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Thermo-optically driven adaptive mirror for laser applications

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ABSTRACT An adaptive mirror is investigated that is based on the deformation of the reflective surface due to thermal expansion of an underlying material that can be locally heated with an external light source. The mirror is made from a glass plate coated with a 1-mm-thick layer of a material with a large thermal expansion coefficient that was finally sputter coated with a thin gold film. The adaptive mirror is thermo-optically heated with an incandescent lamp. To generate the desired temperature pattern an aperture mask is used. The deformation of the adaptive mirror is measured with a Michelson interferometer. It is shown that the spatial resolution and amplitude of the deformation are sufficient for the application as an adaptive mirror. As a possible application the suitability of this mirror type as part of a laser resonator to generate a super-Gaussian mode is discussed.

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1 Introduction

For many laser applications intensity distributions other than the TEM_{00} fundamental mode are desired [1]. Among different custom modes the super-Gaussian mode (also referred to as the top-hat mode) features advantages which are important for numerous purposes, such as higher extraction efficiency of laser radiation out of the laser rod due to a higher spatial overlap with the pump distribution and the generation of higher harmonics in the field of non-linear optics [2]. The intra-cavity generation of custom modes requires a resonator mirror with a surface that deviates from a conventional flat or spherical surface. The intensity distribution emitted from a cavity can be customised by replacing one of the mirrors with a graded-phase mirror. With such an optical element, it has been shown that the generation of a super-Gaussian mode can easily be achieved with good efficiency [3, 4]. The main goal is now to replace the currently fixed graded-phase mirror with an adaptive mirror to allow for continuous and controlled variations of the generated laser-beam properties during laser operation.

However, currently known adaptive optical systems such as deformable mirrors with piezo-actuators [5, 6] and electrostatically deformable membrane mirrors [7, 8] are not suited for intra-cavity beam control of lasers in the visible and near-infrared spectral region. Either they cannot be modulated with sufficient spatial resolution or they cannot withstand the power levels reached in modern laser systems. A solution can be found with the use of an adaptive mirror that is thermo-optically driven with an external light source. The pattern of the light source irradiated onto the mirror may be temporally constant, as with an incandescent lamp in combination with a mask, or it can be dynamic with the projection of a temporally varying pattern. For this purpose two mechanisms are possible: thermal expansion and thermally induced change of the refractive index.

In this letter we concentrate on an adaptive mirror generated by thermal expansion of the underlying material. The mirror consists of a glass substrate carrying a layer with a large thermal expansion coefficient that is coated with a reflective film. The layer is heated by irradiation with a spatially varying pattern. The pattern is generated with the emission of an incandescent lamp in combination with a mask. The pattern is then imaged onto the adaptive mirror, where the radiation is absorbed and the layer is locally heated. We investigate the deformation behaviour of such a thermo-optically driven adaptive mirror and show that such an adaptive optical element could be used to customise the intensity distribution in a cavity to create for example a super-Gaussian mode.

2 Experiment

The experimental arrangement is shown in Fig. 1. The deformation of the adaptive mirror is investigated with a Michelson interferometer illuminated with a He-Ne laser at 632 nm and monitored with a CCD camera. The adaptive mirror is manufactured using a glass plate with a 1-mm-thick coated gel layer (Sylgard 184, Dow Corning, Inc.). The surface of the gel layer is sputter coated with a 40-nm thin gold film. Such a reflector is by no means suitable for high-power laser applications, but it is well suited to study the feasibility of the principle of the adaptive system. The gel layer has a large expansion coefficient of about $\alpha = 9.6 \times 10^{-4}\,^{\circ}\mathrm{C}^{-1}$. In this arrangement an incandescent lamp is used to provide the heating radiation. As a mask a pinhole with a diameter of $D =$ 1 mm drilled in a 0.5-mm-thick aluminum sheet was used.

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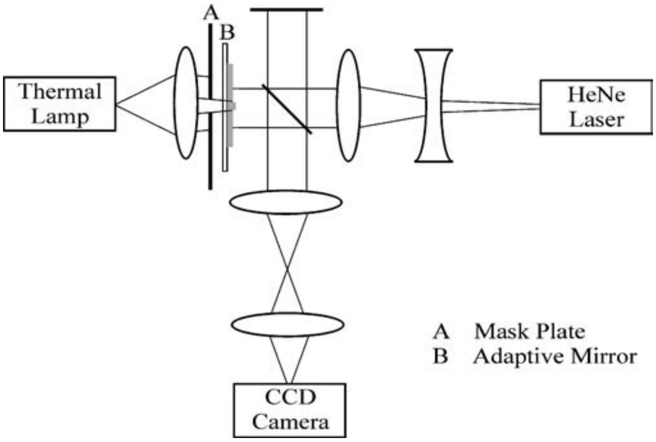

FIGURE 1 Experimental arrangement

The maximum power of the radiation transmitted through the mask was $P = 7$ mW. Figure 2 shows the absorption spectrum of the 1-mm-thick gel layer measured with a spectrophotometer (Perkin Elmer Lambda 19) and the emission spectrum of the black-body radiation at 1450 °C, which is close to the emission spectrum of the lamp. As can be seen from Fig. 2 there is only a partial overlap between the spectral lamp emission and the absorption in the layer. The measured transmittance through the absorber without a gold layer is 82%. Considering the Fresnel reflection of 4% at the interfaces, an effective transmittance of 0.9 can be estimated. Due to the double path in the case of the gold-coated layer the absorbance amounts to about 22%. The interference patterns of the adaptive mirror with and without heating are shown in Fig. 3. The interferometer is slightly misaligned to produce a stripe pattern for a convenient measurement of the deformation. The relief through the centre of the deformed area along the line A–A is shown in Fig. 4. With the irradiated power of 7 mW, corresponding to an absorbed power of 1.54 mW, a thermal expansion of 1 μm is achieved in the centre of the spot. With a thermal expansion coefficient of $\alpha = 9.6 \times 10^{-4}\,°\mathrm{C}^{-1}$ for Sylgard and a layer thickness of 1 mm this corresponds to a peak temperature rise of 1 °C. The width of the deformation at FWHM is about 1.6 mm.

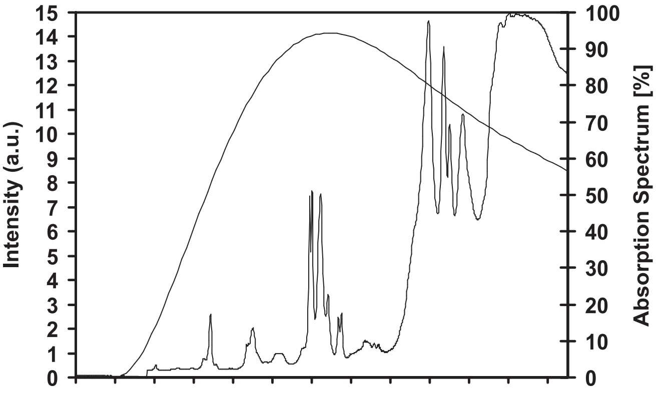

FIGURE 2 Absorption spectrum of the gel layer (*right-hand scale*) and the black-body radiation at 1450 °C (*left-hand scale*)

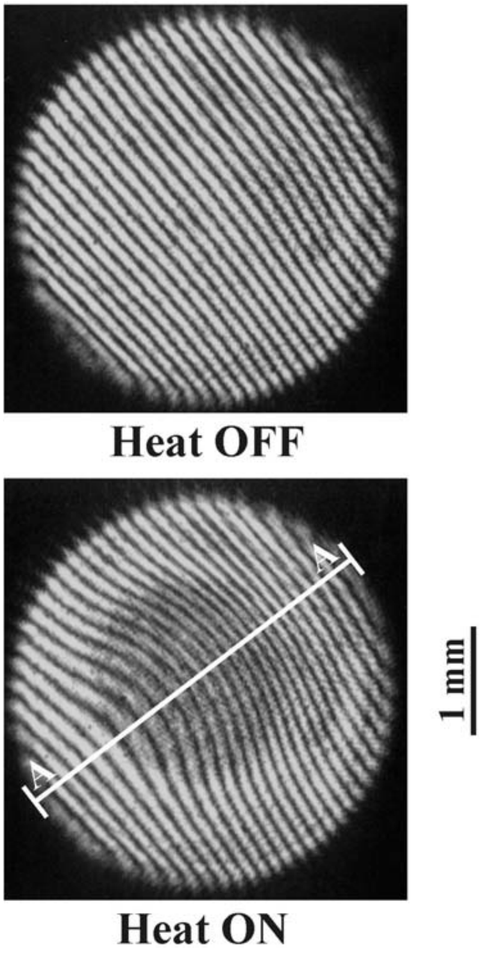

FIGURE 3 Interference pictures of the thermo-optically driven adaptive mirror with and without heating a 1-mm-diameter spot

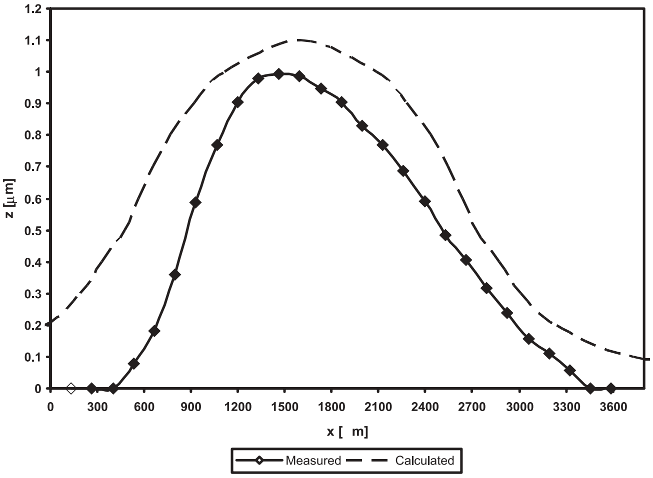

FIGURE 4 *Solid line*: deformation of the heated spot of Fig. 3 measured along A–A. *Dashed line*: calculated deformation according to Fig. 6

A temporal sequence of the surface deformation was recorded with a CCD camera in connection with a PC. The deformation of the mirror surface as a function of time in the centre of the irradiated spot is shown in Fig. 5 for an irradiated heating pulse of 7-s duration. From the figure the build-up

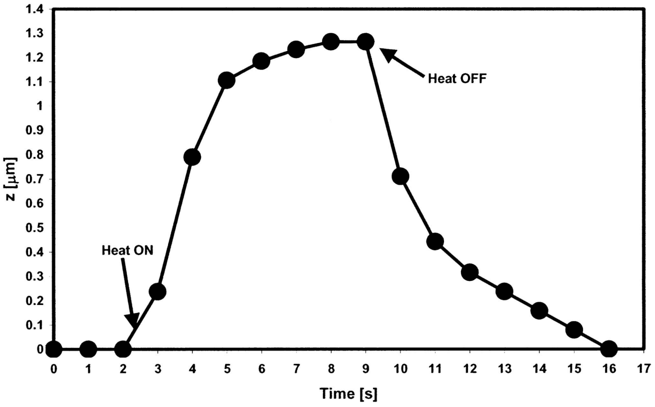

FIGURE 5 Deformation of the mirror surface as a function of time in the centre of the irradiated spot for an irradiated heating pulse of 7-s duration

and decay time to 50% of the maximum deformation can be estimated to be 1.5 s.

The heating process and the resulting deformation were calculated numerically with the computer program NM SESES [9] for the given geometry and material parameters. The chosen parameters are given in Table 1. The resulting deformation is shown in Fig. 6. The thermal expansion with a 1.1-µm height corresponds reasonably well with the experimental results.

With the measured FWHM of the deformation of about 1.6 mm, the lateral resolution is expected to be sufficient for the use of this adaptive mirror as a laser resonator mirror for customising the intensity distribution in the cavity. This problem has been treated in the literature [1] for the generation of a top-hat or super-Gaussian intensity distribution in the laser beam. In [1] the required shape of the mirror was approximated by an annular depression with a depth of 90 nm generated by evaporation of the dielectric mirror. The annular depression had radii of 2.87 mm by 0.93 mm. Even this very coarse approximation led to a super-Gaussian mode of order six [1]. Figure 7 shows the shape of the desired phase front on the graded-phase mirror (dashed line) and the described approximation (dotted line). If an annular stop of suitable dimensions is used in connection with a thermo-optically driven adaptive mirror as described above, the phase front given by the solid line can be expected. It is much closer to the desired phase front than the solution of [1], and it can easily be adapted to the desired peak deformation by adjusting the power of the incandescent lamp used for heating. The figure shows that the lateral resolution is sufficient for the application as an adaptive mirror to customise the intensity distribution in a laser cavity to generate a super-Gaussian mode. For laser experiments a high-quality mirror is required that can withstand the high laser power and prevent heating of the active layer by the laser radiation itself.

	Glass	Sylgard 184
Expansion coefficient	5.1×10^{-7} 1/K	9.6×10^{-4} 1/K
Thermal conductivity	1.38 W/mK	0.15 W/mK
Poisson number m	0.17	0.49
Elasticity coefficient	70 000 N/mm^2	0.36 N/mm^2
Layer thickness	1 mm	1 mm
Heated spot radius		0.5 mm
Absorption coefficient		2 cm^{-1}
Absorbed power		1 mW
Reflectance of Gold layer		100%

TABLE 1 Set of parameters used for the numerical simulation

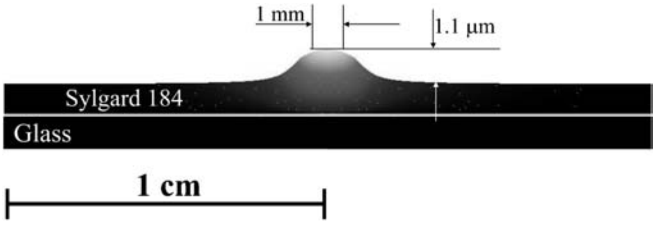

FIGURE 6 Numerical simulation of the thermally induced deformation of a 1-mm Sylgard layer. The height is magnified 10^3 times

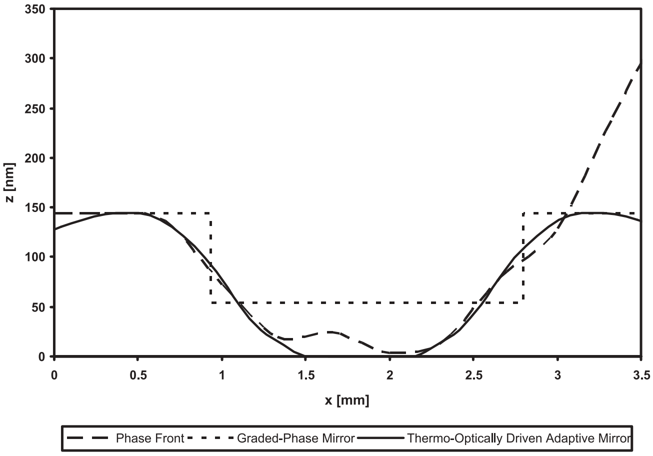

FIGURE 7 *Dashed line*: the shape of the phase front on one mirror of a cavity with a super-Gaussian intensity distribution. *Dotted line*: the shape of the graded-phase mirror used in [1]. *Solid line*: the shape of a possible thermo-optically driven adaptive mirror with a suitable mask

3 Conclusion

In conclusion, we have demonstrated the feasibility of an adaptive mirror using a glass plate with a 1-mm-thick coated gel layer (Sylgard 184, Dow Corning, Inc.) that was sputter coated with a 40-nm thin gold film. The adaptive mirror was thermo-optically heated with an incandescent lamp. As a mask a pinhole with a diameter of $D = 1$ mm drilled in a 0.5-mm-thick aluminum sheet was used. The measured FWHM of the deformation is about 1.6 mm. The lateral resolution is sufficient for the application as an adaptive mirror to customise the intensity distribution in a laser cavity to generate for example a super-Gaussian mode.

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REFERENCES

1 M. Gerber, T. Graf: ‘The Propagation of Custom Laser Modes and the Calculation of the Eigenmodes in a Laser Resonator’. In: *Proc. ALT-02 Int. Conf. Advanced Laser Technologies, 2002*, pp. 13–20 [Proc. SPIE **5147**, 13 (2003)]
2 R. Craxton: IEEE J. Quantum Electron. **QE-17**, 108 (1994)

3 P.A. Bélanger, C. Paré: Opt. Lett. **16**, 1057 (1991)
4 M. Gerber, T. Graf: IEEE J. Quantum Electron. **QE-40**, 741 (2004)
5 T.Y. Cherezova, S.S. Chesnokov, L.N. Kaptsov, A.V. Kudryashov, V. Samarkin: in *Proc. 2nd Int. Workshop Adaptive Optics for Industry and Medicine, Durham, UK, 12–16 July 1999*, pp. 187–192
6 H. Baumhacker, G. Pretzler, K.J. Witte, M. Hegelich, M. Kaluza, S. Karsch: Opt. Lett. **27**, 1570 (2002)
7 D. Burns, G.J. Valentine, W. Lubeigt, E. Bente, A.I. Ferguson: SPIE Proc. **4629**, 129 (2002)
8 G. Vdovin: 'Current Performance Limits for Micromachined Membrane Deformable Mirrors'. In: *Proc. 2nd Int. Workshop on Adaptive Optics for Industry and Medicine, Durham* (World Scientific, Singapore 1999) pp. 118–121
9 NM Numerical Modelling GmbH, 8400 Winterthur, Switzerland