Adaptive-optics system for correcting femtosecond laser radiation

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The closed-loop adaptive optical system based on the deformable bimorph mirror, Shack-Hartmann wave front sensor, and an electronic control system is presented. A phase conjugation algorithm is used for correcting the laser beam. The use of radiation pulses of 10 TW power from a titanium-sapphire laser allows the power density at the focus of a parabolic mirror to be increased by 50 times.

Laser systems with high output pulse energy are now extensively used in the research all over the world. Unique energy characteristics of such lasers are achieved due to compression of radiation pulse duration down to the femtosecond level. However, the quality of beams emitted by such lasers is very low, because of the complex nonlinear interactions of the radiation with optical elements of the laser system.[1] Wave front aberrations prevent obtaining the focal spot on a target close to the diffraction limit in size, which decrease the efficiency of using such laser systems.[1]

Correction of the phase structure of radiation with traditional beam-forming optics allows only partial solution to the problem, since in some time the thermal deformations of optical elements of a laser system can cause unpredictable dynamic distortions of the wave front. One of the efficient ways to improve the beam quality in this situation is the use of deformable mirrors controlled by an adaptive-optics system, whose operation is based on the control over the wave front quality of the output laser beam.[2]

A traditional adaptive-optics system is shown in Fig. 1. Taking into account the peculiarities of lasers with high pulse energy, it is worth using a bimorph adaptive mirror as a wave front corrector.[3] A bimorph mirror consists of a substrate with a reflecting coating firmly glued to two-plate actuator disks made of piezoelectric ceramics. The internal actuator disk with solid electrodes serves a corrector for the general curvature of a surface. The electrodes on the external surface of the second disk are made as parts of sectors, which are used for reconstruction of various low-order aberrations. Such mirrors allow efficient correction for low-order aberrations with the amplitude up to 10–30 μm using a small number of controlling electrodes. Besides, mirrors of this type are characterized by a high radiation tolerance; the manufacturing of a cooled bimorph mirror is also possible.[3]

As a wave front analyzer, it seems quite appropriate to use a Shack-Hartmann wave front sensor.[4] High accuracy, small size, convenient tuning and alignment, wavelength invariance, wide range of the input beam aperture, and stability to vibrations make this wave front sensor indispensable for the adaptive optics systems. A progressive scan video camera with a standard output TV signal (like Watec WAT-103) set in the sensor can record pulses shorter than the half-frame duration and allows one to use a wide spectrum of standard video capture tools.

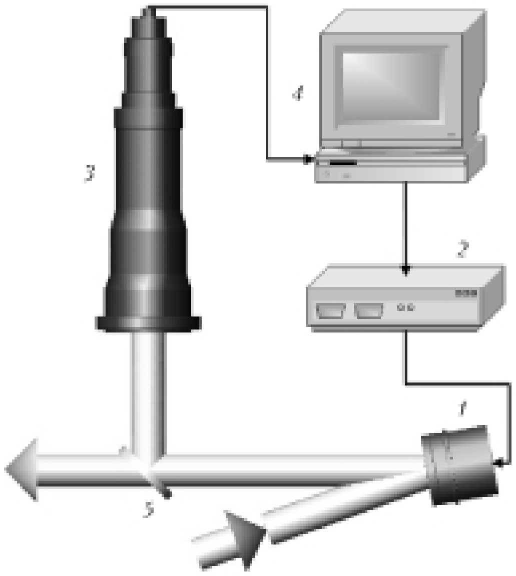

Fig. 1. Schematic of an adaptive-optics system: wave front corrector *1*, corrector control unit *2*, wave front sensor *3*, computer *4*, beam-splitting plate *5*.

The software employed allows the user to perform all the necessary operations with the optical system: tuning and aligning the system, measuring the reference wave front, recording the corrector response function, measuring the current wave front, calculating correcting voltages, control over the electronic control system, display of the correction results on a monitor.

The principle of wave front correction consists in changing the deformable mirror profile in such a

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way that the phase distribution of the output beam corresponds to a preset distribution. For analysis of the phase distribution at the system output, a part of the energy of the beam reflected from the correcting mirror was directed to wave front sensor *3* by a beam-splitting plate *5* (Fig. 1). After analysis of the current phase distribution at the system output, the computer program calculates the set of voltages to be applied to electrodes of the deformable mirror for correction. Voltages are applied with the help of the electronic corrector control system. To provide for high productivity and reliability of the data transfer, the computer and the control unit communicate through a USB interface.

Since the main task of correction of femtosecond laser radiation is to form a good intensity distribution in the far zone, a plane wave front is usually taken as a reference one. The correction process includes three main stages: recording the reference wave front, measuring the response functions, and compensating for the distortions. The reference wave front is recorded using a radiation source having the needed phase distribution, wavelengths close to the wavelength of radiation to be corrected, and the aperture no smaller than the diameter of the beam to be corrected. Measurement of the response functions of a deformable mirror is organized directly in the beam to be corrected. This facilitates the system design and provides for higher accuracy of correction due to the fixed position of the deformable mirror about the beam. To determine the response functions, two wave fronts are measured: one without voltages across the mirror electrodes, and another with voltage applied to one electrode. The difference between these wave fronts is just the response function of the mirror electrode. This procedure is repeated for the whole set of the electrodes. The results are stored in a computer in the form of a file of specialized format.

Correction of femtosecond laser pulses is possible because of strong correlation between neighboring pulses. In fact, we measure one pulse, but correct the phase distribution of the next pulse. It is just this effect that allows direct measurements of the response functions to be performed using the laser beam to be corrected. Because the pulse repetition frequency and the vertical sweep frequency of the wave front sensor are different, the sensor may record a series of empty frames. Since it is very difficult to synchronize the laser and the wave front sensor operation at the instrumental level, a specialized program was developed. This program rejects empty frames and stores only the frames having a laser beam image.

For the first time, this adaptive system was installed and tested on the ATLAS laser system in Garching, Germany.[5] The laser system had the following characteristics: pulse duration of 150 fs, pulse repetition frequency of 10 Hz, energy up to 1.5 J. Application of the adaptive system allowed dynamic correction of the wave front of the output radiation with the frequency of about 2 Hz. Due to correction, we succeeded in increasing the power density in the far zone from 10^{18} W/cm^2 to 5×10^{19} W/cm^2, and the Strehl factor from less than 0.1 to 0.8, and thus we obtained a spot close to the diffraction limit at the focus of a parabolic mirror[5] (Fig. 2).

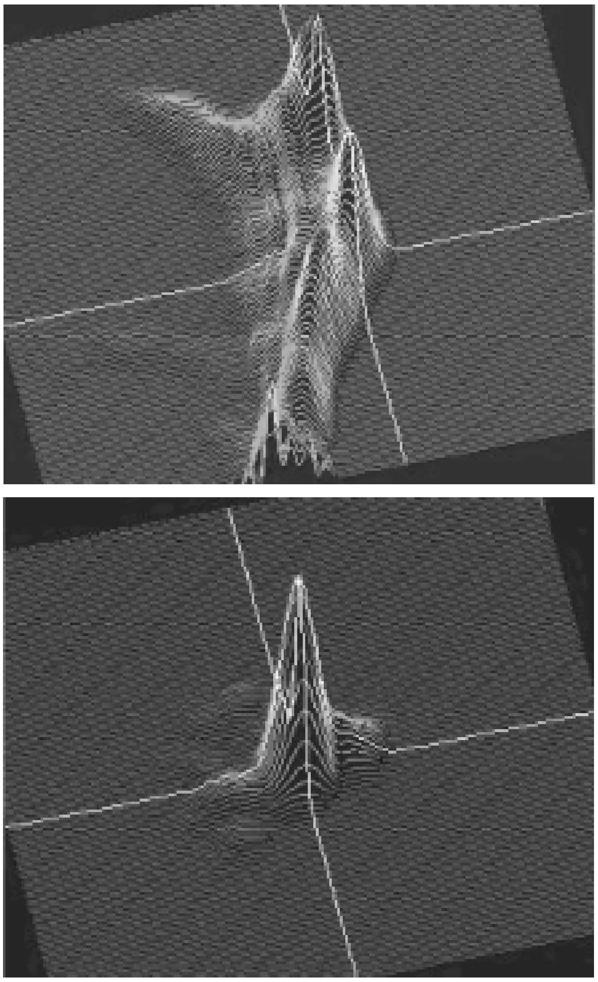

Fig. 2. Radiation intensity distribution in the far zone before and after correction.

The results obtained demonstrate high efficiency of the adaptive-optics system in application to correction of radiation of the modern high-power femtosecond lasers.

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