Adaptive laser resonator control with deformable MOEMS mirrors

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ABSTRACT

Adaptive laser resonators with deformable MOEMS mirrors under closed-loop control are discussed and experimental results are presented. The requirements for deformable mirrors and for closed-loop control systems of these mirrors are analyzed. Several deformable mirrors have been characterized and the results are presented. Currently available membrane mirrors deform under laser load and need further development before they can be used for aberration correction of solid state lasers above some tens of Watts. Nevertheless, the results are encouraging and the requirements are within reach of currently available technology. Finally, we demonstrate an Nd:YVO_4-laser with a closed-loop adaptive resonator and more than 6 W of output power. The closed-loop system was able to compensate artificially introduced aberrations from a phase plate.

Keywords: adaptive optics, MOEMS mirrors, deformable mirrors, membrane mirrors, aberrations, solid state lasers, high-power lasers, laser resonators

1. INTRODUCTION

Dynamic control over the spatial phase of coherent laser radiation opens up new possibilities for scientists and engineers who are trying to develop high-power lasers with diffraction-limited beam quality. The coherent light from diffraction-limited TEM_{00}-beams must have perfectly spherical wavefronts. Generating such beams is possible if the resonator is made up of perfect, aberration-free optical components. However, the active media of high-power solid state lasers generally show severe optical aberrations due to their large internal temperature gradients. Therefore, the efficiency with which the pumping light can be converted into a diffraction-limited or nearly diffraction-limited laser beam is quite low. Efficient generation of TEM_{00}-beams from aberrated active media is possible only if the aberrations can be compensated inside the resonator. Deformable mirrors make this possible. MOEMS mirrors are in principle ideally suited for this task because they can be made with a high density of actuators. A high density of actuators is required because the beam of a solid state laser inside the resonator has a small diameter. In this paper we first discuss the aberrations of solid state lasers, the requirements for mirrors that are suitable for correcting the aberrations, and the feedback loops that are necessary to control the mirrors. We then present measurements of surface figure and stroke of several MOEMS mirrors and finally present experiments of the closed-loop performance of a solid state laser with a deformable mirror.

2. ABERRATIONS IN SOLID STATE LASERS

Textbooks usually treat laser resonators that consist of spherical mirrors and ideal lenses. The optical eigenmodes of such stable, spherical resonators without gain are the familiar Gauss-Laguerre and Gauss-Hermite modes. Real laser resonators obviously need a gain medium in order to sustain the optical oscillation and produce useful output. The eigenmodes of ideal spherical resonators with gain are complex Gauss-Hermite modes[1]. The theory for real and complex Gaussian modes is well developed and calculating the mode size and beam quality of these modes for any stable, spherical resonator is straightforward. In principle, it is also straightforward to design for any given transverse dimensions of the gain medium a suitable stable laser resonator that could only support the fundamental transverse mode. All that would need to be done is selecting the mirror curvatures such that the aperture in the laser resonator that restricts the mode size is about equal to the size of the fundamental mode. This resonator would then deliver a beam of diffraction-limited beam quality. However, in practice, designing a laser resonator with diffraction-limited beam quality

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and with high conversion efficiency from pumping power to laser power is not that easy. Quite often, it is simply impossible. There a two main reasons for this.

First, the refractive power of the thermal lens of a solid state laser medium depends on the pumping power, and, to a lesser extent, on the power of the laser beam circulating inside the resonator and on other parameters such as the cooling conditions. The mode size in a laser resonator which is designed to support only the fundamental mode is sensitive to very small changes in the refractive power of the thermal lens. Small, unavoidable fluctuations in the pumping power, the laser power, or the cooling conditions will thus result in large changes of the fundamental mode size. In case these fluctuations lead to an increase of the fundamental modes size, the output power of the laser will drop sharply, because the fundamental mode will experience strong diffraction losses at the aperture in the resonator. In case the fluctuations lead to a decrease of the fundamental mode size, higher-order modes will start to oscillate and the beam quality will deteriorate. High stability of the refractive power of all resonator components including the active medium is thus required for stable fundamental-mode operation of the laser.

A second, more serious problem is the presence of aberrations in the active medium. The thermal lens usually has aberrations of the order of $\lambda/10$ for solid state lasers with a few Watts of output power and aberrations of several λ for high-power lasers with hundreds of Watts of output power. Even in the presence of aberrations one usually tries to design the resonator by neglecting the aberrations because there is no analytical theory for laser resonators with aberrations. The phase contribution of all resonator components is thereby approximated by their second-order term, i. e. their focal power. We will call this resonator the “corresponding spherical resonator”. Most of the time, diffraction-limited beam quality is required and therefore the *corresponding spherical resonator* should be laid out to support the Gaussian TEM_{00} mode only. However, this procedure will lead to a resonator with strong diffraction losses because the TEM_{00} mode is an eigenmode only of the aberration-free resonator. The diffraction losses could even prevent the laser from oscillating at all but in any case they will lead to low output power and low efficiency. Interestingly, the beam quality is hardly affected by the aberrations and the output beam is still close to diffraction-limited[2]. If, on the other hand, the *corresponding spherical resonator* were designed to support higher-order Gauss-Laguerre or Gauss-Hermite modes, one would obtain a resonator with low diffraction losses. The output power and efficiency would be high but the beam quality would be low.

The problem of thermal lensing has been recognized from the beginning of the development of solid state lasers, while the influence of aberrations has only been recognized recently[3,4,5]. This is certainly due to the fact that in most cases the influence of aberrations on the diffraction losses can only be analyzed numerically. Numerical analysis does not give insight into the underlying mechanism how aberrations can be thought to affect a resonator. It also does not further intuitive understanding of the dependence of output power on the various parameters needed to describe the aberrations.

Thermal aberrations can be reduced by a suitable geometry of the active medium, such as the disk or slab geometry, and proper pumping and cooling of the active medium. However, at average powers of several hundred Watts, even novel laser concepts such as the thin disk laser are limited by aberrations. Therefore, the ability to correct the aberrations would greatly enhance the beam quality and the efficiency of high average power lasers. Static control of the thermal lensing and the aberrations could improve the performance of these lasers somewhat but a real breakthrough can only be obtained by dynamic, closed-loop control. This is a consequence of the high sensitivity of TEM_{00}-resonators to aberrations and thermal lensing. As we described above, for high average power lasers, even slight variations of the pumping power or the intracavity laser power will change the thermal lensing enough to either drive the resonator into the unstable regime or into the multimode regime.

3. REQUIREMENTS FOR ADAPTIVE ABERRATION CORRECTION OF SOLID STATE LASERS

3.1 Aberration correction based on nonlinear schemes

Aberration correction requires phase conjugation of the aberrated beam by some optical element. Nonlinear phase conjugation based on stimulated Brillouin scattering (SBS) has been used successfully in the past but has some severe drawbacks. The nonlinear SBS mirrors require high laser powers in order to obtain a reflectivity close to unity, limiting most SBS-schemes to pulsed lasers. Another drawback is that it is difficult to design a laser resonator based on an SBS mirror that generates a TEM_{00}-beam. Usually, resonators with an SBS mirror will produce a laser beam of poor quality. Forcing the resonator to produce a TEM_{00}-beam by inserting suitable apertures will result in a setup that is basically as sensitive to misalignment and changes in the refractive power as a conventional TEM_{00}-resonator. For this reason, SBS schemes have mostly been used in aberration correction of master-oscillator-power-amplifier (MOPA) systems. The great advantage of SBS-schemes is that they do not need a feedback loop because the nonlinear process automatically generates the conjugate phase.

Another nonlinear phase conjugation scheme that has recently been used in order to correct the aberrations of solid state gain media is based on four-wave-mixing in the gain media itself. This scheme is promising but power scaling still has to be demonstrated[6].

3.2 Aberration correction based on deformable mirrors

Deformable mirrors hold great promise for aberration correction because they can be computer-controlled and unlike nonlinear SBS-mirrors their phase and amplitude reflectivity should not be influenced by the incident beam. In addition, laser resonators with deformable mirrors would make it possible to study the influence of aberrations on diffraction losses and beam quality by generating controlled aberrations. One could also produce specific aspherical resonators that would generate laser beams with Super-Gaussian intensity distributions and close to diffraction-limited beam quality but higher extraction efficiency than conventional resonators.

The closed-loop system for controlling the deformable mirror needs an input parameter in order to generate the drive signals for the mirror actuators. Two different approaches for the closed-loop system are possible. The input parameter can be either the wavefront aberration of the laser resonator or a parameter that depends on the laser beam quality.

The first approach, which is based on the measured wavefront aberration of the resonator (not the laser beam) as the input signal has the advantage that the required shape of the deformable mirror can be directly calculated from this signal. The deformable mirror could be brought into the right position in a single step if the influence function of the deformable mirror were known with high accuracy and the mirror deformation were a linear combination of the actuator signals. Most deformable mirrors are nonlinear devices in the sense that the influence function of each actuator depends on the signals applied to the other actuators. Also, the influence functions are generally not precisely known because they change as a function of temperature or due to material creep. In this case, a few iterations of the control loop are required in order to achieve the desired mirror deformation. The biggest problem of this approach is measuring the wavefront aberration of a resonator during laser operation with high precision. The measurement would need to have an absolute accuracy of $\lambda/10$ or better and this is almost impossible to achieve over long periods of time, especially for high-power lasers that will be used in an industrial environment.

The other, better approach is based on a blind algorithm and a single input parameter that is monotonically increasing with the beam quality or brightness of the laser. The signal could, for example, be the fiber coupling efficiency of the laser beam, the second-harmonic conversion efficiency, the Strehl ratio, the power-in-the-bucket signal, or even the efficiency of a materials processing application. If far-field measurements such as the Strehl ratio or a power-in-the-bucket measurement are used, it is important to keep the near-field constant. After all, beam quality is the product of the near-field diameter and the far-field divergence of the laser beam. If the adaptive optics system would decrease the far-field divergence while the near-field diameter of the beam is increasing, this could result in a reduction of beam quality instead of an improvement. Measuring near- and far-field dimensions of the beam and calculating the beam parameter product $w \cdot \theta$ would be possible, too. The beam parameter product would then form the single input parameter that has to be maximized by the control loop. The advantage of this single-parameter approach for the control loop is that it does not rely on the absolute accuracy of a difficult wavefront measurement of the resonator. The disadvantage of this approach is that the optimum mirror shape can not be directly calculated from the single measured parameter. Instead, an iterative procedure is required and genetic algorithms are frequently employed for this.

4. MOEMS MIRRORS FOR SOLID STATE LASERS

4.1 Types of deformable mirrors

Adaptive optics for high-power laser applications requires deformable mirrors, such as membrane mirrors or bimorph mirrors, as opposed to segmented mirrors, because the energy loss in segmented mirrors is not acceptable and would in most cases destroy the mirror. Also, a segmented mirror would create diffraction losses due to phase jumps or changes in phase gradients between neighboring segments. Segmented mirrors are often classified as “zonal devices”, because each actuator is only acting on a certain zone of the mirror. Deformable mirrors, on the other hand, are so-called “modal devices” because there is always crosstalk between neighboring actuators due to the stiffness of the membrane. The crosstalk also depends on the type of actuator that is employed. Sometimes large actuators such as ring-shaped or pie-shaped actuators are used that make it possible to produce desired mirror shapes by applying a voltage to just a single actuator. On the other hand, small piezoelectric "push-pull" actuators produce a fairly local deformation of the membrane which results in a "more zonal" behavior. The membrane has to be flexible enough and there have to be enough actuators in order to create steep phase gradients and a high fidelity of the required surface shape. Since a thin membrane will require more actuators to create a smooth surface than a thick membrane, there is a tradeoff between membrane thickness and the number of actuators.

4.2 MOEMS mirror technology

Different types of adaptive mirrors have been investigated in our laboratory; several micro-machined membrane deformable mirrors (MMDM) manufactured by OKO Technologies[7], a bimorph mirror from the Institute on Laser and Information Technology of the Russian Academy of Sciences[8] (RAS), Moscow, and a bimorph mirror which manufactured at Muenster University of Applied Sciences (called MUAS mirror in the following). An interferometric measurement of the surface shape has been performed over the whole pupil of all mirrors, although, due to boundary constraints, just the central part of the membrane area of a MMDM can be used for aberration compensation.

Micromachined membrane deformable mirror

MMDMs are the most frequently employed adaptive mirrors due to their moderate cost. They have been described in several publications[9,10,11,12,13]. OKO Technologies MMDMs consist of a thin silicon membrane stretched over an array of up to 79 hexagonally arranged actuators. The membrane is grounded and it is deformed via electrostatic attraction between membrane and electrodes (Figure 1). To ensure movement in both directions – the membrane can just be pulled, not pushed – it is necessary to apply bias voltage to all actuators. As the deformation scales quadratically with the applied voltage, a useful bias is 70% of the maximum voltage.

The membrane is fixed at its rim; therefore not the whole membrane area can be used for aberration compensation. The useable area is approximately 50%[14]. Figure 1 shows a sketch of a MMDM. Six MMDMs with a diameter of 10 mm, 12 mm and 15 mm and 19 or 37 actuators have been investigated. All of them were coated with 12 dielectric layers for high reflectivity at 1064 nm and could be driven with up to 300 V.

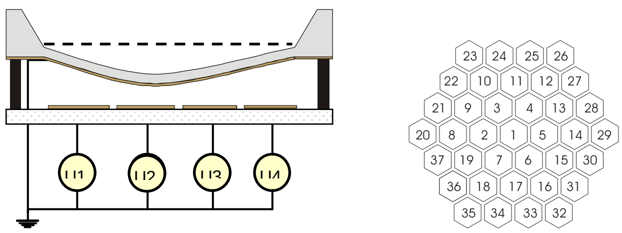

Figure 1 Sketch of the OKO Technologies MMDM and its electrode pattern.

Bimorph mirrors

Both investigated bimorph mirrors consist of a thin piezo-ceramic (PZT) plate glued with its grounded electrode onto either a glass substrate (RAS mirror) or onto a silicon wafer (MUAS mirror). On the other side of the PZT-plate, a patterned electrode is applied. Applying a voltage to an electrode causes the piezo-ceramic to bulge and induces bending of the plate. The deformation of the plate is not exactly proportional to the applied voltage. Our mirrors are supported by a single post in their center. This allows using the whole mirror area for aberration compensation. A dielectric coating with 12 layers provides high reflectivity at 1064 nm. Both mirrors were driven with up to ±75 V.

4.3 Characterizing deformable mirrors

We used a Michelson-Interferometer and a CCD-camera to investigate the deformation of the adaptive mirrors (Figure 3). Placed in one arm of the interferometer, the adaptive mirror was relay-imaged onto a CCD. The recorded interferograms were analyzed with the interferometer software *Quick Fringe*[15]. Optionally, the CCD-camera could be replaced by a Shack-Hartmann wavefront sensor (SHS). When the SHS was used, the reference arm of the interferometer was blocked.

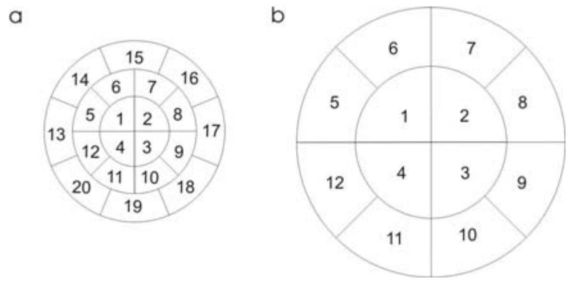

Figure 2 Sketch of the electrode pattern of (a) the MUAS mirror (20 mm diameter) and (b) the RAS mirror (30 mm diameter)

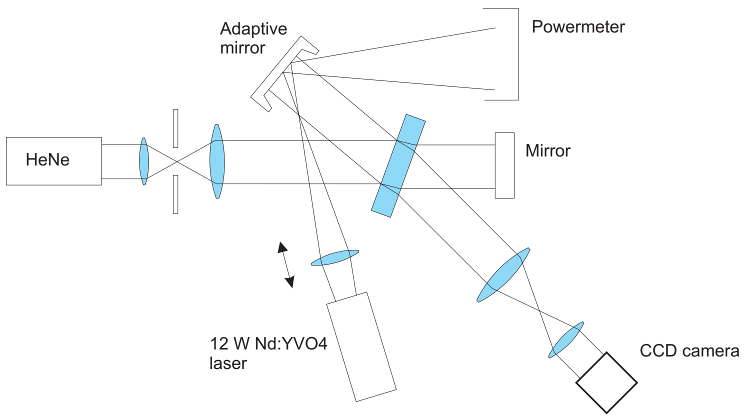

Figure 3 Setup for measuring the deformation of adaptive mirrors.

An Nd:YVO_4-laser with 12 W output power was used to take interferograms under laser load. Adjusting the laser power or shifting a lens made it possible to vary the beam intensity on the adaptive mirror. This allowed recording of possibly present thermally induced deformation of the mirrors.

Actuator influence functions

Six MMDMs and two bimorph mirrors have been characterized in terms of initial and dynamic deformation and sensitivity to deformation under laser load. A comparison of the mirror characteristics is shown in Table 1. Note that the six MMDMs have been purchased over a time span of several years, starting with MMDM 03. An improvement of the production process of these mirrors is visible, for instance in the improvement of initial deformation from 1.8 µm to values around 0.65 µm. MMDMs and the bimorph RAS mirror are comparable in terms of stroke. However, MMDMs have a higher actuator density and a better flatness. Although the actuator density of the MUAS mirror is not comparable to the densities achieved for MMDMs (37 actuators over a 15 mm diameter area), it is – with 20 actuator under a 20 mm diameter area – higher than that of the RAS mirror (12 actuators under a 30 mm diameter area). The MUAS mirror suffers from a large initial deformation of 4 µm and a rather large hysteresis of 21%. With 16% the hysteresis (Figure 4) is also a problem for the RAS mirror. The difference in strokes between the bimorph mirrors can be attributed to the different thicknesses of their substrates. While the RAS mirror had a thickness of approximately 3 mm, the MUAS mirror was just 1 mm thick, but the thickness of both bimorph mirrors is approximately 1000 times larger than the thickness of the membrane of MMDMs. Both bimorph mirrors were not sensitive to thermal deformation induced by incident laser intensity, we did not observe any deformation of the mirror surfaces up to our maximum intensity of 25 kW/ cm^2. Membrane mirrors, on the other hand, exhibit deformations when under laser load. If such a mirror is incorporated in a laser resonator, it could destabilize the laser[16]. In Figure 5, interferograms of the surface of MMDM 18 – the mirror most sensitive to deformations under laser load – are presented. A sharp hump just right of the center of the membrane is clearly visible, increasing in height with increasing laser load.

Mirror	Diameter (µm)	Number of actuators	Initial deformation (PV, µm)	Maximum applied voltage (V)	Maximum stroke (PV, µm)	Single actuator stroke (PV, mm)	Hysteresis (%)	PV deformation under 112 W/cm^2 laser load (µm)
OKO MMDM 03	10	19	1,83	300	2,52	0,25-0,54		0,23
OKO MMDM 04	12	19	1,39	300	5,5	0,5-1,1		0,22
OKO MMDM 09	10	19	0,63	300	10	not measured		0,48
OKO MMDM 10	10	19	0,65	300	9,5	0,35-1,35		0,28
OKO MMDM 17	15	37	0,69	300	4,16	0,15-0,4		0,44
OKO MMDM 18	15	37	0,8	300	5,4	0,4-0,6		1,16
RAS bimorph mirror	30	12	1,5	75 -75	1,3 1,8	0,22-0,48 0,4-0,86	16	0
MUAS bimorph mirror	20	20	4	75 -75	11 4	0,11-0,71 1,31-2,28	21	0

Table 1 Comparison of the characteristics of six MMDMs and two bimorph mirrors

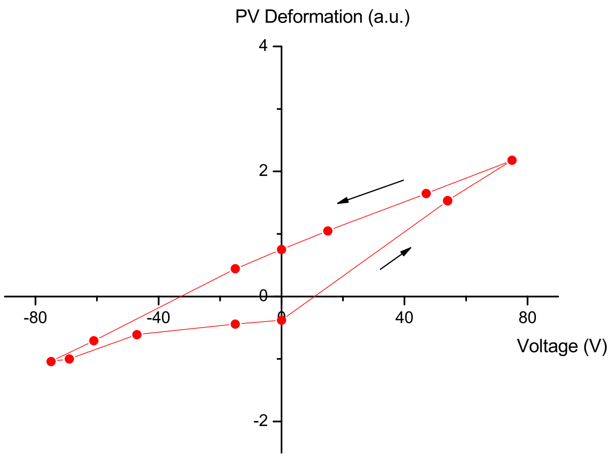

Figure 4 Hysteresis of the RAS mirror measured by ramping one actuator.

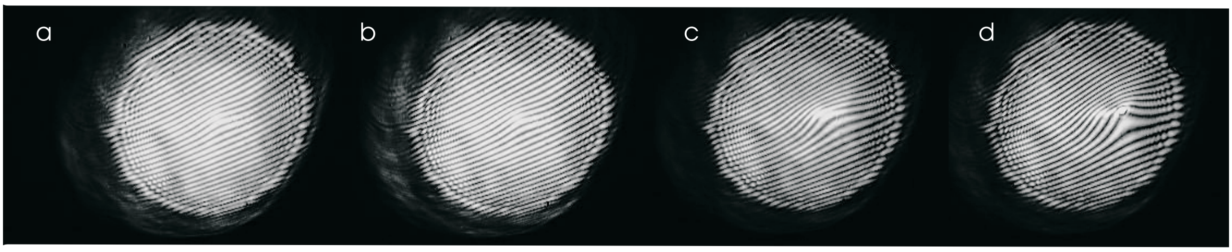

Figure 5 Interferograms of MMDM 18 under laser load of (a) 0 W/cm^2, (b) 8.5 W/cm^2, (c) 52 W/cm^2 and (d) 112 W/cm^2 at 1064 nm. The laser beam diameter varies from 4.3 to 3.6 mm, it is decreasing with power. The deformation due to the laser load is visible as hump shifted just right out of the center of the membrane.

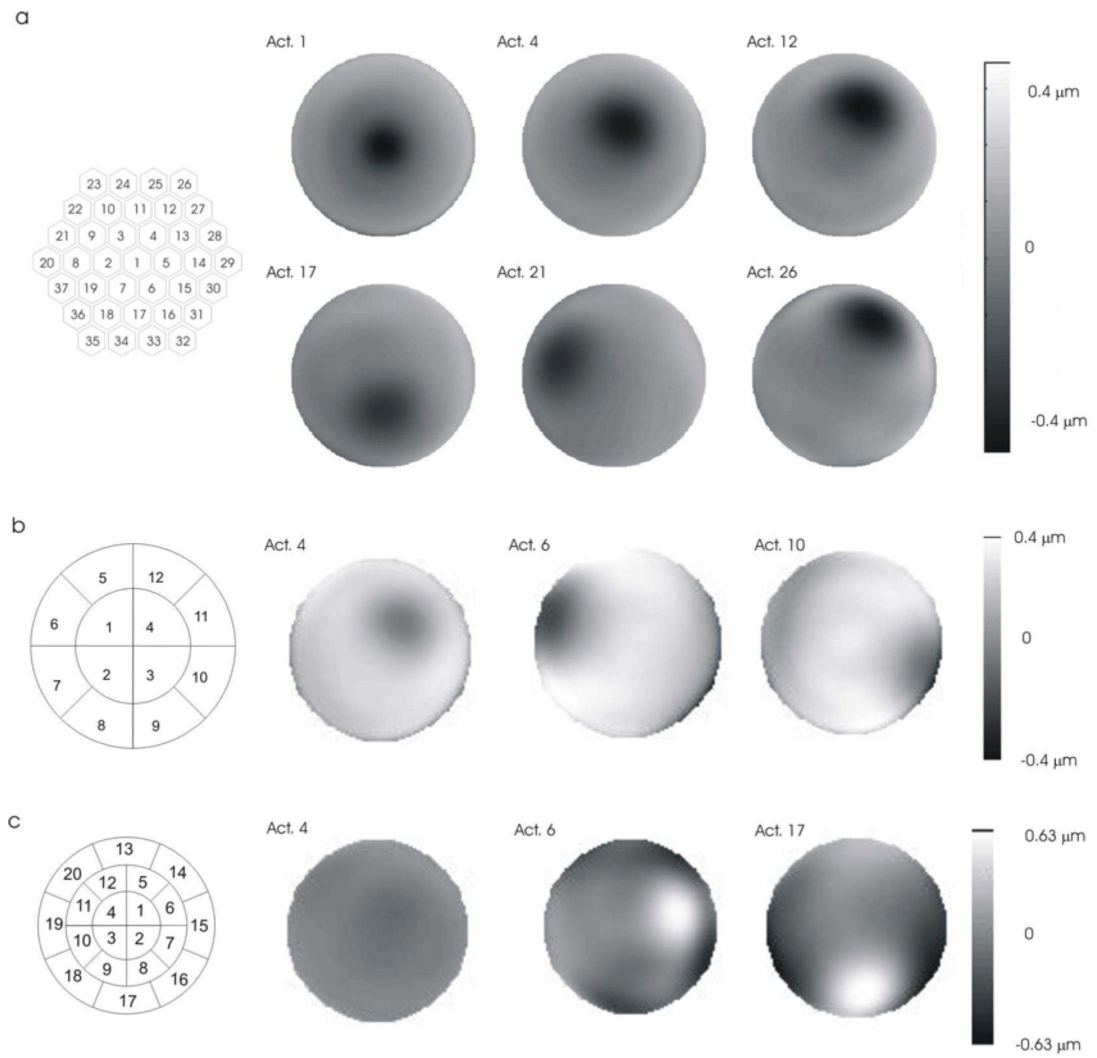

Figure 6 Influence functions of (a) a 15 mm diameter MMDM, (b) the RAS mirror and (c) the MUAS mirror. For all mirrors the whole membrane area is shown. The influence functions have been measured with (a) 300V and (b), (c) 75 V.

Whether a deformable mirror is suitable for a certain application above all depends on its ability to achieve the required surface deformation. Therefore, actuator influence functions of all mirrors have been recorded. Together, these functions provide the influence matrix of the mirror. The inverse of that matrix allows calculating the voltage pattern necessary for achieving a specific mirror deformation. As this influence matrix typically is not square, the singular-value-decomposition method has to be used in order to obtain the inverse matrix[11, 12]. Some influence functions of our mirrors are shown in Figure 6. They have been obtained by successively applying the maximum voltage to every single actuator while the other actuators were still at 0 V. For the MMDMs, this maximum voltage was set to 300 V, for the bimorph mirrors to +75 V and -75 V. In the next step, the obtained influence functions will be used to check the ability of the mirrors to compensate for the aberrations typically found in pumped laser rods. This will also lead to an enhanced actuator design of the bimorph mirrors we manufacture ourselves.

5. MOEMS-BASED ADAPTIVE OPTICS SYSTEMS FOR SOLID STATE LASERS

Applications of MOEMS mirrors to solid state lasers are known in the fields of pulse compression[17,18], spatial mode control[19], active Q-switching of laser resonators[20], aberration correction in master-oscillator-power-amplifier systems[21,22] and closed-loop laser resonator control[23, 24].

A closed-loop MOEMS-mirror-based adaptive laser resonator with at least several Watts of output power and a significant improvement of beam quality or output power due to the adaptive mirror has yet to be demonstrated. This is not an easy task because the mirrors would need to withstand an intracavity laser power in the range of a hundred Watts and possibly several hundred Watts. The work in reference 19 dealt with an open-loop system. It could be shown that the beam quality could be improved by a factor of 2 and modes of different size and shape could be produced. This was not a closed-loop system but suitable voltages for the actuators of a bimorph deformable mirror were manually set. In reference 25, an active Q-switching method using a deformable mirror was suggested. The idea was to periodically drive a laser resonator back and forth between the stable and the unstable resonator regimes. Q-switching occurs when the resonator is moved from the unstable regime to the stable regime due to the rapid decrease of diffraction losses. At the same time, the fundamental mode should completely fill the active medium and the beam quality of the generated pulse should be nearly diffraction-limited. Such a system was demonstrated in reference 20 using a MMDM from OKO Technology. Long Q-switch pulses with a duration of 25 µs, followed by a trail of smaller pulses were generated. Output energy was 200 mJ, average power 48 W, and $M^2 = 6.5$. In reference 21, the beam quality of a master-oscillator-power-amplifier system of 90 W output power could be improved from $M^2 = 5$ to $M^2 = 2.5$ by a deformable MMDM from OKO Technologies in a closed-loop setup. The diffraction limit could not be reached because the mirror didn't have sufficient stroke. Finally, the first closed-loop system using a MOEMS deformable mirror was presented in reference 23. Again, a mirror from OKO Technologies was used. An end-pumped Nd:YVO_4-laser with a hill-climbing algorithm that maximized the power-in-the-bucket signal of the laser beam, delivered an output power of 120 mW. The laser beam had a TEM_{00} intensity distribution. An output power of 8 W was achieved with the same mirror, a genetic algorithm and a side-pumped Nd:$GdVO_4$-laser but the beam quality was not diffraction-limited.

5.1 Set-up

Earlier results have shown that our MMDMs from OKO Technology are probably not suitable for high-power applications and that they are also not able to fully compensate for the typical aberration of an arc-lamp pumped Nd:YAG with several hundred Watts of output power[22]. Therefore, we decided to use these mirrors with a low-power Nd:YVO_4 laser as a starting point to gain insight into the mechanics of intra-cavity closed-loop operation of deformable mirrors. The OKO Technologies MMDM 09 used in our experimental set-up was 10 mm in diameter and contained 19

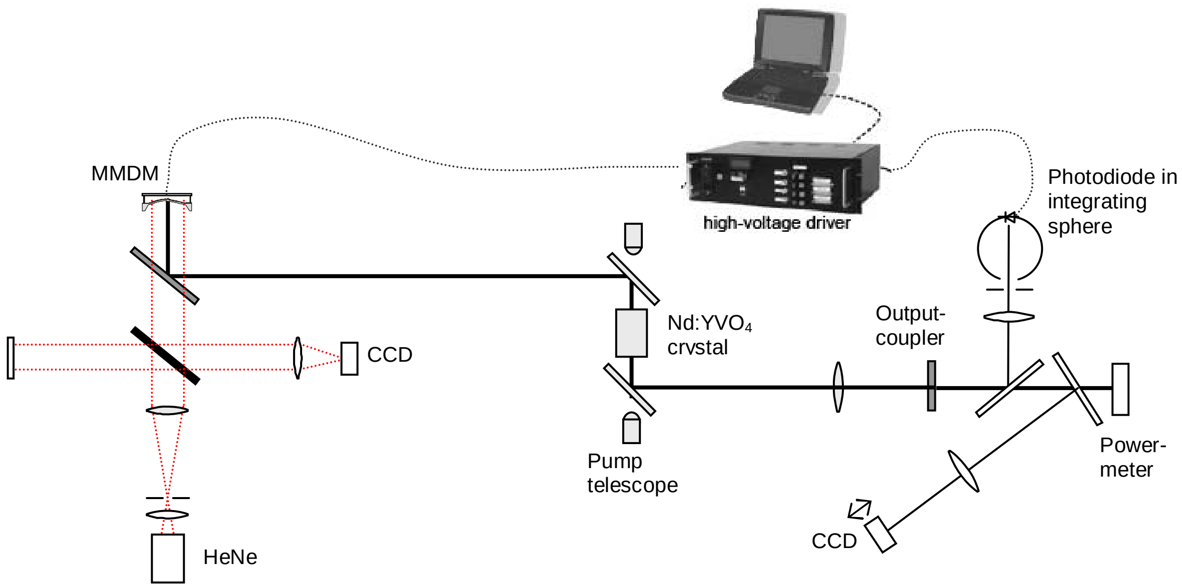

Figure 7 Set-up for closed-loop adaptive optics operation. The feedback signal for the optimization was measured with a power-in-the-bucket sensor (photodiode behind a far-field aperture). A notebook computer was used to optimize the mirror shape by means of a genetic algorithm. The deformation of the adaptive mirror is monitored with a Michelson-interferometer. The beam quality of the laser can be monitored with a CCD camera that is moved through the caustic.

actuators with a maximum stroke of 10 µm at 300 V. It was driven by a 60-channel high-voltage driver[26] connected to a notebook computer via USB. The actuator voltages could be either set manually or be optimized by means of a genetic algorithm[26]. Together with a 4x4x10 mm^3 Nd:YVO$_4$ crystal and a flat output-coupler of 60% reflectivity, the MMDM formed the laser cavity (Figure 7). The crystal was pumped longitudinally with up to 36 W at 808 nm.

The use of a genetic algorithm allows optimizing our laser resonator – a highly nonlinear system – by means of just one feedback signal. In our case this feedback or fitness signal was a power-in-the-bucket measurement. It requires a constant diameter of the laser on the output-coupler, in order to determine the beam parameter product by measuring the far-field diameter. The far-field diameter of higher-order beams is larger than the far-field of a fundamental beam. When the diameter of an aperture, set in the focal plane of the lens, is chosen such that it matches the far-field diameter of our fundamental beam, the throughput through the aperture decreases for higher-order modes. Thus, the current of the photodiode in the integrating sphere is – to a first approximation – proportional to the product of laser output power and beam quality. To ensure the necessary constant beam diameter at the output-coupler, a lens has been used to image the laser rod onto the mirror. However, as the laser did not run highly multi-mode, the diameter of the beam inside the laser rod varied slightly with pumping power. Thus, the beam diameter at the output-coupler also varied slightly.

The resonator was designed for a high-reflector mirror of 2 m radius of curvature. This determined the bias voltage of the MMDM to 225 V, a value not to far from the optimum bias of 212 V for an operating range of 0-300 V of the mirror. During laser operation the deformation of the adaptive mirror could be monitored with a Michelson-interferometer. After optimisation, the beam-quality factor M^2 of the laser was calculated from second-moment diameters of the output beam, measured at several positions along the caustic.

5.2 Experiments

Optimization of the resonator

At first, the resonator design was tested with a conventional high-reflecting (HR) mirror instead of the MMDM. Maximum output power of 7 W with an M^2 of 5.2 was reached at 32 W of pump power. When replacing the conventional HR mirror with the MMDM set to 225 V bias, we measure a maximum output power of 5.6 W at 26.6 W of pump power (Figure 8). The M^2 amounted to 5.0. The drop in output power can be explained by the additional losses the MMDM introduces into the cavity. For both resonators, the beam diameter at the output-coupler stayed relatively constant at 0.55 mm ± 5%. This enables us to use a power-in-the-bucket sensor as feedback signal for the genetic algorithm. With a beam diameter of approximately 4 mm on the MMDM, enough actuators of the mirror are covered to ensure a significant influence of membrane deformations on the laser beam.

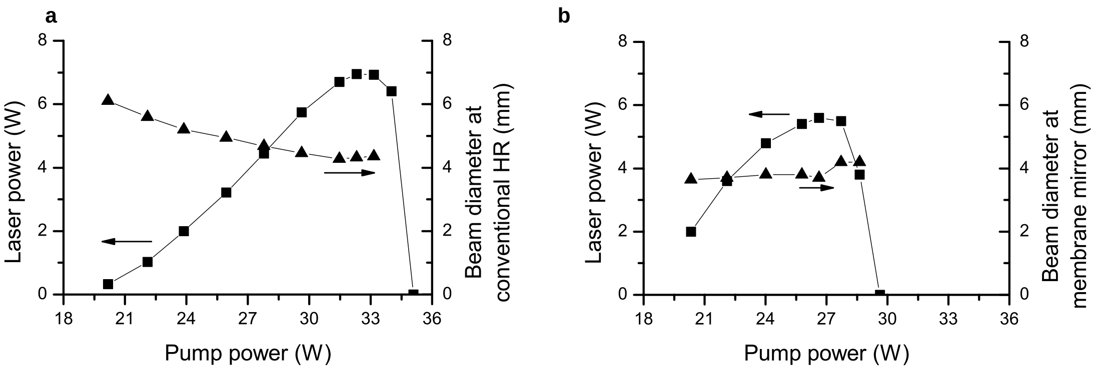

Figure 8 Laser output power and beam diameter at the HR mirror of a resonator with (a) a conventional HR mirror and (b) a MMDM set to 225 V bias voltage as HR mirror.

At this point, the genetic algorithm was initialized. The voltage patterns were applied to the mirror for 5 ms before the fitness signal was recorded. Shorter delay times resulted in large variations of the final laser output power when comparing different optimization runs, while longer delay times slowed down the process unnecessarily. The whole optimization usually required about 30 iteration steps, each with 100 different voltage patterns. This leads to an optimization time of 25 s. Within the first 10 generations, the laser power always reached at least 90% of its final value.

In Figure 9, one example of the normalized fitness signal during optimization is shown. The curve looks fairly smooth, because just the maximum fitness signal – that of best voltage pattern – of each generation is plotted. The optimization starts with random voltage patterns. This means that the laser is not lasing at all at the beginning of the process. Once a voltage pattern is applied that deforms the MMDM in such a way that lasing can start, the power-in-the-bucket feedback signal rises from its zero value. In the next generation, this or slightly changed voltage patterns will be applied again, so that lasing typically starts within the first two or three generations. After lasing has started, the genetic algorithm optimizes the deformation of the MMDM for an optimum feedback signal and thus for maximum laser output power at good beam quality. As no lasing was present at the initialization of the genetic algorithm, we cannot compare the resulting output power and beam quality with values obtained before the optimization. One has to carefully analyze whether the process has really optimized the resonator in terms of aberrations or if it just provided an optimum alignment, which we could as well have achieved without the algorithm.

In our case we found that the genetic algorithm mainly helped to align the cavity. We compared a cavity where all optical components were carefully aligned and the bias voltage of the adaptive mirror was cautiously adjusted manually, with a cavity optimized by the genetic algorithm. The manually and automatically aligned lasers produced 5.6 W and 6.1 W of output power, respectively, with beam quality factors of $M^2 = 5.0$ and $M^2 = 3.6$. Interferograms of the mirror surface of both lasers are shown in Figure 9b and 9c. Slightly shifted to the right from the center of the membrane, the laser beam can be seen as a bright spot. To make it easier to evaluate the interferograms, the beams of both interferometer arms have been tilted to each other in order to get fringes across the beam footprint. In Seidel aberrations, the difference of membrane deformation (across the marked beam area) amounts to 0.16 µm tilt, -0.07 µm defocus, 0.08 µm astigmatism and 0.08 µm coma. Thus the main change the genetic algorithm applied to the area of the deformable mirror underneath the laser beam footprint was tilt.

The MMDM and the genetic algorithm did not only align the resonator in terms of tip/ tilt, but could also align it in terms of defocus, that is, compensate for the thermal lens at different pumping levels. Figure 10 has been obtained by successively applying the genetic algorithm at each pumping level. Laser output power and beam quality ($M^2 = 3.3\ldots4.3$) were constant over nearly the whole range.

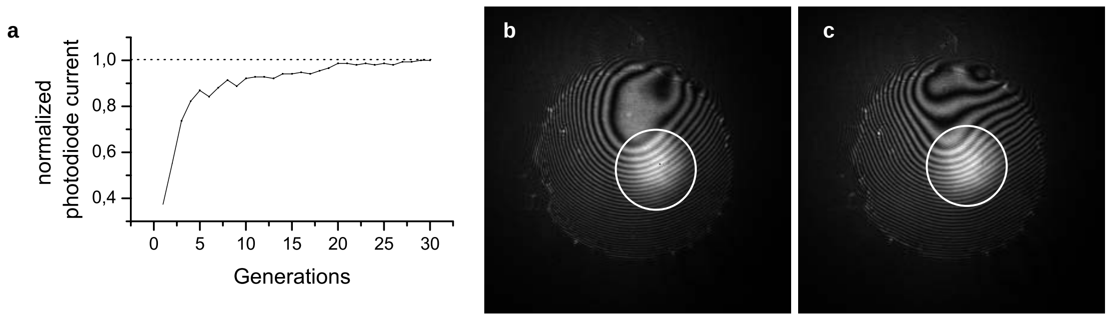

Figure 9 In diagram (a) the photodiode current is shown. It is the feedback signal for the genetic algorithm. The two interferograms on the right show the deformations of the mirror membrane in a (b) manually aligned resonator with a (c) resonator optimized by the genetic algorithm. The bright spot is the laser beam. Membrane deformations have been calculated for the marked area of the membrane.

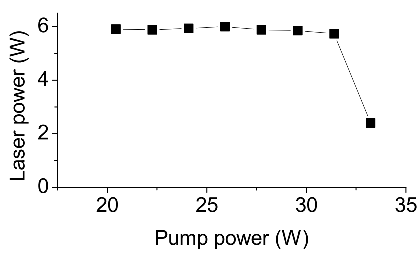

Figure 10 Laser output power after optimization by the genetic algorithm at several pump power levels.

So far, we have just shown the capability of our closed-loop system of aligning a laser resonator. No results of aberration compensation have been shown. To investigate the capability of the system to cope with aberrations at last, artificial aberrations have been inserted into the resonator. These aberrations were produced by a thin glass microscope-coverslip, which had been deformed in the flame of a Bunsen burner in order to produce aberrations. This uncoated coverslip was inserted into the cavity under the Brewster angle. Now, it was no longer possible to start lasing by aligning the cavity manually. However, when optimized with the genetic algorithm, a laser output of up to 4.3 W at $M^2 = 5$ has been achieved.

It is notable that during all presented measurements, the influence of the size of the aperture of the power-in-the-bucket sensor was negligible for the optimization. Even without aperture – and thus using just the laser power instead of the product of laser power and beam quality as feedback signal for the genetic algorithm – we got similar results. We have been careful to set the aperture used in the power-in-the-bucket sensor exactly in the focal plane of the lens. The diameter of this aperture also matched the far-field diameter of a laser beam with $M^2 = 1$ (diameter of the aperture = π * radius of expected far-field), but we have to look more closely into this again.

Stability of the MMDM

The MMDM used in these experiments has been chosen for its large actuator stroke and moderate thermal deformation under laser load (compare Table 1). The membrane did show slight thermal deformations when under laser load (Figure 11). The time constant of these deformations was about 30 s. As deformations of the mirror membrane occurred almost instantly, when caused by laser load from an external laser (see Figure 3), these 30 s have to be a time constant of the whole resonator system. At the moment we explain this long time with the interaction of membrane and laser. When the membrane is deformed, it changes the resonator parameters. The laser beam and thus the laser load at the membrane changes, leading to a new deformation. Anyway, we are still surprised that the time, necessary for reaching stability, is not shorter than 30 s.

With thermal deformations of 0.45 µm peak-to-valley when under 110 W/cm^2 laser load, membrane deformations due to laser load will most likely destabilize a laser resonator already at laser loads well below the relatively high coating damage threshold[27] of more then 144 kW/cm^2. Thus these deformations currently seem to limit the suitability of MMDMs for incorporation in laser resonators rather than the coating damage threshold.

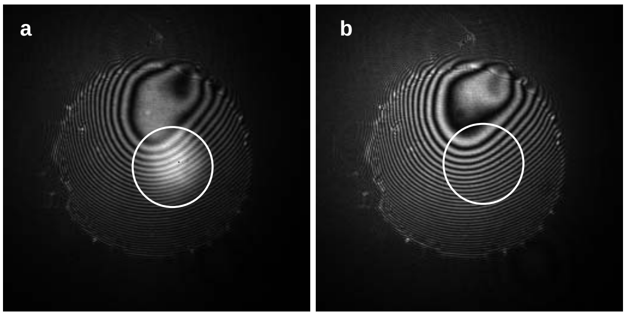

Figure 11 Interferograms of the membrane of the adaptive mirror (a) under laser load, (b) without laser load. In both pictures 225 V bias voltage are applied to the actuators. With an output power of 5.6 W, 60% reflectivity of the output-coupler and a 1/e^2 beam diameter of 4 mm, the power density on the membrane amounts to 110 W/cm^2. This led to a thermal deformation of 0.45 µm peak to valley across the beam footprint.

6. OUTLOOK

We have presented results on intra-cavity closed-loop operation of a MMDM. Until now, the laser is just optimized in terms of power, not in terms of beam quality. This could be caused by a feedback signal that is weighted too much by the total laser power and too little by the beam quality. We therefore plan to investigate our power-in-the bucket sensor more closely. Furthermore the MMDM which we used suffered from deformation under laser load. As bimorph mirrors did not show this sensitivity, we plan to go on with the development of bimorph mirrors. Using the recorded influence functions of the mirrors for calculation of their capability to produce the desired surface deformation should help to improve the actuator design to the specific needs for intra-cavity use. In order to be able to use the bimorph mirror together with an genetic algorithm, it is also necessary to reduce the hysteresis of the mirror. This could be done by replacing the PZT with PMN.

7. CONCLUSIONS

Deformable mirrors based on MOEMS technology allow control of the spatial phase of coherent laser light in a cost effective manner. Further development is needed in order to fully exploit the potential of membrane mirrors for high-power solid state lasers. The mirrors should have roughly two to five times higher density of actuators and also two to five times higher stroke compared to currently available mirrors. Also, dielectric coatings with higher reflectivity are needed in order to avoid heating of the membrane at high laser powers. These requirements are within reach of current technology and we anticipate more widespread use of adaptive MOPA systems and adaptive laser resonators in the near future.

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