Adaptive Laser Beam Shaping with a Linearized Transport-of-Intensity Equation

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Abstract: We present a novel method to control the phase and amplitude of a femtosecond laser beam using a linearized version of the transport-of-intensity equation. Simulations show a peak power improvement better than 30%.

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1. Introduction

In order to maximize the peak power at the focal volume of a high-intensity femtosecond laser beam, phase-conjugation (i.e. correction of the phase aberrations of the beam) with adaptive optics (AO) is not enough. Correction of both the phase and amplitude (field conjugation) [1] is needed. Phase and amplitude control has been a field of research for the last two decades in free-space communications [2] and high-contrast imaging in astronomy [3]. We present a novel method to perform field-conjugation on a femtosecond laser using two deformable mirrors (DM). The method is based on a linearized approach of the transport-of-intensity equation and is performed in a single step, contrary to the iterative Gerchberg-Saxton algorithm and its variations used in most of the litterature.

2. Amplitude control method

The problem is to control the amplitude of a laser beam at a plane P_2 by controlling the phase of the beam at plane P_1, for example with a deformable mirror. To retrieve the phase to be applied at P_1, we use the transport-of-intensity equation [4] and we approximate the intensity derivative over z with a finite difference:

$$\nabla(I\nabla\phi) = -\frac{2\pi}{\lambda}\frac{\partial}{\partial z}I \approx -\frac{2\pi}{\lambda}\frac{I_2 - I_1}{\Delta z}, \tag{1}$$

where λ is the beam wavelength, I_1 (respectively I_2) is the beam intensity at plane P_1 (respectively P_2) and Δ_z is the distance between plane P_1 and P_2. Eq. 1 is linear and can be written in matrix form:

$$M_{I_1}(\phi_0 + \phi_1) = -\frac{2\pi}{\lambda}\frac{I_2 - I_1}{\Delta z}, \tag{2}$$

where ϕ_0 is the phase of the beam incident on DM_1 and ϕ_1 is the phase applied by DM_1.

The solution phase $\hat{\phi_1}$ therefore reads:

$$\hat{\phi}_1 = -\frac{2\pi}{\lambda}M_{I_1}^{\dagger}(I_2^t - I_1) - \phi_0, \tag{3}$$

where $M_{I_1}^{\dagger}$ is the pseudoinverse of matrix M_{I_1} and I_2^t is the desired (target) intensity at plane P_2. In order to reduce the number of degrees of freedom of the inverse problem to be solved, the phase ϕ_1 is described as a linear combination of a limited number of phase vectors, e.g. the influence functions of the deformable mirror. M_{I_1} can be considered as an interaction matrix. In practice it is computed according to Eq. 2 where I_2 is registered for each phase vector.

Phase aberrations are corrected with a second deformable mirror at, or conjugated with, plane P_2.

3. Simulation results

Simulations were peformed to estimate the performance of the amplitude control method. The initial, uncorrected intensity at plane $P_1$is represented at Fig. 1, left. The target intensity (Fig. 1, middle-left) at plane P_2 is constant over the DM_2 pupil (to maximize the peak intensity at the focal plane) with a slight apodization so that there is no sharp intensity drop at the pupil edge. Simulation conditions were as follows : DM_1 diameter: 5cm; λ =850nm; propagation distance was set to half the Fresnel distance F_d of the DM actuator pitch a ($F_d = {}^{a^2}/_{\lambda}$) so that the intensity modulation at plane P_2 induced by the phase applied at plane P_1 is maximum [5]. In our case, this corresponds to a propagation distance of 10m for 12 actuators across the DM diameter. The estimated intensity $\hat{I}_2$ at plane P_2 is obtained by a Fresnel propagation of the estimated field at plane $P_1(\hat{\psi}_1 = A_1 \exp\left[i(\phi_0 + \hat{\phi}_1)\right])$.

Fig. 1 shows, on the left, the simulated uncorrected, apodized target and estimated intensities, in the middle, cuts of the uncorrected, target and corrected intensities and, on the right, the estimated solution phase $\hat{\phi}_1$ to be applied by DM_1. The improvement is clearly visible with the estimated intensity much closer to the target intensity than the uncorrected. The improvement in peak power at the focal plane, assuming a perfectly corrected phase, is 33%.

The estimated phase to be applied by DM_1 had a PV amplitude of 2.83 µm (optical), well inside the range of available deformable mirrors.

Once the pseudoinverse matrix $M_{I_1}^{\dagger}$ is obtained (this can be done offline), the only operation to be performed to compute the phase to apply by DM_1 is a matrix product that takes less than 0.02 seconds on a personal computer (128x128 pixel images).

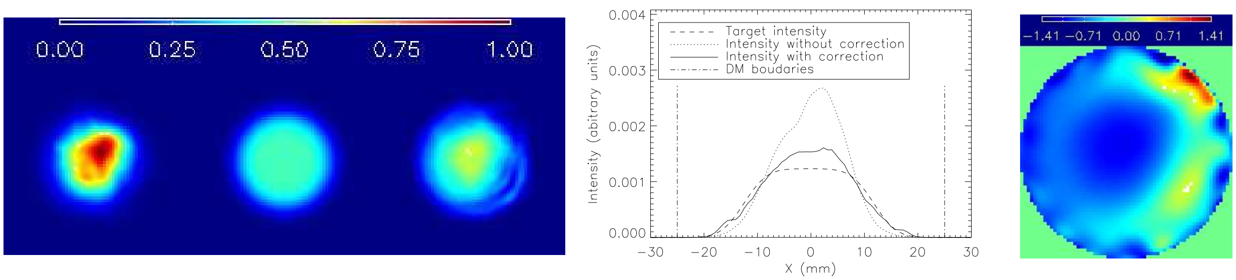

Fig. 1. Left: Uncorrected (at P_1), target and corrected (at P_2) intensities. Middle: cuts of the target (dashed line), uncorrected (dotted line) and corrected (solid line) intensities. Right: estimated phase.

4. Conclusion

We have developed a novel method to control the amplitude of a femtosecond laser beam in order to improve the peak power at the focal volume. The method is non-iterative and allows for a quick estimation of the phase to be applied to a deformable mirror to correct for amplitude aberrations in the laser beam. Computer simulations have shown that a better than 30% increase in peak-power can be expected, which is equivalent to an energy increase of the same amount.

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