No loss spectral phase correction and arbitrary phase shaping of regeneratively amplified femtosecond pulses using MIIPS

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Abstract: Automated pulse compression through adaptive phase distortion compensation and compensation of gain narrowing of femtosecond regeneratively amplified pulses (2.5 mJ, 27.6 fs, transform limited) using a MIIPS-enabled pre-amplification pulse shaper is demonstrated. Rigorous characterization of the shaped pulses is presented.

OCIS codes: (320.5540) Pulse shaping; 320.5520 Pulse compression; (320.7100) Ultrafast measurements

References and Links

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1. Introduction

Ultrashort amplified pulses are uniquely suited for scientific and industrial applications requiring the delivery of laser excitation with high peak intensities (> 10^{18} W/cm^2). Accurate measurement and spectral phase correction of amplified femtosecond pulses are crucial to achieve the highest peak intensities, and delivery of amplified arbitrary phase-shaped intense pulses is critical for reproducible laser control applications. Unfortunately, pulse shaping of amplified pulses results in losses (> 50%) and the possibility of damaging the pulse shaper optics. Here we present the use of a pre-amplification pulse shaper capable of performing multiphoton intrapulse interference phase scan (MIIPS) [1-3] while positioned between an oscillator and a regenerative amplifier. Because the amplifier runs in a saturated regime, the attenuation of the beam caused by the pulse shaper does not affect the amplified output. Therefore one can achieve no net output loss, together with automated spectral phase correction and accurate arbitrary phase delivery of amplified pulses at the sample. We perform a careful verification of the results by implementing a second pulse shaper after the amplification process.

The MIIPS method for femtosecond pulse characterization and dispersion correction is very different from all other methods commonly used. It has been described elsewhere [1,3]; here we give only a brief introduction. MIIPS measures the phase distortions in the pulses and cancels them through the use of an adaptive pulse shaper. There is no overlapping of beams, autocorrelation or interferometry. Phase characterization is achieved by measuring the changes on the second harmonic generation (SHG) spectrum of the pulse caused by phase distortions, and taking advantage of the well known dependence of the SHG spectrum on phase [4-5]. The method requires a pulse shaper that is used to introduce a series of calibrated reference phase functions. The procedure has been compared to the well-known Wheatstone bridge device for measuring resistance, whereby a calibrated resistor is used to measure an unknown resistor. In MIIPS a calibrated phase is scanned across the spectrum to reveal the spectral phase deformations in the pulse. The resulting MIIPS trace, which is a three dimensional plot of second harmonic intensity as a function of wavelength phase mask position, contains all the information required to analytically obtain the second derivative of the spectral phase distortions. Double integration results in the spectral phase. Once the spectral phase of the pulses is measured, the same pulse shaper can be used to compensate said distortions to achieve transform limited pulses. Typically, a small number of iterations of the MIIPS process are carried out to obtain pulse compression that is near the theoretical limit imposed by the bandwidth of the pulses, usually within less than 0.1 rad across the spectrum. This process takes a few seconds and is fully automated. When a sinusoidal reference phase function is used the MIIPS trace shows straight parallel lines separated by π for transform limited pulses. Linear chirp changes the relative distance between these lines, quadratic chirp changes their angle, and higher order distortions lead to changes in their curvature [1]. The MIIPS method is very stable, relatively immune to noise and extremely accurate [3].

Pulse shaping of ultrashort pulses before amplification is not uncommon and has been performed by utilizing prism pairs, grating-pairs, chirped mirrors [6], liquid crystal spatial light modulators (SLM's) [7-8], programmable acousto-optic modulators [9-10] (AOM) or some combination of all of these methods [11-12]. Pulse characterization methods such as FROG, autocorrelation or SPIDER are normally employed to provide feedback to optimize the output. Some of these methods employ a genetic algorithm (GA) in a closed-loop setup that uses information from the characterization as a feedback to determine the direction and magnitude of phase corrections. In all of these studies, two or more optical set-ups (pulse shaper and separate FROG or SPIDER set-up) are needed in order to perform pulse shaping and later pulse measurement. The MIIPS method seamlessly incorporates control and characterization, without the need of an additional pulse characterization setup, which makes it ideal for optimization of amplified femtosecond laser pulses.

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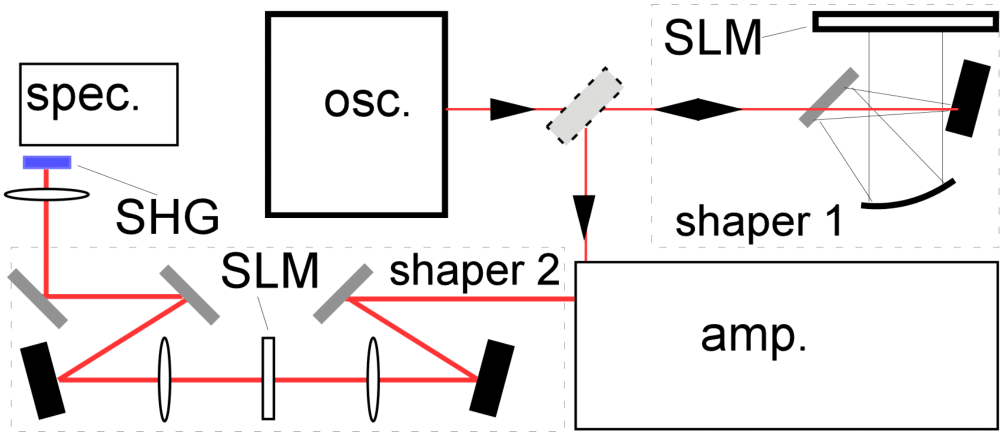

Fig. 1. Schematic of the experiment. The seed fs laser with 45 nm full-width at half maximum was sent through the pre-amplification pulse shaper. Shaped pulses were then amplified in the regenerative amplifier and sent through the second pulse shaper. The beam was frequency doubled and the signal was detected by a compact spectrometer.

2. Experimental section

Experimental results were obtained from a number of commercially available laser systems. These included a 0.7 mJ regenerative amplifier seeded by a titanium sapphire oscillator (45 nm FWHM) or 2.5 mJ regenerative amplifier (Legend-HE-USP) seeded by a Micra™ oscillator (80 nm FWHM). The output pulses were shaped by a reflective 2f pre-amplification pulse shaper (shaper 1 in Figure 1) with a phase-amplitude spatial light modulator (SLM) (CRi SLM 128 D VN) and then amplified in an unmodified regenerative. A second 4f pulse shaper after the amplifier with an older model SLM (CRi SLM 256) was used for phase characterization and to check the delivery of accurate phase functions (shaper 2, in Figure 1). A 0.1 mm KDP crystal was used for the MIIPS measurements. In order to quantify phase characterization and compensation we use the ratio between the pulse duration, which depends on the pulse spectrum and the residual phase distortions, divided by the theoretical transform limit determined only by the spectrum of the pulse and assuming zero phase distortions. This figure of merit does not depend on the spectral shape of the pulse as the time-bandwidth product does. A pulse duration ratio equal to one would imply perfect correction. With MIIPS, ratios <1.02 are typically achieved automatically within a few minutes. All orders of phase distortions are usually reduced from tens of radians to less than 0.1 rad across the bandwidth of the pulse.

3. Results

In Figure 2 we demonstrate how MIIPS automatically corrects phase distortions in the amplified output to achieve the generation of 0.7 mJ, transform limited pulses. The output spectrum (29.0 nm FWHM) of the laser is shown in Fig. 1(a). The second harmonic of uncompensated amplified pulses is shown in Fig. 1b. Due to the accumulated phase distortions from both oscillator and amplifier, the SHG spectrum is only 5.5 nm FWHM and initial pulse duration ratio is greater than 2. An SHG FROG measurement (not shown) agrees with the MIIPS measurement and gives a pulse duration of 75 fs. After MIIPS and application of the compensating phase function, the SHG spectrum was 10 nm FWHM and 32.5 fs FWHM. The pulses were corrected to a pulse duration ratio of 1.005 without loss of output power.

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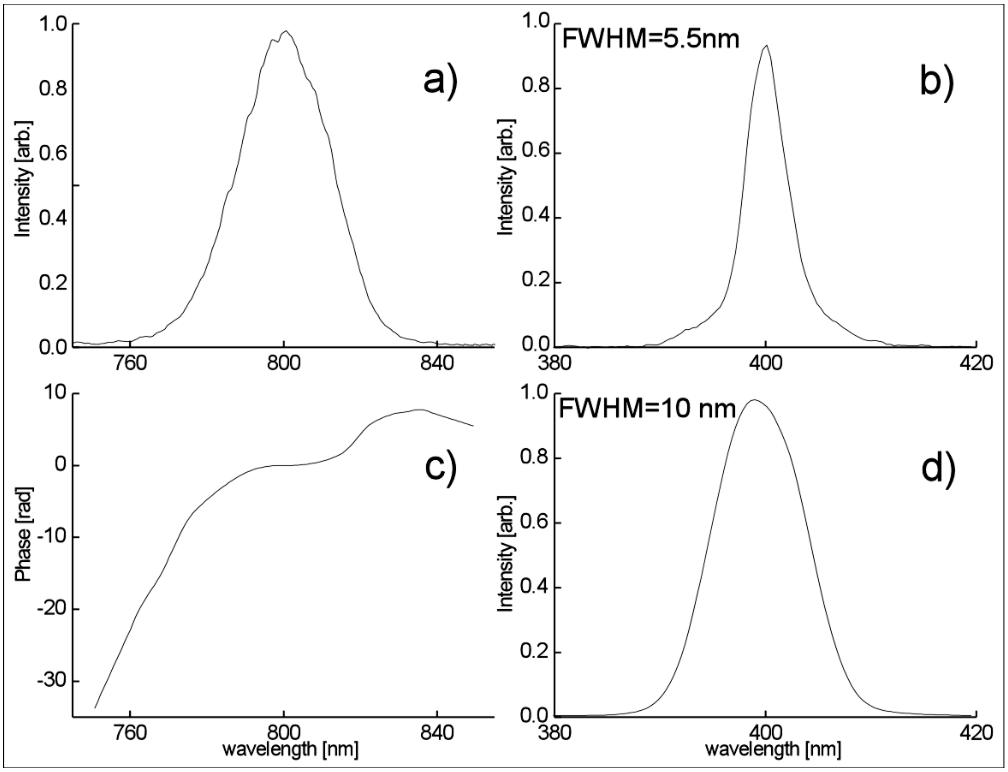

Fig. 2. Automated pulse compression of amplified laser pulses using a MIIPS enabled pre-amplification pulse shaper. (a) Spectrum of the fundamental output. (b) SHG Spectra of the uncompensated pulses, with 75 fs pulse duration. (c) Measured phase distortions. (d) SHG spectra of the resulting 32.6 fs compressed pulses.

In addition to pulse compression, the pulse shaper can deliver amplified shaped ultrashort pulses. The results presented in Fig. 3 demonstrate accurate delivery of arbitrary smooth phase functions as evidenced by the SHG spectrum. For these experiments, we started with phase corrected amplified pulses using MIIPS (a. continuous line). We then introduced a cosine phase function with 2π amplitude and four full periods across the laser spectrum using the pre-amplification pulse shaper. The resulting SHG spectrum of the shaped and amplified pulses was recorded (b. dashed line with open squares). To confirm the accuracy of the spectral phase in the amplified pulses, we introduced the complementary phase function (π-shifted cosine) on the second (external) shaper. We found that the pulses once again became transform limited, and their SHG spectrum again corresponds to that observed for TL pulses (d. open circles). Pulses were confirmed to be TL independently by FROG (not shown). A second set of measurements was performed in which the pre-amplification pulse shaper delivered only the MIIPS spectral phase correction and the second shaper delivered the cosine function (c. dotted line with solid triangles). The resulting SHG spectrum agrees with that obtained when the phase was introduced by the first pulse shaper. From these experiments we learn that accurate phase delivery is possible when the pulse shaper is placed between the oscillator and the regenerative amplifier. The advantages of pre-amplification pulse shaping are avoiding loss of intensity and possible damage of optics in the pulse shaper by the amplified pulses.

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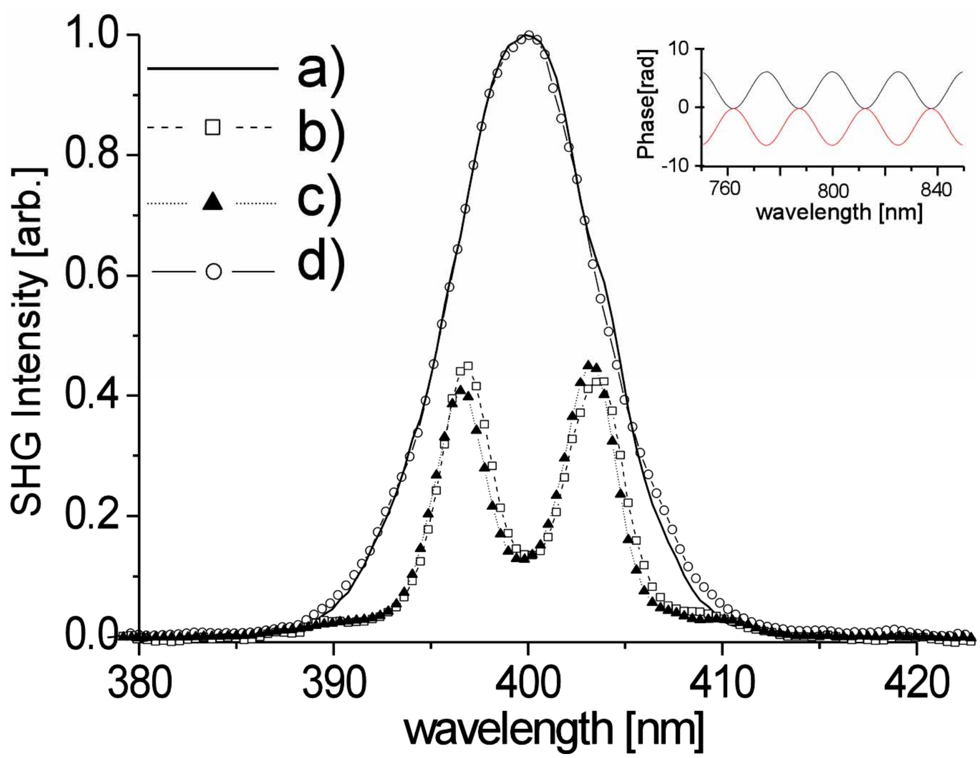

Fig. 3. Accurate delivery of amplified femtosecond pulses shaped by smooth phase functions. The pulses were first corrected by MIIPS before the desired phase functions were introduced. a) SHG spectrum of pulses comressed by MIIPS. b) SHG spectrum of amplified pulses after phase correction and shaped by a cosine function using the pre-amplification pulse shaper. c) SHG spectrum of phase corrected pulses shaped by a cosine function by the external pulse shaper. d) SHG spectrum of the amplified phase-corrected pulses that are shaped by a cosine function by the pre-amplification pulse shaper and then shaped with a complimentary (π-shifted) phase function by the external shaper. Notice that the phase introduced prior to amplification exactly cancels the phase introduced post amplification. The insert shows the two phase functions used.

Accurate delivery of binary (0 or π retardation) phases introduced using the pre-amplification shaper is demonstrated in Figure 4. The pre-amplification pulse shaper was first used to compensate phase distortions to achieve TL pulses (red dashed line in Fig. 4(a)). The compensation phase with a binary phase step was then introduced by the pre-amplification shaper (solid line, Fig. 4(a) insert). The SHG spectrum resulting from this binary step is shown in Fig. 4(a) (solid black line). Fig. 4(b) shows the SHG FROG of the amplified binary phase shaped pulses. To confirm that accurately shaped pulses were delivered, we used the external pulse shaper to introduce a complimentary phase (red dashed line in the insert). The complementary phase at the second shaper exactly cancelled the initial phase step. The pulses were found to be TL as confirmed by their SHG FROG trace (Fig. 4(c) bottom).

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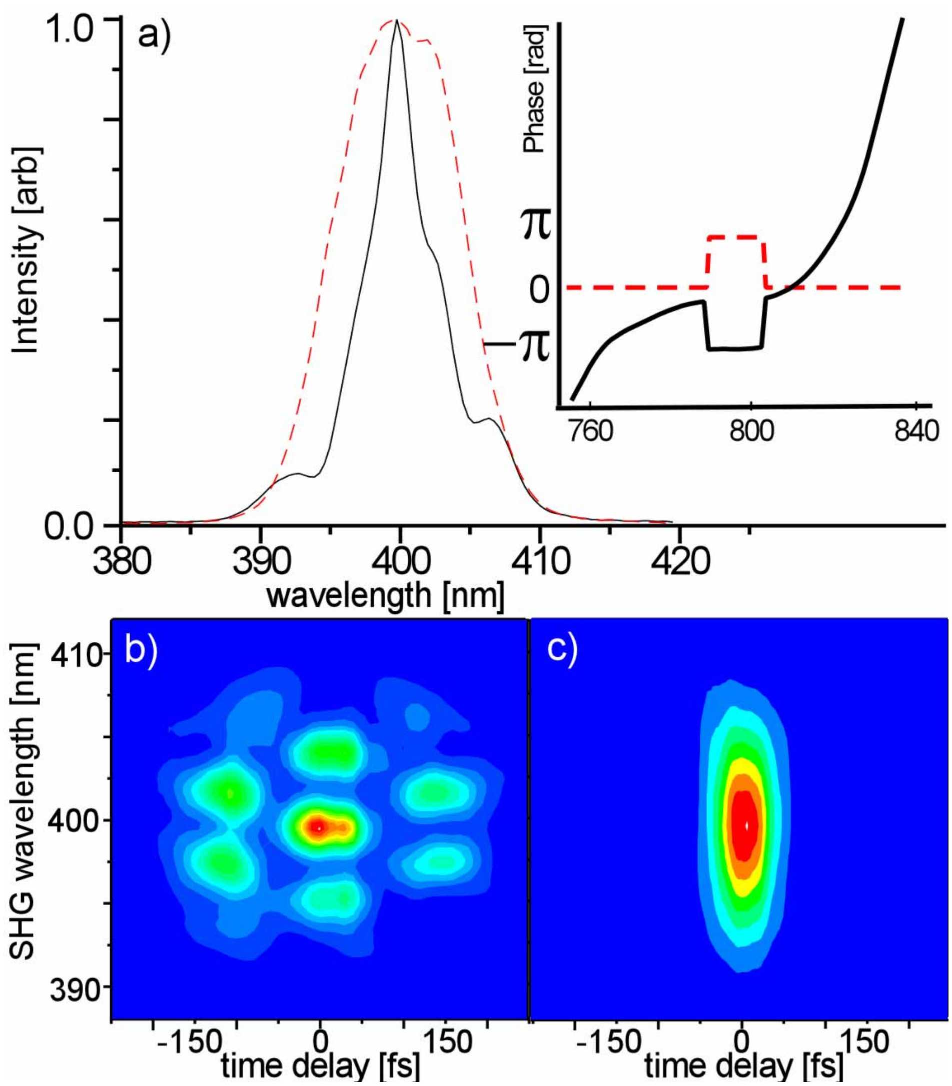

Fig. 4. Accurate delivery of amplified binary phase shaped femtosecond pulses. The pulses were first corrected by the pre-amplification pulse shaper (SHG spectrum, red dashed line) before the binary step functions was introduced (solid line). The insert shows the correction function with the binary step (solid black line). The second pulse shaper was used to introduce the complimentary binary function (red dashed line). b) SHG FROG trace of the amplified binary phase shaped pulses. c) SHG FROG trace of the pulses after the complimentary step function is introduced by the second shaper, the pulses once again become transform limited.

In order to reduce the pulse duration of the amplified laser pulses, we used amplitude modulation to counteract gain narrowing occurring during regenerative amplification. Amplitude modulation together with MIIPS characterization and pulse compression using a Silhouette pulse shaper between the Micra seed oscillator and the 2.5 mJ Legend-HE-USP amplifier resulted (Figure 5) in a much broader output spectrum, from 25.2 nm to 47.6 nm FWHM. The resulting pulse duration decreased from 35.6 fs to 27.6 fs FWHM and the pulse duration ratio decreased to 1.02. These experimental results have been confirmed in two different unmodified regenerative amplifiers. Pulses shorter than 20 fs will be possible by upgrading the amplifiers with broad-bandwidth optics.

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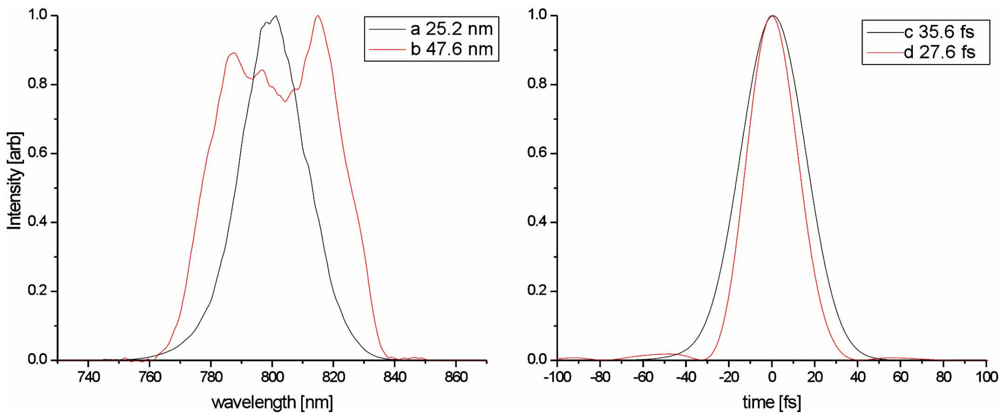

Fig. 5. Increasing bandwidth through amplitude modulation and compression by MIIPS leads to shorter pulses. Spectra (top panel) of the unmodified (a) and amplitude shaped (b) amplified laser with corresponding FWHM. Measured time duration of the pulses (bottom panel) without (c) and with (d) amplitude modulation.

4. Summary

In summary, we have demonstrated and verified that accurate adaptive spectral phase compensation and accurate phase delivery can be achieved using commercially available regenerative amplified pulses while maintaining their pulse intensity. The pre-amplification insertion losses from the adaptive pulse shaper have no effect on the amplified pulse energy. Pre-amplification pulse shaping also avoids the possibility of damaging the shaper optics. Here we have shown this capability on 0.7 mJ and 2.5 mJ systems, but there is no reason for this method not to be applicable in much higher intensity setups. Spectral phase characterization and correction is simplified by the use of the MIIPS method, which is based on analytic phase retrieval, and guarantees the delivery of the shortest pulses because it becomes more sensitive as the pulses approach the transform limit [3].

Acknowledgments

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