Pre-chirp managed nonlinear amplification for >100 W ultrafast sources

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ABSTRACT

We proposed and demonstrated pre-chirp managed amplification (PCMA), in which the seeding pulse was nonlinearly amplified such that the amplified spectrum was substantially broadened. By properly pre-chirping the seeding pulse, the amplified pulse can be compressed with the duration much shorter than the transform-limited duration allowed by the seeding spectrum. Using an Yb-doped rod-type large-pitch fiber as the power amplifier, PCMA has enabled us to generate 75 MHz, ~60 fs, linearly-polarized pulses with >100-W average power.

Keywords: Pre-chirp management amplification; Chirp mirror; Second-harmonic generation

1. INTRODUCTION

Coherent vacuum ultraviolet (VUV) sources enabled by high harmonic generation (HHG) in noble gases require laser intensities of $>10^{13}$ W/cm² and feature low conversion efficiency of $\sim 10^{-7}$. The photon flux (or average power) of such a VUV source can be significantly increased from HHG inside a femtosecond enhancement cavity pumped by a high repetition-rate (~100 MHz) ultrafast laser [1-5]. Although Ti:sapphire lasers were adopted for initial proof-of-principle demonstration [1], Yb-fiber laser systems have become the most suitable driving sources due to their superior average-power scalability and excellent beam quality—two crucial requirements for cavity-enhanced HHG [2, 3]. Recent experimental results from Ref. 6 reveal that the duration of the pulse is of paramount significance—shorter pumping pulses mitigate the ionization-induced enhancement limitations and allow higher intracavity optical intensities, which in turn increases the VUV yield. The authors found that the intracavity peak intensity is clamped at 5.6×10^{13} W/cm² for 175-fs pumping pulses and at 8.2×10^{13} W/cm² for 57-fs pumping pulses [5]. As a result, the VUV radiation generated by the shorter pulses exhibits higher photon energies with a significant increase of VUV photon yield; for example, the power of the 27th harmonic was increased by a factor of 2 [5]. Current high power (>50 W) laser sources for pumping femtosecond enhancement cavities are all based on a chirped-pulse Yb-fiber power amplifier, which consists of a stretcher to stretch the pulses prior to the amplifier in order to avoid nonlinearities, a high power Yb-fiber amplifier, and a compressor to recompress the amplified pulses. Limited by the Yb-fiber gain bandwidth, gain narrowing effect and dispersion management of the large stretching ratio, the resulting amplified and then compressed pulses are of 100-200 fs in duration. Further reduction of the pulse duration well below 100 fs—as required for efficient cavity-enhanced HHG—necessitates a subsequent external nonlinear pulse compression stage, which increases the system complexity and has limited throughput efficiency. In this contribution, we demonstrate a pre-chirp managed nonlinear Yb-fiber amplifier that outputs 75-MHz spectrally broadened pulses with >130-W average power. The amplified pulses are compressed to ~60-fs pulses with 100-W average power, constituting a suitable driving source for cavity-enhanced HHG. The key enabling technique employed in this Yb-fiber laser system is pre-chirp management; that is, fine tuning chirp of the pulses before seeding into a nonlinear Yb-fiber amplifier. We have both theoretically and experimentally demonstrated that such a pre-

chirp management method ensures high-quality compression of the amplified and spectrally broadened pulses [6, 7]. We have shown that, by using an Yb-doped rod-type large-pitch fiber (LPF) as the power amplifier, the pulse energy can be scaled to the μJ -level without the need for conventional CPA technique.

2. PRE-CHIRP MANAGED AMPLIFICATION: WORKING PRINCIPLE

In this section, we analyze and demonstrate direct amplification in an Yb-doped rod-type LPF producing high-quality μJ pulses that are as short as 60 fs after final compression. Design strategies are presented for average power levels of >100 W at 75 MHz repetition rate. The laser system results in both high quality and high energy output pulses, hitherto not reported for direct amplification in fibers. We refer to this amplification regime as pre-chirp managed amplification (PCMA). The high quality μJ pulses are obtained by two key enabling components: (i) the LMA of LPFs leads to intrinsically low fiber nonlinearity resulting in energy scaling; (ii) additionally, introducing a small amount of group-delay dispersion (GDD) (typically between -0.05 and 0.05 ps^2) prior to direct amplification results in high output pulse quality after final compression [7]. Figure 1 shows a schematic of the experimental setup consisting of a fiber-laser front end, a pair of diffraction gratings for pre-chirp management, a rod-type Yb-doped fiber amplifier, and a grating-based compressor.

Fig 1. Schematic of Pre-chirp managed nonlinear amplification in fibers

The distinction of PCMA from CPA is illustrated in Fig. 2. In Fig. 2(a) pulse quality is plotted in terms of Strehl-ratio, i.e., peak-power of the compressed pulse to peak-power of the corresponding transform limited pulse, which is a measure of residual spectral phase-shifts. Also, the pulse peak-power and the B-integral at the compressed output of the nonlinear laser system are shown in Fig. 2(b) and 2(c).

Fig 2. Transition from CPA to PCMA to CPA: (a) compressed pulse quality in terms of Strehl-ratio (b) peak power of the compressed pulse and (c) accumulated nonlinear phase during amplification. The simulation assumes a transform limited 300-fs, 75-MHz input pulse train with center wavelength 1030 nm, an average power of 1 W, a YDFA small-signal peak gain of 3.8/m (corresponding to about 100 W at the fiber output)

The results in Fig. 2 show that for a small positive chirp there exists an optimum point at which high pulse-quality and peak-power is simultaneously possible. The CPA regime corresponds to large stretching or high GDD values, and a

high pulse quality is obtained. A signature of the PCMA regime is massive spectral broadening. The larger bandwidth allows for shorter pulses as compared to the conventional CPA regime. In this case the pulse reduction is about a factor of 8. The nonlinear nature of PCMA manifests itself in high B-integral values for the PCMA regime, another proof of the nonlinear nature of the method.

3. PCMA EXPERIMENTAL RESULTS: PULSE COMPRESSION USING DIFFRACTION GRATINGS

Figure 3 shows the schematic of the high power PCMA system. It consists of an Yb-doped fiber-laser front end, a pair of diffraction gratings for pre-chirp management, a rod-type Yb-doped fiber power amplifier, and a pulse compressor. The fiber-laser front end including a 75-MHz Yb-doped fiber oscillator and an Yb-doped fiber amplifier produces positively chirped pulses with 1.75 W average power. A pair of diffraction gratings (1000 lines/mm) in a double pass configuration is employed to adjust the chirp prior to nonlinear amplification. In this way, we can vary the pre-chirp from positive to negative values. The front end can produce 300 fs pulses that are very close to the transform limit. The power amplifier is a 1.2-m Yb-doped rod-type LPF with a 90- μm diameter core and a 280- μm diameter air cladding for pumping [8]. The mode-field diameter is 80 μm and the pump absorption is 24 dB/m. The LPF is pumped by a 976 nm pump diode. The amplified pulses are compressed by another grating pair (1000 lines/mm) in a double pass configuration with a total efficiency of 77%.

Fig 3. Schematic of the pre-chirp managed amplification system. SAM: saturable absorber mirror, QWP: quarter wave plate, POL: polarizer, LD: laser diode, CFBG: chirped fiber Bragg grating, PC: polarization controller, ISO: isolator, DM: dichroic mirror, LPF: large pitch fiber

Figure 4 plots the output power from the rod-type LPF amplifier versus the absorbed pump power. The seed power prior to the last amplification stage is around 1.5W. Accounting the coupling loss to the LPF, the launched seed power is estimated to be 1 W. At 220-W pump power, 130-W amplified pulses are obtained. The slop efficiency is 67%, which is a reasonable number for Yb-doped fiber amplifier. The beam profile is excellent, as shown in the inset figure.

Fig 4. Power amplifier output versus absorbed pump power. The inset shows the beam profile at 130 W output power (before compression)

Figure 5(a) shows the corresponding optical output spectrum (red curve). The significantly broadened spectrum of the amplified pulse is a characteristic of the nonlinear amplification of PCMA. Figure 5(b) displays the autocorrelation trace of the amplified pulse prior to compression (blue curve) and after compression (red curve). At the system output, average power is 100 W. As shown in Fig. 5(b), the compressed pulses are as short as 60 fs with high pulse quality. To optimize the compressed pulse quality in terms of residual wing structure, we adjust both the grating-pair separation prior to and after the fiber amplifier. An optimum GDD of the pre-chirp exists to achieve nearly transform-limited compressed pulses with negligible pedestal. At 130 W output, the optimum pre-chirping GDD is around 26000 fs^2 and the output pulses are de-chirped by the grating pair with only 2-3 mm separation distance. To evaluate the quality of the compression, the black curve in Fig. 5(a) shows the autocorrelation trace of the corresponding transform-limited pulse that is calculated from the output spectrum, as shown in Fig. 5(a).

Fig 5. (a) Optical spectra before (black curve) and after (red curve) the power amplifier operating at 130 W output power. (b) Autocorrelation traces of the 130 W amplified pulses (blue curve), the 100 W compressed pulses (red curve), and the corresponding transform-limited pulses (black curve).

To illustrate how the pre-chirping GDD affects the spectral evolution, we varied the pre-chirping GDD and then measured the output spectrum at different powers. Figure 6(a) shows the spectral evolution versus increased power when the pre-chirping GDD was set at -11800 fs^2 . It can be seen that the spectrum became narrower at low powers ($< 40 \text{ W}$) due to the spectral narrowing effect caused by a negative pre-chirp. For further increased powers, the spectrum was broadened rapidly. As for a comparison, we changed the pre-chirping GDD to 22000 fs^2 and measured the spectrum at different powers; the results were plotted in Fig. 6(b). Clearly for a positive pre-chirping GDD, the spectrum narrowing

phenomenon was absent and the spectrum was broadened dramatically as the power was increased from 10 W to 40 W. For the power increased from 40 W to 90 W, the spectrum continued to become broader albeit at a pace much slower than spectral broadening of the seeding pulses with negative pre-chirping GDD of -11800 fs^2 .

Fig 6. Spectral evolution with different pre-chirp GDD: (a) -11800 fs^2 and (b) 22000 fs^2 .

4. PCMA EXPERIMENTAL RESULTS: PULSE COMPRESSION USING CHIRPED MIRRORS

Given the small chirp of the amplified pulses, highly dispersive mirrors (HDMs) can be applied instead of a grating pair for pulse compression. In addition to increasing the throughput efficiency and improving the beam quality, the use of a HDM compressor simplifies the experimental setup. Figure 7(a) shows the coating structure of such an in-house designed HDM, including 55 alternating layers of Nb_2O_5 and SiO_2 . The dispersive behavior of this HDM is shown in Fig. 7(b): each bounce provides a dispersion of -2000 fs^2 , four times larger than the dispersion from typical

commercially available chirped mirrors. Such HDMs have been used to compress pulses generated from chirally-coupled-core Yb-fiber lasers [9].

Fig 7. (a) Designed structure of highly dispersive mirrors. (b) Designed (blue curve) and measured (red curve) group delay of the in-house designed highly dispersive mirrors.

To find the best-compressed pulse using HDMs, we adjust the bounces on the mirrors. Figure 8(a) illustrates the compressed pulse duration as a function of number of bounces at different output power levels. At 120 W, the pulse can be compressed down to ~ 70 fs using 6 bounces on the HDMs. Figure 8(b) shows the autocorrelation traces before and after compression with the HDMs as well as the compression with the diffraction grating pair. Compared with the diffraction grating compressor, the pulse compressed with the HDMs (red curve in Fig. 8(b)) shows a wing structure mainly caused by uncompensated higher-order dispersion. An accurate characterization of the spectral phase for the amplified pulses allows precisely designing the dispersion of HDMs to improve pulse compression. Dispersion compensating wedges can be employed as well to achieve continuous GDD compensation to remove the residual pedestals in the compressed pulses.

Fig 8. (a) Compressed pulse duration by HDMs as a function of number of bounces for different output power: 120 W (black curve), 103 W (red curve), 90 W (blue curve), 73 W (pink curve), and 55 W (green curve). (b) Comparison of compressed pulse by HDMs and transform limited pulse.

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5. PCMA EXPERIMENTAL RESULTS: HIGH-POWER SECOND-HARMONIC GENERATION

Recent investigations of the EUV power scaling show that shorter driving wavelengths yield higher conversion efficiencies. Pumping an enhancement cavity by 5-W, 155-fs pulses at 518 nm has demonstrated a significant improvement of HHG average power [10]. To show applicability of the PCMA system for shorter wavelength generation, we use a 0.5 mm long BBO crystal to perform a frequency doubling experiment.

Fig 9. Second harmonic generation (SHG) output power and conversion efficiency for different IR power at 60 fs pulse duration.

Figure 9 shows the second-harmonic generation (SHG) output power and conversion efficiency for different IR power at 60 fs pulse duration (compression with a grating pair). For IR power levels below 30 W, the conversion efficiency increases dramatically. At 71 W pump power the conversion efficiency reaches 32% and we obtain 21 W of SHG. To prevent BBO crystal damaging, we limit the maximum IR power at 71 W; at this power level, the conversion efficiency is far from saturation. The pulse duration of the SHG is estimated to be around 50 fs. Figure 10 shows a picture of the experimental setup achieving high power SHG.

Fig 10. Picture of high power SHG setup

6. CONCLUSION

In conclusion, by optimizing the input pulse chirp prior to nonlinear amplification, pedestal-free compressed pulses at various output power levels can be produced. We carefully studied the effect of pre-chirp on pulse amplification and compression, and found that the optimum pre-chirping GDD increases from negative to positive with increasing output power. The compressed pulses are as short as 60 fs with average powers as high as 100 W at a 75 MHz repetition rate. With μJ pulse energy, this high-repetition-rate PCMA system constitutes a simple and suitable laser source for several applications, in particular, driving extreme nonlinear optics in femtosecond enhancement cavities.

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