Remote characterization and dispersion compensation of amplified shaped femtosecond pulses using MIIPS

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Abstract: We report on the remote characterization and dispersion compensation (pulse compression) of femtosecond pluses using multiphoton intrapulse interference phase scan (MIIPS). The results presented here were carried out at a distance of 28.9 m from the target. The method could be used with targets placed kilometers away. The amplified pulses arrive at the remote target within one percent of transform limit or accurately phase-shaped by user defined phase functions. From our experiment we measure the group velocity dispersion of air at 800 nm to be 20.1±1.5 fs^2/m, which is in good agreement with published values. We consider this method for remote characterization and dispersion compensation to be an important step towards the development of reliable applications requiring the propagation of ultrashort pulses to remote targets.

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

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1. Introduction

Interest in remote sensing for industrial, environmental and homeland security applications using amplified femtosecond pulses has increased considerably in the last few years [1-5]. In all cases, the laser-target interaction is nonlinear in nature; and nonlinear optical processes depend on the spectral phase of the pulse [6, 7]. Because the propagation of ultrashort pulses to a remote target causes distance-dependent phase distortions, accurate characterization, and dispersion compensation (spectral phase correction) are critical for reproducible measurements based on nonlinear optical excitation. Here we present a method that achieves both of these requirements.

Characterization of femtosecond pulses is usually carried out by autocorrelation, frequency resolved optical gating (FROG)[8], or spectral interferometry for direct electric field reconstruction (SPIDER) [9]. These methods require good beam pointing stability and are mode quality dependent, both of these conditions are difficult and sometimes impossible to achieve in real-world remote sensing applications. Furthermore, these methods require the overlap of beams, in a setup that would need to be located at the remote target.

MIIPS is a single beam characterization and dispersion (any order) compensation method that does not require overlapping beams, and is not dependent on beam quality, making it ideal for remote applications [10-11]. MIIPS has been successfully demonstrated to measure and correct the phase of femtosecond pulses transmitted through scattering biological tissue [11]. The method introduces a reference phase, using a pulse shaper, to retrieve the unknown phase distortions in the pulse. Because the method uses a pulse shaper, it can make spectral phase corrections to achieve transform limited pulses. With MIIPS, characterization and phase correction are automated and completed within a few seconds. The resulting pulses are within 1% of the transform limit at the remote target.

2. Experimental section

Pulses from a titanium sapphire oscillator (K&M Labs, 45 nm FWHM) were shaped in a modified reflection geometry zero-dispersion shaper [12] consisting of a dual-mask SLM, and a 830 g/mm gold coated grating. The shaped pulses were amplified in a 1 kHz regenerative amplifier. After phase correction the output pulses were 35 fs FWHM and had pulse energy of 0.8 mJ. The beam was collimated and pointed towards the remote target using a Galilean telescope to a maximum distance of 28.9 m. The remote target was a 1 cm diameter pellet made of compressed KDP powder. The scattered frequency-doubled light generated at the target was collected and dispersed by a compact spectrometer. Group velocity dispersion measurements were carried out tracking changes in the compensation phase when MIIPS was carried out at different distances from the laser source.

3. Results

The MIIPS method is based on measuring the intrapulse interference caused by spectral phase distortions $\phi(\omega)$ in the beam [10-11]. Briefly, a reference phase function is introduced using the pulse shaper while the frequency doubled spectrum of the beam is recorded. Changes in the spectrum caused by intrapulse interference [6, 7] are well understood and allow one to calculate the phase distortions analytically [10-11]. Once $\phi(\omega)$ is known, the pulses are automatically corrected by applying the inverse of $\phi(\omega)$ using the shaper. Typically, the first

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iteration yields compressed pulses within 20% of the transform limit. After 3-6 iterations the MIIPS routinely converges to pulses $\tau_{pulse}/\tau_{TL} < 1.01$ at the target.

To validate the method for phase retrieval from pulses traveling longer distances, as needed for remote sensing applications, we first measured the spectral phase of the pulse 2.8 m from the exit aperture of the amplifier. The residual spectral phase, shown in Fig. 1, contains all distortions from the oscillator, amplifier and optics after the beam leaves the amplifier.

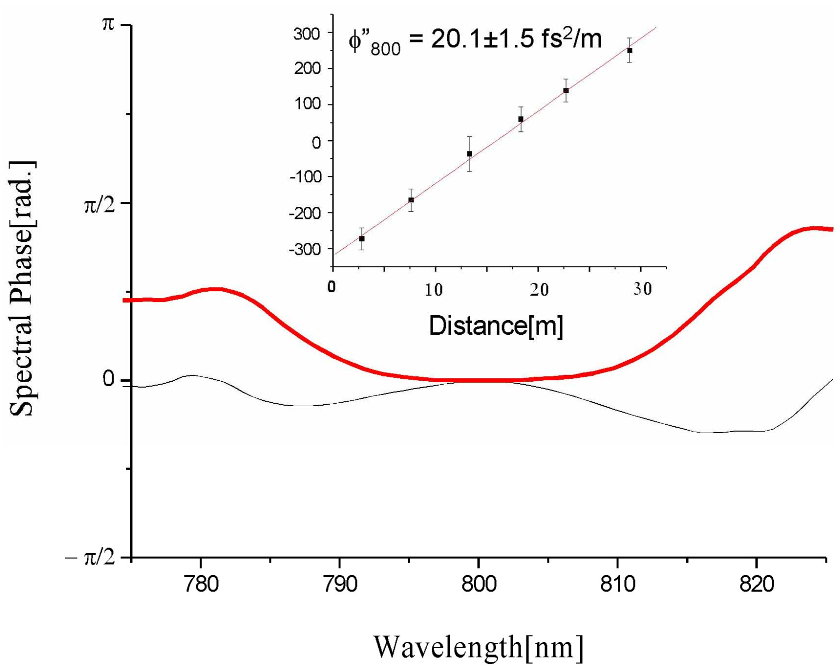

Fig. 1. Accumulated phase caused by propagation of femtosecond pulses in air. The black line is the retrieved phase measured 2.8 m from the amplifier. The red line is the retrieved phase after the pulses propagate in air 28.9 m from the output source. Inset: Measurement of the group velocity dispersion of air at 800 nm, obtained from the slope from a number of intermediate measurements.

The beam was directed to intermediate distances 7.6, 13.3, 18.3, 22.7 and 28.9 m, away from the amplifier. The same number of mirrors (protected silver) was used in all the experiments to preserve a constant non-air contribution to the phase distortion. The accumulated phases for the shortest and longest distance are plotted in Fig. 1. From measurements made at intermediate distances we obtained a value for the second derivative of the phase ϕ'' at 800 nm, and from the slope of these values we obtain the group velocity dispersion of air (see Fig. 1 insert). A linear fit of the data yields 20.1±1.5 fs^2/m, which is in good agreement with previously published values [13]. This measurement was performed at 21 ^oC, under 35% relative humidity. After correction using MIIPS, the residual phase distortions were on the order of 0.1 rad across the entire bandwidth of the pulse. The maximum phase distortion that can be compensated by the present setup is ~ 45000 fs^2, enough to compensate propagation through 2 km in air. This range can be easily expanded using different focusing optics, a different spatial light modulator, or taking advantage of the compression optics in the amplifier to reduce linear chirp, leaving high order phase distortions for automated compression. MIIPS per se has no range limit as long as sufficient signal can be detected.

To demonstrate accurate delivery of arbitrarily shaped pulses to a remote target, the pulses were first compensated and then a binary phase (Fig. 2, top) or a sinusoidal function

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(Fig. 2 bottom) was introduced by the pulse shaper. When the shaped pulse interacts with the remote target, frequency-doubled light is scattered and its spectrum is recorded. The remote signal (black dots) at 28.9 m is in excellent agreement with the signal obtained from 2.8 m (red line, Fig. 2) indicating that accurately phase shaped pulses were delivered at the remote target. MIIPS corrects the dispersion accumulated by the laser pulses as they travel to the target, resulting in the excellent agreement.

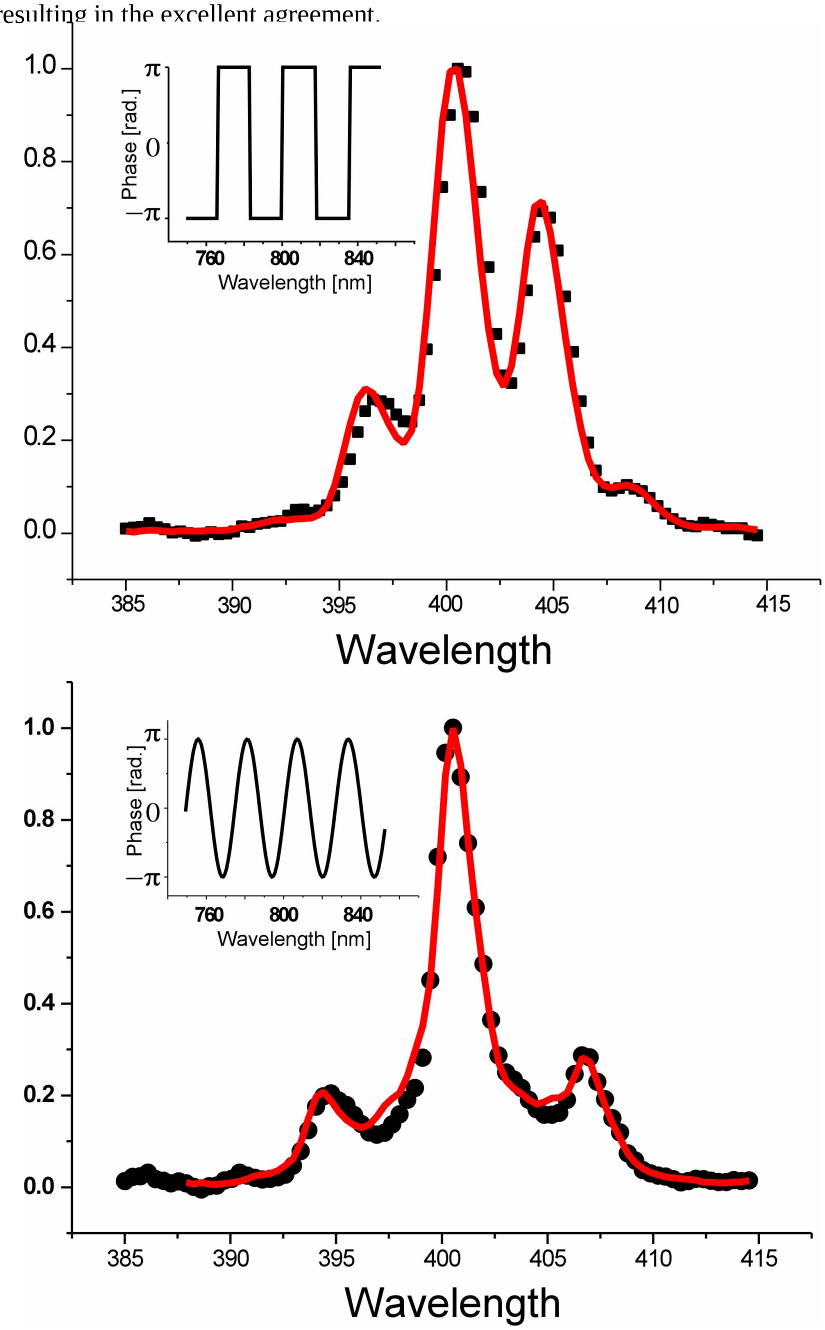

Fig. 2. Frequency doubled spectra of pulses shaped with a binary (top) and a sinusoidal (bottom) phase functions recorded at a distance of 2.8 m (red light) and 28.9m (black dots). The excellent agreement between the near and remote measurements indicates that phase distortions were successfully corrected.

Remote MIIPS can be used for ultrafast laser compensation, and pulse shaping. Because it is a single beam method it is not affected by mode quality or overlap between different beams. This makes it very practical for remote sensing applications. MIIPS can compensate moderate self phase modulation resulting from the propagation of intense pulses in air, however, expanding the beam can help avoid this problem and would ensure the remote delivery of transform limited or accurately shaped pulses. The MIIPS method presently takes a few seconds to complete the spectral phase measurement and pulse compression. For applications involving a moving platform or a moving target, we envision the construction of a calibration table based on static MIIPS measurements (taking into account temperature, humidity, scattering and pressure) that can be stored on the computer to achieve sub-second phase corrections based on ranging data.

In summary, we have demonstrated a reliable method for remote phase characterization, correction of phase distortions and accurate delivery of amplified and phase-shaped laser pulses using MIIPS. The results show that this method can be used without alteration for distances of interest in remote sensing applications (100 m to few km).

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