# Adaptive Optics for Laser Beam Shaping

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## ABSTRACT

### Introduction

Adaptive optics (AO) is a system technology that achieves the desired goal of adding or removing aberrations to or from light wavefronts, to improve image clarity and resolution for delivery to a vision system, biological or machine [1]. Aberrations are effects caused by optical elements and non-linearity phenomena, such as refraction index dependent on wavelength, intensity, or geometrical issues. They cause light to scatter in space, instead of focusing on a point, and produce wavefront deviations from flat to deformed (curved or irregular), thus blurred or distorted images.

Astronomical observations are where the concept of AO first emerged: it was used to correct the dynamic wavefront distortion brought on by atmospheric turbulence and enabled the telescope to achieve diffraction-limited imaging from the ground, increasing resolution and improving the noisy signal. Soon, AO was quickly developed and used in the realms of astronomy, industry, civil, and medicine. [2–4]

The automatic AO control system typically comprises three components: a wavefront sensor, a wavefront controller, and a wavefront corrector. This system can actively adapt to changes in external conditions and maintain a satisfactory functioning state while detecting, regulating, and correcting the optical wavefront in real time.

An innovative application can be using adaptive optics for laser beam shaping.

There are different laser beam shaping systems: liquid crystals, multimode fibers, and deformable mirrors (DM). The latter method makes working with even very intense pulses possible.

Through DM wavefront modification, ultrashort laser beams with different energy distributions in the focal point can be obtained. The interaction with the material would change and the same processing could be expected to be done in less time.

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To prove this, in this study, the main components of AO were introduced into the optical path of a pulsed picosecond laser. Then the beam was deformed in circular and elliptical configurations, to take maximum advantage of the elevated average power of the elliptical beam, and basic laser processing was performed on a white zirconia disk and compared.

**Methods**

The ultrafast laser used is a 355nm picosecond laser. The processing setup is composed of a Raylase Superscan V galvanometric scanner, an F-theta lens that assures a focused beam diameter of about 10 µm evaluated at $1/e^2$ intensity with an ellipticity of 90%, and a 3-axis movement system. The adaptive optics system used consists of a piezoelectric bimorph deformable mirror from *Dynamic Optics*, a wavefront camera, and the control unit, see Figure 1.

DM is the core element of AO systems. It can be made of different numbers of actuators, different stroke capabilities, or different types. The microelectromechanical DM type used can achieve perfect focus and great beam shaping from Gaussian to flat top, square flat top, etc. The interface for controlling the actuators is provided by the *PhotonLoop* wavefront measurement and control software by *Dynamic Optics*.

In addition, a beam enlarger system was used to accurately evaluate the effective beam size and distribution in the focal plane, since the resolution of the CMOS camera is comparable with the dimensions to measure. It consists of a collimating lens 30 mm in focal length, a mirror to direct the beam to a magnification lens focusing 1000 mm, two metallic mirrors to fold the beam and maintain a compact size, and a camera that captures the focused beam. Using a calibration factor of 33x, the beam size and shape can be measured, knowing the pixel dimension of 181,5nm.

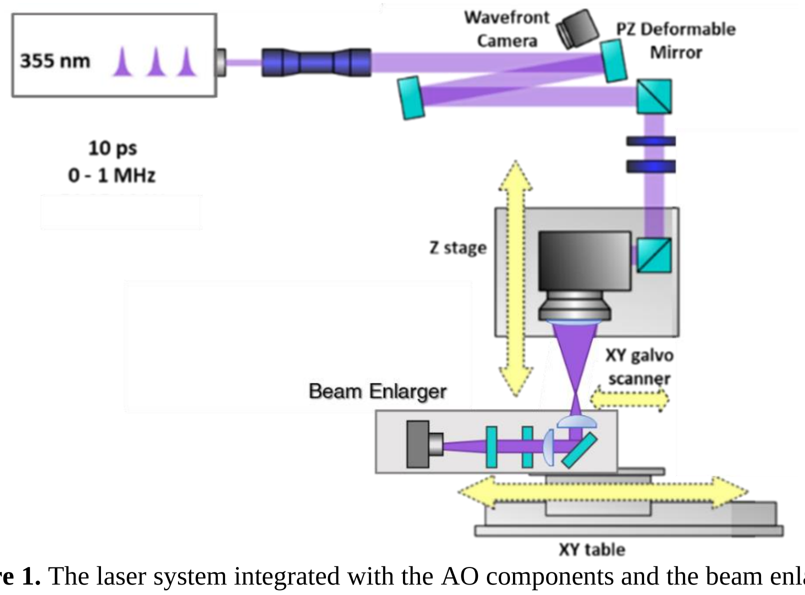


**Figure 1.** The laser system integrated with the AO components and the beam enlarger.

The beam shaping procedure consists of turning on the deformable mirror, firing the laser into the beam enlarger, and evaluating live the shape of the focused beam through the software of the camera. Meanwhile using the *PhotonLoop* software live wavefront can also be seen. Then, once the deformable mirror has been calibrated, the actuators can be moved to correct the wavefront. Particularly, after the calibration, the modes of the analysed wavefront can be seen: by operating in closed loop control, you can act directly on the actuators, by modulating the values of the individual contributions of the Zernike decomposition (Figure 2 left).

Zernike polynomials can be used to quantitatively model and to curve-fit a complex wavefront pattern linked to aberrations. They provide a collection of fitting coefficients that each reflect a different kind of aberration. Acting mainly on the Defocus and Astigmatism x and y, the two beam shapes obtained can be seen in Figure 2 right: the circular with 8 µm of diameter, and the elliptical with 5x40 µm of axes, so that the area of the elliptical beam was 3 times the area of the circular beam.

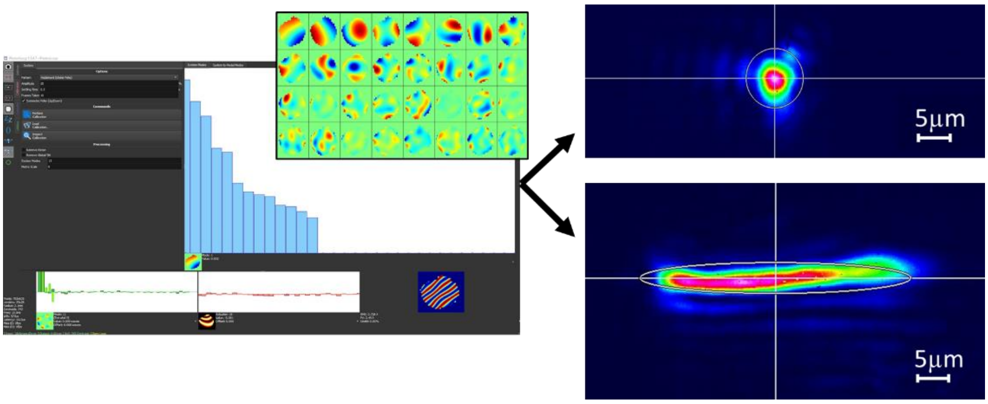


**Figure 2.** PhotonLoop software (left) - Circular (top right) and Elliptical (bottom right) beam.

The geometry to be marked on the zirconia disk is a 1.5x1.5mm square filled with 30 µm parallel lines. The processing parameters are 300 kHz of laser frequency, 5 passes, scan speed varying from 300 to 900 mm/s, and laser power varying from 2W to 6W, to achieve approximately the same fluence in the condition marked by "*" (see Table 1). Number 3 and 4 conditions were tested for comparison. For the elliptical beam, the scanning direction coincides with the longest semi-axis.

**Table 1.** Laser parameters for the different conditions tested.

| **Condition** | **Beam Shape** | **Scan speed [mm/s]** | **Power [W]** | **Fluence$_{pul}$ [J/cm$^2$]** |
|---|---|---|---|---|
| **1*** | Circular | 300 | 2 | 13,27* |
| **2*** | Elliptical | 900 | 6 | 12,73* |
| **3** | Circular | 300 | 6 | 39,80 |
| **4** | Circular | 900 | 6 | 39,80 |

## Results

The imprint left by the circular beam is discernible from that of the elliptical beam in the first shot (highlighted in yellow in Figure 3 top left). The groove's width of the elliptical beam is smaller than the circular, in fact, in that direction the beam size was smaller.

The depths are about 10 µm for the two confrontable conditions in fluence 1 and 2 (*), but the processing times for the circular beam is 2,5 s instead of 0,8 s for the elliptical one.

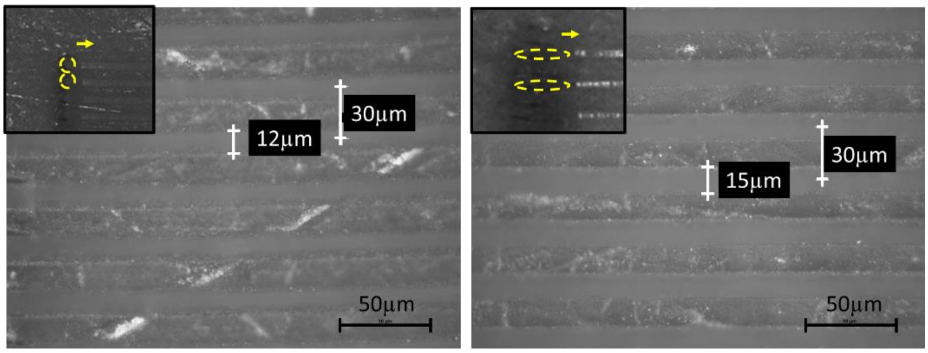


**Figure 3.** Microscope images of the imprint and grooves made by circular beam condition 1 (left), and elliptical condition 2 (right).

The channel obtained from condition 3 is twice as deep and takes twice as long as condition 1, while the channel obtained from condition 4 is 10 µm deep, the processing time is 0.8 s but the groove is 15 µm wide.

## Conclusions

Adaptive optics is a very promising technique in several fields. In the AO system, deformable mirrors are highly effective optical tools for removing wavefront aberrations, and above all they can be used for high intensity laser pulses.

In this work, the use of adaptive optics for laser beam shaping was tested and a piezoelectric DM was used to modify the wavefront of the laser beam to obtain circular and elliptical beam shape. In particular, the circular with 8 µm of diameter, and the elliptical with 5x40 µm of axes were obtained, getting three times the area.

The final aim was to make full use of the available power of the ultrafast laser used. The same depth was achieved for a less wide groove in three times less time.

These outcomes demonstrate the effectiveness of the methodology, opening horizons for numerous applications and developments in the laser manufacturing industry.

## References

[1] Tyson R. K. (2022) Principles of adaptive optics, *Academic Press.*

[2] Liu L et al (2022) Application of Adaptive Optics in Ophthalmology. *Photonics* 9, 5 288.

[3] Vacalebre M et al (2022) Advanced Optical Wavefront Technologies to Improve Patient Quality of Vision and Meet Clinical Requests. *Polymers* 14, 23 5321.

[4] Altıner B et al (2023) Adaptive output regulatio of the adaptive optics system. *Journal of Vibration and Control* 29, 5–6 1091–1104.