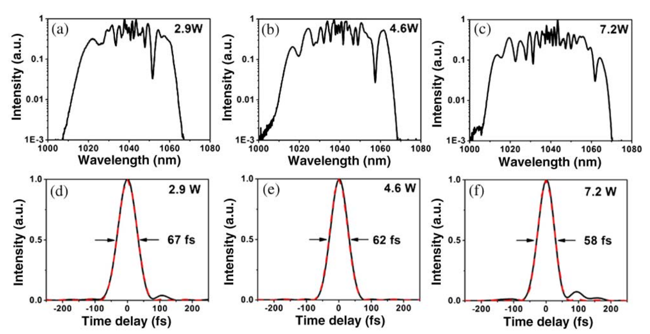

Fig. 3. (Color online) Results of pulses amplified by different pump power. (a)–(c) Output spectrum and (d)–(f) pulse shape retrieved by PICASO algorithm (black curves) and corresponding transmitted limited pulses (red dashed curves).

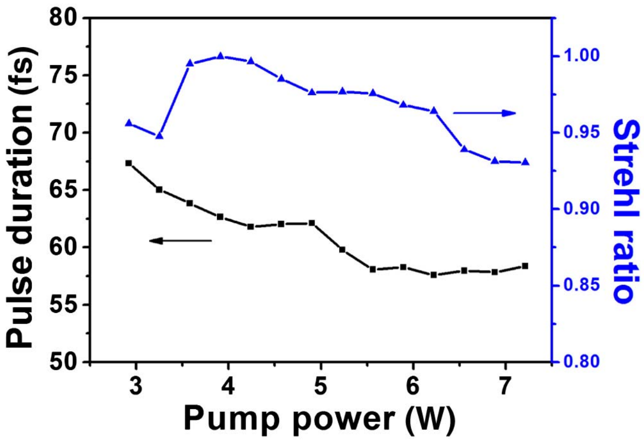

Fig. 4. (Color online) Pulse duration and Strehl ratio of the dechirped pulse versus pump power.

of the chirp before compression, the typical characteristic of parabolic pulses. To be mentioned, the most excellent compression is achieved producing 60 fs TL pulses with nearly no pedestal under 4.6 W pump power. When pump power deviates from 4.6 W, the pulses show little pedestal compared with the TL ones.

To analyze semi-quantitatively, the Strehl ratio is employed to evaluate the pulse temporal quality. The Strehl ratio and FWHM duration evolutions versus pump power are summarized in Fig. 4. It is shown that the FWHM duration decreases monotonically with increasing pump power from 3 to 5.5 W, owing to the SPM-induced spectral broadening. When the pump power is higher than 5.5 W, the gain narrowing effect becomes more serious and limits spectral broadening. As a result, the spectrum and pulse duration do not change much. However, the Strehl ratio shows a different evolution from the FWHM duration. The rise of the Strehl ratio represents the pulses evolving to parabolic pulses more completely in the gain fiber with the increased pump power from 2.9 to 3.5 W. For pump power in the range of 3.5 W ~ 6.2 W, the >0.95 values of the Strehl ratio demonstrate the helpful nonlinear pulse preshaping to complete the self-similar evolution to finally obtain TL pulses after compression. Meanwhile for pump powers higher than 6.2 W (>20 dB gain), the drop of the Strehl ratio can be explained by the inversion-ratio-related gain spectral profile induced pulse distortion. Higher pump power induces a shorter gain center wavelength and narrower gain bandwidth [13]. When the central wavelength of the gain derives from that of pulses seriously, the unavoidable gain-shaping effect makes the pulses accompanied by pedestal. However, it is noticeable that the Strehl ratio remains well above 0.925 in the whole pump power range, indicating the parabolic pulse amplification.

In summary, we have demonstrated a nonlinear preshaping method to optimize the initial pulse for the next self-similar amplification stage. In this facility, the pulse is shaped in the process of a pulse with negative chirp propagating in positive GVD fiber and interplay between SPM and GVD. By adjusting the separation of gratings, the pulse duration, bandwidth, and spectral shape are optimized to promise parabolic amplification in a short-gain fiber and linear chirp over a large range of pump power. With this scheme, the self-similar amplification is realized in a ~2 m Yb-doped fiber with pump power tuned from 2.9 to 7.2 W. After compression, the system outputs TL ~60 fs pulse. As well as clean TL pulses, this method can promise more pulse energy and peak power with a larger core diameter of gain fiber and higher pump power.

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