International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas

MOEMs devices designed and tested for future astronomical instrumentation in space

Frédéric Zamkotsian

Patrick Lanzoni

Severin Waldis

Wilfried Noell

et al.

International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo, Nikos Karafolas, Proc. of SPIE Vol. 10566, 1056608 · © 2008 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308190

MOEMS DEVICES DESIGNED AND TESTED FOR FUTURE ASTRONOMICAL INSTRUMENTATION IN SPACE

Frederic Zamkotsian[1], Patrick Lanzoni[1], Severin Waldis[2], Wilfried Noell[2], Veronique Conedera[3], Norbert Fabre[3], Thierry Viard[4], Christophe Buisset[4]

[1] Laboratoire d'Astrophysique de Marseille, CNRS, 38 rue Frederic Joliot Curie, 13388 Marseille Cedex 13, France
[2] IMT, University of Neuchatel, Rue Jaquet-Droz 1, CH-2007 Neuchatel, Switzerland
[3] Laboratoire d'Analyse et d'Architecture des Systemes, 7 avenue Colonel Roche, 31077 Toulouse cedex, France
[4] Thales Alenia Space, 100 Bd du Midi, BP 99, 06156 Cannes La Bocca Cedex, France

Frederic Zamkotsian, Tel : + 33 (0) 4 95 04 41 51, e-mail : frederic.zamkotsian@oamp.fr

ABSTRACT

Next generation of astronomical instrumentation for space telescopes requires Micro-Opto-Electro-Mechanical Systems (MOEMS) with remote control capability and cryogenic operation. MOEMS devices have the capability to tailor the incoming light in terms of intensity and object selection with programmable slit masks, in terms of phase and wavefront control with micro-deformable mirrors, and finally in terms of spectrum with programmable diffraction gratings. Applications are multi-object spectroscopy (MOS), wavefront correction and programmable spectrographs. We are engaged since several years in the design, realization and characterization of MOEMS devices suited for astronomical instrumentation.

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 three applications of MOEMS in observational astronomy:

1) Programmable Multi-Object Spectroscopy masks
Multi-Object Spectroscopy (MOS) is becoming the central method to study large numbers of objects. 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
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 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.

3) Programmable Micro-Diffraction Gratings (PMDG)
Programmable spectral tailoring of instruments will allow new observational capabilities. PMDG devices are able to select wavelengths in a complete spectrum, leading to the realization of programmable spectrographs. Sensitivity as well as signal to noise ratio

of the instrument will be increased. Application in Darwin-like missions will permit to optimize and enhance exo-planet detection and characterization.

2. PROGRAMMABLE SLIT MASKS

Multi-Object Spectrographs (MOS) are the major astronomical instruments for studying primary galaxies and remote and faint objects, whose light spectra are strongly shifted to infrared wavelengths. Current object selection systems are limited and/or difficult to implement in next generation MOS for space and ground-based telescopes. Programmable multi-slit masks are a very suitable solution for this task. A promising solution is the use of MOEMS devices such as micromirror arrays (MMA) or micro-shutter arrays (MSA), which both allow the remote control of the multi-slit configuration in real time. Next generation ground-based MOS will also benefit from these developments. The typical size of these micro-elements is around 100µm, and MMAs [1,2] are designed for generating reflecting slits, while MSAs [3] generate transmissive slits. MSA has been selected to be the multi-slit device for Near Infrared Multi-Object Spectrograph (NIRSpec) for the James Webb Space Telescope (JWST), 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 [3].

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. [4]. Within the framework of the JRA Smart Focal Planes (part of the European FP6 Opticon program), the LAM and the Institut de Micro-Technologies (IMT) of University of Neuchatel (Switzerland) have engaged a collaboration in order to demonstrate a European MOEMS-based slit mask. We develop and microfabricate a novel MMA suited for MOS. Based on our simulations and measurements, we have fixed several parameters: one micromirror per astronomical object, which corresponds to the baseline for NIRSpec, 20° tilted micromirror used for the "ON" position, minimizing the parasitic light, flat mirror surface, uniform tilt angle over the whole array for optimising the optical design of the instrument, a fill factor of more than 90% and a low driving voltage below 100V. The micro mirror array has also to work at cryogenic temperatures.

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 locked 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.

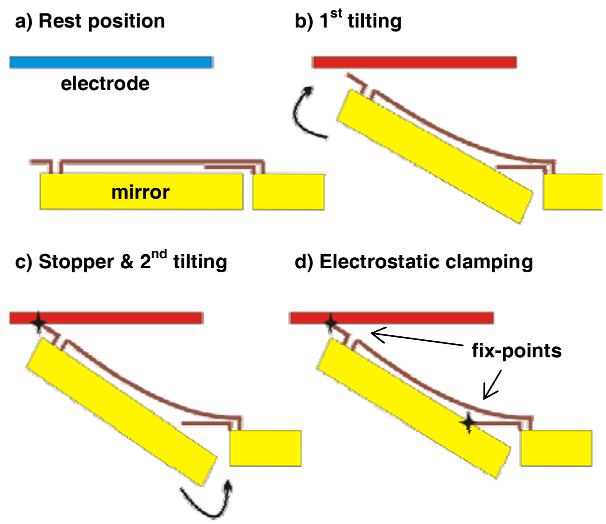

Fig. 1: Schematic view of the actuation of the mirror and electrostatic locking mechanism

A first small test array of 5x5 micro-mirrors was successfully micro fabricated using a combination of bulk and surface micromachining. 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) [5].

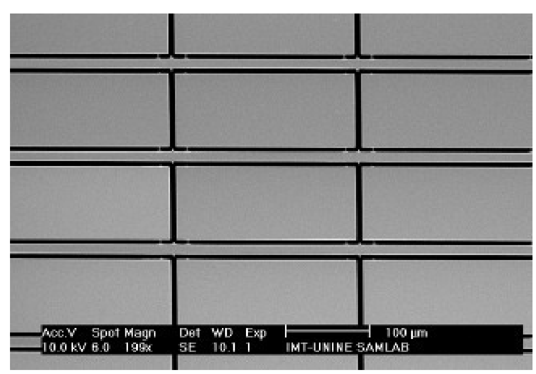

Fig. 2: SEM image of a small 5x5 micro-mirror array

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 with a low-coherence source, 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 [6].

Using our characterization benches, preliminary characterization is done on this first 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 10 nm peak-to-valley is measured, with 1nm roughness. These mirrors can be electrostatically tilted by 20° at an actuation voltage of 90V. 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 locking mechanism is designed in order to ensure this goal. The locking performance has been measured on single micro-mirrors and an angle difference of only 1 arc-minute has been obtained on our first prototype.

The cryogenic compatibility is crucial for the application in an infrared (IR) MOS. The operating temperature must be below 100 K for near and mid IR and below 40 K for far IR. Our MMA is designed such that all structural elements have a matched coefficient of thermal expansion (CTE) in order to avoid deformation or even flaking within the device when cooling it down to the operating temperature. The mirrors are covered with a gold layer for IR operation, whereas gold has a different CTE than silicon. As the silicon mirror is 10 µm thick and the coating is 60 nm thin, we estimate that the induced deformation will be small.

For characterising the surface quality and the performance of our MMA's at low temperature, we have developed a cryo chamber optically coupled to a high-resolution Twyman-Green interferometer [6]. The interferometer provides a sub-nanometer accuracy by using phase-shifting technique. The cryo-chamber allows pressure down to 10^{-6} mbar and temperatures down to 60 K. A dedicated PCB interface and mechanical support were developed, which allows working in vacuum and which avoids additional stress on the MMA device, which itself is packaged in PGA chip carrier. The PGA is inserted in a ZIF-holder integrated on the PCB board (Fig. 3).

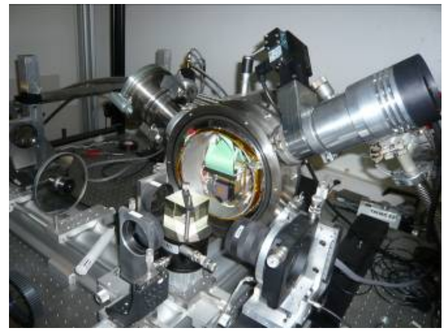

Fig. 3: Cryogenic set-up
mounted on the interferometric bench.

The micromirrors could be successfully actuated before, during and after cryogenic cooling at 92K (Fig. 4) [7]. We could measure the surface quality of the gold coated micromirrors at room temperature, below 100K and being actuated: there is a slight increase of the deformation from 35 nm to 50nm PtV, due to CTE mismatch between silicon and gold layer (Fig. 4). This small deformation is still well below the requirement for MOS application at IR. This value could be decreased if needed by using double-side coated mirrors, easily feasible in our process flow.

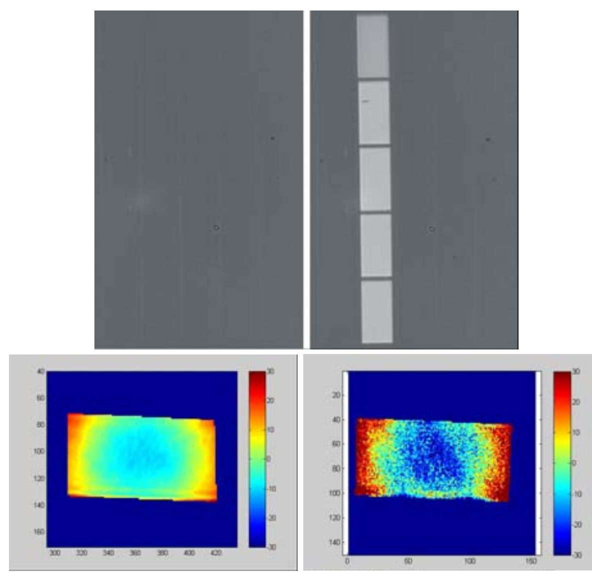

Fig. 4: Testing of a micro-mirror array at 92K (0V and 90V applied); 100x200 μm^2 mirrors surface deformation at room temperature and at 92K

Large arrays of 20'000 micromirrors per array are under development.

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 only as micromolds for electroplating or masters for hot-embossing. 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.

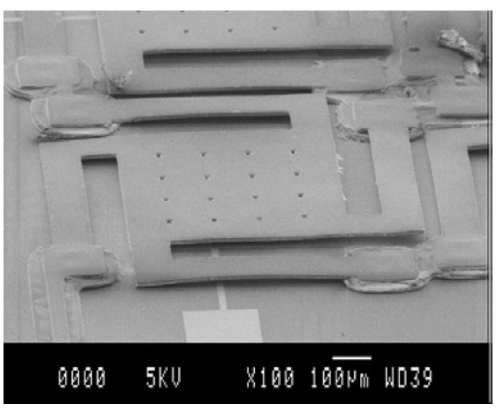

Fig. 5: View of a polymer actuator with a 580µm plate by scanning electron microscope

Mirrors with very efficient planarization and active actuators have 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. 5). We measure a pure piston motion, with a maximal displacement larger than 2µm for 30 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. We use our dedicated surface characterization bench in the time-averaged interferometry configuration, and a 6.5kHz resonance frequency was measured (Fig. 6). This frequency is well suited for AO systems which require operating frequency up to 1.5-2 kHz.

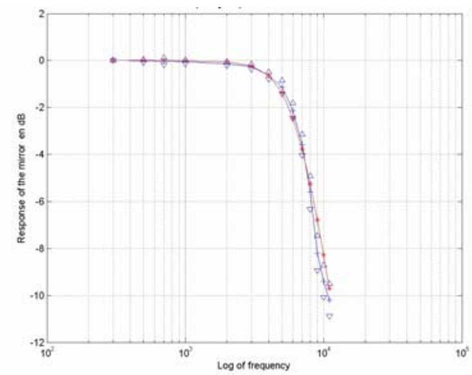

Fig. 6: Frequency response of the polymer-based actuator. A theoretical curve of a second-order system with f_r=6.5kHz and Q=0.7 is fitted

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. 7a). 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 V, for the central actuator. Influence functions have been measured on this MDM prototype. The deflection obtained when applying 25 V on the different actuators successively is shown in Fig. 7b. [8].

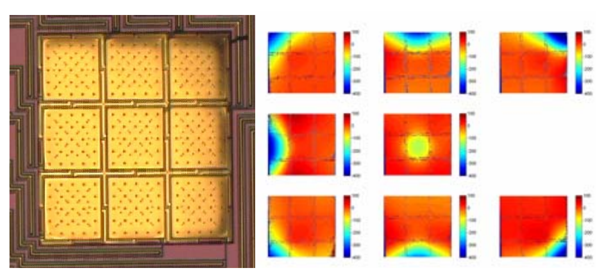

Fig. 7: a) Micro-deformable mirror prototype with 3x3 actuators (200x200µm^2 for each actuator) and a continuous membrane on top. Structural material is polysilicon; b) Influence functions of LAM prototype (one actuator, middle right, is stuck on the substrate)

AO systems are based on linear matrices operations. 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. After a calibration procedure and by fitting the response by a 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 3.5nm [8]. Effect of the adjacent actuators location on this linearized response (crossed non-linearities) is under study.

Based on our FEM models, a complete deformable mirror made with polymer materials is under development [8]. In a further step, driving electronics could be integrated in the Si substrate.

4. PROGRAMMABLE MICRO-DIFFRACTION GRATINGS (PMDG)

Programmable Micro-Diffraction Gratings (PMDG) are a new type of micro-opto-electro-mechanical systems (MOEMS), opening new observational capabilities in future astronomical instrumentation. LAM is involved with Thales Alenia Space in an ESA study. Within this study, key parameters have been defined and characterization benches at LAM have been modified specifically for the PMDG device characterization. A PMDG device realized by Silicon Light Machines (SLM) in USA has been purchased (Fig. 8) and measurements have been realized.

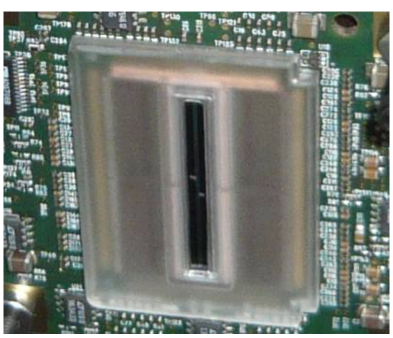

Fig. 8: PMDG device realized by SLM.

Programmable gratings are based on a serial of parallel ribbons with alternating fixed and movable ribbons. Typical dimensions are 5µm-wide and 200µm-long ribbons. By using electrostatic force, ribbons are actuated. This structure is common in the RF-MEMS used for switching very quickly signals along lines. However, in PMDG, the number of parallel ribbons is very high (up to several thousands), they must be identical from ribbon to ribbon and their surface quality has to be at the level of optical quality.

When all ribbons are in the same plane, this device is a reflector and the light is sent back (Fig. 9). When movable ribbons are pulled down, the shape of the reflecting surface is like a square grating, diffracting the light in the different diffraction orders. If the stroke is equal to λ/4, the light is completely switched in the diffraction directions; for values ranging from 0 to λ/4, only part of the light is diffracted. A few ribbons are efficient enough to diffract the light.

By using a mask in the Fourier plane, it is possible to block out the reflected light in the dark state while in the bright state, light is sent out. Two modes are then foreseen:

- Digital mode: light is switched ON and OFF only
- Analog mode: stroke of the movable ribbons are set precisely in order to send out only a part of the incoming light, generating "grey tones".

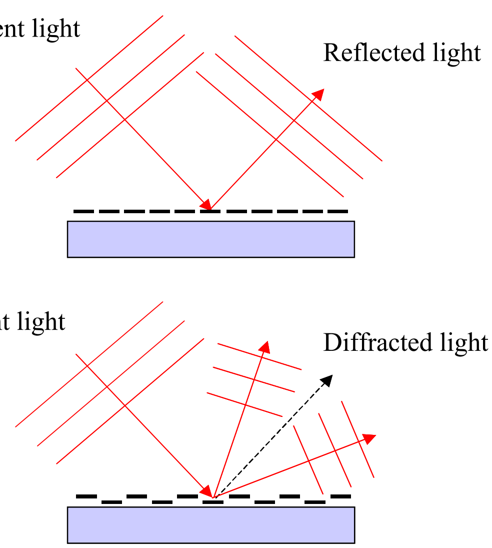

Fig. 9: PMDG principle.

Most applications are based on 0^{th} and 1^{st} orders operation. Zeroth order operation means that 0^{th} order is transmitted and all other orders blocked, and first order operation means that 1^{st} order (+1 and/or -1) is transmitted and all others are blocked. Either configuration could be used according to the requested performances. The diffraction efficiency is usualy better in the 0^{th} order while the 1^{st} order operation gives a better contrast easily (0^{th} order with optimised optical architecture could deliver also a good contrast). The number of ribbons used by PMDG "pixel" determines the separation between the 0^{th} order and the 1^{st} orders. For a complete separation and then a better contrast, usually three ribbon-pairs (periods) are needed, i.e. 6 ribbons.

A PMDG component is a good candidate for making a tuneable spectrometer. The principle is to place the component in the focal plane of a first diffracting stage (using a grating for instance) and to use the PMDG as a wavelength selector by reflecting the selected wavelengths and by switching-off the others (by diffracting them). It becomes then possible to realise a programmable and adjustable filter in λ and $\Delta\lambda$ (Fig 10).

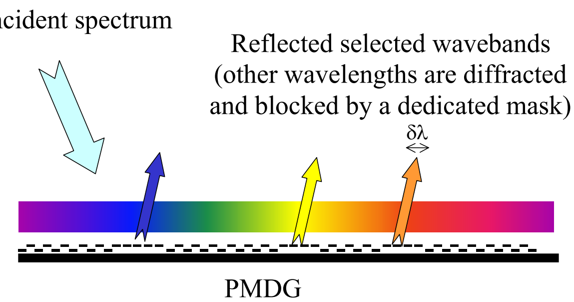

Fig. 10: Principle of wavelengths selection by using a PMDG. Selected wavelengths are reflected while others are diffracted and blocked by a mask in Fourier plane.

The Darwin mission will search, detect and characterize exo-planets, using high-contrast nulling interferometry, coupled with spectroscopic observation. The search of possible life forms on targeted exo-planets leads to implement a spectrometer able to detect absorption peak of H_2O, CO_2 and O_3 molecules (Fig. 11). The Darwin mission, presently under study at Thales Alenia Space, operates in the far IR range (6 µm to 20 µm) with a very small field of view. These characteristics are very favourable with the use of a PMDG device

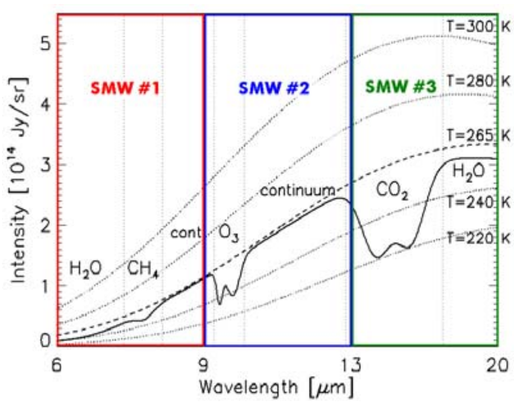

Fig. 11: Typical spectra in DARWIN mission, exo-planet without and with life signatures H_2O, CO_2 and O_3.

By implementing a PMDG device in a spectrograph, the detector array is replaced by a single detector [9]. Our observational strategy becomes:

- In the detection mode, the full spectrum range (6 µm to 20 µm) is focused on the single detector during the planet detection phase. This allows to increase the signal to noise ratio by roughly a factor of 14 ($\sqrt{200}$) or to decrease the integration time by the same factor. The detection phase might be then much shorter.
- If the detection is positive, we can then tailor the transmitted wavelengths through the PMDG by adding the three interesting wavelength bands, let's say for revealing $H_2O + CO_2 + O_3$. The level of the measured flux indicates if absorption peaks are present. An additional measurement along the continuum bands may be requested for reference. This method leads to a higher SNR than recording separately the peaks, and we can then conclude faster on the presence or not of an atmosphere.
- If the previous step is successful, the PMDG device can be programmed for recording the spectra by blocks of wavelengths or wavelength by wavelength. According to the level of signal of the target, we can adjust the resolution of wavelength bins for optimising the SNR value.

This new strategy shows the following advantages:

- Lower detection time
- Selecting and gathering the flux coming by the (three) interesting zones on one single detector
- Increase SNR
- Adapt the wavelength range to the desired target (magnitude, type of atmosphere, fine line measurement …)

One of LAM benches dedicated to the characterization of MOEMS has been redesigned and re-arranged to a Darwin-like demonstrator breadboard. We have simulated from Fig. 11 typical exo-planet spectra and implemented them in the PMDG device, using the analog mode. Whole demonstrator throughput response including wavelength dependence is included in our model. Optical response in the spectral channel is shown in Fig. 12; it reproduces very finely the expected spectrum from Fig. 11. Exo-planet spectra without and with life signatures are shown. [9]

The major application of PMDG technology for space missions is the realization of spectrometers, wideband sharp-edge filters or dichroïc plates with fully adjustable transmission, by means of the PMDG analog control. A new generation of instruments is foreseen that offers new functionalities which cannot be achieved by means of conventional optics:

- Correct spectral transmission defaults of the instrument.
- Adjust the instrument spectral properties during the mission.

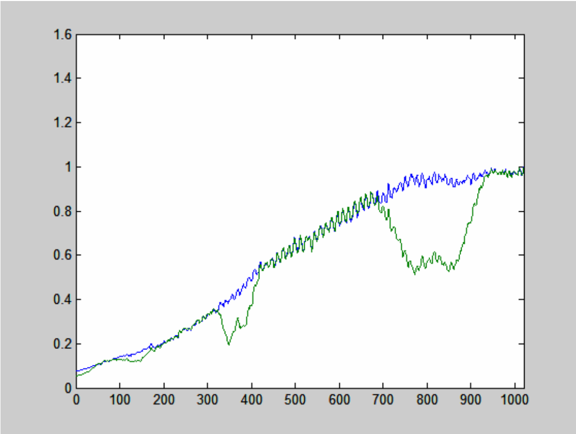

Fig. 12: Exo-planet spectra without and with life signatures.

5. CONCLUSION

MOEMS devices are still under development, but they show great advantages for future astronomical instrumentation. Main applications are programmable slit masks for multi-object spectroscopy, micro-deformable mirrors for wavefront correction, and programmable diffraction gratings for programmable spectrographs.

We are 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, a new class of components based on micro-mirror arrays. 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. Our demonstration of operation below 100K is a key result. Large arrays of 20’000 micromirrors per array are under development.

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, 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. Realization of a complete polymer-based MDM is under way. Configurations for use in space applications are possible.

Programmable diffraction gratings show new functionalities for future space instruments, including spectrometers, wideband sharp-edge filters or dichroïc plates with fully adjustable transmission. Successful implementation in Darwin-like mission has been demonstrated on a breadboard. Exo-planet spectra without and with life signatures could be clearly measured.

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

This work is partly funded by CNRS, Provence-Alpes-Cote d'Azur regional council, Conseil General des Bouches-du-Rhône county council, and European FP6 Opticon program. The results on PMDG devices have been achieved in the frame of the ESA contract 20519/06/NL/SFe.

REFERENCES

1. R. Burg, P.Y. Bely, B. Woodruff, J. MacKenty, M. Stiavelli, S. Casertano, C. McCreight and A. Hoffman, “Yardstick integrated science instrument module concept for NGST”, in *Proceedings of the SPIE conference on Space Telescope and Instruments V*, SPIE **3356**, 98-105, Kona, Hawaii (1998)
2. F. Zamkotsian, K. Dohlen, D. Burgarella, V. Buat, "Aspects of MMA for MOS : optical modeling and surface characterization, spectrograph optical design", in *Proceedings of the NASA conference on "NGST Science and Technology Exposition"*, ASP Conf. Ser. **207**, 218-224, Hyannis, USA (1999)
3. H. Moseley, S. Aslam, M. Baylor, K. Blumenstock, R. Boucarut, A. Erwin, R. Fettig, D. Franz, T. Hadjimichael, J. Hein, A. Kutyrev, M. Li, D. Mott, C. Monroy, D. Schwinger “Microshutter arrays for the NGST NIRSpec”, in *Proceedings of the SPIE conference on Astronomical Telescopes and Instrumentation 2002*, Proc. SPIE **4850**, Hawaii, USA (2002)
4. F. Zamkotsian, J. Gautier, P. Lanzoni " Characterization of MOEMS devices for the instrumentation of Next Generation Space Telescope", in *Proceedings of the SPIE conference on MOEMS 2003*, Proc. SPIE **4980**, San Jose, USA (2003)
5. S. Waldis, F. Zamkotsian, P.-A. Clerc, W. Noell, M. Zickar, and N. de Rooij, "Arrays of high tilt-angle micromirrors for multiobject spectroscopy, " *IEEE Journal of Selected Topics in Quantum Electronics* **13**, pp. 168–176, 2007
6. A. Liotard, S. Muratet, F. Zamkotsian, JY Fourniols, "Static and dynamic MOEMS characterization by phase-shifting and time-averaged inteferometry", in *Proceedings of the SPIE conference on MOEMS 2005*, Proc. SPIE **5716**, San Jose, USA (2005)
7. F. Zamkotsian, E. Grassi, S. Waldis, R. Barette, P. Lanzoni, C. Fabron, W. Noell, N. de Rooij, "Interferometric characterization of MOEMS devices in cryogenic environment for astronomical instrumentation", *Proc. SPIE* **6884**, 2008
8. F. Zamkotsian, V. Conedera, H. Granier, A. Liotard, P. Lanzoni, L. Salvagnac, N. Fabre, "Electrostatic polymer-based micro deformable mirror for adaptive optics", *Proc. SPIE* **6467**, 2007
9. F. Zamkotsian, P. Lanzoni, T. Viard, C. Buisset, "New observational concept for Darwin-like missions using a MOEMS-based programmable spectrometer", in Proceedings of the SPIE conference on Astronomical instrumentation 2008, Proc. SPIE **7013**, Marseille, France (2008)