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Focus optimization at relativistic intensity with high numerical aperture and adaptive optics

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ABSTRACT

Improved focusing of laser beams using high numerical aperture systems is an efficient route to increasing intensities in the ultrafast regime to relativistic levels. We experimentally demonstrate a new method of optimizing the focus of a high-power laser, using second harmonic generation at full intensity in a low-pressure gas to provide a figure of merit for optimizing the shape of a deformable mirror via a genetic algorithm. Nonlinear and thermal aberrations are corrected, and aberrations introduced by filters are avoided. The method is applied to focus a millijoule, short pulse (30 fs), high repetition rate laser system to relativistic intensity in both near IR and mid IR regimes.

1. Introduction

To achieve relativistic intensities in the ultrafast regime using millijoule laser pulse energies, ultrashort pulses are typically focused with high numerical aperture optics, such as off-axis parabolic mirrors (OAPs). However, wavefront aberrations resulting from these optics can be significant. In addition, when approaching the diffraction limit, aberrations caused by laser system distortions, thermal lensing, and self-phase modulation may also be important. Due to the difficulty of direct measurement of laser focus at high intensity, wavefront correction and focus optimization is of significant importance. The analogous problem of correcting wavefront distortions is well known in the field of astronomy. To correct for atmospheric aberrations, high resolution telescopes utilize adaptive optics to reshape incoming wavefronts [1]. Relying on reference beams to measure atmospheric distortions, adaptive optics can be programmed to compensate for these and other distortions and produce much higher quality images.

A typical adaptive optic is a deformable mirror (DM) with an array of controllable actuators to deform the mirror surface. Such a mirror may also be used to optimize the focal quality of a high-NA focusing optic in a high-intensity, high-repetition-rate laser system. DMs together with genetic algorithms (GAs) have already been utilized in several high power laser facilities. Traditional ways of determining the mirror shape include direct measurement of the wavefront [2], optimization of second harmonic generation (SHG) in a nonlinear crystal [3] and *in-situ* optimization of surface SHG [4]. But, these methods all require attenuation of the beam to avoid damage to detection optics. An alternative method uses the second harmonic signal generated in a plasma by the full power of the focused laser light to provide feedback for the optimization process. This allows the DM to correct for additional wavefront distortions that may not occur while the beam is attenuated (e.g. thermal distortion of optics, thermal lensing, and self-focusing). It also avoids possible wavefront aberrations introduced by the attenuation optics. In addition, the optimization is no longer constrained to a specific focal plane, which is a shared disadvantage of the three techniques mentioned above. Since near-vacuum is maintained in between optimization and experiment, shifting of optics due to pressure change in conventional methods no longer exists. The use of optimization techniques to enhance other phenomena generated from intense laser–matter interactions has also been demonstrated recently [5–8].

Harmonic generation occurs in gaseous media when high intensity light ionizes atoms and plasma is formed. In addition to the possibility of coherent X-ray generation and nonlinear Thomson scattering, frequency doubling may also be observed [9–11]. SHG in a plasma formed by a high-NA focus is due to the formation of an electron density gradient by the ponderomotive force. The electron gradient breaks the isotropy of the gas that would normally prohibit the generation of even order harmonics. The second order polarization in an underdense plasma is given by [10]:

$$P(2\omega) = \chi \left[\frac{1}{2} \nabla E^2 + \frac{2}{\epsilon_p} E \left(E \cdot \nabla \ln n_e \right) \right] \quad (1)$$

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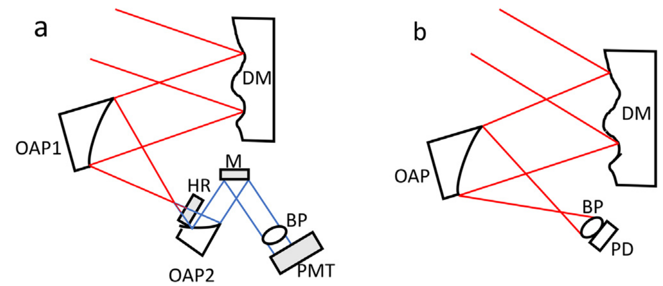

Fig. 1. (a) Diagram of the experimental setup for 800 nm beam. DM: Xinetics 37 channel deformable mirror; OAP1: 2-inch diameter $f/1.4$ off-axis paraboloid; HR: 800 nm high reflector; OAP2: 1-inch diameter $f/1$ off-axis paraboloid; M: flat mirror; BP: 340 nm ∼460 nm bandpass filter; PMT: photomultiplier tube. (b) Diagram of the experimental setup for 2 μm beam. DM: Xinetics 37 channel deformable mirror; OAP: 2-inch diameter f/1.3 off-axis paraboloid; BP: 900 nm ∼1050 nm bandpass filter; PD: photodiode detector.

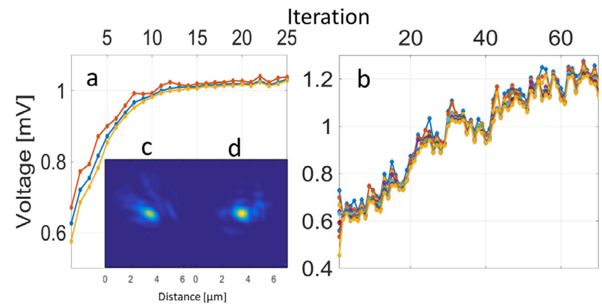

Fig. 2. Second harmonic signal of 800 nm light (a) and 2 μm light (b) generational improvement charts. Focal spot images are taken for deformable mirror shape before (c) and after (d) correction for the 800 nm case.

where E is the electric field, n_e is the electron density, χ is the susceptibility and ϵ_p is the relative permittivity. The first term has zero curl and cannot radiate. Therefore, a better-corrected and smaller focus will produce a stronger second harmonic signal both by producing steeper electron density gradients and by delivering higher intensity. Generation of second harmonic signal is a characteristic of laser–plasma interactions at high intensity using both overdense and underdense plasma targets [12].

In this paper, we demonstrate that in an $f/1.4$ focusing condition the beam focal quality can be improved two-fold using a genetic algorithm to optimize the wavefront. Experiments have been done with both 800 nm and 2 μm light, at millijoule levels and with pulse durations of a few tens of femtoseconds. The relationship between the fundamental and second harmonic signal is measured to be quadratic in both cases. The phase distortion introduced by the back-filled gas in the experimental chamber is determined to be negligible in both cases.

2. Experimental methods

The experiments were performed using the λ^3 high repetition rate (500 Hz) laser facility at the Center for Ultrafast Optical Science (CUOS) at the University of Michigan. The experimental layout for the 800 nm beam is shown in Fig. 1(a). The deformable mirror is controlled by 37 programmable piezoelectric actuators. The beam reflects off the DM at an incident angle of 8°, and then propagates 2 m to a vacuum chamber through an anti-reflection coated, 3 mm thick fused silica window. A 2-inch diameter gold-coated $f/1.4$, 60° OAP focuses the 30 fs, 3 mJ pulses inside the chamber. Initial alignment of the paraboloid is performed by maximizing the brightness of a visible spark generated in ambient air with attenuation to low intensity. The chamber is then filled with 4 Torr of helium. A broadband dielectric mirror reflects most of the fundamental light while passing the second harmonic. The beam is recollimated by a 90°, $f/1$ OAP and directed out of the chamber through a MgF_2 window by a flat, silver mirror. A second filter (Hoya B390) provides further discrimination against the fundamental. The signal is then measured with a photomultiplier tube (PMT). The PMT signal is fed into a boxcar integrator and the boxcar output is read by the control computer via a standard data-acquisition device. The computer runs a genetic algorithm [5,13] to find the mirror configuration which produces the maximum second harmonic. 25 shots are averaged within the evaluation of 1 child in the genetic algorithm optimization process.

The experimental setup for the focus optimization in the mid-infrared regime is shown in Fig. 1(b). An optical parametric amplifier [14] (OPA) with two BBO crystals is used to generate a 1 mJ, 2-μm-wavelength beam with ∼40 fs pulse duration. A mirror-based telescope expands the beam to the size of the DM, which then directs the light into a vacuum chamber backfilled with 40 Torr of air. The chamber window and initial alignment are all the same as the experiment above. A 50 mm diameter $f/1.4$ OAP focuses the beam, and a 20 mm diameter silicon photodiode with a 0.90 μm to 1.05 μm bandpass filter is used to collect the SH signal. A lock-in amplifier and a control computer with data-acquisition card are used to integrate, amplify, and record the signal. The same genetic algorithm is used to find mirror configurations that optimize the SH signal.

3. Results and discussion

Generational improvement charts for the genetic algorithm are shown in Fig. 2. The algorithm takes the SH signal as figure of merit and produces 100 mirror figures for each generation from the 10 best figures of the previous generation. A mutation rate of 5% is applied to introduce variation between generations. The algorithm starts from a fixed figure, which has 30 Volts on all 37 actuators. Three best children are plotted in Fig. 2(a) while all ten children are plotted in (b) to show the higher noise level.

The improvement saturates after 20 generations in the 800 nm experiment, taking 60 generations in the 2 μm case. The SH signal is enhanced by 70% and 100%, respectively. To further evaluate the performance of the technique, images of the focus before and after optimization are acquired with a 60 X microscope objective and CCD camera at low power. A comparison of the focal quality for 800 nm is also shown in Fig. 2(c) and (d). The focal spot size of the 800 nm beam is 1.7 μm, suggesting a peak intensity of $1.1 \times 10^{18}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$ and $a_0 = 0.7$. Due to the limitation of the camera's detection range, a focal spot image is not taken for the 2 μm beam but instead is approximated to be $^{2\ \mu\mathrm{m}}/_{0.8\ \mu\mathrm{m}} = 2.5$ times larger than the spot size measured with 800 nm beam. The estimated laser intensity of the 2 μm beam is thus $5.9 \times 10^{16}\ \frac{\mathrm{W}}{\mathrm{cm}^2}$ and $a_0 = 0.4$. The corrected focus has a higher peak intensity, better circularity, more energy above the noise level, and a larger fraction of energy in the main spot. These features indicate that the technique indeed does optimize for highest focal intensity. A calculation of Strehl ratio is performed based on the following definition: the ratio between the peak intensity of an image divided by the peak intensity of a diffraction-limited image with the same total flux [15]. The beam profile in the λ^3 system is measured to be close to Gaussian. The Strehl ratio is improved from 0.65 before optimization (Fig. 2(c)) to 0.95 afterwards (Fig. 2(d)).

Fig. 3 presents the data acquired to investigate the SH scaling laws for the two cases. As is shown in Eq. (1), SH signal is strongly dependent on better focus for higher intensity and steeper electron density gradient, both of which scale with laser energy. In the 800 nm case a waveplate is rotated to control the input power, whereas, in the 2 μm case, calibrated neutral density filters are placed before the paraboloid to control attenuation. This would vary the laser energy without changing the pulse duration, and thus the SH signal is only