Novel unimorph deformable mirror with monolithic tip-tilt functionality for solid state lasers

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ABSTRACT

We present a new type of unimorph deformable mirror with monolithic tip-tilt functionality. The tip-tilt actuation is based on a spiral arm design. The mirror will be used in high-power laser resonators for real-time intracavity phase control. The additional tip-tilt correction with a stroke up to 6 µm simplifies the resonator alignment significantly. The mirror is optimized for a laser beam footprint of about 10 mm. We have modeled and optimized this mirror by finite element calculations and we will present design criteria and tradeoffs for this mirrors. The mirror is manufactured from a super-polished glass substrate with very low surface scattering and excellent dielectric coating.

Keywords: deformable mirror, laser, adaptive optics, bimorph, unimorph

1. INTRODUCTION

Adaptive deformable mirrors provide control of the wavefront of coherent or incoherent light. These mirrors are therefore universal tools of fundamental importance. They can be used to correct for the aberrations of large, light-weighted primary mirrors in space-based telescopes, to reduce the impact of optical aberrations in retinal imaging systems, or to correct for the aberrations of wide-field microscopes. In the past, deformable mirrors were also very successfully used to enhance the brightness of solid-state lasers [1,2,3].

Heat management of a deformable mirror is one of the issues that are of particular importance in high-power intracavity wavefront correction. Deformable mirrors are very sensitive to temperature gradients which cause them to deform like a bimetallic strip. The very nature of the delicate, thin deformable mirror surface precludes efficient heat conduction to a solid heat sink. Only the very thin and flexible mirror support elements could conduct heat away from the mirror but due to their small cross sections they are basically very good insulators. Consequently, heat generation in the deformable mirror has to be kept as low as possible. Deformable mirrors used in lasers need to have a coating with an extremely high reflectivity. A reflectivity of up to 99.998% in conjunction with a residual transmission of only 20 ppm is possible for our concept and may be required for laser applications.

The mirror concept we present is a unimorph deformable mirror which we have developed over the course of many years. It is intended for high-power lasers but other applications are now pursued as well. The most prominent feature that distinguishes this mirror concept from many others is that it employs an optical glass substrate that is super-polished and coated with a dielectric (or metallic) coating before the deformable mirror is assembled. This ensures that we can achieve a highly reflecting and extremely low-scatter optical surface that rivals the best passive optics. Furthermore, our deformable mirrors use very thin substrates and pre-fabricated ceramic PZT actuators. This leads to considerably larger stroke than that of most other mirror concepts. Finally, our mirror also has integrated tip-tilt functionality which simplifies and automates the resonator alignment. The main advantages of this mirror technology are

- very low surface scattering due to the use of super-polished glass
- excellent coatings, even suitable for high power lasers
- active diameter of the mirrors of only 10 mm
- large strokes can be achieved even for small mirror diameters
- integrated monolithic tip/tilt functionality based on a spiral arm design

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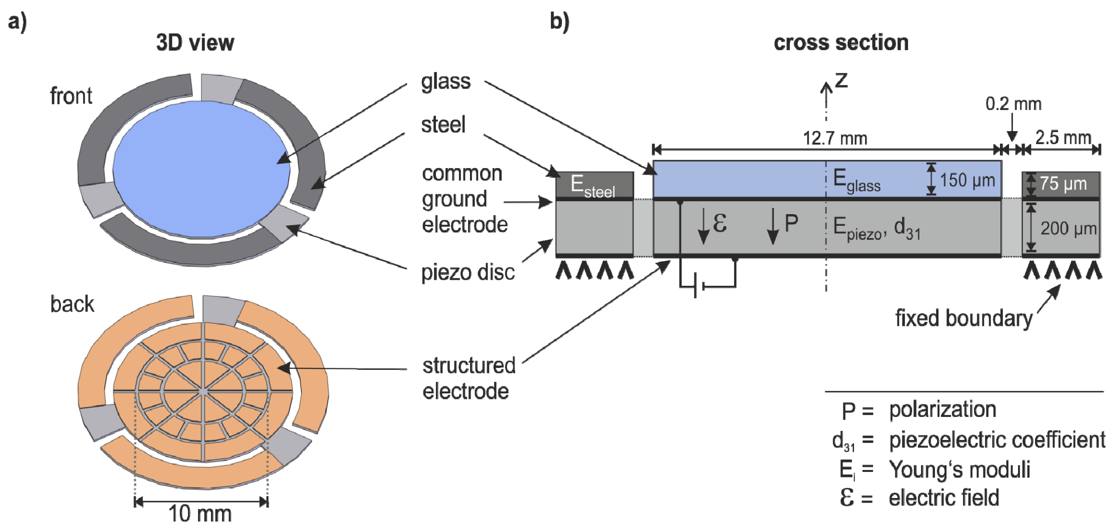

Fig. 1: a) Three-dimensional view of the unimorph structure b) corresponding cross section

We have modelled these mirrors by analytical models as well as by the finite element method. This allows us to quickly design new mirrors tailored to specific applications. We characterize our mirrors by the maximum stroke they can deliver for various Zernike modes, under the boundary condition that the Zernike mode has to be created with a certain fidelity, usually defined by the Maréchal criterion.

2. MIRROR DESIGN

Figure 1 shows our concept for a mirror with a 10 mm active optical aperture. The structure is based on a laser-cut 3-arm piezoelectric disc (see Fig. 2). The piezoelectric disc is sandwiched between two metallic electrodes, an unstructured ground electrode on the front side and a structured back side electrode. The cutting of the piezo ceramic plate and the electrode structuring is done by laser ablation with a picosecond laser. Due to cold material processing we avoid the downsides of unwanted thermal side-effects of the piezo material. Three steel segments are bonded to the arms of the piezo plate to facilitate tip-/tilt actuation of the arms. The central disc of the piezo element is bonded to a passive glass disc. The glass disc is a thin disc of super-polished high-quality optical glass furnished with a high-reflective coating.

When a voltage is applied to the piezo disc the piezoelectric element strains azimuthally and radially due to the reverse piezoelectric effect. For the reverse piezoelectric effect, the strain is proportional to the piezoelectric coefficient d_{31}. The different relative strains of the glass/steel segments and the piezo disc result in lateral stress between the layers causing the laminate to deform. The transverse displacement per unit voltage obtained by such a unimorph structure (flextensional mode) is typically much greater than that of bulk piezoelectric material (extensional mode). This is a significant advantage of unimorph mirrors compared to mirrors based on piezo stacks or piezo bars.

The total thickness of the unimorph structure and the thickness ratio between the passive glass/steel layer and the active piezoelectric layer crucially affect the achievable total displacement. In order to investigate the effects of several critical design parameters, we use analytical models based on the electro-elastic theory and Kirchhoff's thin plate theory

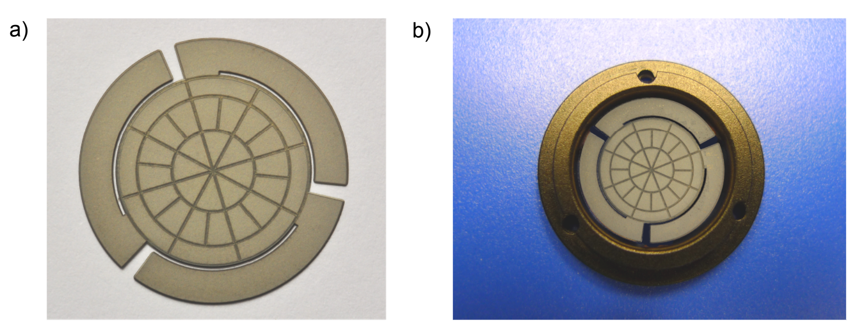

Fig. 2: a) Laser cut piezo disc b) Piezo disc in 3-point-fixture

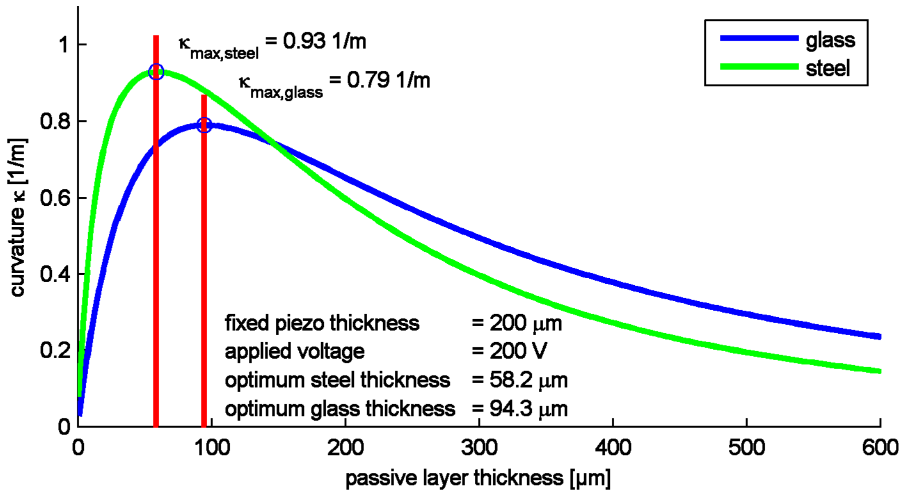

Fig. 3: Curvature of the laminate structure as a function of the passive layer thickness for a given piezo thickness of 700 µm and an applied voltage of 400 V

as well as numerical FEM simulations. For the mirror fabrication we use commercially available piezoelectric discs. On delivery, these discs already show an astigmatic deformation caused by thermal stresses which are induced during the production process of the piezoelectric material. In order to provide the required surface flatness the piezo discs have to be ground and lapped. A sufficient flatness can be achieved for a minimum piezo thickness of about 200 µm for the designated disc diameter of 18.1 mm. As already stated, the achieved deformation per unit voltage of the central disc and the three arms crucially depends on the thickness of the passive glass and steel layers. Figure 3 shows the maximum achievable curvature of the laminate which is directly proportional to the achievable stroke for the piezo/glass and piezo/steel laminate structures. According to these results the optimum glass thickness leading to the highest deformation is about 100 µm. The optimum layer thickness for the steel segments is about 60 µm due to the higher Young's modulus. Compared to unimorph mirrors based on the screen-printing technology, our fabrication method allows to maintain the optimum thickness ratio between the passive and active layers with at the same time very thin laminate structures leading to large stroke. A good reference on the advantages and severe limitations of unimorph and bimorph deformable mirrors with screen-printed actuators is the dissertation of Rodrigues [4].

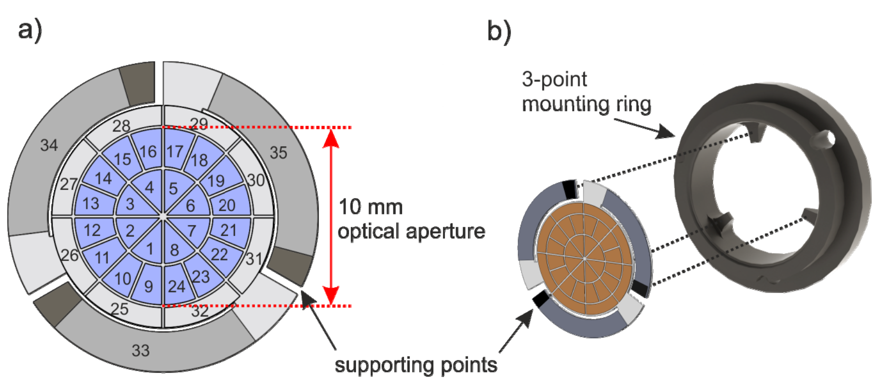

Fig. 4: a) Electrode pattern b) Mounting of the 3-arm mirror

Table 1: Material properties and dimensions used in our numerical models

Component	Property	Value
Piezo disc	Material:	PIC 255 (Physik Instrum.)
	Disc thickness (µm):	200
	Disc diameter (mm):	18.1
	Poisson ratio γ:	0.36
	Young's modulus ***E*** (GPa):	62.9
	Piezoelectric strain constant d_{31} (mV^{-1}):	-174×10^{-12}
	Thermal expansion coefficient (10^{-6} K^{-1}):	~ 6
Bonding layer	Material:	Ultra-low outgassing UV-curable adhesive
	Thickness (µm):	~ 10
	Young's modulus ***E*** (GPa):	~ 6
Passive glass disc	Material:	N-BK10 (Schott)
	Disc diameter (mm):	12.7
	Disc thickness (µm):	100
	Poisson ratio γ:	0.208
	Young's modulus ***E*** (GPa):	72
	Thermal expansion coefficient (10^{-6} K^{-1}):	~ 5.88
Passive steel segments	Material:	High-grade steel
	Thickness (µm):	60
	Poisson ratio γ:	0.3
	Young's modulus ***E*** (GPa):	210
	Thermal expansion coefficient (10^{-6} K^{-1}):	10.8

3. NUMERICAL SIMULATION

Another critical design parameter is the segmentation of the back side electrode into separate actuators. This electrode pattern determines the amplitudes and the fidelities of the mirror deformations that can be achieved. In the past, we have carried out extensive numerical calculations to analyze and compare different electrode patterns with respect to the amplitude and the fidelity with which certain low-order Zernike modes can be created [5]. Our numerical model allows to adapt and optimize the electrode pattern for a specific mirror design. Our proposed mirror design features a 35-electrode keystone pattern, 3 electrodes to actuate the arms, 24 electrodes inside the 50 mm optical aperture, and 8 electrodes forming an additional outer ring outside the active area. This electrode pattern enables a high-fidelity Zernike reproduction with sufficient stroke. The electrode which is located between the passive glass/steel layers and the active piezo layer serves as a common ground electrode for all actuators. The mirror geometry with the optimized electrode pattern, along with the boundary conditions, is shown in Fig. 4.

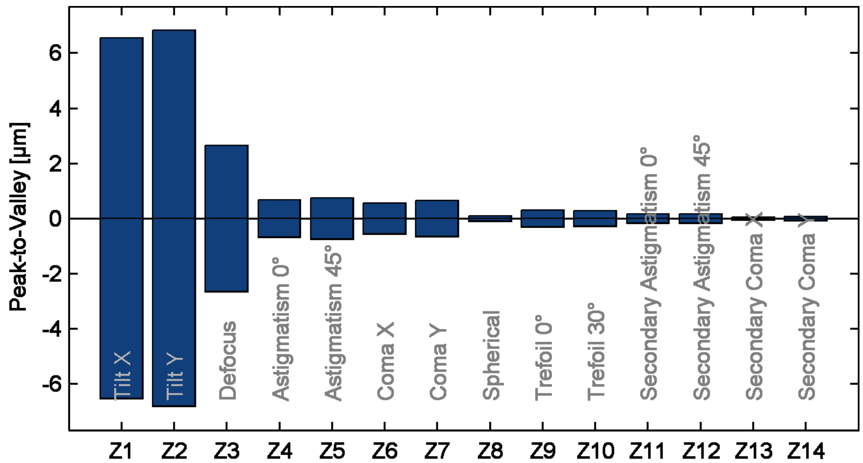

Fig. 5: Numerically calculated amplitudes of low order Zernike modes for our mirror design

3.1 Zernike Reproduction

The results of the numerical finite element simulation are plotted in Fig. 5. The graph shows the achievable Zernike amplitudes of the proposed mirror design. The evaluation of the surface deformation has been carried out across the central 10 mm diameter optical aperture. We applied fixed boundary conditions to the three mounting points. The Zernike amplitudes have been calculated under the condition that the residual rms wavefront error maintains the Maréchal criterion $\lambda/14$ for $\lambda = 1064$ nm ensuring diffraction-limited Zernike reproduction and that the actuator voltages stay inside the maximum allowed voltage range of -100 V to 100 V. This voltage range is determined by electric field breakthrough and reverse poling of the piezoelectric material. We could have easily designed the mirror to achieve significantly higher amplitudes. However, this would require a thinner structure which would increase the residual wavefront deviation and the un-powered mirror deformation.

3.2 Thermal Influence

The operational temperature range for many applications requires a careful selection of the materials used. Even small mismatching of thermal expansion coefficients would lead to significant surface deformations. In Fig. 6, the peak-to-

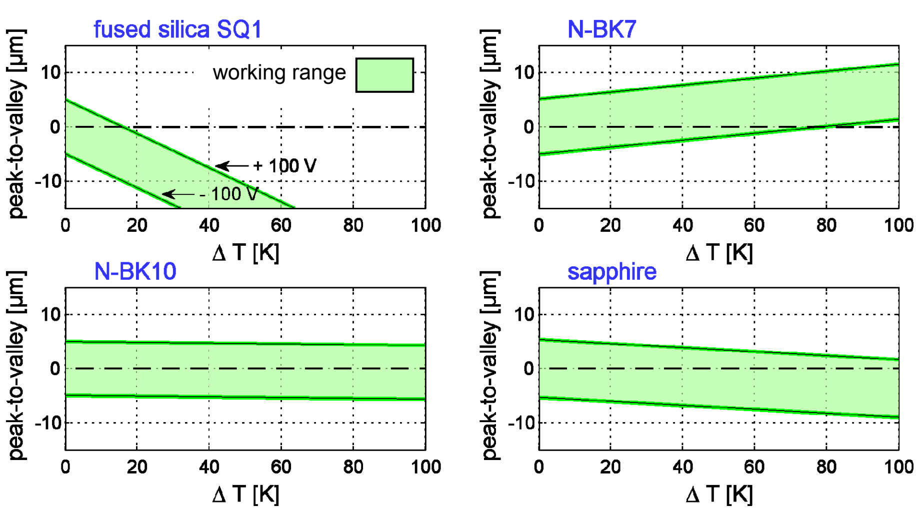

Fig. 6: Defocus Z_3 amplitude for different passive substrate materials, depending on temperature change

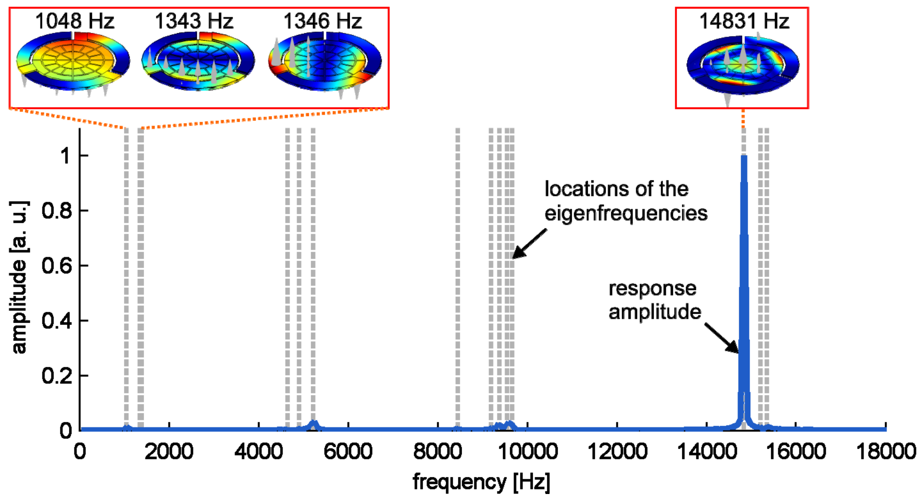

Fig 7: Frequency response analysis: First eigenfrequencies along with the corresponding eigenmodes

valley deformation across the optical aperture of our mirror design is shown, depending on the environmental temperature change for different passive substrate materials. The thermally induced deformation of the three arms has not been calculated as this deformation will not influence the central disc area. A temperature change will cause a uniform bending of the arms, only resulting in a piston Zernike term. Based on the calculations, we have chosen N-BK10 as passive substrate material. Due to the near-perfect matching of the coefficients of thermal expansion of the piezo material PIC 255 and N-BK10 there is almost no thermal deformation (see Fig. 6). The working range for the defocus amplitude is thus independent from the temperature. A word of caution is nevertheless required. Thermal expansion coefficients are usually not very well known and slightly different values could actually lead to a behavior similar to that for sapphire shown in Fig. 6.

Compared to most other mirror concepts, our mirror design allows to select the materials used as passive layers with respect to the active piezoelectric layer in order to minimize thermally induced deformations. For example, mirrors based on the screen-printing technology show very strong temperature dependence due to the large difference of the thermal expansion coefficients of silicon and the piezoelectric material.

3.3 Dynamic Characteristics

A high temporal correction bandwidth of the deformable mirror can be achieved by providing high mechanical resonance frequencies and at the same time sufficiently high structural damping. Additionally, electronic damping can be effected by smart control systems where the electrode actuation counteracts the occurrance of resonance oscillations. Fig. 7 shows the results of a frequency response analysis of our mirror design. The first natural frequency occurs at f_1=1048 Hz and corresponds to a piston like mode shape. The next modes are tilting modes, occurring at 1340 Hz. All of the lowest modes shown in Fig. 7 are actually caused by bending of the three support arms. All of these modes could easily be moved to frequencies that are twice as high by increasing the stiffness of the three support arms. This would only entail a reduction of the tip/tilt amplitude. The resonance frequencies of the mirror without the support arms are well above 4600 Hz.

4. CONCLUSION

We have presented a novel concept for a unimorph mirror design that has the potential to be used for intracavity wavefront correction in high-power laser resonators. Due to the use of super-polished optical substrates with high reflective coating the mirror can be used for beam shaping in medium and high power solid state lasers. The performance of the mirror concept has been optimized by means of analytical models and numerical FEM calculations. While preparing this paper a first prototype of our mirror concept is being built.

5. ACKNOWLEDGMENTS

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REFERENCES

[1] R. R. Stephens, and R. C., Lind, "Experimental study of an adaptive-laser resonator," *Optics Letters* **3**, 79-81 (1978).

[2] K. E. Oughstun, "Intracavity adaptive optics compensation of phase aberrations," *J. Opt. Soc. Amer.* **71**, 862-872 (1981).

[3] P. Welp, “Festkörperlaser mit resonatorinterner Kompensation von Aberrationen durch adaptive Spiegel,” dissertation, University of Münster (2008)

[4] G. Mendes da Costa Rodrigues, "Adaptive optics with segmented deformable bimorph mirrors," dissertation, Université Libre de Bruxelles (2010)

[5] S. Verpoort and U. Wittrock, "Actuator patterns for unimorph and bimorph deformable mirrors," Applied Optics **49**, G37–G46 (2010)