Wave-front correction of high-intensity fs laser beams by using closed-loop adaptive optics system

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Abstract We developed an adaptive optics system to correct the wave-front distortion of an intense fs laser beam from our multi-TW laser system, Jiguang II. In this paper, the instruments of the adaptive optical system are described and the experimental results of the closed-loop wave-front correction are presented. A distorted laser wave-front of 20 wavelengths of P-V values was corrected to 0.15 wavelength of P-V values. The beam quality of the laser system varies from 3.5 diffraction limit to 1.5 diffraction limit.

Keywords: Shack-Hartmann wave-front sensor, adaptive optics system, femtosecond laser, diffraction limit.

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1 Introduction

The chirped pulse amplification (CPA) technique has greatly facilitated the development of ultra-short, ultra-intensity laser technology, and peak power as high as PW level has been obtained with the table-top laser facility[1—3]. The rapid progress on ultra-strong femtosecond laser enables us to take the experiments on the fields of the ultra-fast X-ray sources, electron acceleration, and relativistic plasma physics, etc.[4—6]. However, for those experiments on high power laser interaction with matter, the power density on the target plays a more important role than the peak power. Up to now, most efforts have been concentrated on increasing the energy, reducing the pulse duration, and temporally cleaning the pulses from the CPA systems to boost the peak power. Inevitably the cost for building a large CPA laser device is very high and it is impossible to realize the goal for most laboratories. Therefore, it is a significant technique to pursue a high beam quality for ultra-strong lasers[7]. In fact, for a hundreds-TW level CPA laser facility, the power density of focus spot varies from 10^{18} to 10^{21} W/cm^2 because of different beam quality.

It is important for a high power laser facility to get good beam quality. There are many factors, such as temperature gradient, astigmation, optical aberration, which will impact the beam quality of the laser system[8]. In general, the wave front will become worse and worse after multi-amplification in the high power laser facility, which leads to an undesirable beam profile and focus ability. By using an adaptive optics system, we can correct the distortion of wave-front in the CPA Ti:sapphire laser system[9]. As usual, for a high power laser facility, the output laser beam quality was about 3 to 5 diffraction limit without AO system and it can be corrected to 1.5 diffraction limit with AO system. In this paper, we report the wave-front correction for our 20TW Ti:sapphire laser facility (Jiguang II), of which the beam quality was corrected to 1.5 diffraction limit from 3.5 diffraction limit with an adaptive optics system.

2 Adaptive optical system

The configuration of the adaptive optical system consists of the wave front sensor, which is based on Shack-Hartmann principle of wave front measurement, deformable bimorph mirror as a wave-front corrector, control unit for bimorph mirror and software, which is intended for work with PC computer[10].

2.1 Shack-Hartmann wave front sensor

Shack-Hartmann wave front sensor was composed of a mini lens array and a CCD camera. It separated a laser beam into many mini parts, and then focused them onto a focal plane, shown as in fig. 1(a). If the laser beam was an ideal plane wave front, the

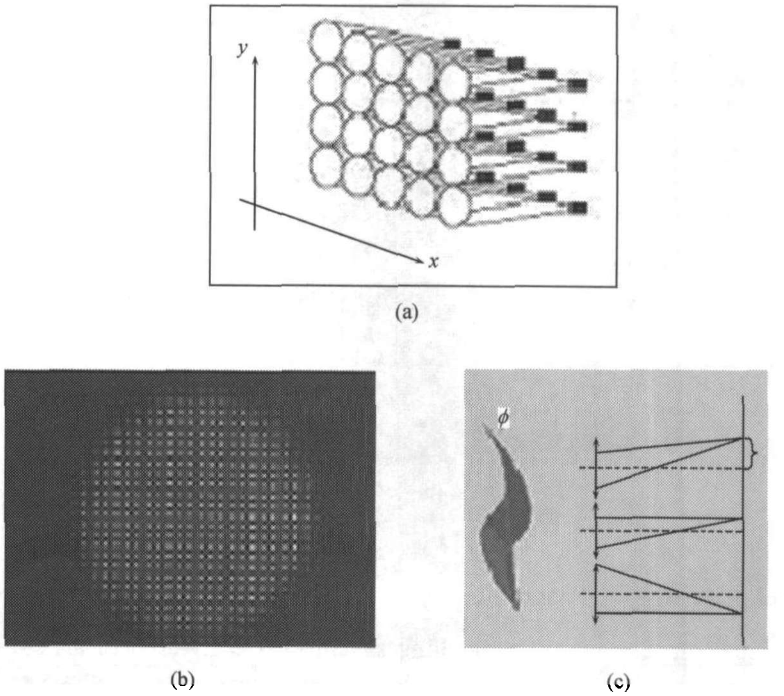

Fig. 1. The principle of Shack-Hartmann wave front sensor, the array of lenticule (a), the spot array of plane beams (b), and the spot of aberration beams (c).

focal spots on CCD camera would be a group of regular spots. It is shown as in fig. 1(b). While the real laser beam was not a plane wave front, it would have some aberration. Thus the focal spots were a group of irregular spots, shown as in fig. 1(c). We could evaluate the beam quality by calculating the difference between ideal and real spot distribution.

2.2 Deformable bimorph mirror

The bimorph mirror consists of a glass, copper or quartz substrate firmly glued to a plate actuator disk made from piezoelectric ceramic. Applying the electrical signal to the piezoceramic plate causes tension of the piezodisc. Glued substrates prevent this tension, and this results in the deformation of the reflective surface. To reproduce different types of aberrations with the help of such corrector, the outer electrode is divided into several controlling electrodes, which have the shape of a part of a sector. The size as well as the number of such electrodes depends on the number and the type of the aberrations to be corrected. The scheme of deformable bimorph mirror is shown in fig. 2.

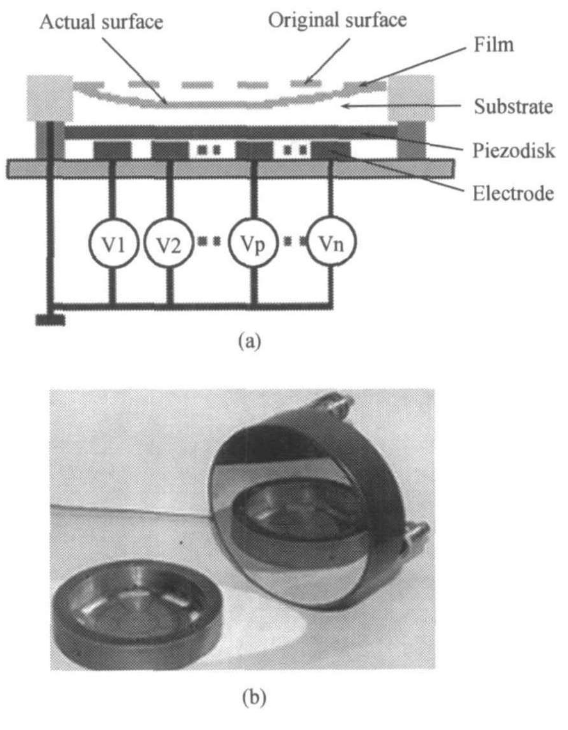

Fig. 2. Scheme of the deformable bimorph mirror.

2.3 Signal processing and controlling system

The signal processing and controlling system was composed of a PC-card, signal processing software, computer and a group of voltage controllers. When the computer received the information of wave front aberration from the Shack-Hartmann wave-front sensor, signal-processing software would calculate the voltage values which should be set on the electrodes of deformable mirror and send an order to the voltage controller. The controller could send a specific voltage to the electrodes, which caused the deformable mirror to change its surface correspondingly.

3 System design

We install the system between the compressor box and experiment chamber, and the schematic layout is shown in fig. 3. The laser beam was injected onto the deformable mirror, and reflected by a mirror and splitter, the contribution of which was about 99:1. The transmission beam was accepted by wave front sensor, which can get the aberration of the beam. According to the aberration, the deformable mirror changed the reflected surface to correct the wave front of the beam. Thus, the wave front of the laser after the compressor was corrected before entering the experiment chamber.

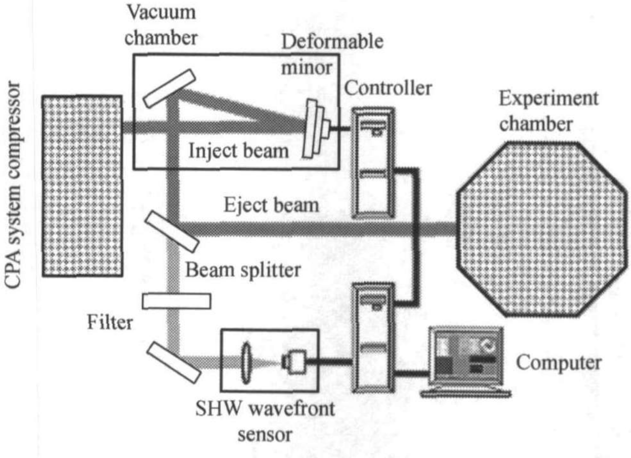

Fig. 3. Scheme of the system setup.

When the system worked, we applied some voltage to deformable mirror and used the SHW to measure the wave front of the laser beam. Then the voltages to be applied to all electrodes of the bimorph mirror were calculated. And these voltages multiplied by a coefficient were applied to electrodes of deformable mirror. In this case the wave front was not absolutely compensated and the residual distortions were measured by SHW. Again voltages to be applied to corrector electrodes were calculated and applied with the coefficient until getting a good wave front.

4 Experiment results

It is very important to choose the reference wave front correctly in the AO system. In general, there are two ways to get the reference wave front[11, 12]. One is using an ideal wave front that was calculated as an ideal plane wave front. Another is using a real laser source with very good beam quality, such as LD laser, He-Ne laser, which should be expanded to the same beam size with the actual laser source. As a preparation work, we must know the aberration of the laser beam which was the difference between ideal wave front and actual wave front. The wave front was measured by Shack-Hartmann wave front sensor. Fig. 4(a) was an ideal wave front of laser beam, and fig. 4(b) was an actual laser beam wave front.

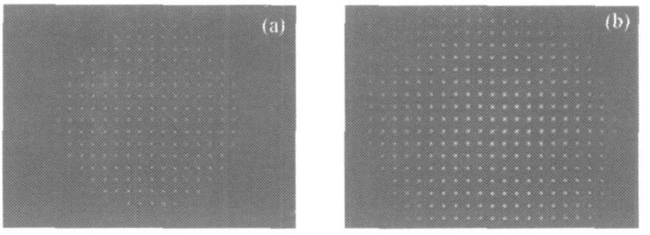

Fig. 4. Wave front of laser beams using Shack-Hartmann wave front sensor.

In the experiment, the beam size of our laser system was about 30 mm; we got the actual wave front using the SHW, and compared it with the ideal wave front. The interference figure is shown in fig. 5(a). According to the figure, we can calculate phase distribution and aberration of the beam. The phase distribution is shown in fig. 5(b). It was shown that the value of peak to valley (P-V), which was the best aberration, was about 20λ. λ was the laser wavelength. The laser beam with such beam quality cannot be fo-

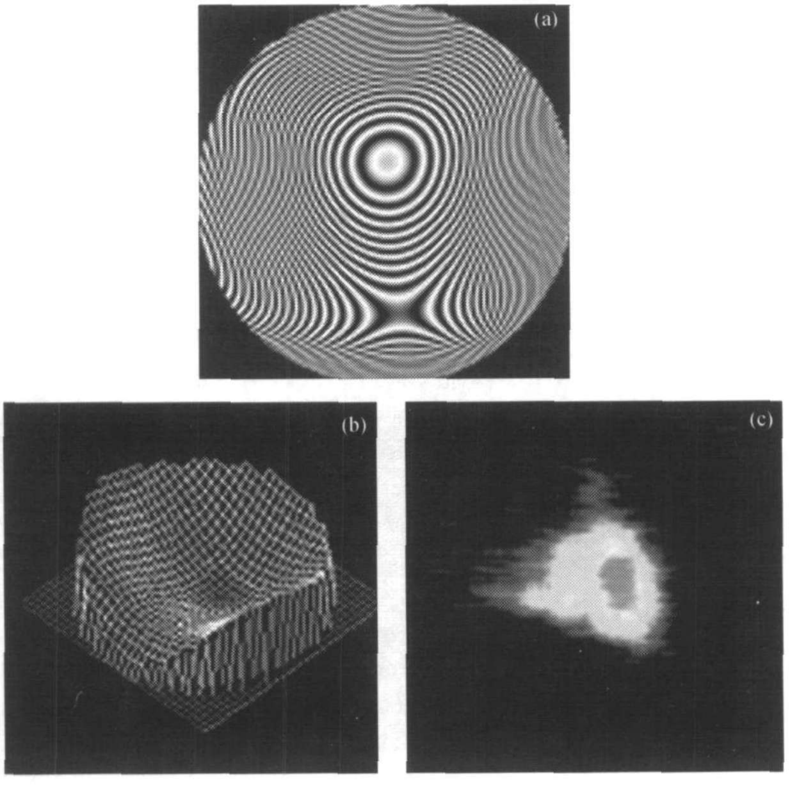

Fig. 5. Phase distribution and focused spot before wave front correction.

cused into a very small spot. Using a 4 m focus lens, we got the focused spot distribution, shown as in fig. 5(c). The results show that the spot size in horizontal and vertical direction were about 568 μm and 432 μm, corresponding to the 4.2 and 3.2 diffraction limit.

According to the aberration measured by the SHW, we applied the right voltage to the deformable mirror. With the wave front correction, the interference figure would be changed accordingly. When it reached the ideal wave front, the interference figure would be regular and smooth, shown as in fig. 6(a). The phase distribution is shown in fig. 6(b). It was shown that the value of peak to valley (P-V) was about 0.15λ. In order to see such small distortion, we enlarge the coordinate value of fig. 6(b). With the same focus lens, we also got the focused spot distribution, shown as in fig. 6(c). The results show that the spot size in horizontal and vertical direction were about 200 μm and 214 μm, corresponding to the 1.5 and 1.6 diffraction limit.

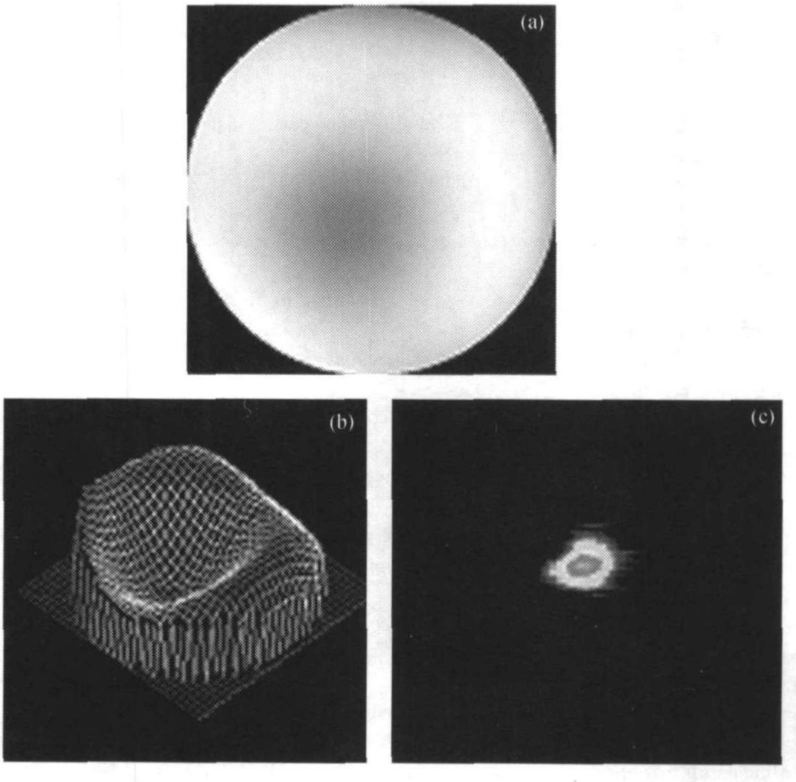

Fig. 6. Phase distribution and focused spot after wave front correction.

In general, there are two ways to use AO system in the CPA laser system. One is in time domain. The AO system was installed in the stretcher or compressor, which compensated the distortions in time domain and could get shorter pulse duration. Another is in spatial domain. Like what we have done, researchers installed the AO system after compressor of CPA system, which just compensated the spatial distortions and could not affect the pulse duration.

5 Conclusions

In summary, the wave-front correction with an adaptive optics system has yielded significant improvement in the focus ability of the 20TW laser beam. A distorted laser wave-front of 20 wavelengths of P-V values was corrected to 0.15 wavelength of P-V values. Correspondingly, the beam quality of the laser system varies from 3.5 diffraction limit to 1.5 diffraction limit. Based on the improved focused spot, the power density was advanced one order of magnitude with the same laser facility. Otherwise, after wave front correction, the focused spot shape was also regular. And the laser intensity contrast ratio with background was improved greatly[13], which is significant for those experiments on high power laser interaction with matter.

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