We devise a laser-controlled adaptive optical element which operates intracavity under high intensity radiation. This element substitutes a conventional mechanically deformable mirror and is free of critical heat-sensitive components and electronics. The deformation mechanism is based on the projection of a CW control laser onto a specially designed mirror. Mounted to a water-cooled heat sink, the mirror can handle laser radiation beyond 3 MW/cm$^2$. The properties of the adaptive optical element including the maximum correctable wavefront pitch of 800 nm are discussed. The successful implementation in a multipass thin disk amplifier is presented. An improvement of the beam quality by a factor of three is achieved. We identify measures to enhance the performance of the adaptive optic towards efficient operation in a high-power laser system.

Adaptive optics (AO) have become an important tool for beam correction and shaping in laser systems, addressing a large variety of ongoing research topics. Considering the low-power regime, their application ranges from the medical sector for ophthalmoscopy to astrophysics for laser guide stars. For high-power laser oscillators and amplifiers, thermally induced wavefront aberrations of the laser beam are a major challenge. Good beam quality can still be achieved through implementation of AO components in the setup withstanding high-intensity radiation. This enables applications of high-power laser systems which require excellent beam quality, such as laser effectors for space debris removal with an earth-based system. A widely employed AO component is the deformable mirror (DM), commonly equipped with electronically addressed actuators on the backside to perform deformations mechanically. With the development of high-reflective coatings such mirrors have been successfully applied in high-power cw laser setups, allowing intensities up to 1.5 MW/cm$^2$. The correction of wavefront aberrations and the enhancement of a laser beam’s quality has been achieved with this type of mirror in serial and parallel two-stage amplifiers. To correct for low-order aberrations, tip/tilt mirrors and lens systems may be used. In an alternative implementation of the DM, specifically designed for low mechanical noise, resistors substitute the mechanical actuators to generate heat induced deformations. Good results...
have also been demonstrated with a third, pneumati-
cally adapted type of the deformable mirror. Inserted
in the cavity of a thin disk laser this approach enables
a near diffraction-limited beam quality of $M^2 \approx 1.4$ at
pump powers of about 2 kW and output powers of
up to 815 W [11]. The drawback of the design is
its limitation to the compensation of spherical wave-
front distortions, thus higher order aberration terms
can not be corrected for.

In this paper we introduce a laser-controlled approach
for the adaption of the DM, thermally addressing
its surface by absorbing radiation of an intensity-
modulated laser beam. To avoid confusion, we want
to clearly distinguish between the control laser adapt-
ing the mirror and the primary laser being corrected
by the AO. Instead of placing the actuators directly
on the mirror, a generic spatial light modulator re-
motely modifies the AO surface via the control laser
radiation. The removal of the actuators enables the
installation of the mirror on a heat sink for opera-
tion of the AO at high primary laser power beyond
3 MW/cm$^2$. The AO is primarily designed for opera-
tion in a thin disk amplifier (TDA) [12], which con-
sists of a thin laser active element placed on a heat
sink. The TDA layout allows for efficient cooling of
the active medium and high amplification power, but
also suffers from heat induced deformations. The de-
signs of our DM and the TDA are similar and the
process causing wavefront deformations in the TDA
is expected to be analog to the compensation mecha-
nism of the DM, as both are heat induced processes.

Thus our AO is expected to allow for an efficient cor-
rection of aberrations in a TDA. The AO is tested in
a multipass thin disk amplifier (MTDA).

The adaptive optic shown in Fig. 1 a) consists
of three components: (1) The deformable mirror
is a 500 µm thin, round Schott RG1000 filter with
a diameter of 25 mm, absorbing below a wave-
length of 1000 nm. It is provided with a highly
reflective coating of 99.9 % at 1030 nm wavelength
(with 960 nm cut-on wavelength) and glued to a
water-cooled copper heat sink. The mirror has
been tested at radiation of 3 MW/cm$^2$ without
any damage. The coating is designed to withstand
intensities up to 50 MW/cm$^2$. (2) The mirror is ad-
dressed using a diode laser (control laser) at 808 nm
wavelength with an output power of 80 W whose
beam is spatially intensity modulated with a Digital
Light Processing (DLP) chip. The chip consists
of a 1024x768 micromirror array that displays a
grayscale picture, which is projected on the mirror’s
surface using a relay lens system. (3) A second diode
laser (readout laser) at 980 nm wavelength is used
to record wavefront deformations in the beam path
(i.e. deformations of the mirror’s surface and – when
implemented in the MTDA – of the laser disk as
well) that can be measured with a Shack-Hartmann
Sensor (SHS). Results of the wavefront evaluation
are analyzed with a computer and used to adjust the
mirror via the DLP chip image, making the system
closed loop controllable. Applying the AO system
for the correction of wavefront deformations of a
primary laser, the laser beam is coupled into the path
of the readout laser beam. For the analysis of the
beam quality, it is projected onto a $M^2$ measurement
system after the AO.

There are two critical parameters that determine the
performance of an adaptive optic, its resolution and
the maximally correctable wavefront pitch. Fig. 2 a)
shows the mirror surface dilation for the sharp edge
picture of Fig. 1 b) at different intensities. A peak
value of 400 nm enables corrections of distortions
in the reflected wavefront up to 800 nm. The
inlay shows the linear dependence on the irradiated
intensity of approximately 62 nm/(W/cm$^2$). The
maximal pitch is mainly limited by the intensity of
the control laser at the DLP chip, which we restrict
to 50 W/cm$^2$ in order to prevent damage of the
chip. Due to high losses of more than 75 % at the
DLP chip, caused for example by the coating, the
fill factor and dead times in the control algorithm
of the micromirror array, the intensity drops down to
6.1 W/cm$^2$ at the DM. The dilation falls off to the
edges due to a non-uniform power distribution in
the control laser beam and due to heat dissipation
to the unaddressed surface area of the DM. With a
higher dynamic range of the irradiated intensity and
a more sophisticated DLP chip pattern a smoother
distribution of the dilation is expected, reproducing
the flat plateau.

The second performance parameter, the resolution
of the AO, can be determined from the measurement
of Fig. 2 a) as well. We define it as the width $d$ of the edge, from 10% to 90% of the maximal dilation. For the following discussion, we will distinguish more precisely between the resolution $d_m$ directly on the mirror and the resolution $d_{wp} = S \cdot d_m$ of the wavefront picture with an image scaling factor $S$. The resolution on the mirror $d_m$ is mainly limited by heat dissipation and mechanical stress between glass substrate and heat sink, it is independent of the irradiated intensity. For improvement, the manufacturing process of the DM needs to be revised. By increasing the image size between DLP chip and DM with a scaling factor $1/S$ ($S < 1$), the adaptive area on the mirror is enlarged while $d_m$ remains unchanged: The relative resolution of the mirror is enhanced. The uncorrected wavefront is scaled with the same factor before the DM to match the enlarged adaptive area. Rescaling the corrected wavefront between DM and SHS with $S$ keeps the beam size constant within the setup but reduces $d_{wp}$ by $S$. An example is given in Fig. 2 b) which shows imprints of the DLR Logo onto the readout laser wavefront. We double the radius of the mirror’s adaptive area, switch from a 1:1 image scaling between DM and SHS ($S_1 = 1$) to a 2:1 scaling ($S_2 = 1/2$) and enlarge the readout laser beam before the DM respectively. The resolution of the AO improves by a factor of two, with $d_{wp} = 1.7$ mm deduced from Fig. 2 a) for the latter setup.

The setup of the multipass thin disk amplifier is based on the concept of the relay neutral gain module (NGM) as described in detail in [13, 14]. The primary laser at 1030 nm wavelength with a spot-size of 5.4 mm diameter and an input power of 1 W propagates through seven NGM, each consisting of an Yb:YAG laser disk (LD) for amplification and our DM for wavefront corrections in successive conjugated planes. Folded telescopes realized with plane and curved mirrors on a ringlike aluminum structure redirect the beam in all NGM on the same LD and DM. The respective relay lens systems generate a 1:1 image scaling between LD and DM, corresponding to a resolution as depicted in Fig. 2 b), center. The LD is pumped at 940 nm wavelength with a pump spot diameter of 8 mm and a maximum power of 1750 W. After passing through the MTDA, the primary laser beam quality is measured with a camera on a translation stage according to ISO standard. The readout laser is coupled into the propagation path of the primary laser beam before the MTDA and directed on the SHS. The DM can be replaced by a plane mirror for removal of the AO from the setup.

In order to illustrate the successful application of the AO system in the MTDA, the quality of the amplified primary laser beam with and without the DM implemented in the setup has been measured and will be discussed in the following. The beam quality defined according to ISO 11146 has been chosen as the relevant factor since it comprises the key demands for a long-range high-power laser device, a high intensity at a large distance. The beam quality $M^2 = \pi \beta_0 / \omega_0$ for a given wavelength $\lambda$ restricts the smallest achievable beam waist $\omega_0$ in dependence of half the divergence angle $\beta_0$. A large $M^2$-value implies a large beam waist or divergence angle, thus at far distances the intensity, scaling inverse quadratically with the beam size, will strongly decrease.

The beam quality has been measured on the two main axes of the beam for different pumping powers of the MTDA, with and without the AO implemented (i.e. with the deformable mirror or a plane mirror in the beam path installed). The results on both axes are similar, Fig. 3 a) shows their mean values. The shaded area depicts the uncertainty in the beam quality measurement, which is calculated from the fit of the $M^2$-formula on the beam caustic. At low pump powers, no change of the beam quality is measurable. In that power regime, the additional deformation due to the thermal load is negligible with respect to deformations of the laser disk itself. Increasing the pump power leads to a rapid deterioration of the beam quality if the AO system is not installed. However, with the DM implemented in the MTDA, the beam quality stays at a constant level of $M^2 = 5$ and is limited by the resolution of the deformable mirror. At the highest applied pump power of 1750 W an enhancement of the beam quality by a factor of three from $17 \pm 3$ to $5.4 \pm 0.5$ has been achieved. Regarding the perfor-
mance of a long-range high-power laser system this corresponds to a threefold increase of the accessible propagation range at a predetermined intensity. For the respective measurement point, the wavefront deformations before and after compensation by the AO system are depicted in Fig. 3 b). Aberrations related to tip-tilt and defocus errors that do not affect the beam quality value are removed, they could be handled with lens and mirror systems. The wavefront is corrected up to the resolution limit of the deformable mirror.

The heat induced deformations of the wavefront are expected to be stable over long periods of time as the laser is operating in a state of thermal equilibrium. The dynamics of the AO are therefore of secondary interest at the moment, but may be improved significantly in the future. The physical limit for the response time is set by the thermal expansion time constant $\tau$ of the DM with $\tau = (0.6 \pm 0.2)$ s. One iteration in the control loop takes about 8 s and about five iteration steps are needed for the loop to converge from the inactive AO to the optimal correction.

The results regarding the improvement of an amplified laser beam’s quality via compensation of wavefront aberrations with the AO system are very promising for the operation in a high-power MTDA. Necessary advancements include a reduction of the beam quality limit $M^2 = 5$ with the DM implemented. Presented experiments regarding the relay imaging between DLP-Chip and DM have shown that an adapted image scaling (i.e. switching from $S_1$ to $S_2$ scaling) will enhance the resolution of the AO system, thus allowing for wavefront corrections at a smaller scale, pushing the limit of the achievable beam quality to three or better. A higher dynamic range of the control laser intensity and further development of the DLP chip pattern for a smoother distribution of the mirror dilation will assist this process. Advances in the mirror geometry, e.g. a reduction of mechanical stress between glass substrate and heat sink, are expected to increase the resolution and thereby the beam quality even more. The response time of the AO is low, especially compared to an electronically addressed DM, but the dynamics do not pose an issue for our application. After implementing the discussed improvements, the system will be ready for the connection to a high-power primary laser beam to test the setup in a high-power MTDA.

A laser-controlled adaptive optic with the mirror deformed by absorption of an intensity-modulated laser beam has been introduced and its implementation in a multipass thin disk amplifier presented. Mounted to a water-cooled heat sink and free of heat-sensitive elements, the mirror withstands intensities exceeding 3 MW/cm$^2$. We have shown improvements in the quality of an amplified laser beam by a factor of three and identified measures to enhance the performance of our adaptive optic, paving the way for a successful application in high-power laser devices.

We thank Elke Schmid for preliminary work, and Daniel Sauder and Thomas Dekorsy for valuable discussions and critical reading of the manuscript.

References

[1] Austin Roorda, Fernando Romero-Borja, Donnelly III, William J., Hope Queener, Thomas J. Hebert, and Melanie C.W. Campbell. Adaptive optics scanning laser ophthalmoscopy. Optics Express, 10(9):405, 2002.

[2] Jie Liu, Jianli Wang, Yuning Wang, Donghe Tian, Quan Zheng, Xudong Lin, Liang Wang, and Qingyun Yang. Research on the compensation of laser launch optics to improve the performance of the IGS spot. Applied Optics, 57(4):648, 2018.

[3] Bruno Esmiller, Christophe Jacquelard, Hans-Albert Eckel, and Edwin Wnuk. Space debris removal by ground-based lasers: main conclusions of the european project cleanspace. Applied Optics, 53(31):I45, 2014.

[4] Supriyo Sinha, Justin D. Mansell, Robert L. Byer, John D. Gonglewski, Mikhail A. Vorontsov, and Mark T Gruneisen. Deformable mirrors for high-power lasers. Proc. SPIE, 4493:55–63, 2002.
[5] Sven Verpoort, Peter Rausch, Ulrich Wittrock, Scot S. Olivier, Thomas G. Bifano, and Joel Kubby. Characterization of a miniaturized uni-morph deformable mirror for high power cw-solid state lasers. Proc. SPIE, 8253:825309, 2012.

[6] Ulrich Wittrock, Alexis V. Kudryashov, Alan H. Paxton, Ivo Buske, and Hans M. Heuck. Adaptive aberration control in laser amplifiers and laser resonators. Proc. SPIE, 4969:122, 2003.

[7] Stuart J. McNaught, Hiroshi Komine, S. Benjamin. Weiss, Randy Simpson, Adam M. Johnson, Jason Machan, Charles P. Asman, Mark Weber, Gina C. Jones, Marcy M. Valley, Andrew Jankevics, David Burchman, Michael McClellan, Jeff Sollee, Jay Marmo, and Hagop Injeyan. 100 kw coherently combined slab mOPAs. Conference on Quantum Electronics and Laser Science Baltimore, 2009.

[8] Xin Yu, Lizhi Dong, Boheng Lai, Ping Yang, Shanqiu Chen, Wenjin Liu, Shuai Wang, Guomao Tang, Jisi Qiu, Zhijun Kang, Yueling Liu, Hao Liu, Yong Liu, Zhongwei Fan, and Bing Xu. Adaptive aberration correction of a 5 j/66 ns/200 hz solid-state nd:yag laser. Optics Letters, 42(14):2730, 2017.

[9] Boheng Lai, Lizhi Dong, Shanqiu Chen, Guomao Tang, Wenjin Liu, Shuai Wang, Xing He, Kangjian Yang, Ping Yang, Bing Xu, Chao Wang, Xianda Liu, Qingsheng Pang, and Liu Yang. Hybrid adaptive optics system for a solid-state zigzag master oscillator power amplifier laser system. Chinese Optics Letters, 14(9):091402–91405, 2016.

[10] Marie Kasprzack, Benjamin Camuel, Fabien Cavalier, Richard Day, Eric Genin, Julien Marque, Daniel Sentenac, and Gabriele Vajente. Performance of a thermally deformable mirror for correction of low-order aberrations in laser beams. Applied Optics, 52(12):2909, 2013.

[11] Stefan Pichler, Birgit Weichelt, Andreas Voss, Marwan Abdou Ahmed, and Thomas Graf. Power scaling of fundamental-mode thin-disk lasers using intracavity deformable mirrors. Optics Letters, 37(24):5033, 2012.

[12] A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower. Scalable concept for diode-pumped high-power solid-state lasers. Applied Physics B, 58(5):365–372, 1994.

[13] J. Mende, G. Spindler, J. Speiser, and A. Giesen. Concept of neutral gain modules for power scaling of thin-disk lasers. Applied Physics B, 97(2):307–315, 2009.

[14] J. Mende, G. Spindler, T. Hall, E. Schmid, J. Speiser, and A. Giesen. Implementation of the concept of neutral gain modules in thin-disk lasers. Applied Physics B, 108(4):779–792, 2012.
Figure 1: a) Adaptive optic setup: The deformable mirror (DM), placed on a water-cooled heat sink, can be addressed with the control laser beam. The beam is intensity modulated by the DLP chip, exemplarily featuring the pattern shown in b). The readout laser beam is used to capture the mirror’s deformation in its wavefront measured by the SHS. The aberrations are analyzed with a computer and results are fed back to the DLP chip, making the system closed loop controllable. Telescopes between the components ensure proper relay imaging. When implemented in a laser system, the primary laser whose wavefront needs to be corrected follows the readout laser path but is projected on a M² measurement system for beam quality analysis.

b) Exemplary wavefront adaption: If a sharp edge is depicted on the DLP chip, a sharp cut-off in the control laser beam intensity leads to a defined plateau on the mirror surface. The wavefront of the readout laser is deformed as schematically illustrated with (A) and (B) in a) and recorded in the SHS picture.

Figure 2: a) Dilation of the mirror surface: Horizontal cut through the wavefront picture of the SHS with a sharp edge depicted on the DLP chip, as shown in Fig. 1 b), at different intensities irradiated on the DM. The inlay illustrates the linear dependence between peak dilation and intensity on the AO. The decreasing dilation towards the edge results from non-uniform power distribution of the control laser beam and heat dissipation in the mirror material.

b) Resolution of the AO visualized with the DLR Logo as the DLP chip pattern: The left picture shows the DLP chip pattern, which leads to different wavefront distortions in the other two pictures depending on the image scaling of the relay lens systems applied in our setup. In particular, switching from a 1:1 scaling between DM and SHS ($S_1$) to a 2:1 scaling ($S_2$) improves the resolution by a factor of two. As in the sharp edge pictures, a non-uniform dilation with respect to the original pattern is visible.
Figure 3: a) Measurement of the beam quality $M^2$ as a function of the pump power $P_{\text{Pump}}$ with and without the AO implemented (i.e. the deformable or a plane mirror installed). At $P_{\text{Pump}} = 1750$ W, the beam quality can be enhanced by a factor of three. The shaded area depicts the uncertainty in the measurement.

b) For the measurement point at $P_{\text{Pump}} = 1750$ W with the AO installed, the wavefront pictures recorded with the SHS before and after the compensation process by the DM are shown. Tip-tilt and defocus terms in the aberration are removed as they do not affect the beam quality.