High fidelity femtosecond pulses from an ultrafast fiber laser system via adaptive amplitude and phase pre-shaping

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Abstract: We report the generation of a 12.6W average power, 50MHz repetition rate pulse train, compressible to high fidelity 170fs pulses, from an ultrafast ytterbium-doped fiber laser system via adaptive amplitude and phase pre-shaping.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.4370) Nonlinear optics, fibers; (320.5540) Pulse shaping; (320.7090) Ultrafast lasers.

1. Introduction

Ytterbium-doped fibre laser systems, coupled with the chirped-pulse amplification (CPA) technique, have allowed the realization of compact ultrafast laser systems producing high average power at various repetition rates [1]. Power scaling in fibre CPA systems is non-trivial, because a number of factors can degrade the pulse fidelity at the output, such as uncompensated material dispersion, nonlinearity, and a non-uniform spectral gain profile with finite width. Due to the optical confinement and long interaction length of the fiber geometry, nonlinear effects, most notably self-phase modulation (SPM), are a critical consideration in constructing fiber CPA laser systems. However, conventional approaches in mitigating SPM have limitations; temporal stretching is physically limited by the finite size of the grating compressor, while the scaling of large-mode-area (LMA) fibers will eventually undermine the advantages of fiber geometry. Hence, novel approaches in mitigating SPM are necessary for further power scaling in fiber CPA laser systems while maintaining pulse fidelity.

Adaptive pulse shaping allows for the generation of high-fidelity pulses by controlling the spectral phase profile [2]. However, due to damage limitations, pulse shaping often needs to be implemented prior to high power amplification in CPA systems [3]. In fiber CPA systems, amplitude-only shaping has recently been demonstrated to control the nonlinear-phase modulation induced by SPM at low energy [4], but it cannot compensate for higher-order spectral phase due to the material dispersion. Our group recently demonstrated a phase-only shaping to produce high-quality pulses in a high-energy fiber laser system [5].

In this paper, we report our latest experimental result in generating high-fidelity femtosecond pulses in a fiber CPA system by adaptive amplitude and phase pre-shaping [6]. A pulse shaper based on a dual-layer liquid crystal spatial light modulator (LC-SLM) was implemented in the fiber CPA system for amplitude and phase shaping prior to amplification. The LC-SLM was controlled using a differential evolution (DE) algorithm, to maximize a two-photon absorption (TPA) detector signal produced by the compressed fiber CPA output pulses. We show that our approach compensates for both accumulated phase from higher-order material dispersion and nonlinear phase modulation. A train of pulses with an average power of 12.6 W at a 50 MHz repetition rate was produced from the fiber CPA system, compressible to high fidelity pulses with a full-width at half-maximum (FWHM) duration of 170 fs.

2. Experiments

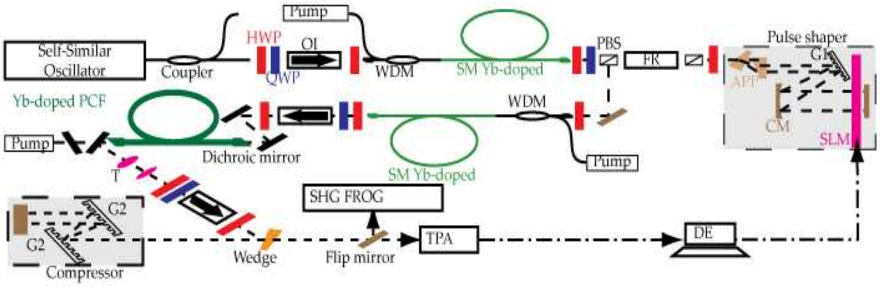

Fig.1. Schematic of ultrafast ytterbium-doped fiber laser setup with amplitude and phase pre-shaper.

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The experimental setup is schematically illustrated in Fig.1. The seed source was a passively mode-locked Yb-doped fiber oscillator, operated in the self-similar regime. The laser produced a train of chirped pulses with a duration of 2 ps at a 50 MHz repetition rate, and a 16 nm spectral FWHM at a 1042 nm central wavelength. The oscillator produced an average power of 30 mW, corresponding to a pulse energy of 0.6 nJ. The pulses from the oscillator were amplified in a single-mode (SM) core-pumped Yb-doped fiber, before being sent into a pulse shaper via a free-space optical circulator. The pulses were then sent into the second pre-amplifier before being launched into the final amplifier, comprising a 1.7 m long double-clad LMA polarization-maintaining Yb-doped photonic-crystal fiber, with an active core diameter of 40 μm (NA=0.03) and an inner cladding diameter of 200 μm (NA=0.55). The train of pulses, at this point, had a maximum average power of 12.6 W, corresponding to a pulse energy of 252 nJ. Finally, a fraction of the output, taken from the Fresnel reflection of a wedge, was compressed using a pair of gold-coated 900 lines/mm holographic gratings.

The pulse shaper consisted of a 4f setup [7] arranged in a reflective configuration with a dual-layer 128 pixels LC-SLM placed at the Fourier plane, allowing for the modulation of both the phase and amplitude of the spectral components of the pulses. An adaptive loop to control the phase and amplitude modulation applied by the LC-SLM to the pulse train was implemented to maximize the signal from a GaAsP TPA detector, using a DE algorithm [8]. The algorithm controlled every Nth pixel of the SLM, which were then interpolated onto 128 pixels at each layer.

3. Results and discussions

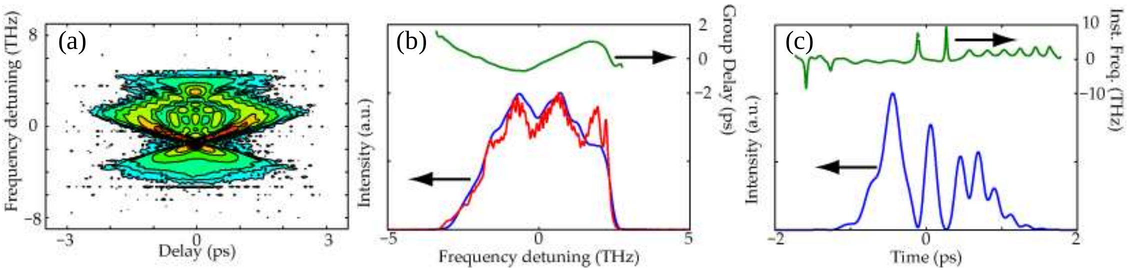

Fig.2. SHG FROG characterization of unshaped pulses.

Firstly, the pulses from the compressor were characterized without intentional shaping by the pulse shaper (by not applying any voltage to the SLM). The separation of the grating pair in the compressor was adjusted to maximize the intensity of the TPA detector, resulting in a grating separation of 10.2cm. The output pulses were then characterized using SHG FROG. In order to emphasise any low intensity structure, figure 2(a) shows the square-root of the measured SHG FROG traces, after interpolation onto a 128x128 Fourier grid. The spectral and the temporal intensities were then retrieved, as well as the group delay and the instantaneous frequency, from the trace, as shown in Fig. 2(b) and (c). The root-mean-square (rms) retrieval errors of the trace were less than $8\text{x}10^{-3}$. There is an excellent agreement between the retrieved and measured spectra as shown in Fig. 2(b) by the blue and red curves, respectively.

The mainly parabolic profile of the group delay shown in Fig. 2(b), and the side-lobes in the temporal intensity profile shown in Fig.2(c), are a strong indication that the dominant effect on the output pulses of the CPA system was the accumulated third-order dispersion (TOD). These results are expected, since there was no compensation element for the TOD placed in our system. In addition, the departure of the group delay profile from parabolic suggests the presence of nonlinear phase-modulation, whose amount increases with power level. This increase in accumulated nonlinear phase modulation causes the side-lobes of the temporal profile to not decrease monotonically, as seen in Fig.2(c).

The accumulated nonlinear-phase modulation evident in the above characterization is expected, since there was no specific stretching of the pulses prior to amplification in our fiber CPA system. The estimated upper limit of the accumulated nonlinear phase was $\phi_{NL}= 1.6\pi$ rad, of which the contribution prior to the pulse shaper was 0.7π rad. In this calculation, an exponential amplification with a constant gain per unit length with flat spectral gain profile in the fiber amplifiers was assumed.

Having characterized the pulses without intentional shaping, the optimization was then performed using the DE algorithm. The algorithm controlled an increasing the number of SLM pixels, from every 8th pixel, to every 4th pixel at generation 51, and finally to every 2nd pixel at generation 101, between pixels 16 to 112 of the SLM. In addition, pixels number 12 and 116 were still controlled, resulting in a final total of 51 controlled pixels on each layer of the SLM. The DE algorithm was run for 450 generations, starting from random initial candidate solutions, and took 65 minutes to complete.

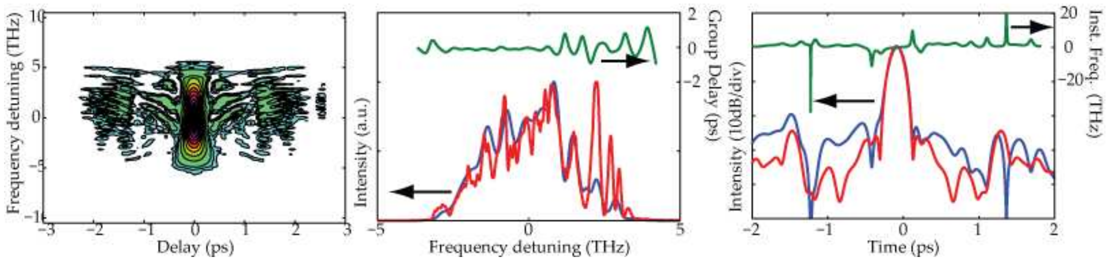

Fig.3. Schematic of ultrafast ytterbium-doped fiber laser setup with amplitude and phase pre-shaper.

After the optimization, there was little diversity among the members of the population, and the TPA signal was improved by a factor of 4.3. The pulses resulting from the optimization were characterized by the SHG FROG. Fig.3. once again shows the square root of the SHG FROG trace. The rms retrieval error was less than $1.5\text{x}10^{-2}$, which was mainly due to the large area the trace occupies on the Fourier grid. The temporal FWHM of the retrieved profile is 170 fs. Although the square-root of the measured SHG FROG trace exhibits wings that extend up to 2 ps delay, they have very low intensity, below 0.5%, and most of the trace mass is concentrated at the center. The temporal profile shows a high quality pulse (note the logarithmic scale in this case) with the main pulse having an excellent agreement with the calculated Fourier transform-limited profile. The pedestal of the retrieved temporal intensity is less than -20 dB everywhere, except for the small satellite pulse at t ~ -1.5 ps.

Although the DE algorithm started with random initial candidate solutions, the optimization results had a high reproducibility. The resulting applied phase and transmission profiles showed little dependence on the initial condition, yielding similar compressed pulse profiles in each case, which implies that our results have to be in the vicinity of the global optimum. In order to obtain the true global optimum, more generations would be required, but with diminishing returns that may not justify the effort. It is important to note that it is not necessary to start from random initial candidate solutions. It is possible to feed a previously optimized data as one of the initial candidate solutions in order to reduce the optimization time.

4. Summary

In summary, we have successfully demonstrated an adaptive amplitude and phase pre-shaping technique for producing high-fidelity femtosecond pulses in a fiber CPA system. We have demonstrated that this technique is very robust, effective, and efficient, in compensating for both accumulated phase from higher-order material dispersion and nonlinear phase-modulation. We did not have to perform painstaking characterization and design to optimize our fiber CPA system to produce the high-fidelity femtosecond pulses presented here. This technique should enable power-scaling to higher energy and/or average power at various repetition rates. In addition to producing high-fidelity compressed pulses, this technique has the potential to produce arbitrary shaped pulses necessary in various applications, including coherent control.

Acknowledgments

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