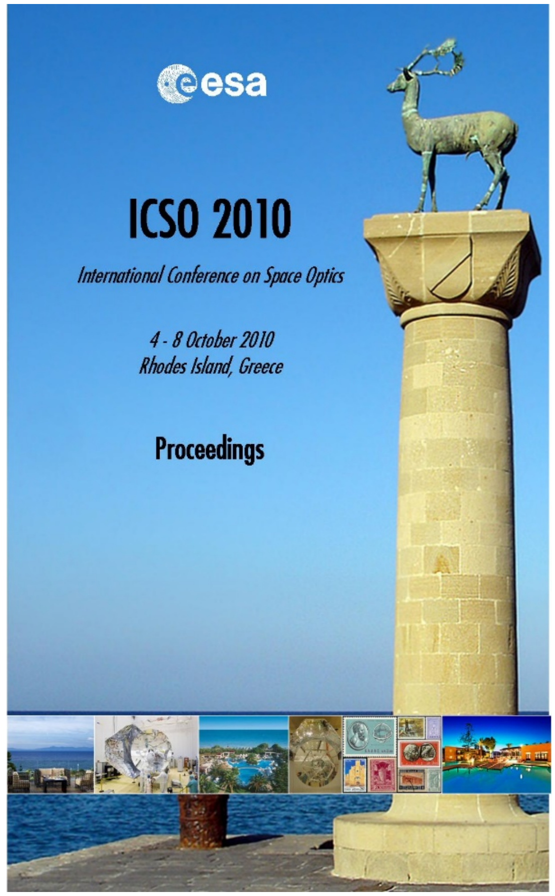
**International Conference on Space Optics—ICSO 2010**

Rhodes Island, Greece

4–8 October 2010

*Edited by Errico Armandillo, Bruno Cugny, and Nikos Karafolas*




# *Micromirror arrays for multi-object spectroscopy in space*

*F. Zamkotsian, P. Lanzoni, K. Tangen, M. Canonica, et al.*

International Conference on Space Optics — ICSO 2010, edited by Errico Armandillo, Bruno Cugny, Nikos Karafolas, Proc. of SPIE Vol. 10565, 105655J · © 2010 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2552590

# MICROMIRROR ARRAYS FOR MULTI-OBJECT SPECTROSCOPY IN SPACE

Frederic Zamkotsian[1], Patrick Lanzoni[1], Kyrre Tangen[2], Michael Canonica[3], Severin Waldis[3], Wilfried Noell[3], Nico de Rooij[3], Laurent Marchand[4], Ludovic Duvet[4]

[1] *Laboratoire d'Astrophysique de Marseille, CNRS, 38 rue Frederic Joliot Curie, 13388 Marseille Cedex 13, France*
[2] *Visitech, Kjellstadveien 5, Lier, P.O.Box 616, N-3003 Drammen, Norway*
[3] *Ecole Polytechnique Fédérale de Lausanne, Jaquet Droz 1, CH-2002 Neuchâtel, Switzerland*
[4] *European Space Agency, Keplerlaan 1, 2200 AG, Noordwijk, The Netherlands*

*E-mail address: frederic.zamkotsian@oamp.fr*

## I. INTRODUCTION

Next-generation infrared astronomical instrumentation for ground-based and space telescopes could be based on MOEMS programmable slit masks for multi-object spectroscopy (MOS). This astronomical technique is used extensively to investigate the formation and evolution of galaxies. MOS with multi-slits is the best approach to eliminate the problem of spectral confusion, to optimize the quality and the SNR of the spectra, to reach fainter limiting fluxes and to maximize the scientific return both in cosmology and in legacy science. Major telescopes around the world are equipped with MOS in order to simultaneously record 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. The EUCLID mission from the European Space Agency (ESA) will study the dark universe by characterizing a very high number of galaxies in shape and in spectrum; this mission has also considered a MOS instrument in its early study phase. Conventional masks or complex fiber-optics-based mechanisms are not attractive for space. The programmable multi-slit mask requires remote control of the multi-slit configuration in real time.

A promising possible solution is the use of MOEMS devices such as micromirror arrays (MMA) [1,2,3] or micro-shutter arrays (MSA) [4]. 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 NASA's Goddard Space Flight Center. They use a combination of magnetic effect for shutter actuation, and electrostatic effect for shutter latching in the open position. By placing the programmable slit mask in the focal plane of the telescope, the light from selected objects is directed toward the spectrograph, while the light from other objects and from the sky background is blocked. For example, a MOEMS-based MOS concept where the programmable slit mask is a MMA is shown in the left-hand side of Fig. 1. In action, the micro-mirrors in the ON position direct the light toward the spectrograph, while the micro-mirrors in the OFF position send the light towards a light trap.

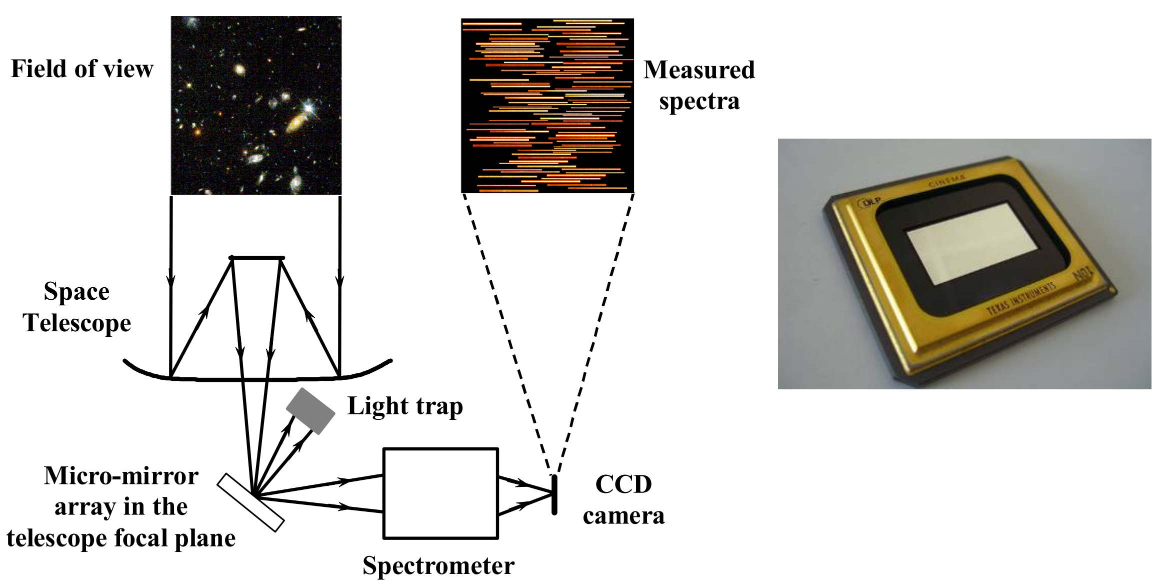



**Fig. 1.** Principle of a Multi-Object Spectrograph with a Micro-Mirror Array.
DMD chip from Texas Instruments (2048 x 1080 micromirrors).

In Europe, an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy [5,6]. A collaboration within the Laboratoire d'Astrophysique de Marseille (LAM) and the Ecole Polytechnique Federale de Lausanne (EPFL) has for purpose to develop a European programmable MMA that can be used as reflective slit mask for MOS. The requirements for our MMA were determined from previous simulation results and measurements [7,8]. It has to achieve a high optical contrast of 1500:1 (goal: 3000:1), a fill factor of more than 90 % and a mechanical tilt angle greater than 20°. Furthermore, the performance must be uniform over the whole device; the mirror surface must remain flat in operation throughout a large temperature range and it has to work at cryogenic temperature.

Visitech is an engineering company experienced in developing DMD solution for industrial customers. The Laboratoire d'Astrophysique de Marseille (LAM) has, over several years, developed different tools for modeling and characterization of MOEMS-based slit masks, especially during the design studies on JWST-NIRSpec [7,8]. ESA has engaged with Visitech and LAM in a technical assessment of a DMD chip for space application. To get more than 2 millions independent micromirrors, the selected component for an EUCLID pre-study is a DMD chip from Texas Instruments that features 2048 x 1080 mirrors and a 13.68µm pixel pitch (right-hand side of Fig. 1). Typical operational parameters are room temperature, atmospheric pressure and mirrors switching thousands of times in a second, while for EUCLID, the device should work in vacuum, at low temperature, and each MOS exposure lasts between 400s and 1500s, with mirrors held in one state (either ON or OFF) during the exposure. A specific thermal / vacuum test chamber has been developed for test conditions down to -40°C at $10^{-5}$ mbar vacuum. Imaging capability for resolving each micro-mirror has also been developed for determining any single mirror failure. Dedicated electronics and software allows us to hold any pattern on the DMD for duration of up to 1500s.

We present in this paper the ability of micromirror arrays (MMA) to fulfil the performances requested for future MOS instruments in space: a silicon-based MMA designed for cryogenic temperatures and tested at 92K, and a commercial array tested in a space evaluation program.

## II. SILICON-BASED MICROMIRROR ARRAY

### *A. Concept, realization and characterization*

A first generation of 5 × 5 MMA fulfilled the requirements presented in the introduction paragraph and was fabricated. The basic concept is shown in Fig. 2. A single cell of the device consists of a silicon mirror suspended by polysilicon beams. The beams are fixed on a frame, which maintains the mirrors together. The frame lies on a spacer that provides a precise distance between the mirror and the electrode. A system of landing beam and stopper beams on the mirror and on the frame was developed to assure a precise and constant tilt angle. When a DC voltage is applied on the electrode an electrostatic force appears between the electrode and the mirror and the micromirror begins to turn until the landing beam touches the landing pad. The mirror starts to turn in the opposite direction until it hits the stopper beams attached on the frame and remained electrostatically fixed in this position [5].

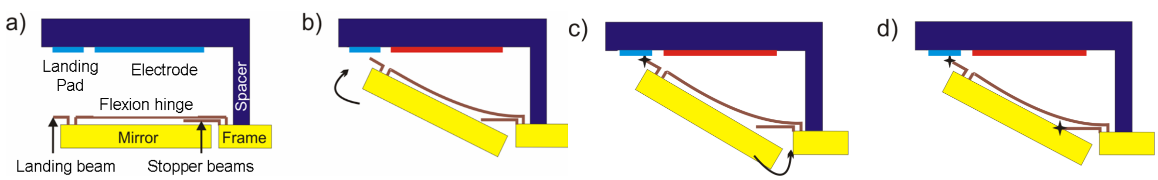



**Fig. 2.** Micromirror for multi-object spectroscopy: (a) Concept of the micromirror device. (b-d) A system of landing beam and stopper beams was introduced that provides uniform tilt-angle over the whole MMA.

For the micromirror array realization, a combination of bulk and surface silicon micromachining was used. The MMA were made of two wafers: one for the mirrors and one for the electrodes, which were processed separately and assembled. The micromirrors were made of single-crystal silicon, assuring optical flat surfaces (Fig. 3 (a)). Silicon being transparent in the infrared range, a gold thin-film coating was deposited on the topside of the mirrors. The cantilever-type suspension was made of a deposited polycrystalline silicon layer deposited on the back of the mirror. The electrodes were also made of single-crystal silicon.

Using our characterization benches, 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 (Fig. 3 (b)). 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.

For applications in modern and future telescopes larger arrays are required. We are developing a new process where the mirror chip is bonded on top of the electrode chip and microfabricated pillars on the electrode chip provide the necessary spacing between the two parts. The first prototypes have been assembled and the largest chip is shown in Fig. 3 (c); it measures 25x22 mm$^2$ and is composed of 200x100 electrostatic actuated micromirrors.

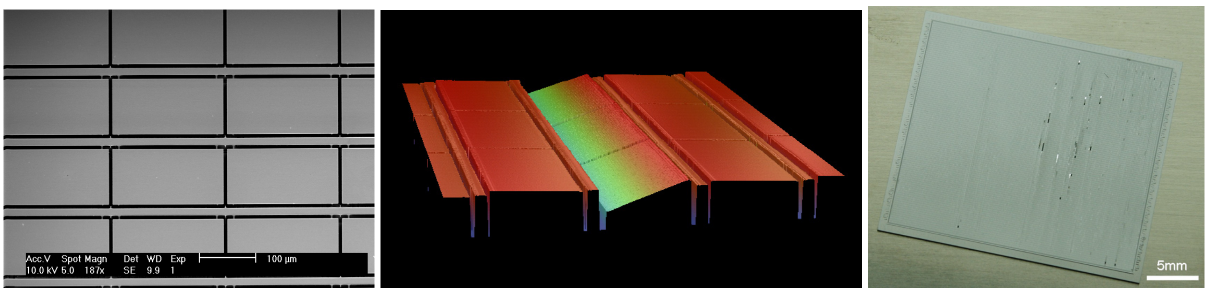



**Fig. 3.** (a) Frontside of the mirror chip with micromirrors of size 100 x 200 µm$^2$. (b) One row is actuated, implementing the long slit mode. The fill factor is 97% along the slit. (c) Assembled MMA of size 25 mm x 22 mm with 200 x 100 micromirrors. Each micromirror is of size 200 x 100 µm$^2$.

*B. Micromirror array operation at cryogenic temperature*

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 10µm thick mirrors are covered with a 60nm thick gold layer for IR operation, whereas gold has a different CTE than silicon.

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 [9]. The interferometer provides a sub-nanometer accuracy, and the cryo-chamber allows pressure down to 10$^{-6}$ mbar and temperatures down to 60 K. The MMA device is packaged in PGA chip carrier. The PGA is inserted in a ZIF-holder integrated on a PCB board. **The micromirrors could be successfully actuated before, during and after cryogenic cooling at 92K** (Fig. 4). 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. 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.

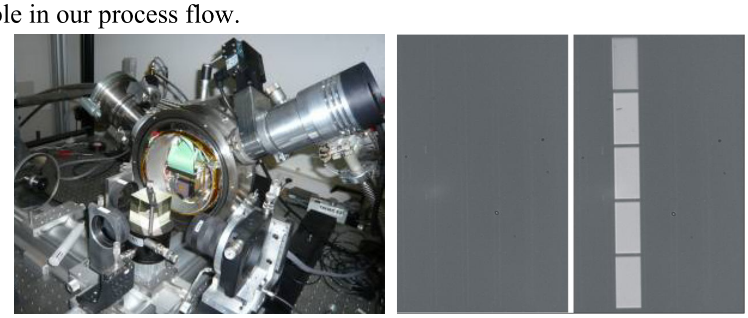


**Fig. 4.** Cryogenic set-up; functional testing of a micromirror array at 92K (0V and 90V applied)

*C. MOS-like tests*

We have developed a bench set-up dedicated to the operational characterization of MOEMS-based slit masks, MMA as well as MSA, in order to be able to measure the key parameters of NIRSpec, including the contrast, defined as the ratio of the rejected light to the transmitted light. First contrast measurements have been carried out on the MMA fabricated by Texas Instrument for projection displays, in order to simulate the actual MOEMS device for NIRSpec, and to establish the test procedure [8]. We can address several parameters with our modular characterization bench, as the size of the source, its location with respect to the micro-elements, the wavelength, and the input and output pupil size.

Three groups of elements are considered (Fig. 5):

- Sources: a large variety of optical sources, point or extended source, laser or white light are used. Two arms define sources by a hole or a group of holes with the proper diameter in order to simulate a typical astronomical field of view. Number of sources, relative location in the field of view, magnitude, wavelength and spectra could be chosen independently on the two arms. The sources are focused on the MMA. Fine tuning stages permit to locate very precisely the sources on the MMA. We can generate by this way the objects of interest as well as the spoiler sources.
- Component environment: injection and collection of the light to and from the MOEMS device with the possibility to configure independently the input and output pupils. The optical aperture in the focal plane of the telescope could be tuned from F/3 to F/50. The output pupil of the characterization bench simulates the size of the grating inside the spectrograph (oversizing of the output pupil is limited in a space instrument). In order to obtain high resolution images of the micro-mirrors, we are also able to use an F/2 output pupil.
- Detectors: a high dynamical range CCD for device imaging and contrast measurement, and a conventional CCD for pupil imaging.

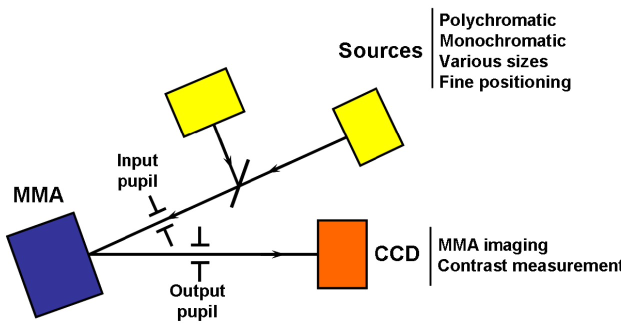



**Fig. 5.** Operational MOS-like test setup

The setup was configured to demonstrate the object selection capabilities of our micromirrors. Two distinct objects are set in the field of view and a 5x5 array is used to select either one or the other object. Here the long slit mode is used, i.e. all five mirrors in a line of the 5x5 micromirror array are tilted at the same time, as illustrated in Fig. 3 (b). Note that the fill-factor along the slit is very high, i.e. 97%. First, both objects are selected, that is the mirror lines where the object is focussed on are tilted. Then only either the right or the left object is selected. Fig. 6 shows the series of images as seen by the CCD camera (spectrograph).

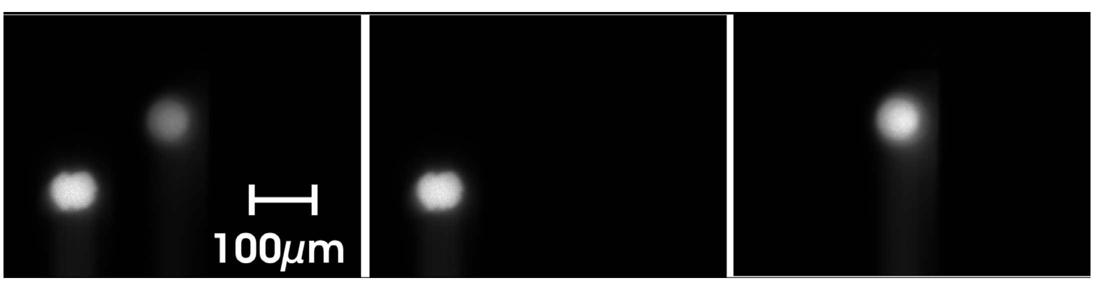



**Fig. 6.** CCD images corresponding to the image plane of the spectrometer. In the first image, two objects are present in the field of view, in the second and third image one out of two objects is selected, blocking completely the light of the other object. The projected object has a diameter of 50µm which corresponds to the size of a typical astronomical object in the focal plane of a telescope.

## III. DMD SPACE EVALUATION

### *A. DMD space evaluation results*

In a MOS, the high precision spectra measurements could be obtained using Digital Micromirror Devices (DMD); these devices would act as object selection reconfigurable masks. The DMD features 2048 x 1080 mirrors on a 13.68µm mirror pitch. For MOS applications in space, the device should work in vacuum, at low temperature, and each MOS exposure would last for typically 1500s with micromirrors held in a static state (either ON or OFF) during that duration. A specific thermal / vacuum test chamber has been developed for test conditions down to -40°C at $10^{-5}$ mbar vacuum (Fig. 7 a). Imaging capability for resolving each micromirror has also been developed for determining degradation in any single mirror. Dedicated electronics and software holds any pattern on the device for a duration of up to 1500s (Fig. 7 b). Data pipeline for data reduction has also been developed for revealing degradation in performance of any mirror. We have adopted three mirror degradation definitions: - the **blocked mirror** when the mirror is stuck, - the **lossy mirror** when the throughput is decreased by more than 20%, and – the **weak mirror** when the throughput is decreased between 10% and 20% [10,11].

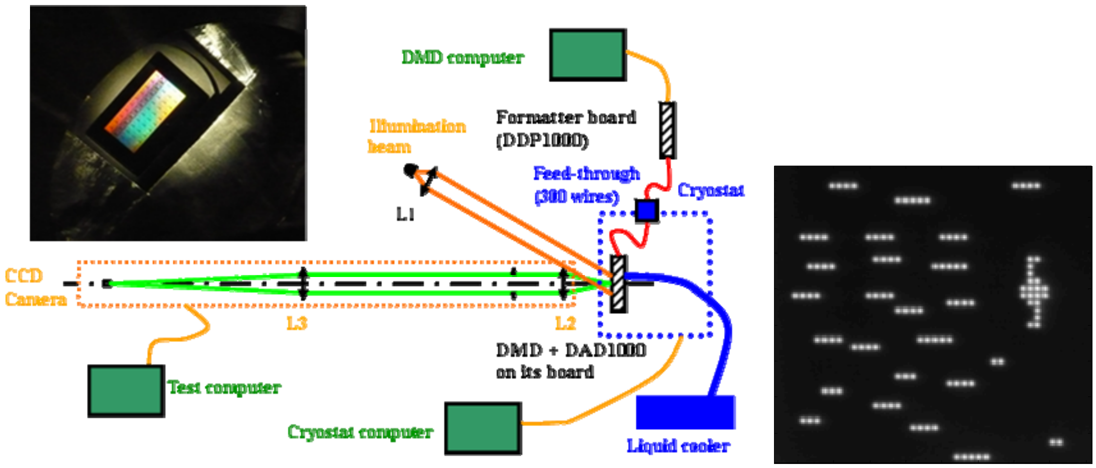



**Fig. 7.** (a) Schematic of the DMD space evaluation set-up; (insert: DMD image in the test chamber).
(b) Typical MOS pattern (individual mirrors are ON)

Our first tests reveal that the DMD remains fully operational at -40°C and in vacuum. Then, a 1038 hours life test in space survey conditions (-40°C and vacuum), has been successfully completed. The device was operating continuously with typical MOS patterns, and optical measurements were done regularly. The number of affected mirrors remains identical through the whole test: 3 blocked mirrors, 7 lossy mirrors and 11 weak mirrors. Blocked mirrors are built-in failures while for the lossy and weak mirrors, a slight variation in number and location could occur but this remains very limited with a maximum variation of ± 2 micro-mirrors. However, all these numbers are very low compared to the 2 million mirrors of the array. Total Ionizing Dose (TID) radiation tests have been completed, establishing between 10 and 15 Krads as the level of TID that the DMD can tolerate; at mission level, this limitation could likely be overcome by shielding the device. Finally, thermal cycling (500 cycles between room temperature and cold temperature, on a non-operating device) and vibrations and shocks tests have also been done; no degradation is observed from the optical measurements [10,11].
**These results do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements.** Insertion of such devices into final flight hardware would however still require additional efforts such as development of space compatible electronics, and original opto-mechanical design of the instrument.

*B. MOS-like tests*

In order to evaluate the capability of a DMD device to select objects in a field of view, we used our operational bench described in paragraph II. The bench is used as a photometric bench, and the FOV is imaged on a 1kx1k camera in order to get enough resolution on each micro-mirror. Each micro-mirror is imaged on about 9 x 9 detector pixels. In comparison with the set-up developed for vacuum and low temperature testing (4 x 4 detector pixels / micro-mirror), the optical magnification is higher in this new set-up; we want then to get a higher photometric accuracy in DMD performance parameters, as well as a higher spatial resolution on each micro-mirror. We set a 24° angle between input and output beam, and both input and output beam have been set to F/3. In front of the camera, we are able to introduce a neutral density filter in order to increase the dynamical range of the bench, this feature is very important for the precise DMD contrast determination.

A FOV containing three objects was imaged on the DMD device surface (Fig. 8 a). In Fig. 8 b, the same FOV is presented, but the DMD is programmed in order to select the left-hand object (the mirrors are ON only on the object to be selected, and the rest of the mirrors are OFF). **This picture shows the full capability of the DMD device to generate any slit pattern (reflective slit) sending the light towards the spectrograph, when all other sources as well as background are hidden by the OFF micro-mirrors.** The contrast of a micro-mirror is defined as the ratio of the throughput when the mirror is in ON position with respect to the mirrors in OFF position. In order to be as accurate as possible, the throughput is integrated within a mask applied on a whole micro-mirror. The background light has been removed. **This gives a final value of the contrast of 2250.** Contrast has been measured on several mirrors and they exhibit identical values.

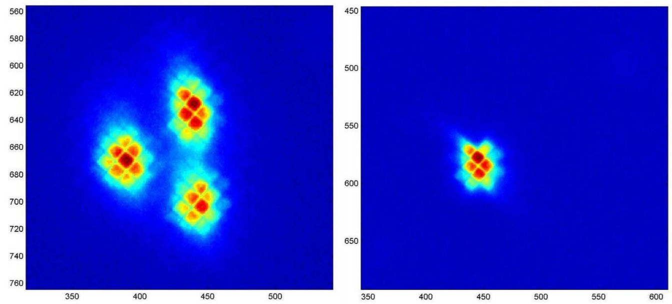



**Fig. 8.** (a) FOV with three objects imaged on the DMD device surface.
(b) Same FOV when the DMD is programmed in order to select the left-hand side object (the mirrors are ON only on the object to be selected, and the rest of the mirrors are OFF).

## IV. CONCLUSION

Large field of view surveys with a high density of objects such as high-z galaxies or stars, benefit of multi-object spectroscopy (MOS) technique. Micromirror arrays based on MOEMS technology could act as reconfigurable slit masks.

A silicon-based MMA has been designed for cryogenic temperatures and tested at 92K, and a commercial array (DMD) has been tested in a space evaluation program. They have shown both their ability to operate properly at cold temperatures.

We have also developed a bench for MOS demonstration using MOEMS devices. Both components have been successfully tested revealing good contrast values as well as good functionality for applying any mask pattern. These developments and tests demonstrate the full ability of this type of components for space instrumentation, especially in multi-object spectroscopy applications.

## ACKNOWLEDGEMENT

The authors would like to thank the SAMLAB at EPFL and the Service Essais at LAM. This work is partly funded by ESA, CNRS, Provence-Alpes-Cote d'Azur regional council and Conseil General des Bouches-du-Rhone county council.

## 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] M. Robberto, A. Cimatti, A. Jacobsen, F. Zamkotsian, F. M. Zerbi, "Applications of DMDs for Astrophysical Research", in *Proceedings of the SPIE conference on MOEMS 2009*, Proc. SPIE **7210**, San Jose, USA (2009)

[4] M. J. Li; A. D. Brown; A. S. Kutyrev; H. S. Moseley; V. Mikula, " JWST microshutter array system and beyond", Proc. SPIE 7594, San Francisco, USA, 2010

[5] S. Waldis, F. Zamkotsian, P.-A. Clerc, W. Noell, M. Zickar, 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] M. Canonica, S. Waldis, F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij, " Development of MEMS-based programmable slit mask for multi-object spectroscopy ", in *Proceedings of the SPIE conference on Astronomical Telescopes and Instrumentation*, Proc. SPIE **7739**, San Diego, USA (2010)

[7] F. Zamkotsian, K. Dohlen, "Performance modeling of JWST Near Infrared Multi-Object Spectrograph," in *Proceedings of the SPIE conference on Astronomical Telescopes and Instrumentation 2004*, Proc. SPIE **5487**, Glasgow, United Kingdom (2004)

[8] 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)

[9] A. Liotard, F. Zamkotsian, "Static and dynamic micro-deformable mirror characterization by phase-shifting and time-averaged interferometry", in *Proceedings of the SPIE conference on Astronomical Telescopes and Instrumentation 2004*, Proc. SPIE **5494**, Glasgow, United Kingdom (2004)

[10] F. Zamkotsian, E. Grassi, P. Lanzoni, R. Barette, C. Fabron, K. Tangen, L. Marchand, L. Duvet "DMD chip space evaluation for ESA EUCLID mission," in *Proceedings of the SPIE conference on MOEMS 2010*, Proc. SPIE **7596**, San Francisco, USA (2010)

[11] F. Zamkotsian, K. Tangen, P. Lanzoni, E. Grassi, R. Barette, C. Fabron, L. Valenziano, L. Marchand, L. Duvet "Space evaluation of a MOEMS device for space instrumentation", this conference, Rhodes, Greece (2010)