A novel athermal approach for high performance cryogenic metal optics

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ABSTRACT

This paper describes a new athermal approach for high performance metal optics, particularly with regard to extreme environmental conditions as they usually may occur in terrestrial as well as in space applications. Whereas for mid infrared applications diamond turned aluminium is the preferred mirror substrate, it is insufficient for the visual range. For applications at near infrared wavelengths (0.8 µm – 2.4 µm) as well as at on cryogenic temperatures (-200°C) requirements exist, which are only partially met for diamond turned substrates. In this context athermal concepts such as optical surfaces with high shape accuracy and small surface micro-roughness without diffraction effect and marginal loss of stray light, are of enormous interest.

The novel, patented material combination matches the Coefficient of Thermal Expansion (CTE) of an aluminium alloy with high silicon content (AlSi, Si ≥ 40 %) as mirror substrate with the CTE of the electroless nickel plating (NiP). Besides the harmonization of the CTE (~ $13*10^{-6}$ K^{-1}), considerable advantages are achieved due to the high specific stiffness of these materials. Hence, this alloy also fulfils an additional requirement: it is ideal for the manufacturing of very stable light weight metal mirrors.

To achieve minimal form deviations occurring due to the bimetallic effect, a detailed knowledge of the thermal expansion behavior of both, the substrate and the NiP layer is essential. The paper describes the reduction of the bimetallic bending by the use of expansion controlled aluminium-silicon alloys and NiP as a polishing layer. The acquisition of CTE-measurement data, the finite elements simulations of light weight mirrors as well as planned interferometrical experiments under cryogenic conditions are pointed out. The use of the new athermal approach is described exemplary.

Keywords: Metal mirrors, athermal design, cryogenic optics, bimetallic bending

1. INTRODUCTION

Metal optics made of Aluminium 6061 have been widely used to fulfill the demands of an athermal instrument design. Diamond turned metal mirrors are standard optical components in mid infrared astronomical instrumentations working at cryogenic temperatures. Structures and optics can be made from the same material (aluminium) to avoid thermal stress due to different CTEs. However, surface roughness, scattering behavior and form accuracy of aluminium mirrors are limited due to the crystallographic and mechanical properties of the substrate material. Mirrors made of zero expansion glass ceramic or silicon carbide (SiC) can be used for cryogenic applications. However, this requires enormous efforts concerning manufacturing and mounting. Therefore the designer tries to avoid the use of glass or ceramics at these working conditions. The use of the same material for optics and structures even for near infrared applications would be a big step forward.

The usage of aluminium substrates with an NiP layer is possible to overcome the performance limitation of aluminium mirrors.

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Various polishing techniques may be applied. Nevertheless the significant mismatch in the CTE has to be reduced for the cryogenic use. Looking at the scaling behavior of the deformation due to the CTE mismatch of a simple bi-metallic plate the determining factors becomes obvious:

$$\text{Deformation} \sim \Delta\text{CTE} * \text{Thickness}_{\text{NiP}} * E_{\text{NiPlayer}} / (E_{\text{substrate}} * \text{Thickness}_{\text{substrate}}^{2})$$

For an athermal approach an expansion controlled AlSi alloy is a promising substrate material. Both the higher Youngs Modulus of AlSi compared to standard aluminium and the small CTE mismatch between AlSi and NiP have a positive impact on reducing the bimetallic bending. Very thin NiP layers, which are necessary for standard aluminium, are not longer mandatory.

1.1 Piston mirror for interferometric beam combiner

The possibility of the manufacturing of complicated or lightweighted structures is another advantage of metal optics. Additionally, the Young's modulus of this new mirror material is 30% higher than for common aluminium alloys. Figure 1 shows a lightweighted piston mirror unit made from AlSi for the interferometric beam combiner LINC-NIRVANA (LN) [1] at the Large Binocular Telescope (LBT). The simulation in figure 2 illustrates the reduced bimetallic effect due to the use of AlSi.

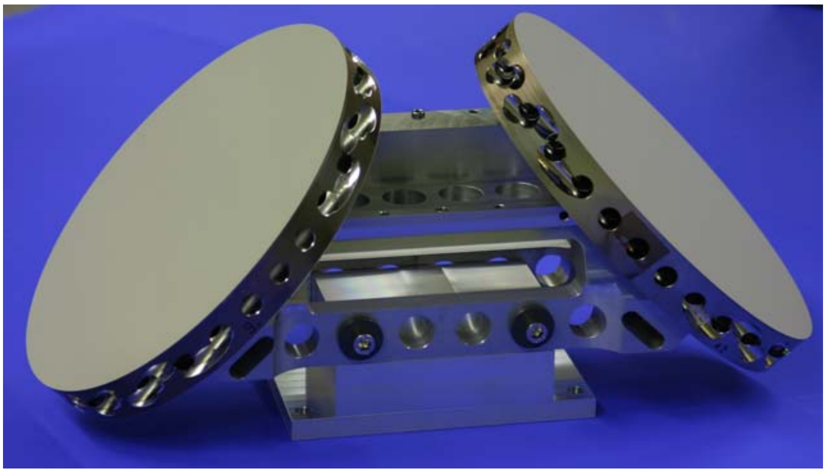

Figure 1: Piston mirror for LBT interferometric beam combiner (working temperature -10°C - +20°C)

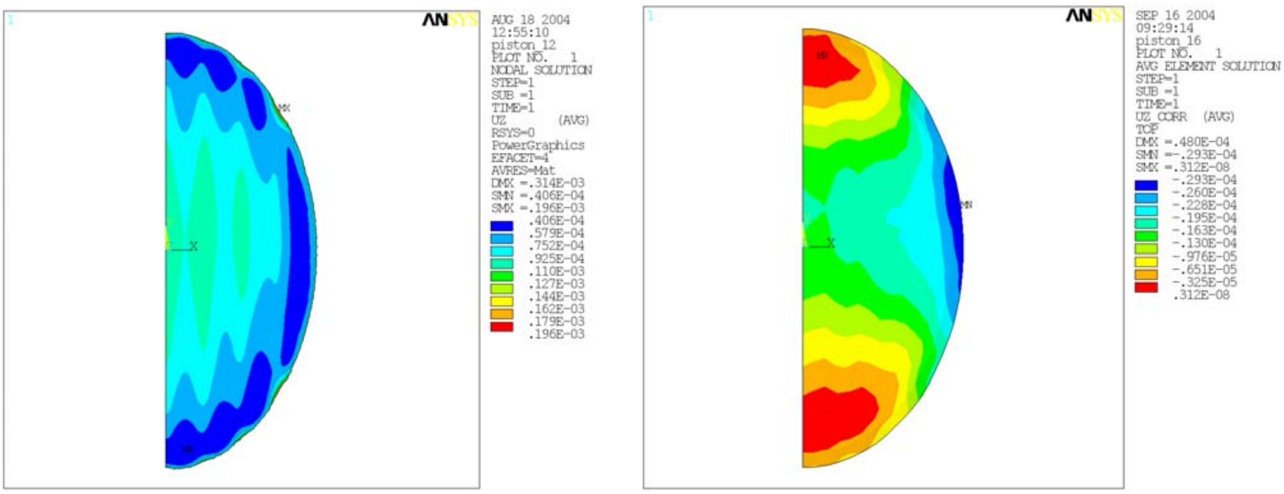

Figure 2: Mirror Al 6061 (left = 66 nm p-v) and AlSi (right = 39 nm p-v) with a 50 µm NiP layer at ΔT = 25 K (simulation)

The LN piston mirror is mounted on a piezo-electric actuator to remove differential piston between the two interferometric arms of the instrument and direct the light into the beam combiner cryostat. A low mass and high eigenfrequency is required. It would be very difficult to achieve this goal if the optics were manufactured from glass or ceramics. The complete unit (without piezo stage) has a weight of only 3.2 kg (mechanical size of mirror surface: 200 x 145 mm). We achieved the target value of $\lambda/10$ p-v (633 nm) for the complete optical surface.

1.2 METimage rotary telescope

METimage is a novel telescope concept for a multi-spectral radiometer with a large swath width and a ground sampling distance of < 1km. This telescope is intended for meteorological application and will be used in a succession-satellite system to the present EUMETSAT polar system (EP). The essence of the METimage concept is a novel rotary telescope designed by scientists at JENOPTIK. The instrument registers the light which is reflected by the earth surface, the atmosphere, clouds or scattered sunlight in several spectral canals from the visible up to the thermal infrared spectral range [2]. It fulfils user requirements for measurements of physical parameters in the atmosphere, of the sea surface and of the land surface to assess meteorologically relevant states. The reflective optics for the rotary telescope is based on a three mirror anastigmat telescope (TMA). It is under development in cooperation with JENOPTIK (supported by the German Aerospace Center DLR, No. 50 EE 0926).

The design of the telescope is athermal, mechanically stable and light-weighted concerning the mirrors as well as concerning the whole telescope structure. It will be realized by the use of identical materials for both the mechanical structure and the optic. Considering mirror requirements like high quality surface flatness, low roughness and non-periodical structures, a combination of the expansion controlled aluminium-silicon alloy with a polishable electroless nickel-phosphorus layer will be used. For all mirrors, FEM simulations in respect to gravity and bimetallic deformation have been carried out. As an example, figure 3 illustrates the changing of radius of curvature introduced by a thermal load of 10 K into the main mirror using the proposed athermal approach. Within a breadboard study, flat, aspherical and freeform mirrors were manufactured in cooperation with Carl Zeiss Jena GmbH (figure 4). For the spectral range from visual to thermal infrared, a diffraction limited optical system is under development.

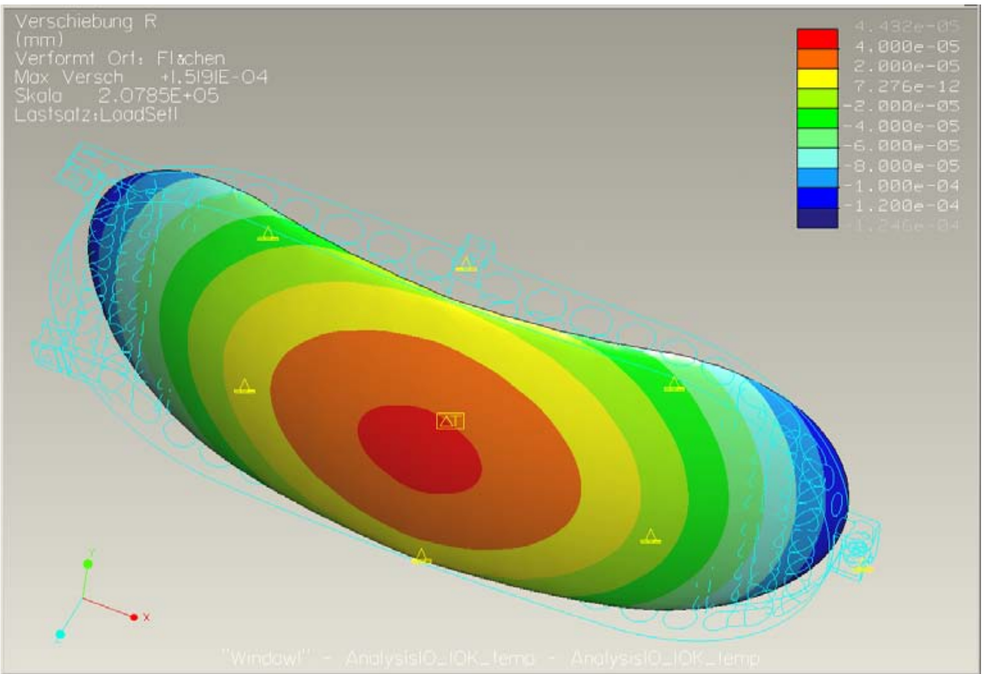

Figure 3: FEM simulation of the main mirror with 50 µm NiP-layer, radius deviation: 160 nm @ ΔT=10 K

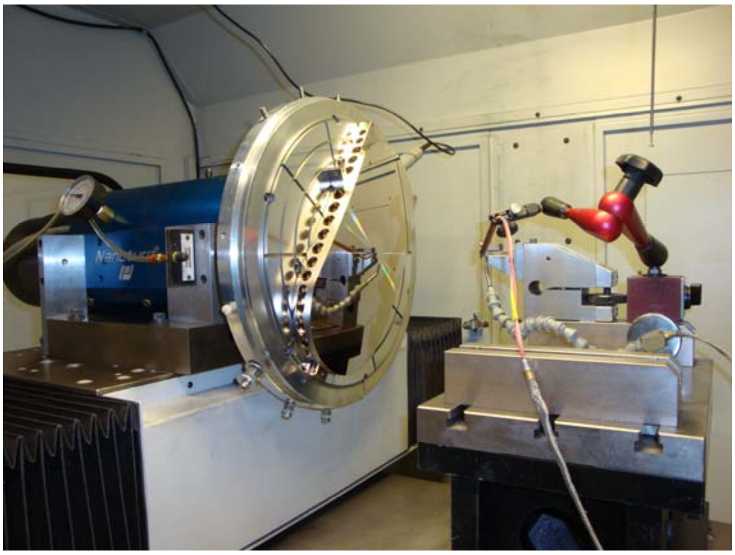

Figure 4: Diamond turning of the main mirror

2. STATE OF THE ART

2.1 Athermal approaches for high quality metal mirrors

The manufacturing of metal mirrors for scientific instrumentation as well as for laser applications is a domain of diamond turning. Besides the traditional single point diamond turning a couple of sophisticated cutting techniques like servo turning, raster fly cutting or diamond milling have been developed during the last decade [3]. Due to the various machine kinematics and CNC controlled relative motion between tool and work piece spheres, aspheres, off-axis segments and freeforms can be realized. The preferred material for athermal designs are aluminium alloys like the space qualified Aluminium 6061. As an example, figure 5 shows a near infrared camera optics based on an Offner design. Using an aspherical mirror, diffraction-limited performance could be reached at the spectral region of 900 nm – 2500 nm.

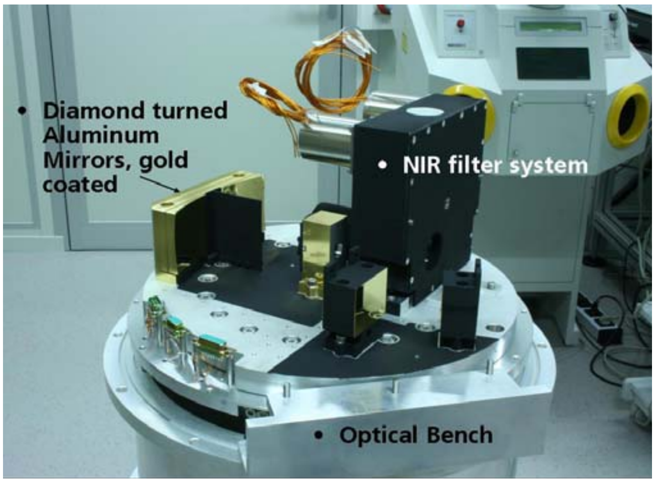

Figure 5: Near infrared optics for the Skinakas-Observatory, developed at Fraunhofer IOF Jena

For a significant number of reflective metal optics, especially at the infrared wavelength, the diamond machined surfaces show a sufficient quality. A typical specification which can be obtained in terms of figure deviations is 350 nm p-v @ (100 mm) ^{2} and a micro roughness of less than 5 nm rms. The micro roughness is limited by the aluminium crystal structure and the so called kinematic roughness which represents the tool marks [4]. These are influenced by feed, tool geometry, spindle runout and machine vibrations and lead to periodic surface artefacts. For the visual wavelength, the turning marks cause diffraction effects, and scattered light becomes more and more a problem. To overcome this limitation, a substrate coated with an amorphous electroless nickel layer is favorable. By polishing the layer with common polishing techniques and zonal polishing methods (ion beam figuring), micro roughness and figure deviation can be significantly reduced (figure 6). Figure deviations below 100 nm p-v @ (100 mm²) and micro roughness < 1 nm rms are state of the art. Due to the amorphous and highly homogeneous structure without grains and local hardness gradients, electroless nickel opens up applications that were previously reserved for glass or ceramic mirrors.

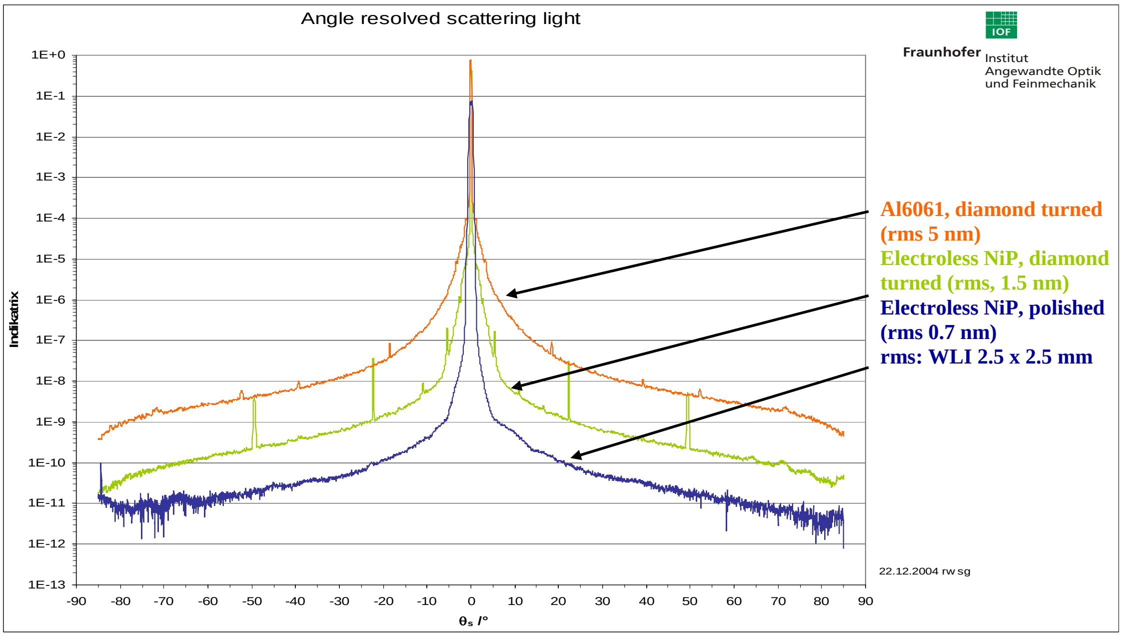

Figure 6: Angle resolved scattering light of diamond turned vs. polished surfaces

The superior quality of telescope optics using this manufacturing process was demonstrated to be reproducible [5, 6]. Looking for high quality metal mirrors, the behaviour under thermal load remains the main issue. In principle there are two possibilities: direct polishing of aluminium surfaces [7] or matching the CTE of the mirror substrate to the polishing layer. The first approach has to consider the ductile and anisotropic behaviour of the crystalline material which increases the risk of producing scratches and scattering light. Another challenge to aluminium surfaces is the need of deterministic local correction methods. For the second approach, substrate materials such as pure beryllium, metal matrix composites (e.g. silicon carbide reinforced aluminium) or powder-metallurgical processed alloys (aluminium-beryllium system [8], aluminium-silicon system) are of interest. Considering the physical properties, machinability, availability and the possibilities for tailoring the CTE, the aluminium-silicon materials have a promising potential.

3. MATERIALS

3.1 CTE measurements

The sample materials of both, aluminium substrate and electroless nickel layer were measured with the Low-Temperature Dilatomater NETZSCH DIL 402 C, which allows measurements of the thermal expansion down to the cryogenic temperature range. The horizontal design with motorized pushrod and moveable furnace makes it possible to place samples in the recess of the tube-type sample carrier. A thermocouple in direct proximity to the sample yields reproducible temperature measurement.

Typical test conditions for low-temperature measurements were applied as follow:

- Testing temperature -180 to 100°C
- Heating rate 1 K/min
- Test chamber filled with helium
- Load (horizontal) 30 cN

For the measurement in a dilatometer, a suitable geometry of electroless nickel samples is required. A cylinder of aluminium is coated with 0.3 mm electroless nickel. Afterwards, the core is milled out and the rest of the aluminium in the inside of the tube is etched out with sodium hydroxide.

The calibration was conducted with a fused silica standard depending on the sample type: while coating samples of NiP in a shape of a tube (OD = 6 mm, ID = 5 mm, L = 12 mm) required a calibration standard of 10 mm length, the substrate specimens of a cylindrical shape (D = 6 mm, L = 20 mm) were calibrated with a standard of 25 mm length.

Before starting a measurement, one heating cycle had been carried out to evaporate possibly entered condensation water caused by the cooling process. Additionally, all measurements were subjected to a repetition cycle directly after completion to control avoidable relaxation effects of the test sample.

The CTE was calculated from the thermal linear expansion data using NETZSCH Proteus software [9, 10].

3.2 Mirror substrate material: expansion controlled aluminium alloys

By changing the alloy composition of the aluminium-silicon system [11], the CTE of the substrate material can be adjusted to a couple of technical relevant materials like steel, glass, titanium or electroless nickel. Commercially available are alloys containing between 20 and 87 wt % silicon (figure 7). By raising the silicon content, the physical properties density and thermal expansion decrease while the specific stiffness increases. Due to a powder-metallurgical production process like spray deposition or melt spinning, the rapidly solidified aluminium alloy becomes fine grained, homogeneous and isotropic (see figure 8). CNC machining techniques like turning and milling can be applied. These are ideal preconditions for opto-mechanical requirements such as: extreme light weight, athermal design, low-stress mounting techniques, as well as the machining of defined reference structures.

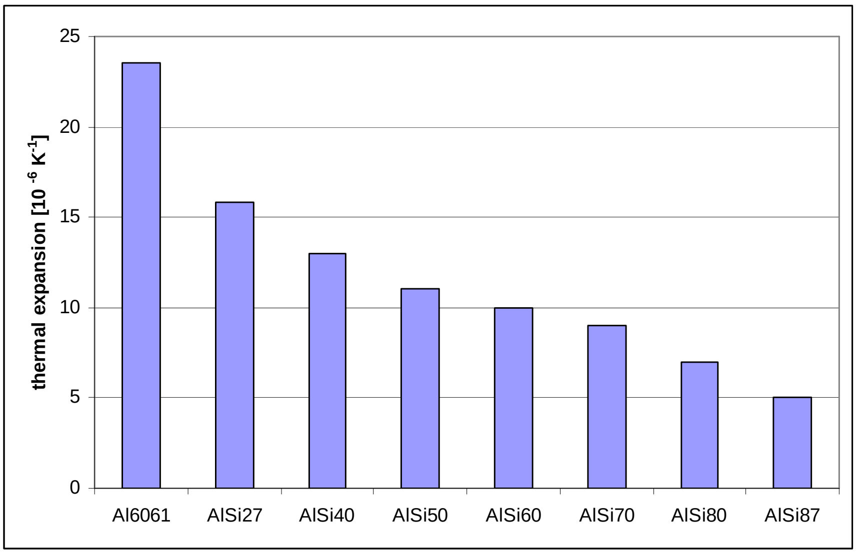

Figure 7: Changing the CTE by different silicon content (20°C)

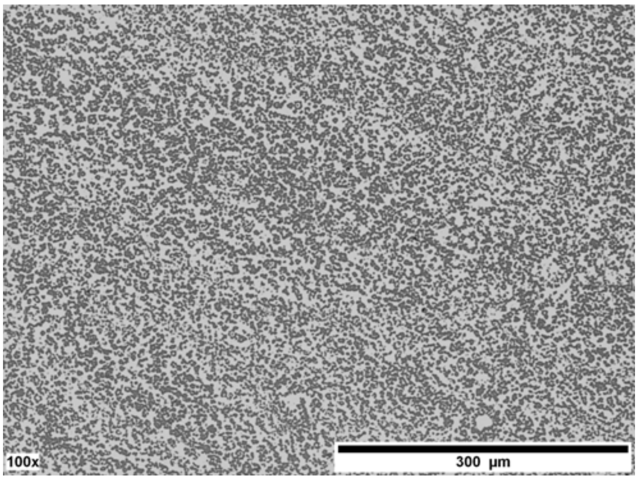

Figure 8: Cross-section at 100X magnification of an aluminium-silicon alloy with a chemical composition of about 40 wt % Si and 60 wt % Al

Looking at the large CTE-mismatch between the common mirror substrate, Al6061 and electroless nickel of about $10*10^{-6}\,K^{-1}$, the benefit of an expansion controlled alloy with a silicon content of about 40 wt % becomes obvious. In this case, the CTE-mismatch can be easily reduced to < $1*10^{-6}\,K^{-1}$. Nevertheless, applications with a strong difference in temperature like cryogenic instruments need a CTE-tuning less than $0.5*10^{-6}\,K^{-1}$. Figure 9 shows the influence of a slightly different silicon content of the CTE as a function of temperature. At the examined temperature range -180 °C – 100 °C a difference of 2 wt % silicon leads to a CTE change of $0.5*10^{-6}\,K^{-1}$. State of the art powder-metallurgical processing permits the production and a verification of the alloying elements with less than 0.5 wt %. This allows for adjusting the thermal expansion of the mirror substrate material at a certain temperature at a $0.1*10^{-6}\,K^{-1}$ level. The CTE curves for different silicon concentrations show almost the same gradient. Consequently, the CTE can definitely be adjusted to electroless nickel with a certain phosphorous content in a relatively small temperature range (some 10 K). For a wide temperature range the stress introduced by different CTE as well as different CTE gradients have to be considered.

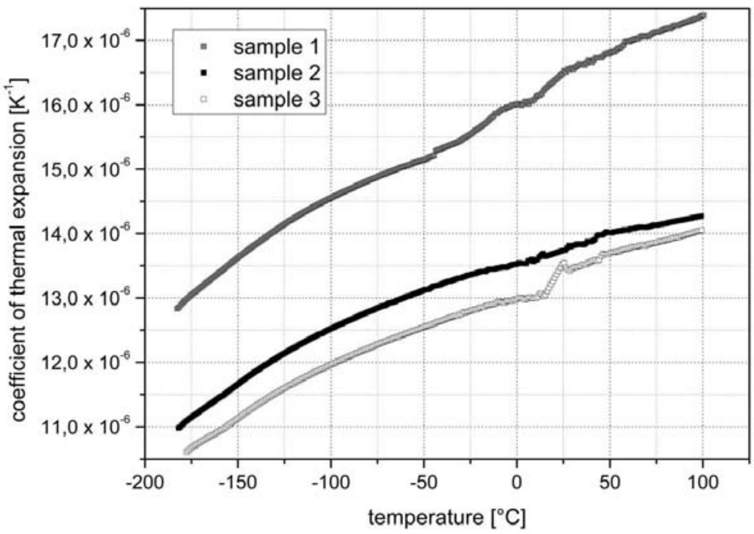

Figure 9: CTE measurement of three AlSi samples with different silicon-content

3.3 Polishing layer: electroless nickel

Electroless nickel, a nickel-phosphor alloy, can be coated on aluminium-silicon alloys by an electrochemical deposition process. For a homogenous layer composition, the nickel content, the pH-value and the bath temperature of the electrolyte have to be constant during the deposition process. Therefore, the temperature, nickel content and the pH-value are monitored and controlled in situ. By keeping the bath temperature and the nickel content constant, different pH-values lead to different phosphor contents in the alloy. The phosphor content is the most significant parameter for tailoring the mechanical and thermal properties of electroless nickel. With a phosphor content over 10.5 wt % it becomes amorphous and isotropic. The phosphor content influences the CTE as well. By raising the phosphor content, the CTE decreases [12]. Figure 10 shows the coefficient of thermal expansion from -180 °C up to 100 °C for a phosphor content of 11.5 wt %. Increasing or decreasing the percentage of phosphor shifts the curve basically parallel. Because of strong tool wear during diamond turning of electroless nickel with less than 10.5 wt % phosphor and electrochemical process restrictions, the potential range is limited to 10.5 to 14 wt % phosphor [13].

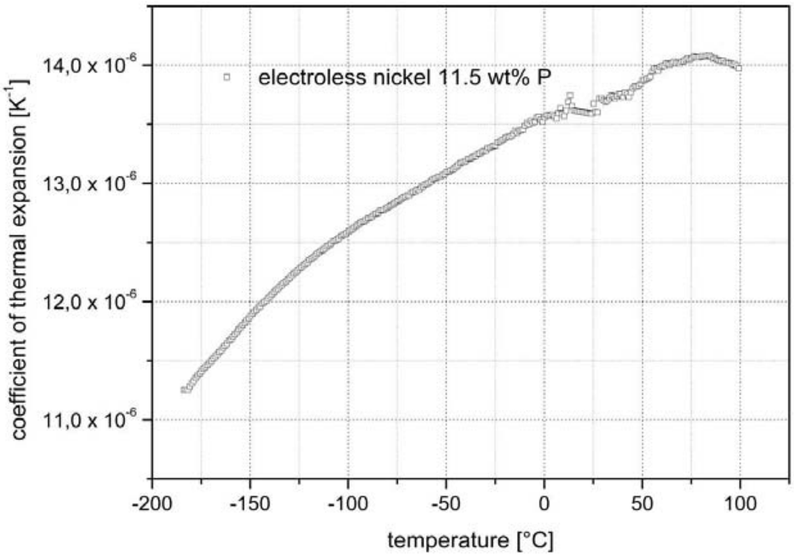

Figure 10: CTE Measurement an electroless nickel tube

The impact of the stoichiometric composition of the thermal expansion behaviour has to be considered carefully. In any case, a highly reproducible layer deposition is mandatory. Nevertheless, a phosphor content (ph-value) controlled process offers a further possibility to match the CTE of the polishing layer to the mirror substrate material.

3.4 Tuning the CTE mismatch for different applications

Figure 11 shows the idealised CTE graphs for an aluminium-silicon mirror substrate and a high phosphorous electroless nickel layer. The two materials have different gradients with one intersection point. For applications working close to the manufacturing temperature the intersection point should be ideally in the middle of the operation temperature range. In this case, the CTE values for both, the substrate material and the polishing layer, are widely similar and the surface form deviation caused by the bimetallic effect is quite small. Present investigations shows that in a temperature range between -40 °C and +40 °C a CTE equalisation of less than $0.2*10^{-6}$ K^{-1} can be certainly realized for the supposed mirror configuration.

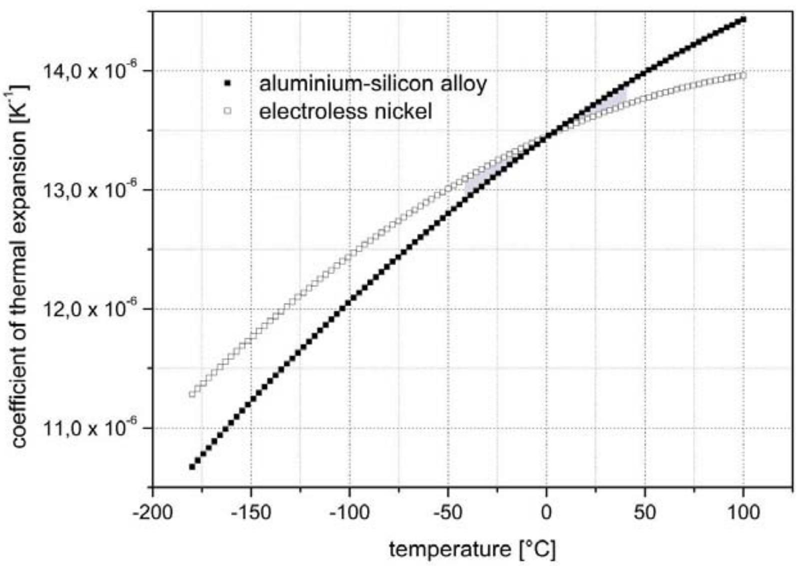

Figure 11: Idealised CTE of aluminium-silicon alloy and electroless nickel for terrestrial applications

Looking at cryogenic applications the above mentioned aspects must be pointed out. For this utilization, the intersection point should be ideally placed as shown in Figure 12. Starting at the manufacturing temperature, stress accumulates until the intersection point and relieves towards the operation temperature. Therefore, adjusting the areas between the CTE curves of the substrate and the polishing layer is one main issue for tailoring the CTE for cryogenic optics.

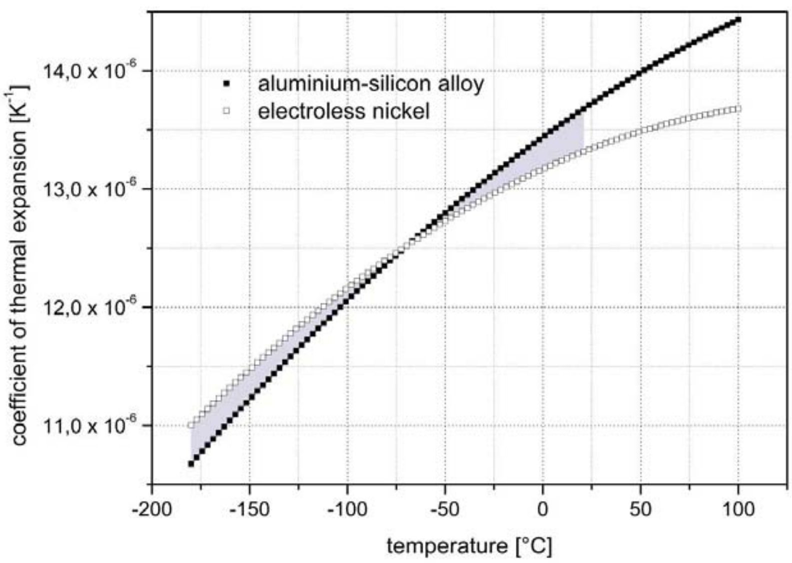

Figure 12: Idealised CTE of aluminium-silicon alloy and electroless nickel for cryogenic applications

Running investigations demonstrate the possibility of a systematic CTE manipulation. Figure 13 illustrates this by means of a selected example.

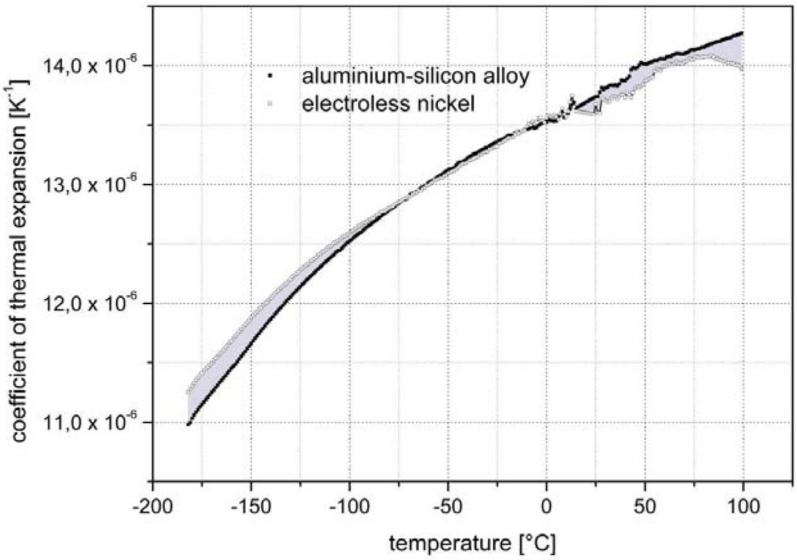

Figure 13: Measured CTE curves of a matched material-composition

4. INTERFEROMETRIC TESTS

The athermal concepts of cryogenic optics with minimal bimetallic deformation will be proven for feasibility and applicability in suitable interferometrical studies. The proposed configuration for alloy composite mirror samples in a maximum diameter of 150 mm constitutes two alternatives for testing: a climatic test chamber CTS T-70/1500 [14] for a temperature range of room temperature to -70°C (a) and a test cryostat for cryogenic temperature environment at -180°C (b). With a FISBA µPhase Interferometer [15] mounted on an optical table both test units can be observed, as shown in figure 14.

(a) Climatic test chamber setup:

The climatic test chamber not only allows for the set up of a specific temperature environment but also for driving gradual temperature changes with a precision of ± 0.1 K. Inside the test chamber, the mirror samples are positioned in a prism mount solely by its dead weight and without exposing mechanical distress by additional clamp-mounting. The post, holding the prism mount itself, is fixed on a carbon fiber breadboard [16] thus avoiding thermal distortion caused by temperature gradient. Although particular attention is paid to the interferometer by inspecting the samples through a window port from outside, the SSD-mode (Static-Synchronous-Detection) at the interferometer must be used, so that the interferometer set up can resist vibrations.

(b) Test cryostat setup:

Optical measurements under cryogenic conditions are realized by means of a liquid nitrogen cooled bath-cryostat [17]. A temperature stability of < 0.1 K can be achieved over a reasonable time. By turning the interferometer in axial direction to the cryostat mirror samples can be measured through a front-side fused silica window. Since the cryostat is mounted on the same bench as the interferometer, phase sampling mode can be used to measure the surface deviation, which guarantees an adequate performance of the system as a whole.

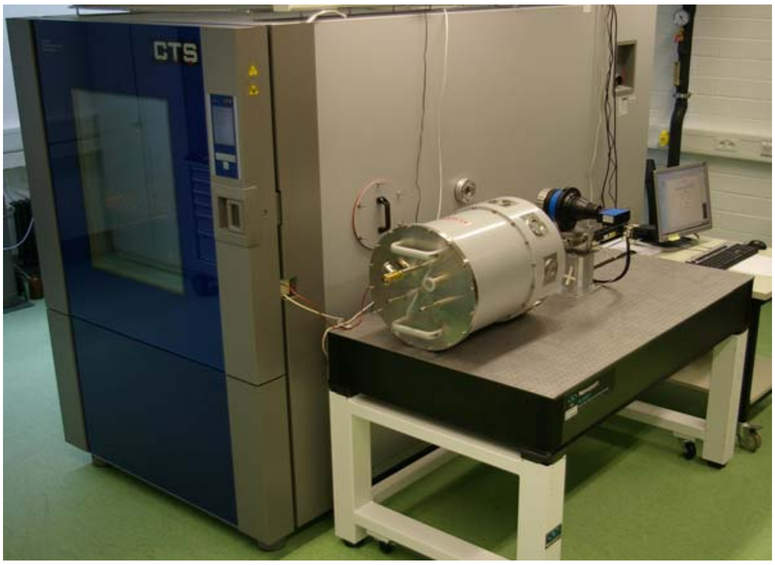

Figure 14: Interferometric test setup composed of the climatic test chamber T70/1500 next to an optical table top assembled with the test cryostat and the FISBA µPhase 2HR interferometer

5. FUTURE PROJECTS

5.1 METIS Imager

The mid-infrared imager and spectrograph “METIS” will be one of the first instruments for the E-ELT. The instrument covers the wavelength range from 3 – 14 µm. Figure 14 shows a study (phase A) for the imager [14].

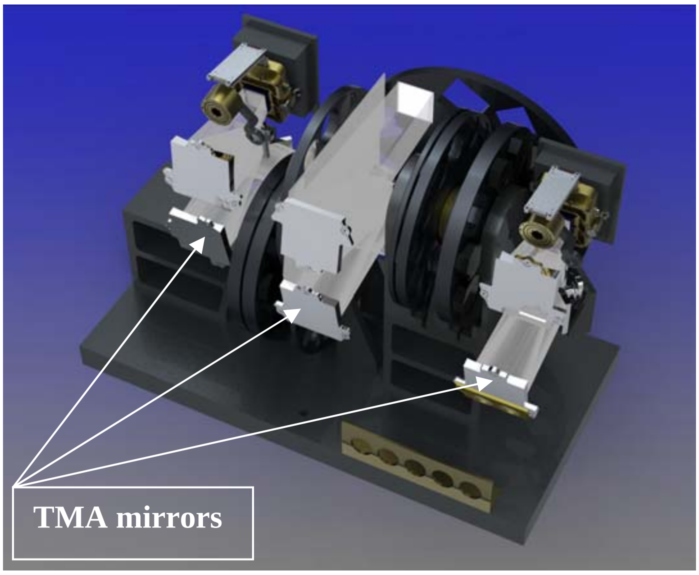

Figure 15: METIS imager with TMA mirrors (maximum mirror size: 100 x 120 mm)

The optical design for collimator and camera is based on aspheric TMA mirrors. Therefore, the imager will be diffraction limited all over the required wavelength range. The surface error of all mirrors should be less than 27 nm rms and the accepted stray light limits the surface roughness to 10 nm rms. These values are hard to achieve with the common diamond turning manufacturing techniques for aspheric metal mirrors. Therefore, MPIA Heidelberg and IOF Jena have planned to build and test prototype METIS mirrors based on the new technique described. Figure 15 shows the planned prototype METIS TMA mounted on the cold plate inside the test cryostat (LN_2). The mechanical mirror design is based on manufacturing and alignment issues. All mirrors are designed with reference structures representing a tight relation to the optical surface. The references will be used during manufacturing, measurement, assembly and system alignment. To avoid figure distortion due to mounting forces the optical area of the mirrors are decoupled from the mounting structure. Finite element simulations in respect to gravity and bimetallic deformation will be carried out. The TMA setup will be initially aligned and characterized at normal temperature and pressure followed by a cryogenic test and characterisation.

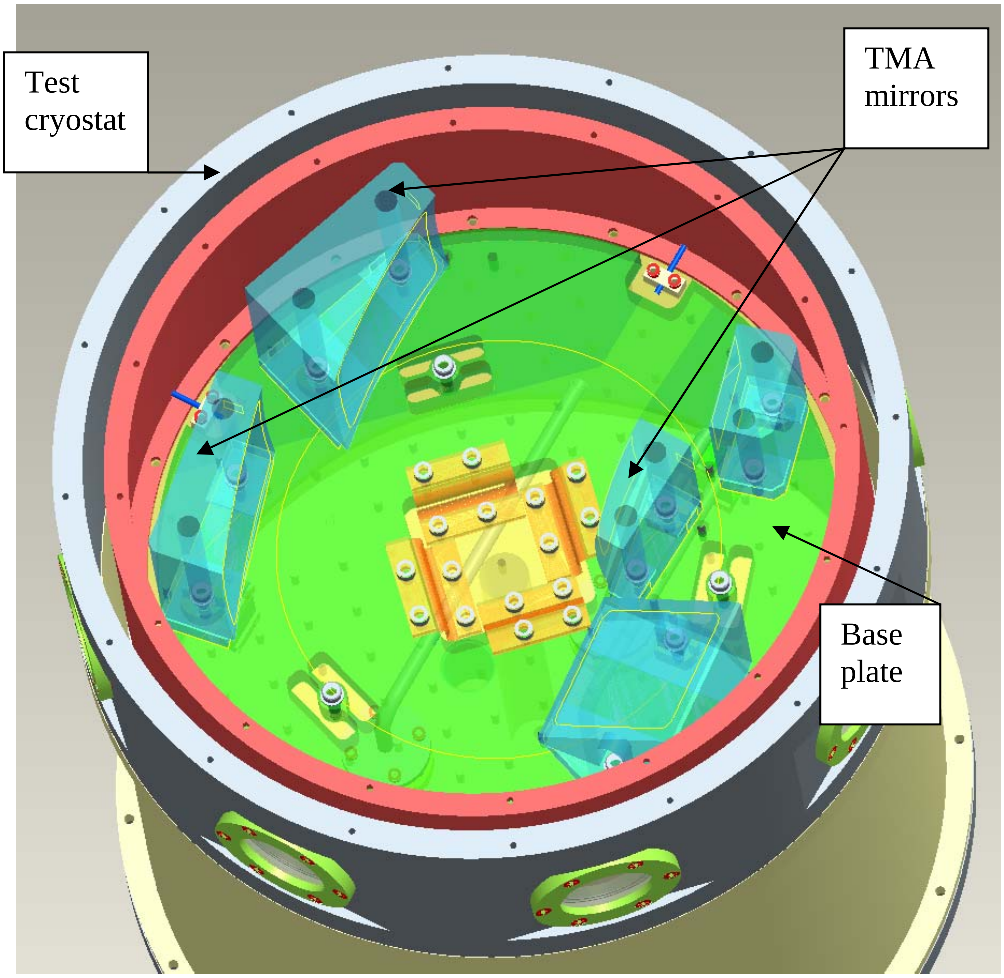

Figure 16: METIS prototype TMA mounted in the test cryostat

5.2 GRAVITY K-Mirror

GRAVITY will be a new interferometric adaptive optics assisted near-infrared VLTI instrument [19]. The wavefront sensors (located inside the VLT Coudé labs) use a K-mirror system for image derotation at ambient temperatures. It is intended to build the mirror system from AlSi (see figure 16) which simplifies the interface to the rotation stage considerably.

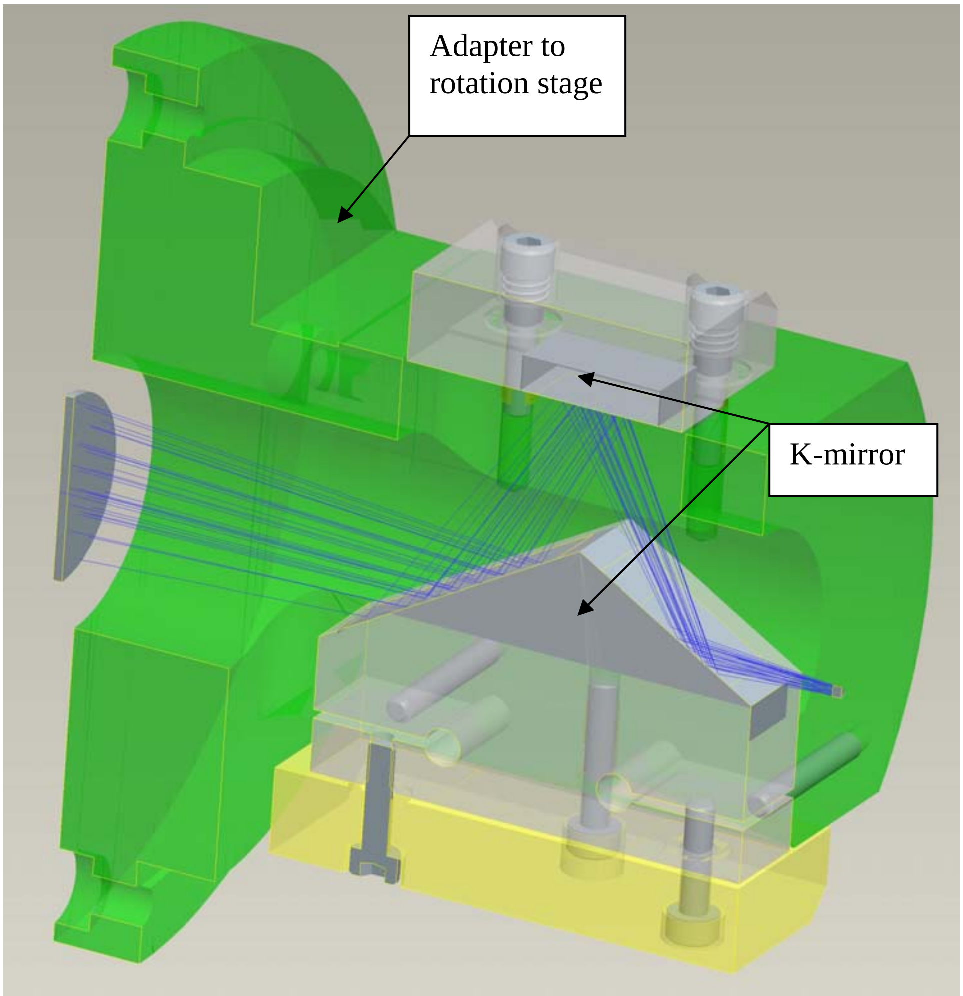

Figure 17: Image derotator (K-mirror) for GRAVITY wavefront sensor

6. SUMMARY

We have described a new material combination for metallic mirrors consisting of tuned aluminium-silicon alloys and NiP layers for different working temperatures. The material combination minimizes the known bimetallic effect of NiP plated metallic mirrors and will open new ways for the design of cryogenic optics and their mounting structures for infrared astronomical cameras. Additionally, the higher Young's modulus of AlSi compared to Al6061 has more potential for stiffer and more lightweighted structures. That fact is especially interesting for fast moving optics.

7. REFERENCES

[1] Herbst, T. et al., “Imaging beyond the fringe: an update on the LINC-NIRVANA Fizeau interferometer for the LBT,“ Proc. SPIE 7734-6, (2010).

[2] http://www.dlr.de/rd/desktopdefault.aspx/tabid-2440/3586_read-10140/

[3] Steinkopf, R. et al., “Metal Mirrors with Excellent Figure and Roughness,” Proc. SPIE 7102-12, (2008).

[4] Gubbels, G. et al., “Rapidly solidified aluminium for optical applications,” Proc. SPIE 7018, (2008).

[5] Risse, S. et al., “Novel TMA telescope based on ultra precise metal mirrors,” Proc. SPIE 7010-41, (2008).

[6] Sweeney, M.N., “Advanced Manufacturing Technologies for Light-Weight; Post Polished; Snap-Together Reflective Optical System Designs,” Proc. SPIE 4771-17, 144-154 (2002).

[7] Rikter, H. et al., “Directly Polished Light Weight Aluminium Mirror,” Proc. SPIE 7018-3, (2008).

[8] Parsonage, T., “New technologies for optical systems utilizing aluminium beryllium,” Proc. SPIE 7018-23, (2008).

[9] NETZSCH Gerätebau GmbH, Wittelsbacher Str. 42, D-95100 Selb, www.netzsch-thermal-analysis.com.

[10] NETZSCH Proteus Software: Analysis, Version 5.1.0 (2009).

[11] Murray, J.L. et al., “The Al-Si (Aluminium-Silicon) System”, Bulletin of Alloy Phase Diagrams, Vol. 5, No. 11984.

[12] Hibbard, “Electrochemically deposited nickel alloys with controlled thermal expansion for optical applications,” Proc. SPIE 2542, (1995).

[13] Dini, “Perspective on Plating for Precision Finishing,” Plating & Surface Finishing, Vol. 79, (1992).

[14] T-70/1500, CTS GmbH, Lotzenäcker 21, D-72379 Hechingen.

[15] µPhase 2HR Digital Compact Interferometer, FISBA OPTIK AG, Rorschacherstr. 268, CH-9016 St.Gallen.

[16] Carbon Fiber Breadboard CA – Series, www.carbonvision.de.

[17] Bath-cryostat, CryoVac GmbH & Co KG, Heuserweg 14, D-53842 Troisdorf.

[18] Lenzen, R. et al., “METIS: System engineering and optical design of the mid-infrared E-ELT instrument,” Proc. SPIE 7735-283, (2010).

[19] Eisenhauer, F. et al., “GRAVITY: Microarcsecond Astrometry and Deep Interferometric Imaging with the VLT,” Astrophysics and Space Science Proceedings, p. 361 (2009).