Nearly diffraction-limited laser focal spot obtained by use of an optically addressed light valve in an adaptive-optics loop

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We demonstrate correction of laser wave-front distortions by use of an adaptive-optical technique based on a light valve. The setup consists of an achromatic and adjustable-sensitivity wave-front sensor and a wave-front corrector relying on an optically addressed liquid-crystal spatial light modulator. Experimental results with strongly aberrated beams focused close to the diffraction limit are presented for the cw regime. Additional experiments with pulses and measurement of damage thresholds show that this approach is relevant for spatial phase correction of ultraintense laser pulses.

Although the spatial and temporal natures of phase distortions in laser amplifiers are somewhat different from those of atmospheric-induced distortions, it is now becoming possible to transfer methods developed in astronomy1,2 to the adaptive correction of laser beams. This transfer is a particularly important topic for the new generation of ultrahigh-peak-power, ultrashort femtosecond pulsed lasers that have been made possible by the introduction of the chirped-pulse-amplification technique.3 Such lasers, with peak power in the 10-TW–1-pW range, are difficult to focus close to the diffraction limit to get the highest possible intensity, typically $10^{20}$ W/cm$^2$ or more, because of aberrations that induce deviations from a perfect spatial phase front. The alternations of the phase are due to thermally induced and nonlinear optical distortions in amplifiers4 and also to static distortions generated in optical elements, such as the gratings used in chirped-pulse-amplification systems. At present one can control (but not eliminate) such aberrations by allowing enough cooling time between shots (typically of the order of several to tens of minutes when one is dealing with glass amplifiers). Getting the highest possible intensity is a difficult goal because it requires an excellent wave front, typically characterized by a rms $\sigma_\lambda$ of better than $\lambda/10$. Such a value is deduced from the Marechal criterion, which states that the Strehl ratio, $S_R = I_p/I_0 = [1 - (2\pi\sigma_\lambda/\lambda)^2]$, will be greater than 80% only if $\sigma_\lambda < \lambda/14$, where $I_p$ is the peak intensity and $I_0$ is the peak intensity obtained with an ideal wave front.

In this Letter we describe a new technique that significantly improves the focal-spot quality by correction of the phase front from a highly distorted laser beam. An achromatic three-wave interferometer is used as a wave-front sensor, whereas an optically addressed non-pixelated liquid-crystal light valve corrects the wave front; the feedback loop is completed with a processing unit that controls the valve according to error signals issued from the interferometer.6

We recall that large phase distortions (several waves) are common in ultraintense laser chains but also that with broadband femtosecond lasers, because of their very short coherence length ($1–10$ $\mu$m), it is impractical to use conventional interferometry. Then, for our application, achromatricity and high dynamic range are the two requirements to be matched by the wave-front sensor, which is why, in this experiment, detection was achieved with an achromatic three-wave lateral shearing interferometer (ATWLSI), as developed by Primot et al.6 The key component of this interferometer is a two-dimensional grating (Fig. 1), which allows the generation of three tilted replicas of the phase front that carry the same amount of energy. By interfering together, these replicas lead to a honeycomb-patterned interferogram. The recovery

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**Fig. 1.** Schematic view of the ATWLSI and its resulting interferogram (two of the three replicated phase fronts are shown). 2D, two-dimensional.
process, based on two-dimensional Fourier analysis of the interferogram, leads to three gradients of the wave front, which are combined to yield the final phase.

The achromaticity originates from the facts that all three arms of the interferometer are geometrically equivalent and that the fringe spacing is independent of the wavelength. The spectral bandwidth is limited to ~670 nm at the working wavelength \( \lambda_0 = 1.064 \, \mu \text{m} \). This bandwidth is required for avoidance of overlap between orders of diffraction from extreme wavelengths and is large enough for applications involving short pulses. One other interesting feature of the ATWLSI is its adjustable sensitivity. Typically, this interferometer gives a measure at \( \lambda/100 \) of a wave front exhibiting distortions of the order of several \( \lambda \). With classical interferometry,\(^7\) difficulties arise in the recovery of the phase from the interferogram because of phase-distortion jumps that exceed one wavelength. On the other hand, geometric-optics-based systems such as that of Shack–Hartmann\(^8\) are able to detect strong phase variations, but the sensitivity of such devices is fixed by the microlenses’ focal length. With an ATWLSI, sensitivity is tunable according to the range of wave-front distortions to be measured. When one is imaging the grating plane (see Fig. 1) onto the CCD, the interferometer is in the zero-sensitivity configuration.\(^6\)

When one is imaging right after this plane, detection of strong variations (dynamic range, 1–100\( \lambda \)) is possible, whereas imaging in forward planes allows more and more accurate measurements (dynamic range, \( \lambda/100–1\lambda \)).

The correction part of our setup is achieved through the use of an optically addressed light valve (OALV) developed at Thomson–CSF.\(^9\) This device, which acts as an electro-optical adaptive phase plate, is a spatial light modulator based on liquid-crystal technology. The OALV uses bulk monocrystalline Bi\(_{12}\)SiO\(_{20}\) (BSO) both as the photoconductive material and as one of the substrates supporting a liquid-crystal layer (see Fig. 2). When addressed optically with incoherent light (\( \lambda_{\text{Writing}} < 500 \, \text{nm} \)), the photoconductive properties of BSO locally transfer the voltage to the liquid-crystal layer. Then, over the entire valve aperture, the liquid crystal exhibits spatial-index variation proportional to the incoherent-light spatial distribution. An IR (\( \lambda_{\text{Ibeam}} > 600 \, \text{nm} \)) beam passing through this active phase plate will have its wave front controlled according to the voltage distribution. Depending on the thickness of the liquid crystal, phase deformation of several wavelengths can be generated. Transverse resolution of the OALV ensures the control of \( 100 \times 100 \) pixels over the beam aperture.

Optical addressing is performed by means of imaging a programmable mask on BSO. In our experiment the mask is generated by a PC and displayed on an electrically addressed liquid-crystal active matrix (EALCAM) made of a 640 \( \times \) 480 pixel array used between cross polarizers (see Fig. 3). The transmission of each pixel of this mask is controlled according to the error signal given by the ATWLSI. The addressing light originates from a low-voltage arc lamp. To avoid having to re-create a pixelization on the valve when we are imaging the active mask, we can add a slight defocusing. Then, we can control the wave front without disturbances owing to diffraction effects.

The experimental setup (Fig. 3) uses a feedback loop between the wave-front sensor and the valve. Depending on the shape of the measured phase, a conjugate active phase plate will be generated when the OALV is optically driven through an iterative process involving a PC. The role of the computer is to recover the phase from the interferogram and, according to this information, to generate a mask to be displayed on the EALCAM. Finally, the focal-spot pattern is monitored on a CCD camera.

At the beginning of the procedure the mask displayed on the EALCAM was uniform. The voltage applied to the transparent electrodes was a 15-V ac current at 15 Hz, and the laser source was a Nd:YAG laser running in a cw mode at a wavelength of 1.064 \( \mu \text{m} \) with 10-mW output power. To create an artificially distorted wave front, we inserted an aberrated plate into the beam path. Iteration 1 of the loop could then start. The distorted wave front was recorded through the ATWLSI, giving the phase measurement \( \varphi_{i-1}(x, y) \) shown on the left-hand side of Fig. 4: Peak-to-peak distortion was 1.7 \( \lambda \) (\( \sigma_{\lambda} = \lambda/2.8 \, \text{rms} \)) over an aperture 6 mm in diameter. The corrected phase profile shown on the right-hand side exhibits a \( \lambda/5 \) peak-

\[ \text{Fig. 2. Operating principle of the OALV: Local BSO illumination spatially modulates the liquid-crystal birefringence, converting a spatial intensity modulation at } \lambda_W \text{ to a spatial phase modulation at } \lambda_R. \]

\[ \text{Fig. 3. Experimental setup showing the EALCAM and the OALV in a feedback-loop.} \]
In a second set of experiments we repeated the first experiment, using the same aberrated plate but with nanosecond pulses emitted from a Nd:YAG Q-switched laser. The pattern of the beam’s near field before and after correction that was obtained with this laser is similar to that of the cw case but slightly more noisy (not shown here). In this particular experiment the laser fluence was limited to 10 mJ/cm², but separate measurements showed that the OAVL could sustain fluence as high as 200 mJ/cm² without any damage. This result demonstrates that such a device can be inserted into a chirped-pulse-amplification chain in a section in which the pulse is chirped in the nanosecond regime and the pulse’s fluence is compatible with the value above. This will be the next stage in our research.

In summary, we have used an achromatic three-wave lateral shearing interferometer combined with an optically addressed light valve to correct a strongly aberrated beam (Strehl ratio, 25%). We have measured the corrected beam in the near field and found in the far field a nearly diffraction-limited spot (Strehl ratio, 96%). The use of an OALV allows one to control the wave-front quality by generating a programmable phase plate without any spurious diffraction effects. Combined with the ATWLSI technique, the OALV provides an attractive and efficient adaptive-optics loop for wave-front control of ultraintense and (or) ultrashort laser pulses.

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