Transform-limited pulses for chirped-pulse amplification systems utilizing an active feedback pulse shaping technique enabling five time increase in peak power

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A fiber-based chirped-pulse amplification (CPA) system with an active feedback loop for pulse shaping is experimentally demonstrated. A spectral processor is used in conjunction with a frequency-resolved optical gating measurement to produce high-quality pulses. Spectral phase and intensity shaping are utilized to generate a clean, high-contrast, transform-limited pulse with 15 dB pedestal suppression in the pulse wing tails, resulting in a five time increase in peak power of the CPA system. © 2012 Optical Society of America

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Optical pulses with parabolic temporal intensity profiles have been shown to be excellent candidates for chirped-pulse amplification (CPA) systems due to their attractive features such as resistance to optical wave breaking, ability to retain their intensity profile during propagation in gain media, and enhanced linearity in chirp [1]. Temporally stretched, linearly chirped pulses reduce the effects of gain saturation, avoid the risk of damage to optical elements, and increase the amount of energy extraction from optical amplifiers [2–5]. Their linear chirp also allows efficient and high-quality pulse compression [6]. Much research has been done to understand the mechanism of parabolic pulse generation and propagation in fiberized systems and to improve their quality. One of the earliest investigations was the demonstration of self-similar propagation of temporal parabolic pulses in optical fibers with normal group velocity dispersion and strong nonlinearity [7]. This concept has been extended to include using dispersion decreasing fiber [8], Raman amplification in optical fibers, active or passive dispersion decreasing fiber [9,10], and tapered dispersion decreasing fibers [11]. Pulse shaping techniques involving amplitude or phase modulation have also been explored to improve pulse quality and increase peak power of CPA systems [1,12–14]. Most recently, a pulse shaping approach involving a technique to dynamically control the pulse intensity in the temporal domain has been investigated [15,16].

It should be noted that, when the desired energy levels are high, due to the combination of dispersion and nonlinear effects, even a small deviation in the pulse profile from the perfect parabolic shape will result in large pedestal generation, therefore degrading pulse quality. Fiber CPA systems are particularly susceptible to this degradation effect due to their small mode areas and long interaction lengths. Consequently, a scheme that can correct pulse shape deviations and thus mitigate effects of nonlinearities in high-power systems is highly desirable. In this Letter, we propose and demonstrate an active feedback loop, which controls both the spectral phase and amplitude of the pulses, resulting in the generation of transform-limited parabolic pulses of a CPA system operating in C-band using an erbium fiber amplifier.

The schematic for parabolic pulse shaping in this experiment is shown in Fig. 1. A mode-locked laser with a repetition rate of 1.25 MHz and 10 dB optical bandwidth of 15 nm serves as the input pulse train. The pulses generated by this laser are temporally stretched to a 1.45 ns duration at FWHM. A commercial spectral processor (Finisar 1000E), based on liquid crystal on silicon (LCoS) technology, is used to modulate the spectral intensity and phase of pulses to generate a parabolic intensity profile. Because of wavelength-to-time mapping, the temporal profile of stretched pulses is also parabolic. An erbium-doped fiber amplifier is used to amplify the generated parabolic pulses to 50 mW average power before a bulk compressor is used to compress pulses to achieve high peak power. An autocorrelator is used to monitor the temporal width and shape of the compressed pulses.

A second harmonic generation (SHG) frequency-resolved optical gating (FROG) system is used to measure the full electric field of the compressed pulses. The FROG spectrogram is analyzed to reconstruct the spectral amplitude and phase profiles of the pulses. This spectral phase information is used to adjust phase modulation by the spectral processor to eventually achieve linear spectral phase.

By combining spectral phase compensation with parabolic optical intensity shaping, we present a technique to realize high-power pulses that retains their parabolic shape while exhibiting clean, high-contrast,

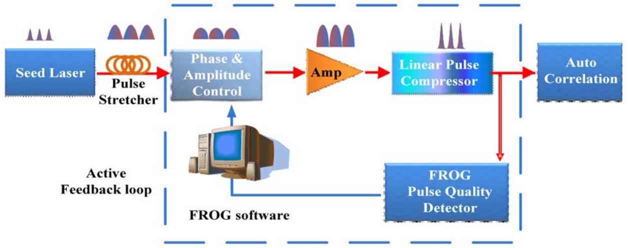

Fig. 1. (Color online) Schematic of feedback loop for parabolic pulse shaping.

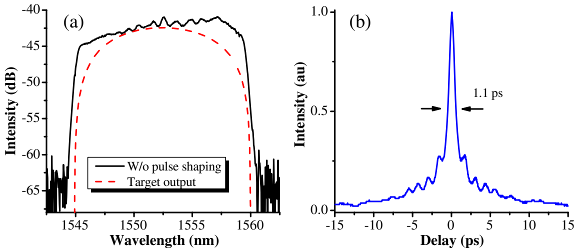

Fig. 2. (Color online) (a) Optical spectrum without pulse shaping (black solid) and desired parabolic output spectrum (red dash). (b) Measured autocorrelation trace of compressed CPA pulse without pulse shaping.

pedestal-free, transform-limited pulses in CPA systems. This method integrates the well-known technique of FROG with LCoS technology, which, to the best of our knowledge, had not previously been done.

The optical spectrum of the pulse without pulse shaping and desired parabolic spectrum are shown in Fig. 2(a). The temporal AC trace of the CPA pulses after amplification and subsequent compression is shown in Fig. 2(b), and is about 1.1 ps.

Initially, only spectral intensity modulation was applied to the input pulses. In Fig. 3(a), a spectral intensity mask is applied to the spectral processor to generate the desired parabolic optical intensity shape (red solid). This spectrum displays a signal to noise ratio of 28 dB and characteristic sharp edges of a parabola. The output pulses after intensity shaping are amplified before being compressed with the bulk compressor. The corresponding autocorrelation trace of the compressed pulses in Fig. 3(b) shows a slightly shorter temporal duration of 1.0 ps FWHM. Clearly, the pedestals reduction is observed on the wings of the AC trace due the change in the spectral intensity.

The amplified pulses were sent to the FROG to retrieve spectral phase information. A FROG spectrogram was constructed by collecting 512 FROG traces with 48 fs delay between traces. Figure 4(a) shows the FROG spectrogram of CPA pulses without pulse shaping. Figure 4(b) shows the FROG spectrogram of CPA pulses with spectral intensity and phase shaping. The error of the FROG retrieval is of the order of 1.5E − 3, showing a very good convergence. It is observed that the shape of the spectrogram changes and the green wings (which indicate chirp, or higher-order dispersion) have been compensated very well.

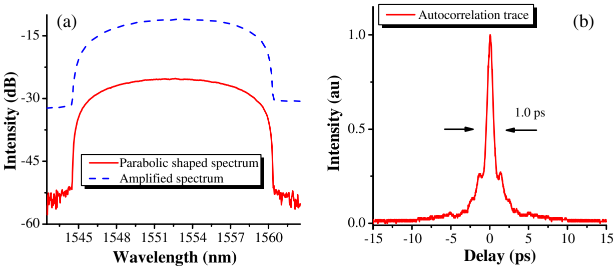

Fig. 3. (Color online) (a) Output optical spectrum after intensity modulation. (b) Measured autocorrelation trace of compressed CPA pulse after intensity modulation.

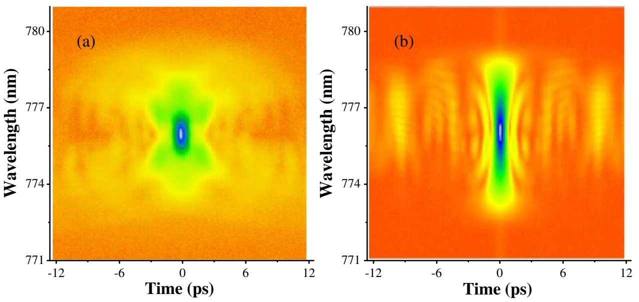

Fig. 4. (Color online) Measured FROG spectrogram of (a) pulses without pulse shaping and (b) pulses with both spectral intensity and spectral phase shaping. Temporal duration of horizontal axis is 24.5 ps; wavelength range is 771–781 nm.

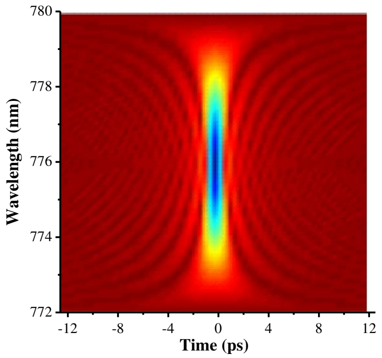

Fig. 5. (Color online) Simulation result of FROG traces of parabolic pulses.

The shape of the FROG spectrogram in Fig. 4(b) indicates a chirp-free pulse. This result is further validated by comparing experimental FROG spectrogram with simulation results. The experimental FROG spectrogram in Fig. 4(b) shows remarkable agreement with the simulated results in Fig. 5, generated by parabolic optical pulses with zero chirp.

Figure 6(a) shows the retrieved spectral phase of the pulse before and after phase modulation. The linear fit of the retrieved spectral phase indicates a maximum deviation of 0.75 radians toward the left tail of the spectrum and almost flat phase across the center, with 0.25 radians rms deviation. In Fig. 6(b), the measured autocorrelation trace of 0.7 ps temporal duration shows excellent agreement with a calculated autocorrelation trace of a

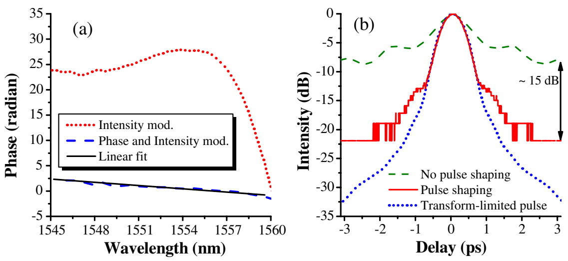

Fig. 6. (Color online) (a) Reconstructed spectral phase with only spectral intensity modulation (red dot), with both spectral phase and intensity modulation (blue dash), and its linear fit. (b) Calculated and measured AC traces in logarithmic scale compared with AC trace of a CPA pulse. Pulse intensity is normalized to unity.

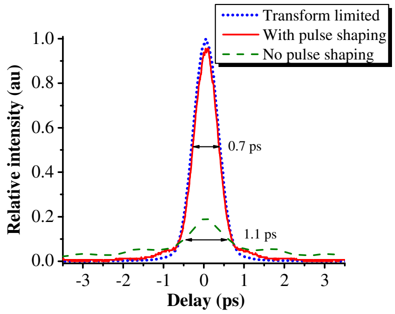

Fig. 7. (Color online) Temporal intensity of AC traces, normalized to energy of calculated AC trace of a transform-limited pulse (blue dot). Measured AC trace of CPA pulse with both spectral intensity and phase shaping (red solid) and without pulse shaping (green dash), are shown.

transform-limited pulse up to 12 dB. The pedestals in the temporal profile of a CPA pulse without pulse shaping have been suppressed by at least 15 dB at 3 ps delay.

If one assumes the saturated output power from the optical amplifier stays the same, the integrated energy of the AC traces can be normalized to unity and are replotted in linear scale in Fig. 7. In this figure, the peak power of a CPA pulse with pulse shaping (red solid) is comparable to the calculated peak power of the transform-limited pulses (blue dot) and shows an almost five time increase compared to a pulse without pulse shaping (green dash). The results clearly show that a substantial amount of energy under the pedestal on the wings has been transferred to the central lobe, significantly increasing pulse peak power.

In summary, we have demonstrated parabolic pulse shaping with both spectral intensity and spectral phase modulation in a CPA system. The use of SHG–FROG together with the spectral processor in an active feedback loop allows dynamic control of spectral phase and intensity modulation, resulting in transform-limited parabolic pulses of 0.7 ps temporal duration after compression with a bulk compressor, and a five time increase in peak power. This approach is highly reliable, versatile, and can be applied to any existing CPA systems. This will be of significance in many CPA applications of fiber laser systems, allowing the generation of high-quality ultrafast pulses.

References

1. D. N. Schimpf, J. Limpert, and A. Tünnermann, Opt. Express **15**, 16945 (2007).
2. D. Strickland and G. Mourou, Opt. Commun. **55**, 447 (1985).
3. A. Braun, S. Kane, and T. Norris, Opt. Lett. **22**, 615 (1997).
4. K. Kim, S. Lee, and P. Delfyett, IEEE J. Sel. Top. Quantum Electron. **12**, 245 (2006).
5. S. Lee, D. Mandridis, and P. J. Delfyett, Opt. Express **16**, 4766 (2008).
6. V. I. Kruglov, A. C. Peacock, J. M. Dudley, and J. D. Harvey, Opt. Lett. **25**, 1753 (2000).
7. D. Anderson, M. Desaix, M. Karlsson, M. Lisak, and M. L. Quiroga-Teixeiro, J. Opt. Soc. Am. B **10**, 1185 (1993).
8. T. Hirooka and M. Nakazawa, Opt. Lett. **29**, 498 (2004).
9. C. Finot, B. Barviau, G. Millot, A. Guryanov, A. Sysoliatin, and S. Wabnitz, Opt. Express **15**, 15824 (2007).
10. C. Finot, J. M. Dudley, B. Kibler, D. J. Richardson, and G. Millot, IEEE J. Quantum Electron. **45**, 1482 (2009).
11. A. Peacock and N. Healy, Opt. Lett. **35**, 1780 (2010).
12. F. He, H. S. S. Hung, J. H. V. Price, N. K. Daga, N. Naz, J. Prawiharjo, D. C. Hanna, D. P. Shepherd, D. J. Richardson, J. W. Dawson, C. W. Siders, and C. P. Barty, Opt. Express **16**, 5813 (2008).
13. D. N. Schimpf, E. Seise, T. Eidam, J. Limpert, and A. Tünnermann, Opt. Lett. **34**, 3788 (2009).
14. D. N. Papadopoulos, I. Martial, M. Hanna, F. Druon, and P. Georges, Opt. Lett. **33**, 1431 (2008).
15. D. Nguyen, M. U. Piracha, D. Mandridis, and P. J. Delfyett, Opt. Express **19**, 12305 (2011).
16. J. Ye, L. Yan, W. Pan, B. Luo, X. Zou, A. Yi, and S. Yao, Opt. Lett. **36**, 1458 (2011).