A new method for measuring the pulse-front distortion of arbitrary shapes in high-power ultrashort laser systems*

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We present a new method that can be used to calculate pulse-front distortion by measuring the spectral interference of two point-diffraction fields in their overlapped district. We demonstrate, for the first time, the measurement of the pulse-front distortion of the pulse from a complex multi-pass amplification system, which exists in almost all high-power laser systems, and obtain the irregular pulse-front distribution. The method presented does not need any reference light or assumption about the pulse-front distribution, and has an accuracy of several femtoseconds.

Keywords: pulse-front distortion, multi-pass amplification, high-power laser system

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1. Introduction

In the last decade, high-power short-pulse laser systems have played an important part in X-ray generation, electron acceleration, fast ignition, and so on.[1−3] Focusing is required in many applications to achieve a high peak intensity. However, because of the pulse-front distortion caused by lenses and misaligned gratings, the temporal property in the far field is apparently different from what we measure in the near field, and the peak intensity in the far field is far below that predicted by the simulation.

Since Bor,[4] and Kemp and Rudolph[5] pointed out that the spatiotemporal distortion appeared after the short pulse had passed through the lens, many measurement methods based on linear[6−7] or nonlinear[8−9] technologies have been presented. In a practical laser system, the pulse-front distortion must be measured and compensated before the compressor for a perfect compression, so the nonlinear method, which requires a short pulse duration, is inapplicable. The linear method based on the spectral interference in Ref. [7] does not need any reference pulse, which is necessary in a short-pulse system with a laser chain about 100 m long. However, its symmetry assumption does not hold in a complex laser system because of the inevitable misalignment of the beam path, the off-axis property of the multi-pass amplification, and the coexistence of different kinds of distortion sources (e.g. gratings, lenses and wedged optics). Therefore, none of the existing methods can be applied to the measurement of a typical high-energy short-pulse system.

In this paper, we propose and demonstrate a new method, with which the irregular pulse-front distortion of a complicated laser system composed of multi-pass amplification can be measured.

2. Experiment

The configuration of the experimental bed for demonstrating the measurement of the pulse-front distortion in a typical four-pass amplification laser system is shown in Fig. 1. The front-end pulse is injected into the four-pass amplification section by lens L1, mirrors M1 and M2, and bounces on the M3 mirror. The beam is reflected off the M4 mirror into the U turn, goes back through the M2 mirror, bounces on the M3 mirror again, exits from the four-pass amplification section after the L7 lens, and enters into the final compressor. Our experiment is performed using a

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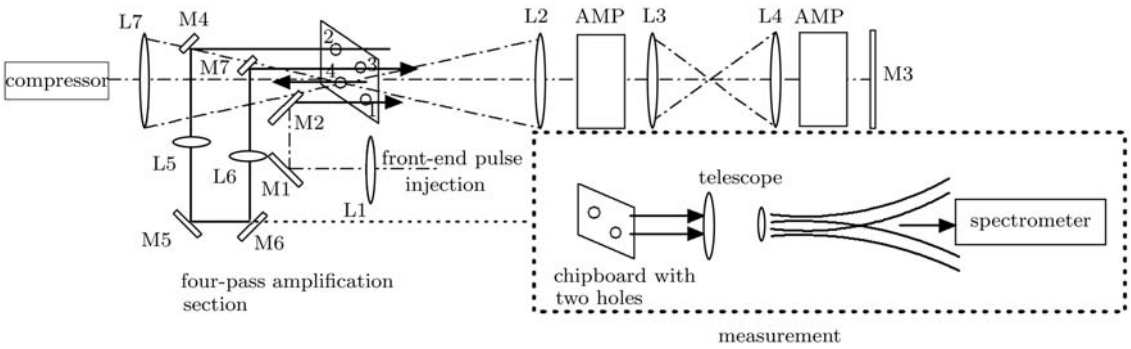


Fig. 1. Schematic diagram of the experimental bed, consisting of a typical four-pass amplification section and a measurement section.

mode-locking fiber laser producing a 200 fs (full width at half maximum) pulse at a 60 MHz repetition rate with a central wavelength of 1053 nm. Considering that the pulse is almost invisible on the sensitive card after the four-pass propagation, we carry out the diagnosis with the second pass output. The beam path for the measurement is shown in the dashed-line frame, where the pulse to be measured passes through a diaphragm composed of two 1 mm diameter holes with a distance 5 mm apart. The two selected beams become thinner and closer after propagation through a 6× telescope. Interference occurs between the diffraction fields of the two thin beams, and the spectral interference is captured by a high-resolution spectrometer (Acton Pro2750). The main procedures we adopt in the experiment are as follows.

i) Make sure that the center of the beam passes through one hole on the chipboard. A quartz slice is perpendicularly inserted into one of the two beams to obtain a higher resolution.

ii) Move the two lenses mounted on the slides to ensure that the two selected beams by the diaphragm are symmetrically incident on them. Make sure that the spectrometer gap is in the center of the overlapped region and the beam is perpendicularly incident on it. Capture the spectral interference fringes, from which we can infer the time delay between the two beams selected by the holes, as shown in Fig. 2.

iii) Move the chipboard and the quartz slice horizontally in the cross section 5 mm equal to the distance between the two holes.

iv) Repeat procedures ii) and iii) until one hole is at the edge of the beam.

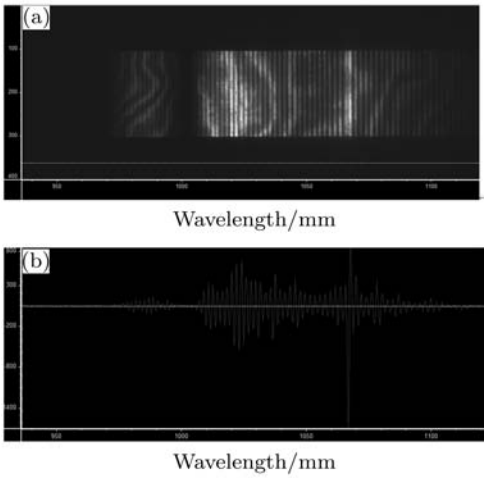


Fig. 2. (a) Spectral interference fringes captured by the spectrometer, and (b) the one-dimensional distribution of spectral interference after noise elimination.

For a 5 cm diameter (in the U turn) laser beam, we finally acquire the spectral interference fringes of 11 close points with an interval of 5 mm between them. The one-dimensional distribution of the spectral interference shown in Fig. 2(b) can be extracted after the subtraction of the two interfering spectra from the spectral interference fringes. According to the formula $\tau = \lambda^2/(c \cdot \Delta\lambda)$, where λ is the central wavelength of the selected fringes (1053 nm in this paper), c is the speed of light, and $\Delta\lambda$ is the period of the fringes, we can obtain the time delay between the points we measured and the pulse-front distribution along the radial direction, which is shown in Fig. 3.

The theoretical simulation is carried out in the absence of the spherical aberration because of the small numerical aperture of the spatial filter lenses. As the pulse-front distortion is wavelength dependent, both the theoretical and the experimental data are acquired at 1053 nm.

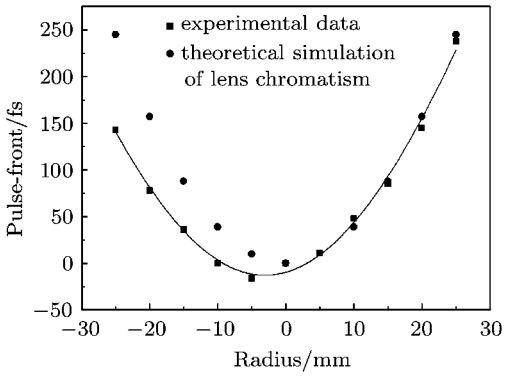


Fig. 3. Pulse-front distortion in the multi-pass amplification section of the high-energy short pulse-system at 1053 nm.

From Fig. 3, we can see that the difference between the theoretical and the experimental data lies in their symmetry. The asymmetry of the pulse-front distribution (black squares), which has never been reported in the previous papers, may result from the misalignment of the beam path, the tilt of the lenses for avoiding damage from ghost points, and the off-axis propagation through the lenses that are inevitable in a high-energy short-pulse system containing the multi-pass amplification section. Of course, the non-parallel surfaces of the optics are also a possible factor.

3. Verification

To investigate whether the method itself can introduce any additional pulse-front distortion and the accuracy that can be acquired, we carry out a verification experiment. As shown in Fig. 4, an ultra-continuum laser is magnified by a telescope consisting of two parabolas without introducing a chromatic aberration, and then enters into the measurement section described in Fig. 1. We acquire interferograms (shown in Fig. 5.) before and after a thin quartz slice with an exact thickness of 504 μm is inserted into each of the two beam paths. Figure 5(a) shows that the method itself will not introduce any pulse-front distortion, despite of the use of the lenses, which can be accounted for by the symmetric incidence. From Fig. 5(b), we can induce that the measured time delay introduced by the slice at 600 nm is 806 fs. The theoretical value is 803 fs, which can be acquired with the thickness and the group velocity. Considering that the error for the thickness of the slice is less than 1 μm, we believe that the accuracy of the method can be up to the order of several fs. The error may result from the high-frequency modulation in the interferograms, which comes from the laser or the spectrometer.

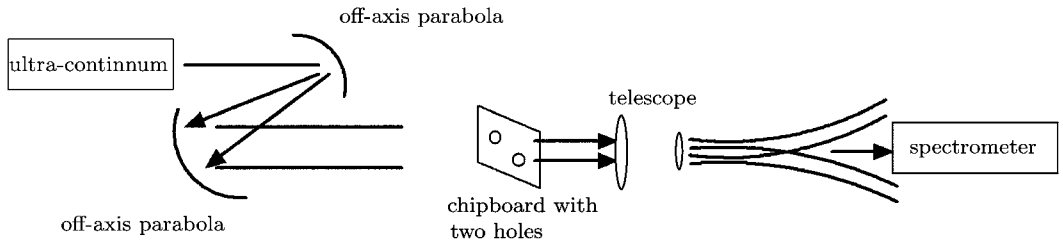


Fig. 4. Configuration of the experimental bed for verification.

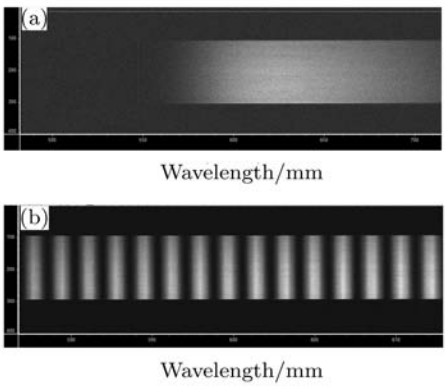


Fig. 5. (a) The initial interferogram and (b) the interferogram obtained after the insertion of two thin quartz slices in the verification experiment ($\Delta\lambda(\lambda = 600\ \text{nm}) = 1.50\ \text{nm}$).

4. Conclusion

We developed a new method based on the measurement of the spectral interferograms of two diffraction beams. Because it does not need a reference light or an assumption about the pulse-front distribution, it can be applied to high-energy petawatt laser systems. Using the method, we measure the pulse-front distortion of the multi-pass amplification section in a typical high-energy petawatt laser system and acquire an irregular shape, which may be induced by the misalignment of the beam path and the off-axis property of the multi-pass amplification. We also experimentally demonstrate that the method itself will

not introduce any pulse-front distortion, and that the accuracy is up to the order of several fs.

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