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Wavefront Correction of Pettawat Laser System by a Deformable Mirror with 50 mm Active Aperture *

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We firstly propose and demonstrate a new economical approach that can correct the wavefront of the petwatt Ti:sapphire laser system with a beam size of 150 mm. By using a deformable mirror with 50 mm active aperture in the end of the laser, the focal spot size is reduced effectively. The experimental results show that the new approach is simple, less-expensive and valid from a technical and economical point. This technique could be applied to correct the wavefront of a large optical beam with a smaller aperture deformable mirror.

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Lately, high-field science has been one of the most rapidly growing research areas in physics. One of main research areas is high field laser-matter interactions.[1] Hence the focused peak intensity and the focused spot-shape are key parameters in most experiments. In order to increase the focused peak intensity of the laser system, an effective method is to reduce the focal spot-size. Two ways are often employed to obtain a smaller focal spot for a higher intensity. One is to use a high quality, small f-number focusing parabola,[2] but it is difficult to machine, align and adjust. In practice, a parabola with a focal length around $f/3$ is a good compromise.[3] The other effective and economical approach is to reduce the focal spot-size by adaptive optic (AO) closed-loop correction.[1,4,5] For AO correction, the deformable mirror (DM) is normally located between the compressor and parabola, to compensate for the aberrations of the whole laser system. With this scheme, several labs get effective focus intensity improvement in CPA laser systems.[1−4,6−10]. However, for a pettawat laser system, beam size is often expanded to larger than 100 mm to protect the gratings and optical components in the compressor. Hence a DM with a larger active aperture has to be used in AO loop, which means a higher cost. In order to achieve a cost-effective solution, Canova *et al.*[11] proposed pre-compensation by placing the small aperture DM in the middle of the laser chain, where the beam is still a smaller size. According to the theoretical simulation of Ref. [11], after 36 m of propagation, the beam profile (beam size being 15 mm) shows about 40% peak-to-valley (PtV) modulation using bimorph DM with 31 electrode actuators and less than 10% modulation using membrance DM with 52 electrode actuators. Therefore, a pre-compensation technique also requires expensive DM with high density of actuator. For the first time, we propose another economical way to correct the wavefront of petawatt (PW), femtosecond (fs) Ti:sapphire laser with beam size of 150 mm. In our scheme, we put the classical bimorph DM with 50 mm active aperture and 31 electrode actuators behind the parabola. After the fs pulse with 150 mm size passes through parabola, the diameter is reduced to 50 mm on the surface of DM. The wavefront sensor was just ahead the focus spot of leaking beam to directly measure the aberration. Therefore, the measured values contain the whole aberrations of the system, even parabola. At the same time, rigorous image-relay on image-conjugation is not necessary. Finally we effectively reduced the focal spot and improved the intensity in the chamber based on our 0.89 PW, 29.0 fs Ti:sapphire CPA laser system.

The wavefront correction is based on our high-power ultrafast intense Ti:sapphire CPA laser system, which achieves the output peak power of 0.89 PW and the pulse duration of 29.0 fs.[12] In our demonstration experiment, the laser operated at 10 Hz, and the output energy from pre-amplifier is about 800 mJ. The pulse propagates in the whole path of the system as described at Ref. [12], while making a pump of the next two amplifiers off. Except for the energy, the beams have the all factors of the petawatt laser, as shown in Fig. 1. Though a great deal of wave-front aberration (WFA) has been avoided by controlling the optical quality of components,[12] some kinds of aberrations from the thermal effect and other nonlinear effects are difficult to be completely avoided. Our AO loop system consists of a wavefront sensor, a bimorph

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DM and a closed-loop controller. The sensor is a four-wave shearing interferometer device (SID4, PHASICS Co., France), which is specially suitable for laser wavefront measuring because of its good accuracy.[1] It is located just ahead the of the focus of the leaking beam, and ensures that the beam size in the sensor is nearly 3.5 mm, as shown in Fig. 1. The DM has an active aperture of 50 mm and 31 electrode actuators. The collimated beam with a 150 mm diameter is incident on the $f/4$ parabola, and the DM is inserted between the parabola and focus as a reflector mirror. By controlling the location of DM, the convergent beam size is nearly 50 mm. The match of the beam size and active aperture is important to optimize the correction. Here we need to mention that the measured values contain not only the aberrations of the whole system, but also the convergence of the beam. Therefore, to obtain the real wavefront, we have to compare the measured distortion with a reference flat wavefront after subtracting the defocus value. This is another merit of our sensor that can also measure the wavefront of convergent or divergent beam.

Firstly, we evaluate the WFAs of the PW laser system before correction. The measured PtV value is 1.237λ and the rms value is 0.183λ, as shown in Fig. 2(a). Meanwhile, the 3D focal spot is directly recorded by 12-bit CCD camera to avoid the distortion from image optics. To display the details of the plane spot, we use a home-developed program based on the bicubic interpolation scheme (in patent application) to deal with the measured results. The focal spot FWHM is signed by a purple line in the plane focal spot. The measured 3D and plane focal spot is shown in Figs. 2(b) and 2(c), and the corresponding full-width at half-maximum (FWHM) is $14.737 \times 12.003\,\mu$m and the energy inside this FWHM area is 26.10%. In order to reduce the focal spot size by correcting the wavefront, the goal is to set the voltages on the DM to yield a wavefront distribution that should be as close as possible to that of the reference. For the classical wavefront correction (WFC) route, The DM is installed between the compressor and parabola mirror, hence the active aperture of DM has to be match with the beam size.[1−4,6−10] We believe that the wavefront could be improved with this solution for our laser system. However, in our case, the diameter of laser beam after the compression is ϕ150 mm.[12] If we adopt the above method, a DM with active diamter of 150 mm is necessary, and this kind of DM is very expensive. In order to achieve a cost-effective solution, we propose a new correction approach based on a DM with an aperture of 50 mm.

It must be pointed out that the high reflective mirror is necessary in the new correction system if the main beam need be used as laser-matter interactions experiments. The reflectivity of the mirror is high enough, and the leaking beam is about 10^{-3}, which is detected by SID4. With the aberrations of wavefront, the focused spot is not enough small. Considering the DM's aperture, it is installed in the optical chain after parabola where the diameter of convergent spherical wave must equal or less than the active diameter of the DM. When we do not load some configuration of voltages on the electrodes of the DM, it only is a plane-reflecting mirror and cannot change the wavefront of spherical wave.[6] If we load voltages, the wavefront of spherical wave will be changed because the DM's shape has changed. The smallest focal spot will be obtained if the convergent spherical wavefront detected by the SID4 is an as perfect as possible spherical wavefront. Now, it is possible to control the phase quality of wavefront because DM can change the wavefront of a convergent spherical wave by the control software of the SID4. The difference between the measured phase and the aimed perfect spherical phase reference with the same defocus is used as the error signal in order to feed the loop back.

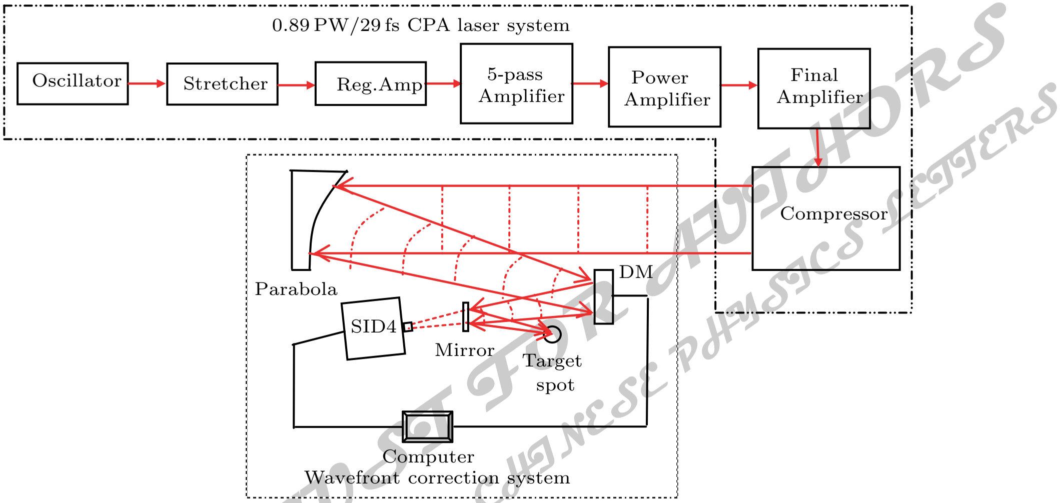

Fig. 1. Experimental setup for measurement and correction of wavefront abberations.

In our scheme, the measured defocus is mainly coming from the convergence of the beam, and do not affect the focal spot. For the above aberrations, the defocus is not contained. To correct the aberrations, the reference wavefront is to add the measured defocus to a flat wavefront. The measured rms value of defocus is 30.4λ. Then we started the adaptive optics wavefront correction loop. The remaining values of rms decrease quickly after several iteration and go to stable. Subtracting the value defocus same as the reference, the correction yields 0.948λ PtV and 0.092λ rms wavefront distortions, as shown in Fig. 3(a). These values represent a Strehl ratio improvement from 0.31 to 0.72. The measured focal spot is shown in Fig. 3, its size of FWHM is accordingly 9.793 × 10.590 μm and the energy inside this FWHM area is 29.37%. As a result, a peak intensity after correction is 2.179 greater than without correction. It will be more valuable being used high field laser-matter interactions.

The corrected experimental results demonstrate that the new correction approach is economical and effective. In fact, Ref. [7] also points out that it is very important to place the DM as close as possible to the end of a laser chain. By far-field vector diffraction formulae in Fourier-transform format for an off-axis parabola using the Stratton-Chu theory,[2,9] the calculated focal spot FWHM with measured amplitude profile and perfect phase is 6.08 × 4.48 μm. We think that the discrepancy between measured and calculated focal spot FWHM is mainly contributed to the uncontrollable, random wavefront fluctuation which comes from air turbulence and thermal drift in the amplifiers.[1,8] The fluctuations between pulses of fs laser cannot be absolutely avoided, especially for a large fs laser system. AO loop did not compensate for the aberrations better than the fluctuation level because it did not compensate for the aberrations of the pulse itself fluctuation.[8] For our Ti:sapphire CPA laser system, the PtV and rms value of the measured fluctuations is respectively 0.810λ and 0.089λ presently. Next step, we hope to improve the focus ability of the laser by reducing the fluctuation of pulse to pulse.

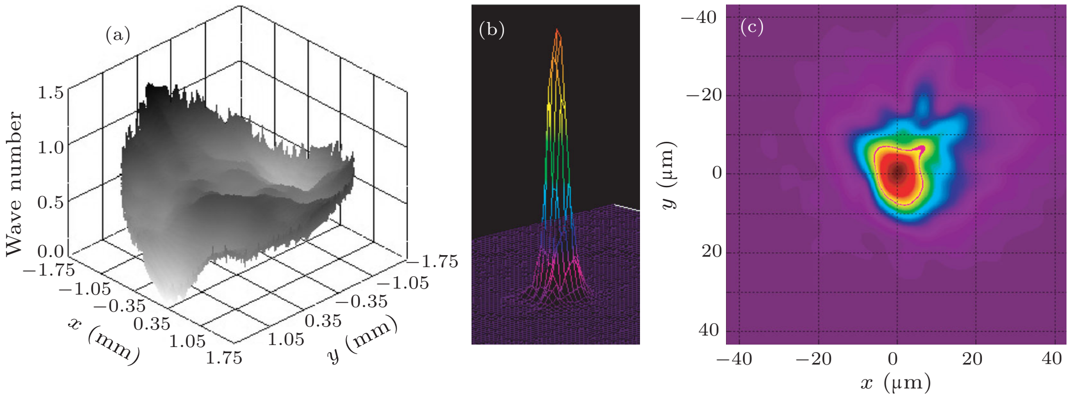

Fig. 2. (a) The 3D phase profile, (b) the 3D focal spot profile and (c) the plane focal spot, without correction.

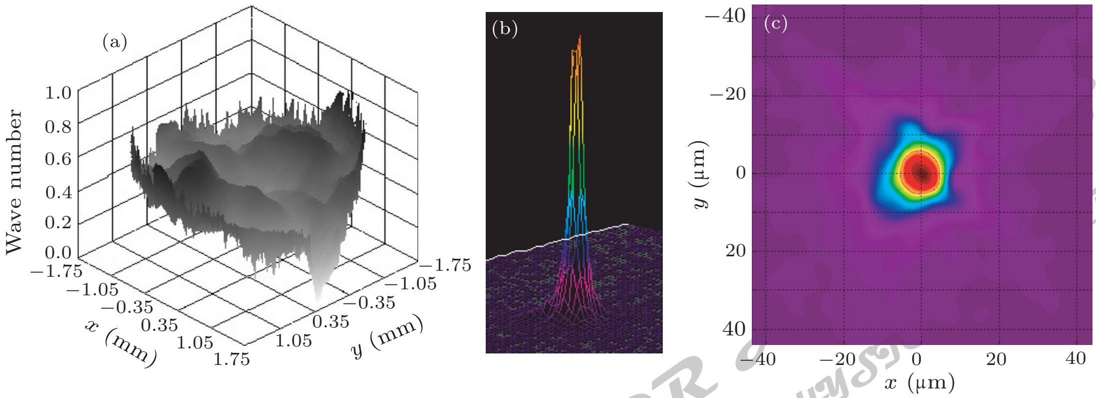

Fig. 3. Corrected results: (a) the 3D phase profile, (b) the 3D focal spot profile and (c) the plane focal spot.

Except for the spot size, we find that the corrected focal spot is near the perfect orbicular spot. This is also very important, if not more important, in the experiment of high field laser-matter interactions.

In conclusion, we propose and demonstrate an inexpensive and simple solution of adaptive wavefront correction for a high-energy laser system with a large beam size. The experimental results based on our petawatt femtosecond laser system show that the new approach using the DM with the small aperture is effective. For practical applications, the only objection of this technique is that it may decrease the reflectivity of the DM. Normally, the reflectivity of the DM is not sensitive when the insert angle of the beam stays under 12°. Therefore, we think that our scheme is more suitable for a parabola with a longer focal length. According to the calculation, the parabola of numerical apeature larger than 2.5 can satisfy the correction condition of the new approach.

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