UNIMORPH DEFORMABLE MIRROR FOR TELESCOPES AND LASER APPLICATIONS IN SPACE

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ABSTRACT

Over the past 5 years we have developed a new type of unimorph deformable mirror. The main advantages of this mirror technology are

- very low surface scattering due to the use of superpolished glass
- excellent coatings, even suitable for high power lasers, can be applied
- active diameter of the mirrors can be between 10 mm and 100 mm
- large strokes can be achieved even for small mirror diameters
- integrated monolithic tip/tilt functionality based on a spiral arm design

We have modeled 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. One example is a mirror for laser applications that has a diameter of 10 mm and can achieve a stroke in defocus mode of 5 µm. The stroke for these mirrors scales as the square of the mirror diameter, meaning that we can achieve, for example, a stroke of 125 µm for a mirror of 50 mm diameter. We will present design criteria and tradeoffs for these mirrors. 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.

I. 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, aberrations that arise in the laser or the beam transport optics of LIDAR systems, or the aberrations of wide-field microscopes.

Deformable mirrors have been very successfully employed in terrestrial astronomical telescopes. Terrestrial applications in lasers and microscopy are currently in the early stages of commercialisation. However, deformable mirrors have never been used in space. The space environment precludes some deformable mirror concepts even though they might be successful in terrestrial applications.

Heat management of a deformable mirror is one of the issues that are of particular importance in space. Deformable mirrors are very sensitive to temperature gradients which cause them to deform like a bimetallic thermometer. Heat can only be extracted from the mirror by radiation because there is no ambient gas pressure. 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. For deformable mirrors that are being used with lasers this means that the mirror needs to have a coating with extremely high reflectivity. Reflectivity of up to 99.999% is possible for the concept we propose and may be required for laser applications.

The mirror concept we propose is a unimorph deformable mirror which we have developed over the course of many years. It was originally 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.

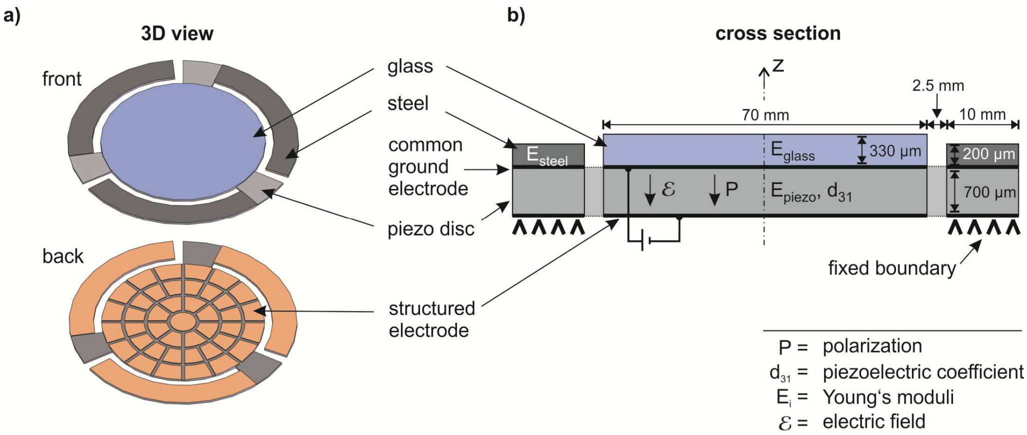

Fig. 1 a) Three-dimensional view of the unimorph structure **b)** corresponding cross section

II. MIRROR DESIGN

Fig. 1 shows our concept for a mirror with a 50 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 electrode structuring is done by laser ablation with a q-switched Nd:YAG marking laser. 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.

In order to fulfill the strict space qualification requirements concerning outgassing and operating temperature range we use a UV-curing epoxy adhesive which has passed the rigorous tests to meet the low outgassing specifications as per NASA ASTM E-595. Advantageous in terms of outgassing is the extremely small free surface of the adhesive layer in our mirror. Outgassing can only occur around the circumference of the mirror structure. In combination with the very small thickness of the adhesive layer (~10 µm) the resultant free surface is approximately 2.25 mm^2.

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 and the active piezoelectric layers 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 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 500 µm for the designated disc diameter of 95 mm. In our mirror design we use piezo discs with a thickness of 700 µm. As already stated, the achieved deformation per unit voltage of the

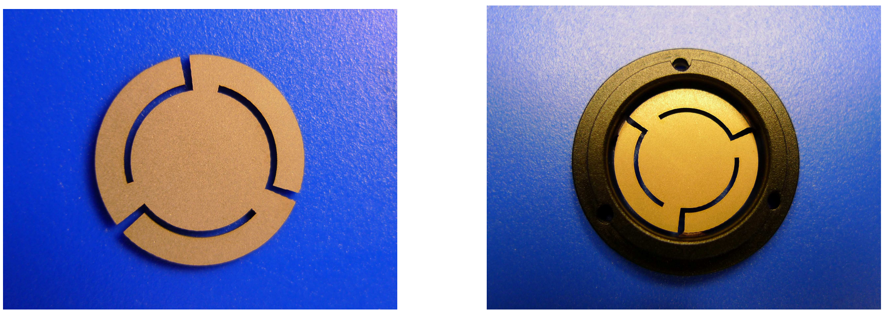

Fig. 2 left: Laser cut piezo disc **right:** Piezo disc in 3-point-fixture.

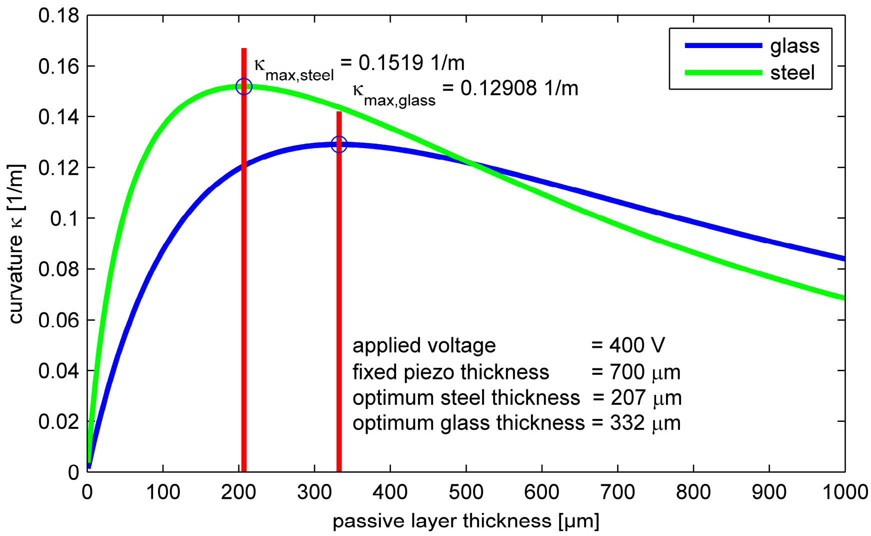

Fig. 3 Curvature of the laminate structure as a function of the passive layer thickness for a given piezo thickness of 700 µm and an applied voltage of 400 V.

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 330 µm. The optimum layer thickness for the steel segments is about 200 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 [1].

III. 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 [2]. Our numerical model allows to adapt and optimize the electrode pattern for a specific mirror design. Our proposed mirror design features a 44-electrode keystone pattern, 3 electrodes to actuate the arms, 25 electrodes inside the 50 mm optical aperture, and 16 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 situated 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.

III.A. 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

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

Component	Property	Value
Piezo disc	Material:	PIC 255 (Physik Instrum.)
	Disc thickness (µm):	700
	Disc diameter (mm):	95
	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):	70
	Disc thickness (µm):	330
	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):	200
	Poisson ratio γ:	0.3
	Young's modulus ***E*** (GPa):	200
	Thermal expansion coefficient (10^{-6} K^{-1}):	10.8

out across the central 50 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 Marechal 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 -400 V to 400 V. This voltage range is determined by electric field breakthrough and reverse poling of the piezoelectric material.

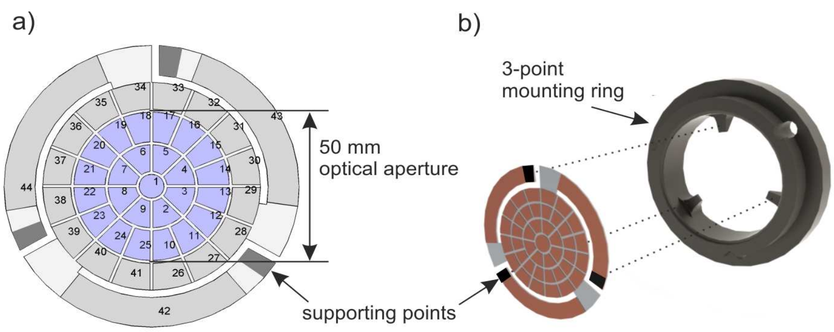

Fig. 4 a) Electrode pattern **b)** Mounting of the 3-arm mirror.

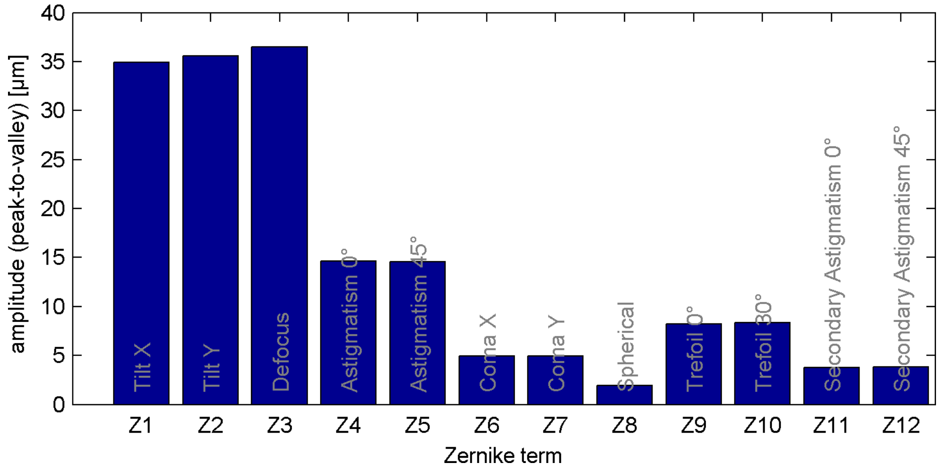

Fig. 5 Numerically calculated amplitudes of low order Zernike modes for our mirror design

We would have easily designed the mirror to achieve significantly higher amplitudes up to 125 µm. However, this would require a thinner structure which would increase the residual wavefront deviation from spherical and the un-powered mirror deformation.

III.B. THERMAL INFLUENCE

The operational temperature range for space 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-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. Fig. 6 shows that 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. The working range for the defocus amplitude is thus independent of 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

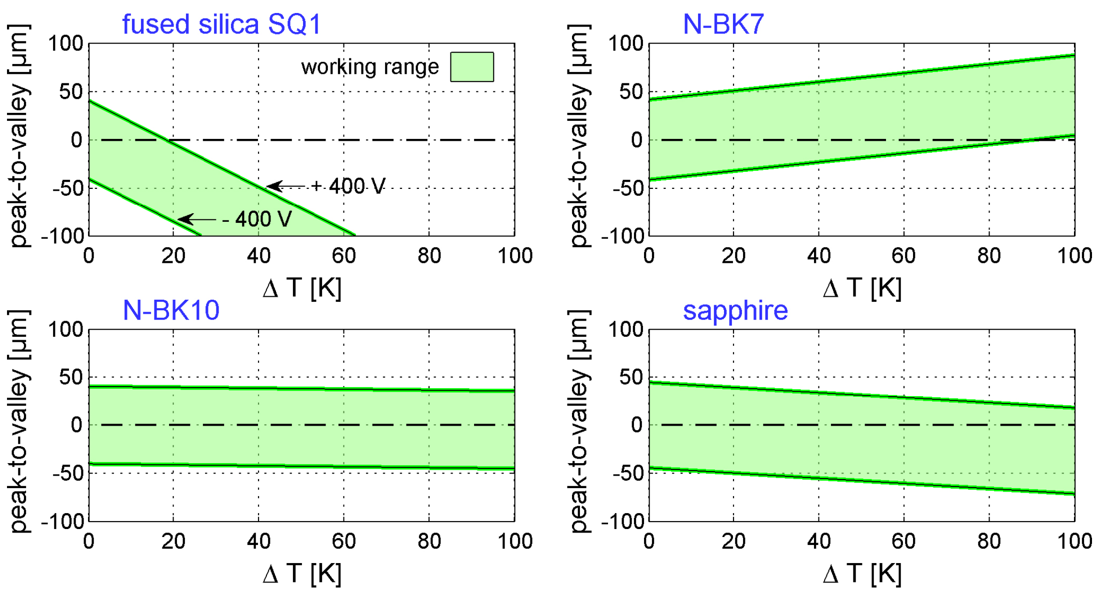

Fig. 6 Defocus Z_3 amplitude for different passive substrate materials, depending on temperature change.

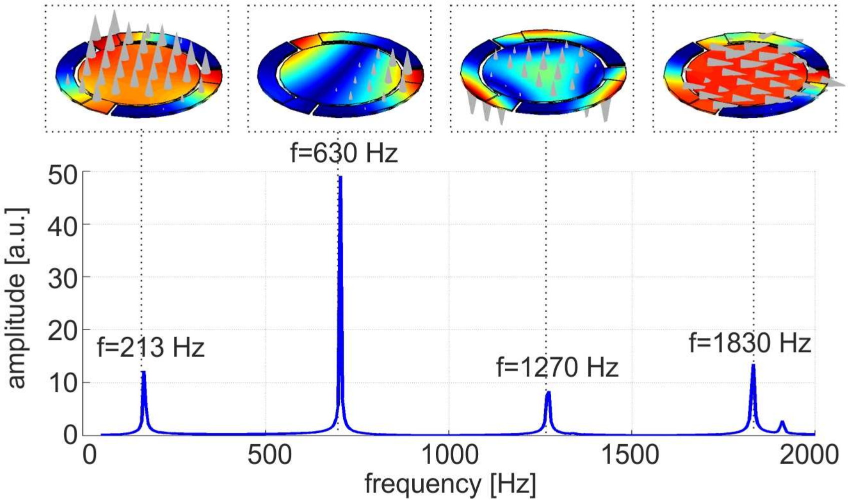

Fig. 7 Frequency response analysis: First eigenfrequencies along with the corresponding eigenmodes.

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.

III.C. 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 $f_1 = 213\,\mathrm{Hz}$ and corresponds to a piston like mode shape. We thus exceed the open-loop bandwidth of 100 Hz. The next mode is a tilting mode, occurring at 630 Hz. All of the four 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 2 KHz.

IV. CONCLUSION

We have presented a novel concept for a unimorph mirror design that has the potential to be used for space applications. 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.

V. ACKNOLEDGMENTS

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