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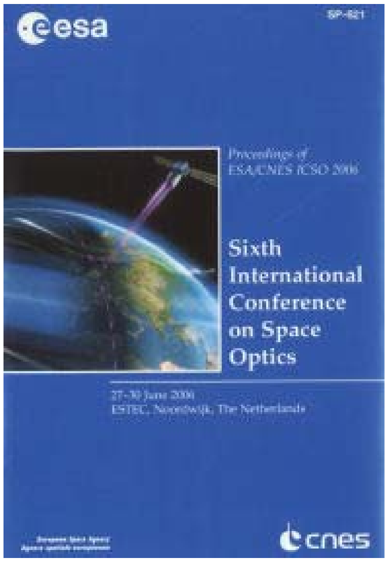

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MOEMS DEVICES FOR FUTURE ASTRONOMICAL INSTRUMENTATION IN SPACE

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ABSTRACT

Based on the micro-electronics fabrication process, Micro-Opto-Electro-Mechanical Systems (MOEMS) are under study in order to be integrated in next-generation astronomical instruments for ground-based and space telescopes. Their main advantages are their compactness, scalability, specific task customization using elementary building blocks, and remote control. At Laboratoire d'Astrophysique de Marseille, we are engaged since several years in the design, realization and characterization of programmable slit masks for multi-object spectroscopy and micro-deformable mirrors for wavefront correction. First prototypes have been developed and show results matching with the requirements.

1. INTRODUCTION

Micro-Opto-Electro-Mechanical Systems (MOEMS) are based on the micro-electronics fabrication process. They are designed for a wide range of applications like sensors, switches, micro-shutters, beam deflectors, and micro-deformable mirrors. The main advantages of micro-optical components are their compactness, scalability, and specific task customization using elementary building blocks. As these systems are easily replicable, the price of the components is decreasing dramatically when their number is increasing. They will be widely integrated in next-generation astronomical instruments, especially for space missions, as they allow remote control.

MOEMS have not yet been used in space astronomy, but this technology will provide the key to small, low-cost, light, and scientifically efficient instruments, and allow impressive breakthroughs in tomorrow's observational astronomy.

The NASA's Origin Program and equivalent programs in Europe bring into fashion what astronomy always wanted to do, explaining where we are coming from by studying the formation of the galaxies and their evolution, as well as the formation and evolution of the planets around nearby stars.

The following gives two applications of MOEMS in observational astronomy:

1) Programmable Multi-Object Spectroscopy masks

Thanks to its multiplexing capabilities, Multi-Object Spectroscopy (MOS) is becoming the central method to study large numbers of objects. However, it is impossible to use traditional ground-based MOS in space. New methods need to be defined and technologies developed. For one of the most central astronomical program, deep spectroscopic survey of galaxies, the density of objects is low and it is necessary to probe wide fields of view. MOEMS provides a unique and powerful way of selecting the objects of interest (whatever the criteria distance, color, magnitude, etc.) within deep spectroscopic surveys. This saves time and therefore increases the scientific efficiency of observations.

2) Wave front correcting deformable mirrors

Telescopes and Instruments are designed to reach scientific performances, but space astronomy is more difficult than ground-based astronomy because of the tough launch and space conditions and harsh environment. To reach the faintest objects, we must get the best Point Spread Function (PSF) with the minimum of energy scattered within the outer areas of the PSF. Also sharp PSFs will allow to reach the best spatial resolution (limit of diffraction) and therefore to potentially resolve objects such as remote interacting building blocks in their way to become giant galaxies, star-forming regions within nearby galaxies or disks around forming planetary systems. The wave front perturbations are either residual optical aberrations in the design of the optical train of the instrument or dynamic deformation of the instrument PSF due to thermal effects on the instrument structure. MOEMS devices should enable the correction of wave front perturbation in next generation big space telescopes.

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2. PROGRAMMABLE SLIT MASKS

Major telescopes around the world are equipped with Multi-Object Spectrographs (MOS) in order to record simultaneously several hundred spectra in a single observation run. Next generation MOS for space like the Near Infrared Multi-Object Spectrograph (NIRSpec) for the James Webb Space Telescope (JWST) require a programmable multi-slit mask. Conventional masks or complex fiber-optics-based mechanisms are impracticable in space. The programmable multi-slit mask requires remote control of the multi-slit configuration in real time. A promising solution is the use of MOEMS devices such as micro-mirror arrays (MMAs) [1,2] or micro-shutter arrays (MSAs) [3]. Next generation ground-based MOS will also benefit from these developments. The typical size of these micro-elements is around 100µm, and MMAs are designed for generating reflecting slits, while MSAs generate transmissive slits. MSA has been selected to be the multi-slit device for NIRSpec and is under development at the NASA's Goddard Space Flight Center. They use a combination of magnetic effect for shutter opening, and electrostatic effect for shutter latching in the open position.

In Laboratoire d'Astrophysique de Marseille, we have developed over several years different tools for the modelling and the characterization of these MOEMS-based slit masks, during the design studies on JWST-NIRSpec. Our models, based on Fourier theory, address two key parameters for the MOS performance: spectral photometric variation (SPV) and contrast. The SPV is the unpredictable photometric variation due to the random repartition of the sources on the slit mask. The SPV requirement is generally < 10%, but as SPV is strongly dependent on the object position and wavelength, the required value cannot be reached. We have proposed a dithering strategy able to solve this problem [4]. Contrast is defined as the total amount of non-selected flux of light passing through the multi-slit device. To avoid spoiler sources (bright stars or galaxies within the instrument field of view) and background to pollute spectra, its value has to be as high as possible. According to the density of objects (stars and galaxies) in the field of view and their magnitude, a contrast requirement of 3000 has been established. We have also developed a characterization bench to measure these parameters. Contrast measurement has been carried out on the MMA fabricated by Texas Instrument [5], in order to simulate the actual MOEMS device for NIRSpec. Effective contrasts of around 500 have been measured for an ON-OFF angle of 10°; this value is exceeding 3000 when the ON-OFF angle is 20°. Effects of object position on the micro-mirrors have been revealed [6]. The effective contrast is the contrast to be considered in an instrument, i. e. the local contrast values integrated on a detector pixel size. Then, in order to reach the requirement, a tilting angle of 20° is mandatory. Additional parameters such as the size of the source, the wavelength, and the input and output pupil size have also been analysed.

Within the framework of the JRA Smart Focal Planes (part of the European FP6 Opticon program), we have engaged a collaboration with the Institut de Micro-Technologies (IMT) of University of Neuchatel (Switzerland) in order to get a first demonstrator of a European MOEMS-based slit mask. Micro-mirrors have been selected and a design has been investigated in terms of performances and feasibility. Based on our simulations and measurements, we have fixed several parameters. In a first approach we set one micromirror per astronomical object, which corresponds to the baseline for NIRSpec. It is essential for this instrument to achieve a high optical contrast of at least 3000:1. The tilted micromirror is used for the "ON" position and the rest position is considered as "OFF". Hence the amount of parasitic light can be drastically minimized that comes from reflections and scattering of the frame surrounding the micromirrors and of the underneath electrodes. A useable tilting angle must exceed 20°. The mirror surface must remain flat in operation throughout a large temperature range. In addition, all micro-mirrors must tilt by the same angle for optimising the optical design of the instrument. The fill factor of more than 90% is essential. One micromirror element has to be at least 100 x 200 µm², in order to correspond with the plate scale of 8m-class telescopes as well as future extremely large telescopes (ELT's). Preferably, the driving voltage for tilting remains below 100V. The micro mirror array has to work at cryogenic temperatures.

From these numbers, we have designed a new micro-mirror array architecture. The micro-mirrors are realized on a mirror chip and actuated electrostatically by a separate electrode chip, fabricated independently and assembled subsequently. The suspension of the mirrors is made of flexion cantilevers underneath the mirror. A clamping mechanism has also been developed in order to set a very precise ON position from micro-mirror to micro-mirror (Fig. 1). Due to the electrostatic force the mirror rotates upwards (b) until the first landing pad, which is attached to the mirror, hits the electrode (c). Then the mirror starts rotating in the inverse direction until it hits the second landing pad, which is attached to the mirror frame (d), and remains electrostatically clamped in this position. Thus the final tilting angle is mostly independent on the actuation voltage and relies merely on a homogenous spacing between the mirror and electrode chips.

A first small test array of micro-mirrors was successfully micro fabricated using a combination of bulk and surface micromachining.

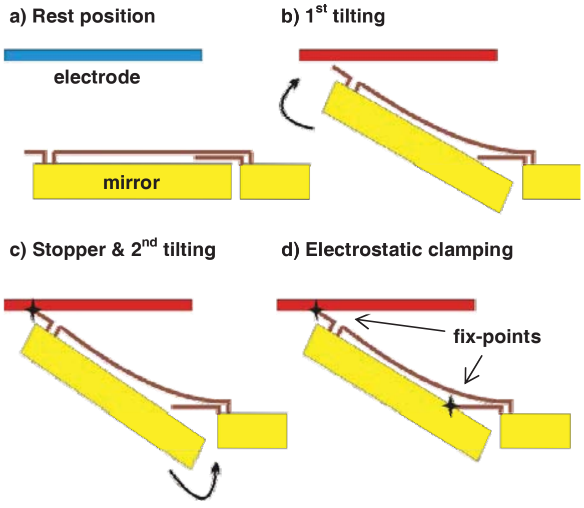

Fig. 1: Schematic view of the actuation of the mirror and electrostatic clamping mechanism

The 100 x 200 µm^2 mirrors are defined by deep reactive ion etching in the 10µm thick device layer of a silicon-on-insulator (SOI) wafer, whereas the suspension of the mirrors is defined by a patterned poly-silicon layer hidden on the backside of the mirrors (Fig. 2) [7].

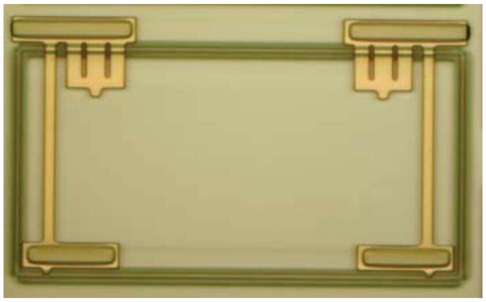

Fig. 2: Optical microscope image of the backside a microfabricated single mirror of a micromirror array. The 100 x 200 µm^2 mirror is suspended by two cantilever flex-hinges. The extra pads at the top will be used for the electrostatic clamping mechanism.

At LAM, a dedicated characterization bench has been developed for the complete analysis of MOEMS devices, actuators or micro-mirrors as well as full arrays. This modular Twyman-Green interferometer allows high in-plane resolution (4µm) or large field of view (40mm). Out-of-plane measurements are performed with phase-shifting interferometry showing very high resolution (standard deviation<1nm). Features such as optical quality or electro-mechanical behavior are extracted from these high precision three-dimensional component maps. Range is increased without loosing accuracy by using two-wavelength phase-shifting interferometry authorizing large steps measurements. Dynamic analysis like vibration mode and cut-off frequency is also measured with time-averaged interferometry [8].

Preliminary characterization is done on a first small test array of 100x200 µm^2 micro-mirrors. The surface quality of the micro-mirror is measured by phase-shifting interferometry, and a total aberration of 15 nm peak-to-valley is measured. This value, better than $\lambda/20$, is within the requirement. In the OFF position the mirrors are slightly out of the frame plane, around 1°. When an actuation voltage is applied, the mirrors began to tilt, and when a certain value below 100V is reached, the mirrors tilt completely and land on the electrode chip. Actuation voltage is dependant with the suspension design for a fixed electrostatic force. The tilt angle is around 13° due to a smaller spacer than expected between the wafers. By adjusting the spacer height, the 20° tilt angle will be reached easily in the next run.

By using our dedicated characterization, we have been able to measure the surface quality in the tilted ON position. The figure of 15nm peak-to-valley is confirmed in this position (Fig. 3).

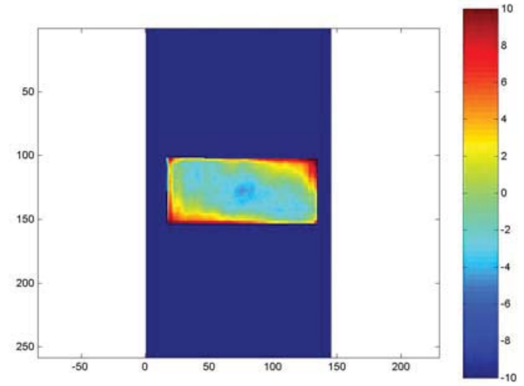

Fig. 3: Surface quality of a micromirror when actuated (ON position). The color bar is between -10nm and +10nm.

In many MOS observations, astronomers need to have the spectrum of the background nearby the studied object. For this purpose, the programmable slit mask must be able to be in a “long slit” mode where several adjacent mirrors parallel to the long side of the mirror must tilt by the same angle. Our clamping mechanism is designed in order to ensure this goal. The clamping performance has been mesured on single micro-mirrors and an angle difference of only 1 arc-minute has been obtained on our first prototype.

The programmable slit devices could be used in a wide range of MOS, both in space and in ground-based instrumentation. For ground-based MOS, they will be mostly designed for infra-red applications, leading to instruments needing vacuum environment and cryogenic temperatures. For all these reasons, we are developing at LAM a vacuum chamber able to go to temperatures down to 30K, for the characterization of these components as well as small size instrument demonstrators.

3. DEFORMABLE MIRRORS

Next generation space telescopes as well as future giant telescopes rely on the availability of highly performing wavefront correction systems. These systems require deformable mirrors with very challenging parameters, including number of actuators up to 250 000 and inter-actuator spacing around 500µm. MOEMS-based devices permit the development of a complete generation of new deformable mirrors. We are currently developing a micro-deformable mirror (MDM) based on an array of electrostatic actuators with attachment posts to a continuous mirror on top, in collaboration with a microtechnology laboratory, LAAS (Toulouse, France).

The originality of our approach lies in the elaboration of layers made of polymer materials, in order to reach high strokes for low driving voltages. We have chosen to develop a process based on Su8 photoresist, used up to now as micromolds for electroplating or masters for hot-embossing. Polymer structures with Su8 are only used in a passive way, for the realization of micro-channels in micro-fluidic applications for example. We propose to use Su8 material as the structural layer of active piston actuators based on the electrostatic force; this polymer exhibits a low Young modulus (E= 6GPa) compared to typical polysilicon structures (E= 158GPa). The same material is also well suited for the continuous mirror realization of a MDM, leading to a complete MOEMS device made with Su8 material.

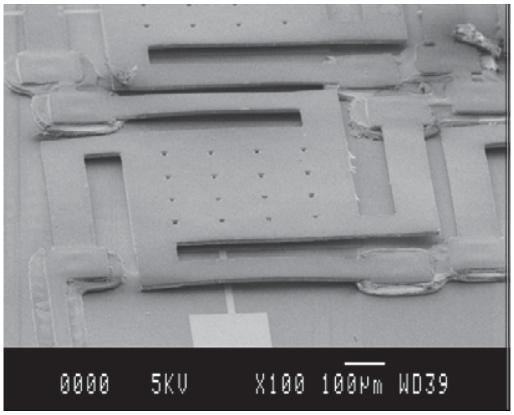

Fig. 4: Views of a polymer actuator with a 580µm plate by scanning electron microscope

Mirrors with very efficient planarization and active actuators have already been demonstrated; the first polymer piston-motion actuator has been realized with a 10µm thick structural layer made of a 580µm square plate, four 580µm-long and 100µm-wide spring arms, and an air-gap of 10µm (Fig. 4). The center of the plate shows small cracks in the Chromium coating (top electrode). When a voltage is applied between the electrodes, we observe a pure piston motion, with a maximal displacement slightly larger than 2µm for 30 volts. Pull-in is observed for 31 volts. We have developed a model by Finite-Element Modeling, considering the Mindlin plate equations, and the results are in close agreement with the measurements [9].

We use our dedicated characterization bench in the time-averaged interferometry configuration for the measurement of the frequency response of this device (Fig. 5). This frequency response function is estimated for an area of ten by ten pixels located at the center of the actuator (node for tip-tilt and astigmatism modes). Experimental points are displayed with error bars calculated by repeating the measurement five times. The response is expressed in dB and is close to a second order system. A theoretical curve of a second-order system with f_r=6.5kHz and Q=0.7 is fitted. Changing the fitting parameters provides error estimation of 0.3 kHz. The cut-off frequency at –3dB is 6500Hz.

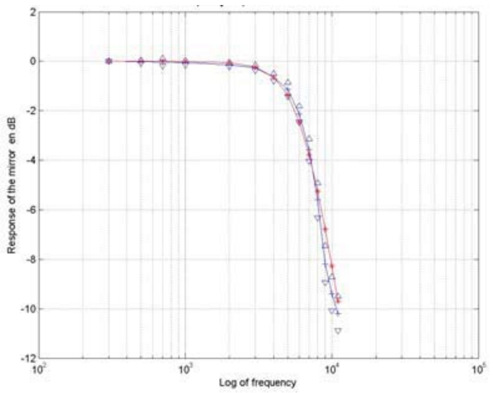

Fig. 5: Frequency response of the polymer-based actuator. A theoretical curve of a second-order system with f_r=6.5kHz and Q=0.7 is fitted

Dynamic analysis like vibration mode and resonant frequency is compared with FEM models, and show a good agreement. The cut-off frequency (6500Hz) is well suited for AO systems which require operating frequency up to 1.5-2 kHz.

AO systems are based on linear matrices operations. The requirement on the linearity of the stroke of the deformable mirror versus the applied command is usually below 10%. In the case of deformable mirrors driven by electrostatic forces, the actuation is highly non linear, due to the dependence of the stroke in V^2, and a dependence with the inverse of the instant gap to the square during actuation. Then, in order to "linearize" the actuation of the deformable mirror, we have developed a dedicated 14-bit electronics with the company Shaktiware, specialized in AO electronics and control loop developments. After a calibration procedure and by fitting the response by a 4th order polynomial, we are able to drive the actuator in terms of stroke and not any more in terms of voltage. The actual location of the actuator versus expected location of the actuator gives a nearly perfect response with a standard deviation of 21nm (Fig. 6) [9].

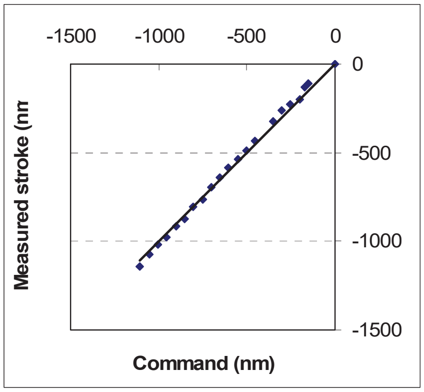

Fig. 6: Response of the polymer actuator, linearized using our dedicated electronics

Polymer materials are usually not suited for space applications. However, Su8 material has no record in terms of space qualification; then an extensive measurement plan is scheduled in the near future. An alternative will be the encapsulation of the device for space applications.

We have also designed a first MDM prototype and realized it at the Memscap foundry in the USA. The architecture is based on an array of nine piston actuators attached to a continuous membrane via attachment posts, with all layers in polysilicon (Fig. 7). The piston actuator is a 200*200µm^2 square plate with four 100µm long-spring arm. The design has been optimized for decreasing the print-through. Spring arms are interlacing and additional platforms are put to fill the edges. A maximum deflection of 350 nm is obtained for 35 Volts, for the central actuator.

Influence functions have been measured on this MDM prototype. The deflection obtained when applying 25 volts on the different actuators successively is shown in Fig. 8. Three classes of actuators can be identified: corner actuators, edge actuators and central actuator. Corner actuators present the maximal deflection for this voltage because of their two free edges. Edge actuators present a deflection slightly lower and the central actuator is significantly stiffer. The corner actuator which is the closest of the minimal altitude point (point of contact between the stuck actuator and the substrate) presents the maximal deflection because of the smaller gap. However the most interesting class is the central actuator, which is the typical actuator in a MDM with higher number of actuators [8].

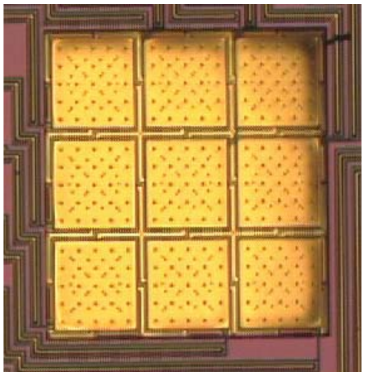

Fig. 7: Micro-deformable mirror prototype with 3x3 actuators (200x200µm^2 for each actuator) and a continuous membrane on top. Structural material is polysilicon.

The actuation non-linearity caused by electrostatic effect and amplified by the gap diminution has also been studied on this device. The same electronics described above has been used, with the same strategy and the actuation behaviour has been perfectly linearized (with a precision of a few nm rms). Effect of the adjacent actuators location on this linearized response (crossed non-linearities) is under study.

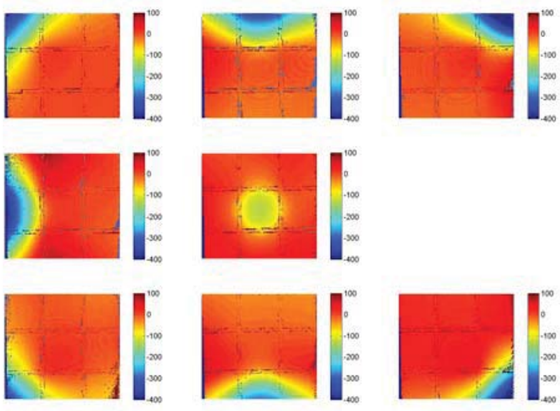

Fig. 8: Influence functions of our micro-deformable mirror prototype (one actuator, middle right, is stuck on the substrate)

Based on our FEM models, a complete deformable mirror made with polymer materials is under development. In a further step, driving electronics could be integrated in the Si substrate.

4. CONCLUSION

MOEMS-based programmable slit masks for multi-object spectroscopy and micro-deformable mirrors for wavefront correction are key components for next generation astronomical instrumentation.

The Laboratoire d'Astrophysique de Marseille is involved since several years in the studies of different aspects of MEMS-based slit mask, as MMA and MSA modeling, original spectrograph concepts and micro-optical components characterization. We are now developing in Europe, with IMT (U. Neuchatel, Switzerland) a new class of components based on micro-mirror arrays. We develop and microfabricate a novel MMA, using a combination of bulk and surface micromachining in silicon. The first results show that the 100 x 200 μm^2 micro-mirrors can achieve most of the requirements including a very good surface quality, which is necessary for high contrast spectroscopy. The device architecture and materials have been selected for future space-compatible applications. Assembly of small test arrays with their electrode chips, as well as design of large arrays are under way.

Micro-deformable mirrors (MDM) are a new generation of deformable mirrors for highly performing wavefront correction systems. We are currently developing in collaboration with LAAS (Toulouse, France), a MDM made of polymer materials, and based on an array of electrostatic actuators attached to a continuous mirror. Efficient planarization and active actuators have been demonstrated; the first polymer piston-motion actuator exhibits a stroke of 2µm for 30V and a resonance frequency of 6.5kHz. Comparison with FEM models shows very good agreement, and realization of a complete polymer-based MDM is under way. Configurations for use in space applications are possible.

These MOEMS devices are not limited for integration in astronomical instrumentation in space. Applications in physics (spectroscopy, beam shaping) or biology (ophthalmology) are also foreseen.

ACKNOWLEDGEMENT

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