DYNAMIC AND PRECISE PIEZO TIP-TILT PLATFORMS WITH SILICON CARBIDE MIRRORS FOR COMPACT OPTICAL INSTRUMENTATIONS IN HARSH ENVIRONMENTS

By Joachim Hengst and Thomas Maillard

For decades, mirrors moved with piezo-ceramic actuators have met expectations for extremely high precision standards & excellent reliability in laboratory applications. Outside the lab, in reconnaissance or aerospace applications, it is a different story. Environmental conditions, that the equipment is exposed to, are generally “not favorable”, an euphemism for “extremely harsh”, considering the tailored performance, precision and reliability. In space applications, from satellite setup and integration to the orbital operation through the launch process, the devices have to survive without damage acceleration, vibrations and shock in thin air or vacuum, surrounded by moisture and corrosive gases, large and quick temperature changes and cosmic rays. Under those conditions the ability to measure and transfer correct data is absolutely critical. Laser beams have to be deflected and steered, performance and survival of the airborne apparatus depends on their precision and long lifetime, without maintenance.

The piezoelectric effect is frequently used in many products, for instance lighters, loudspeakers and signal transducers. Piezoceramic-based actuators use the inverse piezoelectric effect, which causes certain ceramics to deform when an electric field is applied. Preloaded Piezo Actuators from Cedrat Technologies (CTEC), France, are designed with a patented frame which protects the piezo ceramic from tensile stresses and improves its dynamic performance at least by a factor of 2 to 10, depending on the optical payload nature and configuration. “Compact” means low mass, low volume and low power. “Dynamic” means both the ability to provide a short settling time during orbital operation, as well as the capability to withstand and to survive vibrations and shocks during launching conditions. “Precise” means an outstanding below 1µrad (micro-radian) angular resolution (1 mm over 1 km distance), accuracy and stability in pointing the mirror. Scanning, refocusing, pointing and optical path adjustments require different levels of precision in various applications and, of course, mirror accelerations. Whatever the dynamic specifications are for given optical properties (aperture, flatness, reflectivity, etc.), piezo tip-tilt platforms will always require and benefit from a light-weight solution in terms of optical payload, i.e. mirror technology. Micro Satellites are on their way to becoming mass-produced items, and therefore the footprint and power consumption have to be minimized.

Inherent requirements for a tip-tilt platform with a mirror are the following:

- Low weight, low moment of inertia, high stiffness and high resonance frequency to resist shock and vibration
- Good thermal conductivity and low heat capacitance are needed to resist fast- and long-term extreme temperature changes (from 4°K to temperatures up to 400°K)
- Gases and moisture compatibility to resist corrosion, vacuum compatibility
- Manufacturability, SiC can be tailored into complex and stiff shapes with a low weight by a supporting rib structure and with a fine optical surface polish machined directly into the bulk material, without any cracks or delamination (no sandwich-effect: generated by the differences of the CTE-coefficients of those stacked claddings).

There is virtually no delay between the application of an electric field and the volume change of the piezo ceramic. What keeps the mirror from immediately changing its position is the moment of inertia (MoI), which is determined by its weight and shape. To reach extreme acceleration and an optimized dynamic behaviour, weight and mass moment of inertia of the finished mirror, including the mirror fittings, need to be as low as possible.

When mirror materials like glass are compared to ceramic silicon carbide (SiC) mirrors, SiC offers a number of advantages:

- SiC has a higher thermal stability and a higher specific stiffness, paired with the highest resistance to corrosive agents retaining its high hardness
- Glass, fused Silica and glass ceramics do not reach the thermal requirements, SiC has a thermal conductivity which is roughly ten times higher.

The conclusion is that “glassy solutions” (glass, fused silica and similar) are not recommended for such more demanding applications.

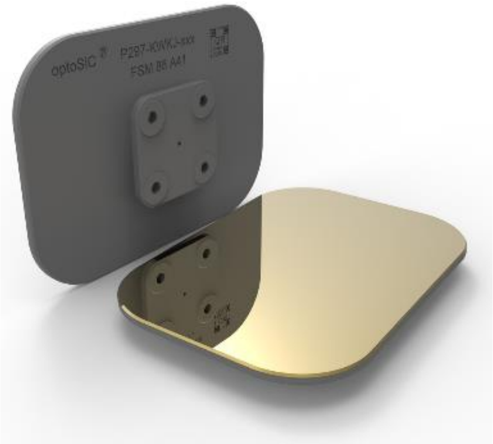


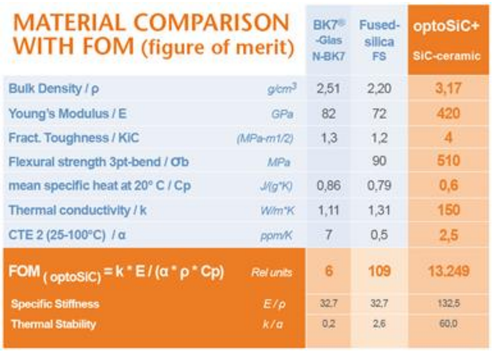
Figure 1: Optional a small mounting foot with large mirror facesheet "table-shaped-mirror"

QUALITATIVE COMPARISON OF THE MATERIAL PROPERTIES

To present the different material properties in a clear manner, that allows a quick assessment of substrate suitability for dynamic mirror applications with simultaneous temperature changes, a FOM index (figure of merit) was established.

$$FOM_{(optoSiC)} = k\frac{E}{\alpha \times \rho \times C_p}$$

It combines the material properties thermal conductivity k, specific heat capacity C_p, density, modulus of elasticity E, and thermal coefficient of expansion α as shown in the table below. It shows the resulting FOM index numbers of materials in relation to their specific stiffness. The higher the value, the better its suitability for the application. optoSiC® is a product brand for finished optical components like mirrors of the optoSiC division in München/ Germany a branch of the France Mersen group.



MATERIAL COMPARISON WITH FOM (figure of merit)		BK7®-Glas N-BK7	Fused-silica FS	optoSiC+ SiC-ceramic
Bulk Density / ρ	g/cm^3	2,51	2,20	3,17
Young's Modulus / E	GPa	82	72	420
Fract. Toughness / KIC	(MPa-m1/2)	1,3	1,2	4
Flexural strength 3pt-bend / σb	MPa		90	510
mean specific heat at 20° C / Cp	J/(g*K)	0,86	0,79	0,6
Thermal conductivity / k	W/m*K	1,11	1,31	150
CTE 2 (25-100°C) / α	ppm/K	7	0,5	2,5
$FOM_{(optoSiC)} = k * E / (\alpha * \rho * Cp)$	Rel units	6	109	13.249
Specific Stiffness	E / ρ	32,7	32,7	132,5
Thermal Stability	k / α	0,2	2,6	60,0

Figure 2

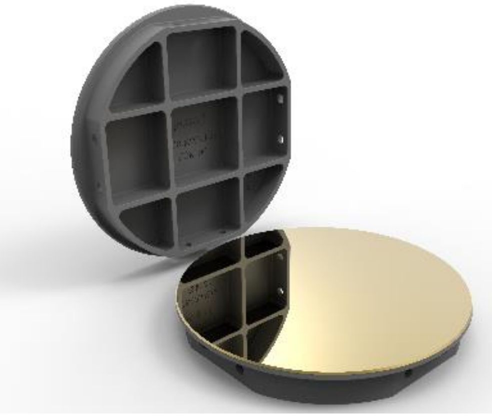


Figure 3

The calculated figure of merit

$$FOM_{(optoSiC)} = \frac{specific\ stiffness \times thermal\ stability}{specific\ heat}$$

for optoSiC-material is more than 120 times as high as the FOM of the other glassy options.

ASTRONOMICAL INFRARED IMAGING SATELLITE PROJECT

In accordance with a space mission requirement, a given IR imaging instrument, for instance, needs a tip-tilt mirror with 130 mm diameter to scan the required field of view. The designed tip-tilt platform is based on 4 piezo actuators driven in "push-pull" mode to steer a rib design optoSiC mirror of 145 grams s. Figure 4. The main characteristics of this platform are given in the table below:

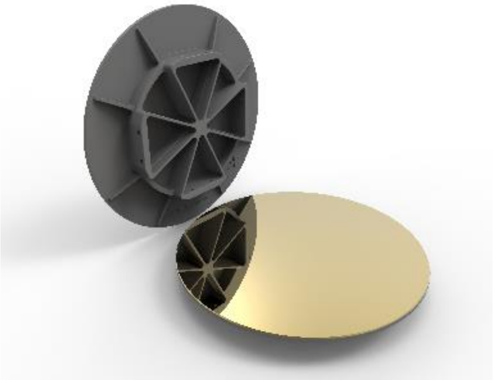


Figure 4

Angular stroke Rx & Ry	> +/- 0.25 mrad from 0 to 80 V
Loaded resonance frequency with 145 g & 130 mm diameter	> 1.5 kHz
System dimensions	< 130×130×130 mm
Optical center to rotation axis	< 30 mm
Shock resistance	800 G (1 G = 9.81 m/s^2) from 800 Hz to 4.0 kHz
Random vibration	7.48 G rms from 20 Hz - 2.0 kHz

Rib designs have been demonstrated to be best for a low center of gravity (CoG) and the optical tilting point of reflection (tip-tilt) is very close to the mechanical rotation center, so the beam displacement can be reduced.

The rib design also provides the best mechanical force transfer into a flexured-mount device (flexure pivot) as a metallic connection to the actuator.

An equivalent glass mirror in terms of optical aperture and properties would roughly multiply the moment of inertia by at least a factor of 5 and would disqualify the platform for the application.

Figure 5 shows the FEM-simulations of the stress analysis for the platform with a SiC mirror submitted to 800 G in transverse direction, which is the worst-case shock scenario.

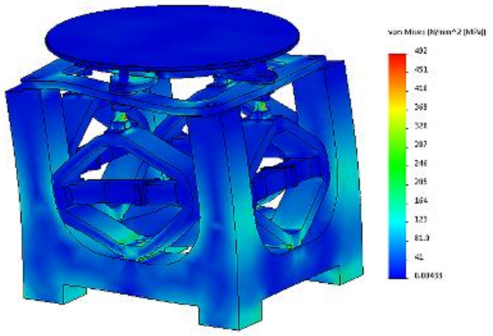


Figure 5: Simulation of stresses in the platform during a 800 G shock as specified in table of Figure 4

Figure 6: Piezo tip-tilt platform with 130 mm diameter light weighted rib structured HR-coated mirror

FREE SPACE OPTICS

These are often used for laser communication applications with a high data transfer rate and wide bandwidth on different platforms for long distances like satellite to satellite, or satellite to ground, and even for deep space communication.

All those point-to-point connection links require extremely high accuracy at increased resonance frequencies and quick beam corrections over long distances with very good pointing stability.

For pointing mechanisms on the ground and in low orbit, voice coils and magnetic actuators are typically used today, but cannot be utilized for Deep Space Applications. More precise and recent designs present higher challenges with tighter specifications in high orbits. Also, the power consumption of the actuator should be minimized to reduce overall module-system weight. This is only feasible, if the moving mirror mass is low.

For this application s. Figure 5, the mirror aperture is in the 30 mm range which is much smaller than the previous application. At the piezo tip-tilt-platform level, the key design issue is to reduce the size of the platform close to the mirror diameter while maintaining a short settling time in order to position the mirror accurately. The short settling time depends both on the mechanical stiffness and on the electrical capacitance of each axis. Using a smaller actuator with a small capacitance will reduce the size of the platform and its power consumption to move fast. Smaller platforms, however, do have a lower stiffness and their settling time is very sensitive to mirror inertia. Once again, thanks to its low inertia capability, the SiC mirror technology will solve the issue and allow the trade-off between low consumption and fast actuation for the platform. The inherent high resolution of the piezo actuator fulfills the demanded positioning accuracy.

Since they can be slim and of low weight, this leads to high stiffness and short response time. Consequently, two birds are killed with one stone.

Figure 7: DTT35XS-SV11

Scan angle (range)	≥ ± 2,5 mrad (mechanical)
Closed-loop bandwidth	≥ 1,0 kHz (for ± 0,05 mrad)
Closed-loop resolution	≤ 0,1 µrad
Position feedback-sensor	Strain Gauge sensor
Vacuum compatibility	≤ 10-6 mbar
Operating temperature	-15°C to +70°C
Vibration and shock external	30 G rms (random vibration), 100 G, 11 ms half-sine shock

CONCLUSION

The resulting piezo steering mirror's mechanism provides the finest resolution while surviving and operating in demanding environmental conditions from the ground into space. These outstanding performances have been reached, thanks to a partnership between a German and a French company creating a system design of all intermediate parts, for instance in opto-mechanical performance the cardanic joint, flexure pivots and a precision mirror with its mechanical connection between the piezo actuators and the ceramic mirror itself. A good example where co-design helps to go beyond current limitations.

AUTHORS

Joachim HENGST,
MERSEN Deutschland Holding GmbH & Co. KG
Niederlassung München
Produktbereich optoSiC
Industrial laser optics and components
Rupert-Mayer-Straße 44
D-81379 München / Germany
www.optosic.com/material-en.html

Thomas MAILLARD
CEDRAT TECHNOLOGIES S.A.
59 Chemin du Vieux Chêne
Inovallée
38246 MEYLAN Cedex FRANCE
www.cedrat-technologies.com/products/actuators