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Wavefront evolution of the signal beam in Ti:sapphire chirped pulse amplifier*

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We studied the evolution of wavefront aberration (WFA) of a signal beam during amplification in a Ti:sapphire chirped pulse amplification (CPA) system. The results verified that the WFA of the amplified laser beam has little relation with the change of the pump beam energies. Transverse parasitic lasing that might occur in CPA hardly affects the wavefront of the signal beam. Thermal effects were also considered in this study, and the results show that the thermal effect cumulated in multiple amplification processes also has no obvious influence on the wavefront of the signal beam for a single-shot frequency. The results presented in this paper confirmed experimentally that the amplification in a Ti:sapphire CPA system has little impact on the WFA of the signal beam and it is very helpful for wavefront correction of single-shot PW and multi-PW laser systems based on Ti:sapphire.

Keywords: wavefront aberration, Ti:sapphire, chirped pulse amplification, wavefront correction

PACS: 42.15.Dp, 42.60.–v, 42.60.Jf **DOI:** 10.1088/1674-1056/28/1/014203

1. Introduction

Ultra-intense ultra-short laser systems are widely studied for their potential to provide an extreme physical environment for high-field science when the output beam is focused by a lens or parabolic mirror.[1,2] The chirped pulse amplification (CPA) technique, proposed by Mourou and his co-workers in 1985,[3] prompted several petawatt (PW) laser systems using the scheme implemented in Refs. [4]–[7]. In CPA systems, neodymium glass (Nd:glass) and Ti:sapphire are two amplification media that can be used to attain PW-level laser emission. Compared to Nd:glass, Ti:sapphire crystals have been considered as an ideal gain medium due to their wide gain bandwidth centered at 800 nm and can achieve extremely short pulse width. In recent years, Ti:sapphire-based CPA scheme has also been employed in many institutions, e.g., the APOLLON 10-PW facility[8] and Shanghai Super-Intense Ultrafast Laser Facility (SULF),[9,10] due to its high stability and conversion efficiency. Gan *et al*. experimentally demonstrated progress in suppressing transverse parasitic lasing (TPL) from a large-aperture Ti:sapphire in 2017, which led to a peak power of 5.4 PW.[11,12]

Nevertheless, a high power density laser needs not only a high peak power, but also a diffraction-limited (DL) focal spot size.[13] As the major limitation of focus ability in a laser system, the wavefront aberration (WFA) is generally distorted by the optical quality of bulky components in the system[14–16] and the nonlinear effect during the amplification process. Thus, controlling and correcting WFAs of laser systems has been a fundamental and necessary work for improving the power density. The distortion caused by the beam edge and the image locations could be reduced by the soft edge aperture and spatial filters. In addition, active wavefront correction that utilizes an adaptive optics system (AOS) is widely used for compensating WFA and attaining a DL focal spot[13,17] in the ultra-short high laser system.

A correction device such as a deformable mirror (DM) is an important component in AOS[14] that needs a laser beam with repetition for closed-loop feedback. However, most of the PW laser systems are working in single-shot frequency, like tens of minutes per shot, because of the thermal effect of the pump source.[11,18] In these single-shot PW laser systems, the DM of the AOS should correct the static WFA in repetitive mode and pre-compensate the dynamic WFA during amplification. In the LULI laser system, which is based on Ti:sapphire/mixed Nd:glass, the thermal effects induced by the flash lamp pumping system have an adverse influence on the wavefront of the signal beam and focus ability of the laser system. To achieve wavefront correction of the signal beam, it is a prerequisite to control and correct static WFA and pre-compensate the dynamic WFA of laser systems before each

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shot.[18]

Despite the fact that the CPA Ti:sapphire-based process has low requirements for the pump laser compared to CPA Nd:glass-based systems and the optical parametric CPA process,[19] the spatial distribution of the amplified laser beam has a close relation to the pump beam.[20] In addition, the thermal effects in CPA Nd:glass-based laser systems inevitably influence the control and correction of the WFAs of the facility.[18] However, few studies report on the WFA evolution of the signal laser in the Ti:sapphire amplification process. Therefore, it is important to experimentally study the wavefront evolution of the signal beam and the influence of TPL and the thermal effects on the WFA of the signal laser during the single-shot amplification process. This paper experimentally investigates the WFA evolution of the signal beam in Ti:sapphire CPA amplification, which can be very helpful for achieving wavefront correction in single-shot Ti:sapphire PW laser systems.

2. Experiment

In most Ti:sapphire PW laser systems, the amplifier is a multi-pass amplifier pumped by a 526.5 nm laser pulse. The experimental setup for wavefront detection in the Ti:sapphire CPA laser is presented in Fig. 1. We studied the three-pass 80 mm-diameter Ti:sapphire amplifier with double-end pumping. This amplifier operating on a single shot every 20 min was used as the power amplifier in a multi-PW laser system.[11] A home-made Nd:glass laser was used as the pump source, and produced a single pulse with 18 ns pulse width and 70 mm diameter. The injected signal pulse energy was set to 400 mJ with 1.2 ns pulse width and 63 mm diameter to ensure amplification. The repetition of the signal in the static mode was 1 Hz.

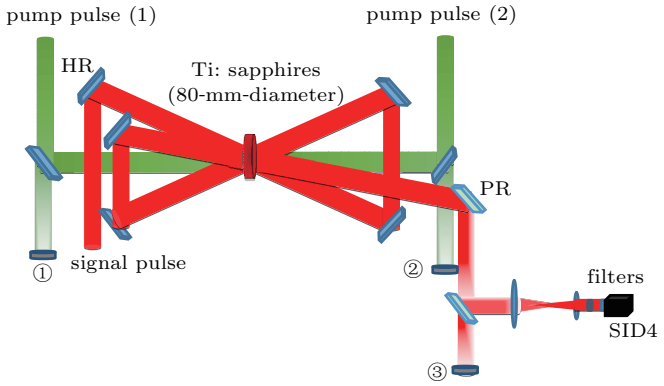


Fig. 1. Experimental setup of wavefront detection in the Ti:sapphire CPA laser system. The signal pulse was amplified by the three-pass 80 mm diameter Ti:sapphire. The output beam was reflected by two uncoated plane reflectors (PR) to protect the SID4. The energies of the pump and signal beams were measured with pyroelectric energy meters ①–③.

After three-pass transmission, the signal beam was down-collimated to 3 mm with an aperture to match the clear aperture of the wavefront sensor (SID4-505, PHASICS). The experimental setup to measure the WFA is shown in Fig. 1. The variation of peak-to-valley (PtV) and root mean square (RMS) errors, the distribution of WFA, and the Zernike coefficients of both the pump and signal beams were compared using the SID4 measurements. Analysis of those parameters revealed that changing the pump conditions caused no significant WFAs. As we changed the pump energy, we also considered the TPL and the thermal effects in the amplification process. The results showed that the TPL and thermal effect have no obvious influence on the WFA of the signal beam at a single-shot frequency.

3. Results and discussion

In order to study the evolution of the signal beam in the amplification process, we measured the WFA of the pump and signal beams at different pump energies, as shown in Figs. 2(a) and 2(b). The TPL was effectively suppressed by using an index matched cladding. The WFAs of the pre-amplified pulses before every amplification were also measured. Figure 2 shows the measured values of PtV and RMS errors under different pump conditions. To confirm the results of the experiment, we measured multiple sets of data under every condition. The data varied within 5% of the measured value and they are shown with the error bars in Fig. 2. The black ones in Fig. 2(a) represent the values of PtV and RMS of the pump beam and the red ones in Fig. 2(b) represent the values of the amplified signal beam. The brown ones in Fig. 2(b) represent the values of the signal beam before each amplification. The amplified output energies are 5.45 J, 11.3 J, 17.08 J, and 19.8 J when the pump energies are 23.4 J, 43 J, 55 J, and 65.67 J, respectively.

The PtV of the pump beam in Fig. 2(a) ranged from 3.035λ to 3.397λ as the energy changed from 23.4 J to 65.67 J. We suspect that the small difference is due to jitter in the output power of the pump laser. Meanwhile, the PtV of the amplified signal beam in Fig. 2(b) is around 0.724λ to 0.805λ, and stays nearly constant before amplification. Increasing the energy of the pump beam, the PtV of the pump and signal beams are comparatively stable. The RMS errors in Fig. 2 (shown as dots), which show the stability of the pump beam and signal beam, are also stable and insensitive to changes in the pump energy.

Although the measured values show fluctuations in Fig. 2, the PtV and RMS errors of the pump and signal beams show stochastic changes and have no obvious correlation. In addition, the data from the signal beam at static and amplified modes are very close. Comparing the PtV and RMS errors of the signal beam in the static and single-shot amplified modes, we initially conclude that the Ti:sapphire CPA has negligible influence on the WFA of the signal beam.

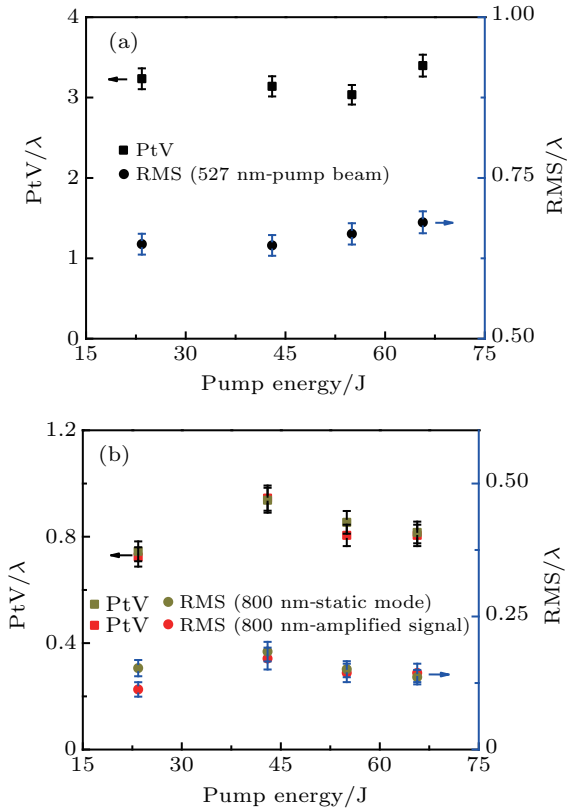


Fig. 2. PtV (squares) and RMS (dots) of (a) the pump beam and (b) the signal beam (static and amplified mode) with different pump energies.

The WFA distribution of the pump and signal beams was measured by SID4 for further analysis, as shown in Fig. 3. The distribution can intuitively describe the evolution of the signal beam WFA during the amplification of the Ti:sapphire amplifier. In Fig. 3, the first row shows the WFA distribution of the pump beam with energies of 23.4 J, 43 J, and 55 J respectively, and the second row is the WFA distribution of the amplified beam under these pump conditions.

In the WFA distribution of the pump beam, the saddle shape was observed in the horizontal direction and the inverted saddle shape was observed in the vertical direction. This indicates that astigmatism along 0° is the main WFA component in the pump beam. The saddle shape and the inverted saddle shape in the WFA distribution of the signal beam deviated from the horizontal and vertical directions. This indicates that astigmatism along 0° is not the only main component in the WFA of the signal beam.

The low-order Zernike coefficients are given in Table 1. For the pump beam, the astigmatism coefficient along 0° is 1.133, which is much higher than that of the other orders. In the amplified signal beam, the astigmatism coefficients along 0° (−0.237) and 45° (−0.169) have almost the same magnitude. The magnitudes of the low-order Zernike coefficients for the amplified signal are different from those for the pump beam; however, they are almost the same as those of the signal pulse in static mode. The wavefront of the signal beam remains relatively stable under the different pump conditions. We can confirm that the WFA of the pump beam has minimal or no impact on the wavefront stability of the signal beam.

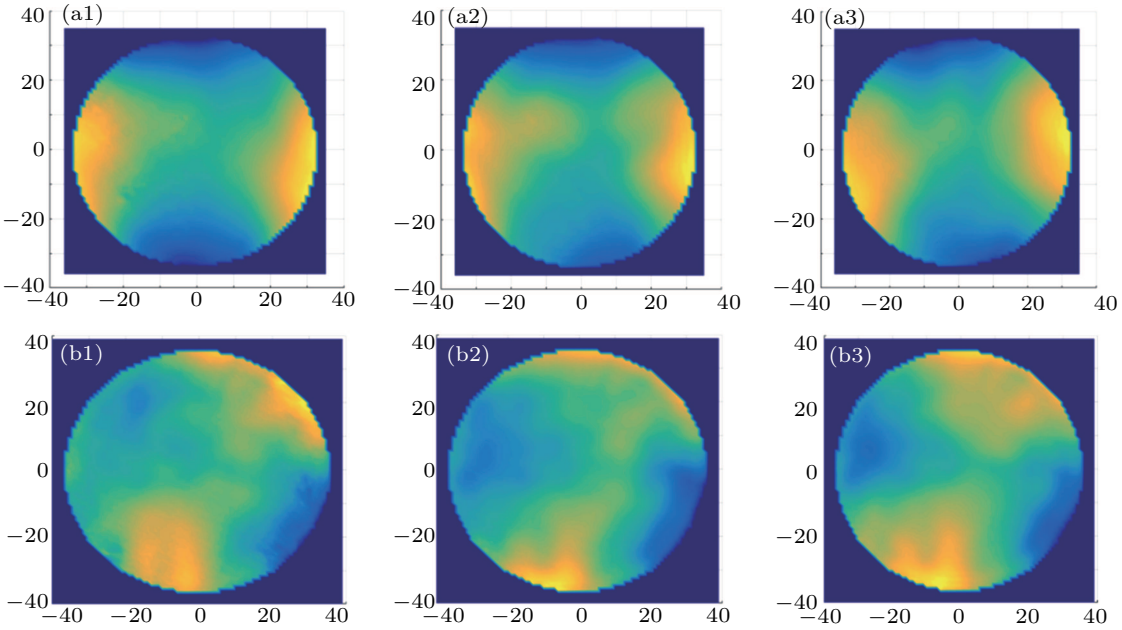


Fig. 3. The WFA distribution under different pump energies: (a) the pump beam and (b) the signal beam.

Table 1. The low-order Zernike coefficients.

	Astig 0°	Astig 45°	Coma *X*	Coma *Y*	Spherical aberr
Pump beam (55 J)	1.133	–0.079	0.061	0.253	–0.028
Signal beam (static)	–0.285	–0.235	0.035	–0.056	0.001
Signal beam (17.08 J)	–0.237	–0.169	–0.078	–0.078	0.031

TPL is very harmful to the amplification in a high-energy Ti:sapphire CPA laser system because it makes the amplified energy drop. Although it was suppressed experimentally in our PW laser system at the normal amplification, it might occur with the increase of the pump energy. It is very important to study the WFA of the signal beam when TPL happens. In Fig. 4, we recorded the values of the PtV and RMS errors of the signal beam at static and amplified modes under different pump conditions without index-matched cladding. The error bars in the figure indicate that the data varied within 5% of the measured value. The amplified output energies are 1.28 J, 2.38 J, and 1.93 J when the pump energies are 23.4 J, 43 J, and 55 J, respectively. The output energies of the signal beam notably decreased when severe TPL happened in the Ti:sapphire crystal.

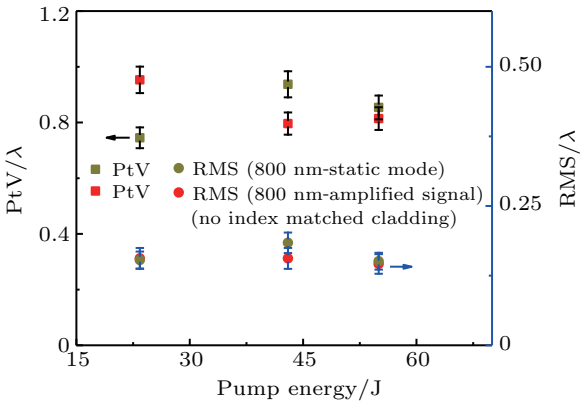


Fig. 4. PtV (squares) and RMS (dots) of the signal beam (static and amplified modes) with different pump energies.

The PtV of the amplified signal beam in Fig. 4 is around 0.953λ to 0.814λ, and it still stays nearly constant before amplification. The RMS errors in Fig. 4 show the same stability. Although severe TPL occurs in the amplification, the WFA of the signal beam shows little change in this progress. The wavefront of the signal beam remains relatively stable even in the amplification with TPL.

Like TPL, the thermal effect of Ti:sapphire caused by high pump energy should be carefully avoided in general, because it can form a thermal lensing effect that reduces the beam quality and harms the optical elements. The cumulative thermal effect in CPA Nd:glass-based systems also shows some influence on the wavefront of the signal beam.[17] Therefore, it is necessary to study the influence of the thermal effect on the wavefront of the signal beam in the CPA Ti:sapphire-based process. In order to study the changes in the wavefront of the signal beam caused by the thermal effect, we recorded three groups of wavefront information of the amplified signal beam with the repetition rate of every 20 min. The WFAs of the signal pulses before and after every single-shot amplification were also measured. The values of the PtV and RMS errors of the signal beam are shown in Fig. 5. Three groups of data asterisked in Fig. 5 were acquired respectively using amplified signal energies of 5.45 J, 11.3 J, and 17.08 J in the fourth, twenty-fourth, and forty-fourth minute. In addition, we obtained the wavefront information of the static signal beam in three minutes before and after every amplification.

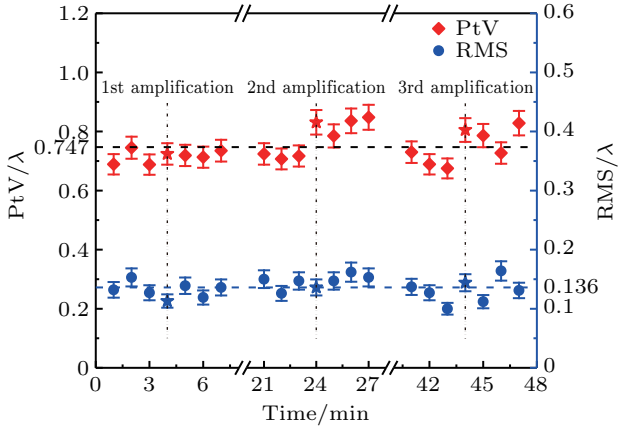


Fig. 5. PtV and RMS of the signal beam in three amplification processes (amplified in the fourth, twenty-fourth, and forty-fourth minute).

In the data for three amplifications, we choose the group with the highest energy amplification to study the influence of the thermal effect on the signal beam WFA in a single-shot amplification. The highest energy amplification requires the highest pump energy and should cause the most obvious thermal effect. The amplified energy was 17.08 J and the pump energy was 55 J. The values of three pulses before amplification were measured every minute with PtV values of 0.73λ, 0.766λ, and 0.797λ and RMS values of 0.137λ, 0.126λ, and 0.135λ. The PtV and RMS values for the amplified pulse were 0.805λ and 0.144λ, respectively, as stated in the beginning of this paper. Part of the pump energy was converted to thermal energy in the Ti:sapphire crystal and it may affect the WFA of the signal. Three pulses after amplification were also measured immediately every minute. We observed PtV values of 0.797λ, 0.754λ, and 0.828λ and RMS values of 0.135λ, 0.109λ, and 0.131λ, respectively. Comparing the values from the three conditions, we found that the PtV and RMS errors of the signal after single-shot amplification were almost the same as those of the amplified pulses and the pulses before amplification. We therefore come to the same conclusion that was reached previously from the other two groups of data at the amplified pulse energies of 5.45 J and 11.3 J.

The evolution of WFA of a signal laser during three amplification processes in a CPA Ti:sapphire-based system with the repetition rate of every 20 minutes is shown in Fig. 5. All of the PtV and RMS values of the signal beam tended to be stabilized around 0.747λ and 0.136λ in one hour while the thermal effect was accumulated. We can conclude that the influence of the thermal effect caused by the pump beam on the signal beam WFA is negligible in the single-shot Ti:sapphire amplifier with a repetition every 20 min.

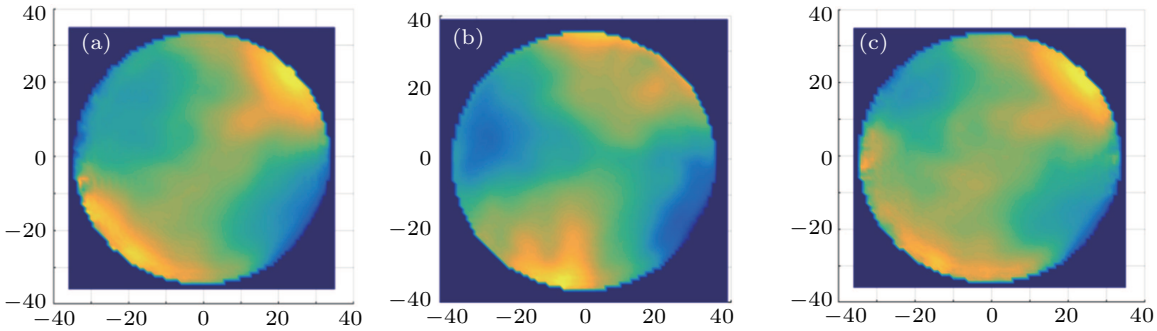


Fig. 6. The WFA distribution of the signal beam: (a) before amplification, (b) amplified, (c) after amplification.

According to the comprehensive analysis of the PtV and RMS errors for the signal beam at different amplified energies, the influence of the thermal effect occurring during the amplification of single pulses does not induce obvious aberrations in the wavefront of the signal beam. We can also draw a comprehensive conclusion by studying the WFA distribution. The contrast of the WFA distribution for the signal beam with 17.08 J amplified energy in Fig. 6 and three different amplified energies in Fig. 3(b) indicates that the thermal effect in a Ti:sapphire CPA, which is working at 20 min every shot, has little impact on the WFA of the signal beam.

4. Conclusion

We studied the evolution of WFA of a signal beam during amplification in a Ti:sapphire CPA. The PtV and RMS errors, the WFA distribution, and the Zernike coefficients, which were compared in this study, show that the pump beam, the TPL, and the cumulated thermal effect (repetition every 20 min) have no obvious influence on the wavefront of the signal beam in the Ti:sapphire CPA. The results of this paper indicate that the amplification in a Ti:sapphire CPA will not cause any dynamic aberrations and it aids in wavefront correction of single-shot PW laser systems based on the Ti:sapphire crystals. In this process, the result of wavefront correction achieved from repetition-pulse status (the static mode) can be directly used in the amplified pulse to supply the physical experiment without pre-compensating the dynamic aberrations.

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