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MOEMS-based new functionalities for future instrumentation in space

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Abstract **– Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. In Earth Observation, Universe Observation and Planet Exploration, scientific return of the instruments must be optimized in future missions. MOEMS devices are based on the mature micro-electronics technology and in addition to their compactness, scalability, and specific task customization, they could generate new functions not available with current technologies. CNES has initiated a study with LAM and TAS for listing the new functions associated with several types of MEMS (programmable slits, programmable micro-diffraction gratings, micro-deformable mirrors). Instrumental applications are then derived and promising concepts are described.**

Keywords: Space instrumentation, MOEMS, New functions

I. INTRODUCTION

Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. In Earth Observation, Universe Observation and Planet Exploration, scientific return of the instruments must be optimized in future missions. MOEMS devices are based on the mature micro-electronics technology and in addition to their compactness, scalability, and specific task customization, they could generate new functions not available with current technologies. CNES has initiated a study with LAM and TAS for listing the new functions associated with several types of MEMS.

Several MEMS devices have been considered in terms of performance and abilities for different functions:

- Programmable slits
- Programmable micro-diffraction gratings
- Micro-deformable mirrors

For the programmable slits, two devices are promising for developing new applications, a silicon-based MMA designed and realized by laboratories and a commercial array. A European development is under way between LAM and EPFL in order to develop micro-mirror arrays for generating reflective slit masks in future Multi-Object Spectrographs. These programmable reflective slit masks are composed of 2048 individually addressable 100 x 200 μm^2 micromirrors in a 32x64 array. Each silicon micromirror is electrostatically tilted by a precise angle of at least 20° for an actuation voltage of 130 V. These micromirrors demonstrated very good surface quality with a deformation below 10 nm, individual addressing using a line-column scheme, and they are working in a cryogenic environment at 162K. The commercial array is the popular DMD device from Texas Instruments. The DMD features 2048 x 1080 mirrors on a 13.68µm pitch and has been previously tested by our team for space applications.

With the programmable slits, several functions have been listed and possible applications found. Functions are selection of objects or parts of a FOV, feeding instruments in two directions, selecting two pointing directions, modulation of the light intensity by zone on a temporal basis, pupil shape configuration, spectral selection and slit masks generation.

Programmable diffraction gratings are a new-class of MOEMS devices. Piston-motion parallel moving ribbons could be set locally as a grating, and then diffract the light. If the incoming light spectrum is dispersed along the device, any wavelength could be selected or removed by tuning the device. We have characterized the performances of two devices: a silicon-based device designed and realized by laboratories (CSEM, LAM, EPFL) and a commercial array from Silicon Light Machines.

With the programmable diffraction gratings, several functions have been listed and possible applications found. Functions are wavelength selection for spectroscopy or spectral tailoring, optical beam selection and attenuation, these two first functions including temporal behaviour, and beam addressing by using the diffraction orders.

Micro-deformable mirrors are used for wavefront correction, mainly in adaptive optics systems. Boston

Micromachines Corporation (BMC) produces the most advanced MEMS deformable mirrors.

With the micro-deformable mirrors, several functions have been listed and possible applications found. Functions are wavefront correction (active or adaptive modes depending on loop frequency), optical beam tailoring and focal plane curvature compensation.

II. MOEMS

Optical MEMS could be useful for designing future generation of instruments. In addition to their compactness, scalability, and specific task customization, they could generate new functions not available with current technologies. These devices have been developed or successfully used in a wide range of ground-based commercial applications, from telecom to life science, and from imaging to spectroscopy. MOEMS are not yet widely used for space application, but this technology will most likely provide the key to new science and instrumentation. The first major application will be the micro-shutters array in NIRSpec for JWST.

A. Micro-Mirror arrays

Texas Instruments' Digital Micromirror Devices (DMD) [1], are the most popular MOEMS devices available on the market. If the prime use is for displaying images, numerous applications may be thought: multi-object selection, spectral selection, hyperspectral imaging, confocal microscopy … However, the flexibility in terms of applications is balanced by the rigidity in terms of customization: TI (or related companies) proposes only a limited number of components (array format and size of the mirrors) and sometimes, three possible coatings on the protecting window (UV, visible, IR). In terms of space compatibility, a full campaign has been already conducted through an ESA contract and do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements (vacuum, -40°C, mirror in tilted position during 1500s) [2].

In Europe, an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy [3]. 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 project is called **MIRA**. The requirements for our MMA were determined from previous simulation results and measurements [4]. It has to achieve a high optical contrast of 1000:1 (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.

CONCEPT AND FABRICATION

Our MMA concept is based on the electrostatic double plate actuator. A micromirror is suspended by two flexion hinges, which were attached to a sustaining frame. To generate an electrostatic force, an electrode is placed underneath the micromirror and pillars are placed to set a precise electrostatic gap. A stopper beam is placed under the frame to set precisely the tilt angle of the micromirror after actuation and electrosatically lock it in this position.

The 100 x 200 μm^2 micromirrors were made of single-crystal silicon, assuring optical flat surfaces. 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.

For MMA realization, a combination of bulk and surface silicon micromachining was used. They were made of two wafers: one for the mirrors and one for the electrodes, which were processed separately and assembled by wafer level bonding. For applications in modern and future telescopes large arrays are required. We developed 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. Prototypes of MMA with 2048 individually addressable micromirrors (64 x 32 mirrors) have been successfully realized (Fig. 1) [5].

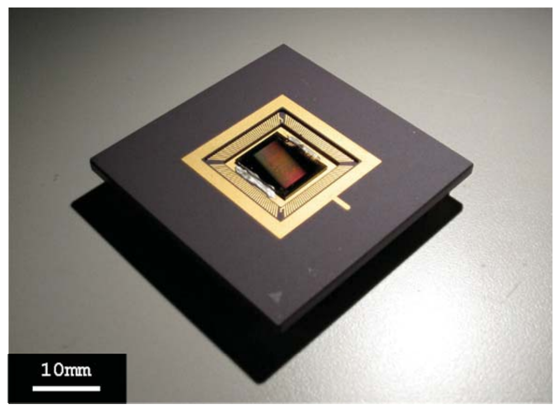

Figure 1. 64 x 32 micromirror array with high fill factor in the vertical direction provinding long slits. Each mirror measures 200 x 100 μm^2.Two wafer level bonding steps are required to process these arrays.

MICROMIRROR ARRAY CHARACTERIZATION

MMA have been tested at LAM on bench set-ups dedicated to the characterization of MOEMS devices.

Micromirror surface flatness measurement and actuation

The surface quality of the micromirror is measured by phase-shifting interferometry, and a total deformation of 10nm peak-to-valley is measured, with 1nm roughness. These mirrors can be electrostatically tilted by 24° at an actuation voltage of 130V. In many MOS observations, astronomers need to have the spectrum of the background nearby the studied object ("long slit" mode). Our locking mechanism is designed in order to ensure this goal and a performance of a few arc-minutes angle difference has been obtained on first prototypes.

The fill factor characterized by SEM was 82.3% for the mirror surface and 98% in the direction along the micromirror lines.

Individual addressing of the mirrors is based on a line-column scheme. As a proof of concept, a 2 x 2 sub-part of a MMA of 32 x 64 micromirrors was actuated successfully [5].

Contrast measurement

The contrast of a micromirror was characterized on a dedicated optical bench at LAM. A light source having a diameter of 200 µm has been focused on a micromirror. Two pictures were recorded: for a micromirror at rest (OFF state) and for a micromirror tilted (ON state). The light intensity of each picture was integrated over the micromirror surface and the ratio between the pictures provided the contrast. Finally, for a micromirror tilting by 24°, a contrast ratio of 1000:1 was obtained.

Operation at cryogenic temperature

In order, to avoid spoiling of the astronomical objects spectra by the thermal emission of the instrument, the micromirror array has to work in a cryogenic environment.

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. The interferometer provides a sub-nanometer accuracy, and the cryo-chamber allows pressure down to 10^{-6} mbar and cryogenic temperatures (Fig. 2).

Our MMA is conceived 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 down to the operating temperature, especially on the mirrors themselves be covered with a gold layer, gold having a different CTE than silicon.

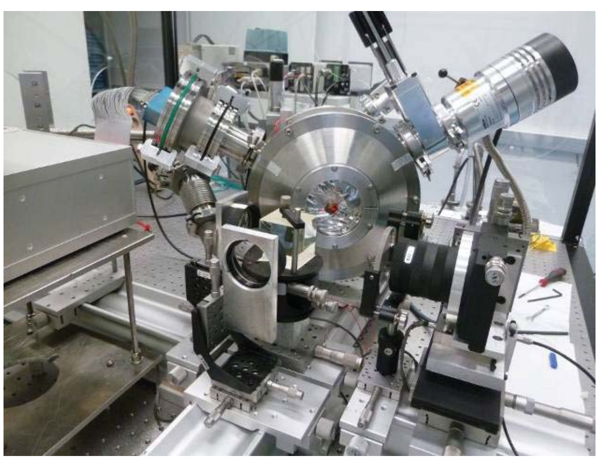

Figure 2. Cryogenic chamber installed on our interferometric setup. MMA with 64 x 32 micromirrors is integrated (100 x 200 µm^2 micromirrors).

The chamber has a glass window that allows observing and measuring the sample chip during cryogenic testing. The micromirror device is illuminated and imagined by a CCD camera on the outside; the micromirror device is rotated such that the light of the tilted mirrors (ON state) is sent to the CCD camera. The presence of a glass window at the entrance of the chamber is an issue for getting fringes with a high contrast. Thanks to the use of a plate in the reference arm identical to the chamber window, we could get a high contrast in our measurements.

The MMA device is packaged in PGA chip carrier (Fig. 1). The PGA is inserted in the chamber on a ZIF-holder integrated on a PCB board. Large copper surfaces on the PCB facilitate cooling down the system. A 100-pins feed-through connector links the chip with a custom built MMA control electronics. Temperature sensors are connected to the aluminum support and to the grid zip connector adjacent to the sample chip, in order to monitor the tests.

The micromirrors could be successfully actuated before, during and after cryogenic cooling at 162K (Fig. 3). Several lines of 32 micromirrors were successfully tilted with a driving voltage of 148V. We could measure the surface quality of the gold coated micromirrors at room temperature and at 162 K without large deformation difference.

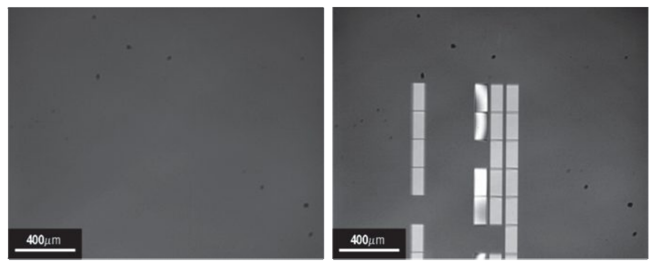

Figure 3. Interferometric observations of the lines of micromirrors during the cryogenic experiment at 162K: micromirrors at rest (OFF state) and in ON state when 148V is applied. Mirrors are tilted by 24°.

B. Programmable Micro-Diffraction Gratings

Programmable Micro-Diffraction Gratings (PMDG) are a new type of MOEMS components, built with the mature micro-electronics technology. We use a PMDG device made by SLM [6] (Fig. 4). It is constituted of 1086 "pixels" with 6 ribbons / pixel (3 fixed, 3 variable in Z location). The width of the ribbons is 3.775µm, and the gap width is 0.475µm, leading to a pitch of 4.250µm; the length of the ribbons is 220µm supported between two posts (Fig. 4).

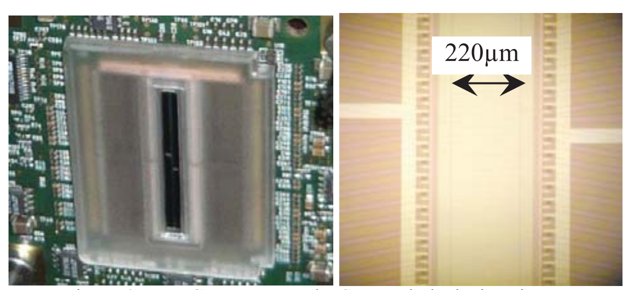

Figure 4. PMDG components by SLM, whole device picture and detail of the ribbons (length 220µm).

A window with an anti-reflecting coating in the visible is protecting the device. The PCB board is connected to an external electronics box through a flex cable, and the electronics is linked to the computer with a serial cable. We have developed the serial link configuration and the driving software in Matlab, in order to drive directly the PMDG device via the serial link.

Our measurements were conducted in the 0^{th} order with a filtering of the higher orders in the Fourier plane. When the ribbons are in the rest position, they are all in the same plane, generating a flat mirror-like surface. When the ribbons are actuated and set at λ/4 position, these pixels diffract the incoming light, and, while this light is blocked in the Fourier plane, they appear dark on the CCD camera. A close-up view focused on a few PMDG pixels is shown in Fig. 5, where all ON and one ON – one OFF pixels are displayed. Note that this feature is obtained only in the active area of the PMDG, i.e. within 150 µm located at the centre of the ribbons. Outside the active area, no diffraction occurs and the Al-coated surfaces reflect light.

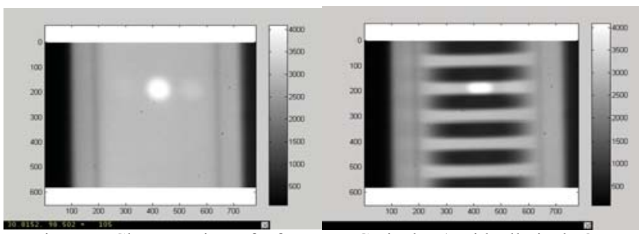

Figure 5. Close-up view of a few PMDG pixels; a) with all pixels ON, b) with a serial of one ON and one OFF pixels.

For spectrum tailoring, the incoming light is dispersed and then imaged on the PMDG surface. According to the wavelength λ arriving on each pixel, the OFF state is obtained when the stroke of the ribbons is equal exactly to λ/4. A calibration step is required for determining the right voltage to be applied for obtaining this condition. We can then implement the optimal OFF position for any wavelength on any pixel. These values have been measured for all PMDG pixels in the field of view. The contrast is determined as the light flux ratio between ON and OFF states. The measured contrast is better than 30 all over our wavelength band (550 – 650 nm). [7]

C. *Micro-Deformable Mirrors*

Boston Micromachines Corporation (BMC) [8] produces the most advanced MEMS deformable mirrors. Their main parameters are approaching the requirements values, i.e. large number of actuators (up to 4096), large stroke (up to 5.5 µm), good surface quality, but they still need large voltages for their actuation (150 – 250 V). Space qualification is an issue and to our knowledge, tests have been conducted for that purpose. This year, NASA has selected BMC for two Phase 1 contracts, in order to develop devices and electronics suited for space applications (main goal: wave-front control in space-based high contrast imaging instruments).

III. INSTRUMENTAL FUNCTIONS

For each MOEMS type, functions have been listed. Position of the MOEMS device in the optical design is noted as “i” if the device is in the image plane, or “p” if the device is in the pupil plane.

A. *Functions with Micro-Mirror arrays*

In the following table, new functions using micro-mirror arrays are listed and described. Full description of these functions is given in the following paragraphs.

TABLE I. FUNCTIONS WITH MICRO-MIRROR ARRAYS

Function	Position	Description
F1	i	Selection of objects or part of FOV
	p	Pupil configuration
F2	i	Flux orientation in two directions (feeding two instruments with the same FOV)
	p	
F3	i	Observation along two directions and possible combination (two FOV observed with a single instrument)
	p	
F4	i	Temporal modulatin of the flux within FOV or part of FOV
	p	
F5	i	Spectral selection, large FOV programmable spectrograph

1) *Function F1: selection of objects or part of FOV and pupil configuration*

Using micro-mirror arrays located in the image plane of an optical system, objects or part of FOV could be selected. This function is one of the first investigated functions with this type of MEMS in astronomy.

Multi-object spectroscopy (MOS) allows measuring infrared spectra of faint astronomical objects that provides information on the evolution of the Universe. MOS requires a slit mask for object selection at the focal plane of the telescope. Next-generation infrared MOS for ground-based and space telescopes could be based on MOEMS programmable slit masks. For the near infrared spectrograph (NIRSpec) of JWST, a MEMS-based programmable array has been developed and fabricated by NASA. During the early-phase studies of the European Space Agency (ESA) EUCLID mission, a MOS instrument based on a MOEMS device has been assessed. A promising possible solution is the use of MOEMS devices such as micromirror arrays (MMA) [9,10,11] or micro-shutter arrays (MSA) [12].

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. In Europe an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy [3,5]. 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.

A schematic view of this function is shown in Fig. 6.

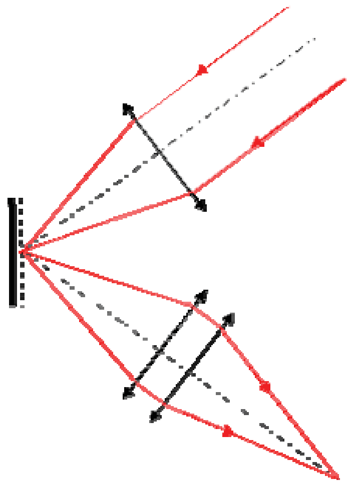

Figure 6. Function F1: selection of objects or part of FOV

Any windowing (open and/or close) application could be foreseen in this function, including coronography or masking of any part of the FOV, following any shape. This application is limited by the "resolution" of the device, i.e. the number of micro-elements in the device versus the FOV.

If the micro-mirror array is located in a pupil plane, the pupil could be tailored as desired. Application in apodisation or in masking part of the pupil is possible. Removing wavefront defects or simulating a diaphragm is possible as well. However, the size of the pupil is limited to the size of the array if a monolithic pupil is considered; buttable components (MIRA) may lead to larger pupils.

2) Function F2: Flux orientation in two directions

Flux incoming on the micro-mirror array located in an image plane could be oriented in two directions, for feeding for example two instruments with the same FOV (or part of the same FOV). This function could be applied simultaneously or sequentially. Then the collecting optics is unique and fully shared by the instruments.

On the MOEMS device requirements, the tilt angle positions of the device must be precisely determined in order to feed properly the instruments.

This function could also be used as an achromatic beamsplitter.

A schematic view of this function is shown in Fig. 7.

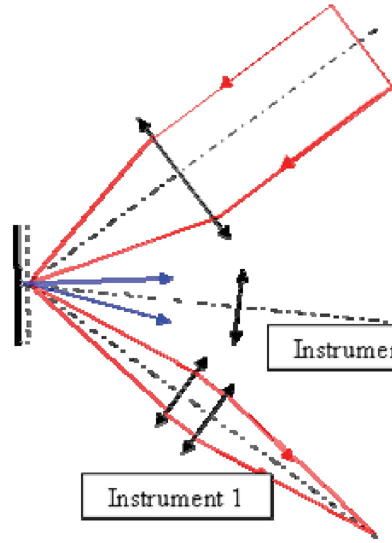

Figure 7. Function F2: Flux orientation in two directions

If the micro-mirror array is located in a pupil plane, the function is identical. However, the size of the pupil is limited to the size of the array if a monolithic pupil is considered; buttable components (MIRA) may lead to larger pupils.

3) Function F3: Observation along two directions and possible combination

This original function permits to use and/or combine flux coming from two directions in the same instrument, simultaneously or sequentially.

A schematic view of this function is shown in Fig. 8.

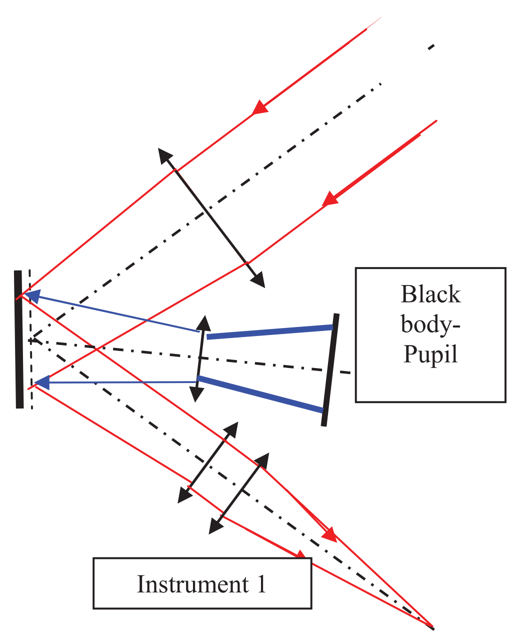

Figure 8. Function F3: Observation along two directions and possible combination

For example, this function could be used in an instrument were a fast calibration is needed after each exposure, on the sky or on a black body inside the instrument. The tilting speed is a key requirement in this application.

Instrument design as well as system feasibility have to be investigated.

4) Function F4: Temporal modulatin of the flux within FOV or part of FOV

Temporal modulation of the optical beam is possible with the micro-mirror arrays, thanks to their high resonance frequency. Within each exposure the position of each micro-mirror could be changed from one stable position to the other stable position, modulating then the incoming flux on this mirror, i.e. on the associated detector pixel(s). This function is commonly used with these devices (for example DMD components from Texas Instruments) for display applications.

In our case, saturation of the signal could be avoided on the FOV or part(s) of the FOV.

The incoming signal could also be modulated for application in heterodyne or synchronous detection. The signal to noise ratio could then be increased by orders of magnitude. This concept could be used in the infra-red or in the visible for discriminating the signal and the noise.

Dynamical masking of the FOV or part of the FOV is also possible with application on faint objects detection, “programmable neutral density filter” generation or tailoring the incoming beam according to detector dynamical range.

Limitation of this function is linked to the resonance frequency of the micro-elements as well as the contrast of the device.

A schematic view of this function is identical to function 1, and shown in Fig. 6.

5) Function F5: Spectral selection, large FOV programmable spectrograph

For this concept, the principle is to use a MOEMS component to select the wavelengths. Two MOEMS components could be considered, programmable micro-diffraction gratings (PMDG) and micro-mirror arrays like the Digital Micro-Mirror Device (DMD) from TI. Indeed, this component is placed in the focal plane of a first diffracting stage (using a grating for instance) and is used as a wavelength selector by reflecting or switching-off the light (by diffraction for the PMDG or by deflexion for the DMD). It becomes then possible to realise a programmable and adjustable filter in λ and $\Delta\lambda$ (Fig 9).

For a point-like object, a 1D MOEMS device is required. One dimension demonstration has been already obtained, using a PMDG device [7,13]. For a 1D FOV, a 2D device is mandatory, limiting the MOEMS choice to a micro-mirror array (Fig. 9). Then, on the DMD surface, the spatial dimension is along one side of the device and for each spatial point, its spectrum is displayed along the perpendicular direction: each spatial and spectral feature of the 1D FOV is fully adjustable and/or programmable for each exposure or even during an exposure by using the temporal behaviour of the component.

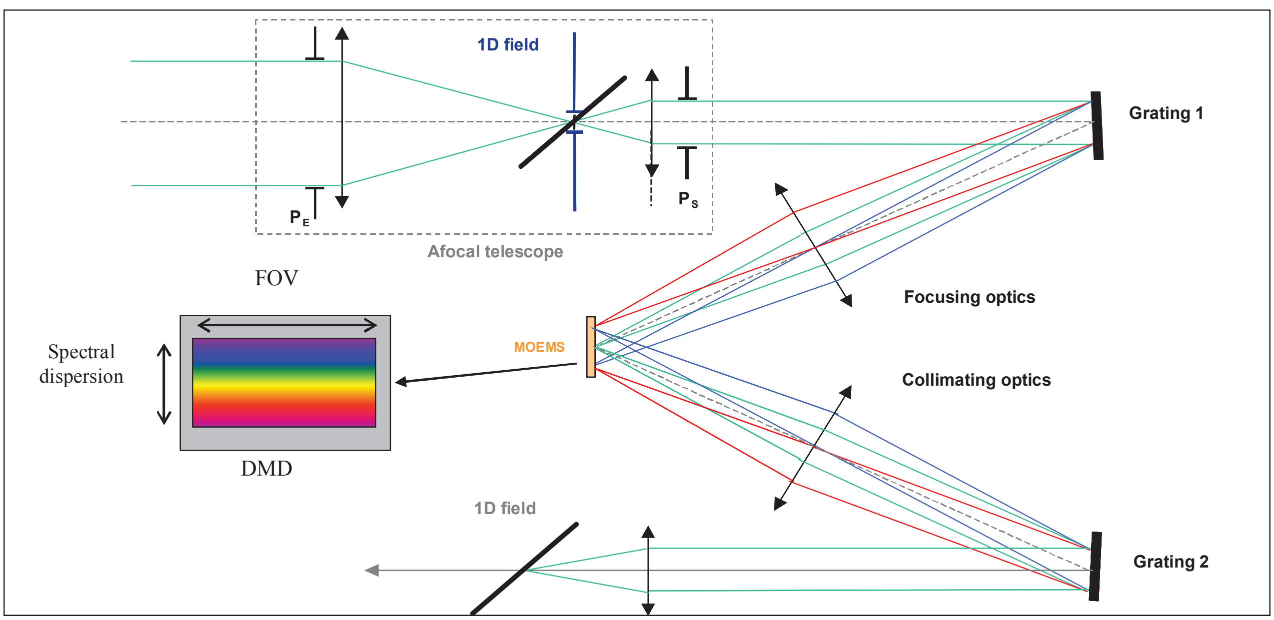

Figure 9. Function F5: Spectral selection, large FOV programmable spectrograph

B. Functions with Programmable Micro-Diffraction Gratings

In the following table, new functions using Programmable Micro-Diffraction Gratings (PMDG) are listed and described. Full description of these functions is given in the following paragraphs.

TABLE II. FUNCTIONS WITH PROGRAMMABLE MICRO-DIFFRACTION GRATINGS

Function	Position	Description
F1	i	Spectral selection
F2	i	Flux selection
F3	i	Temporal modulation of the flux
F4	i	Flux re-orientation by diffraction effect

1) Function F1: Spectral selection

Using a PMDG located in the image plane of an optical system, spectrum of the source could be tailored. This function is one of the first investigated functions with this type of MEMS, in astronomy [7,14]. The spectral resolution is directly linked to the number of micro-elements in the device.

A schematic view of this function is shown in Fig. 9.

2) Function F2: Flux selection

PMDG used as a flux selector is based on the diffraction efficiency of the device. By placing a stop in the Fourier plane, the diffracted light could be blocked (OFF position) while the non-diffracted light goes out of the optical system (ON position). In a more complex optical design, the diffracted light could be the ON position.

3) Function F3: Temporal modulation of the flux

Temporal modulation of the optical beam is possible with a PMDG, thanks to ribbons high resonance frequency. Within each exposure the position of each ribbon could be changed in an analog or digital way, modulating then the incoming flux on each PMDG pixel. This function is commonly used with these devices for display applications. The image is obtained by columns, and lines are populated using an additional scanning mirror [6,15].

4) Function F4: Flux re-orientation by diffraction effect

This potential function could be really efficient if the diffraction efficiency of the grating could be adjusted by realizing blazed gratings. Realization of blazed gratings at the scale of the PMDG ribbons, i.e. around 4µm, is a challenge.

C. Functions with Micro-Deformable Mirrors

In the following table, new functions using micro-deformable mirrors are listed and described. Full description of these functions is given in the following paragraphs.

TABLE III. FUNCTIONS WITH MICRO-DEFORMABLE MIRRORS

Function	Position	Description
F1	p	Wavefront correction (active or adaptive modes depending on loop frequency
F2	p	Optical beam tailoring
F3	i	Focal plane curvature compensation

1) Function F1: Wavefront correction

Using a micro-deformable mirror located in the pupil plane of an optical system, wavefront could be corrected. This function is one of the first investigated functions with this type of MEMS in astronomy. Active or adaptive modes are used depending on loop frequency. Atmosphere turbulence, optical system aberrations, alignment residuals, dynamical effects (thermal, gravity) could be corrected.

The wavefront correction is directly linked to the number of actuators, their stroke and their resonance frequency.

The actual size of the micro-deformable mirror is also limiting the FOV, due to the Lagrange invariant of an optical system.

2) Function F2: Optical beam tailoring

Optical beam tailoring is of prime interest for laser beams. Devices able to operate under high optical fluxes are mandatory.

3) Function F3: Focal plane curvature compensation

If the micro-deformable mirror is located in an image plane, focal plane curvature could be corrected. This function is limited by the stroke of the component, usually from few microns to tens microns.

IV. CONCLUSION

Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. In Earth Observation, Universe Observation and Planet Exploration, scientific return of the instruments must be optimized in future missions. They could generate new functions not available with current technologies. New functions associated with several types of MEMS (programmable slits, programmable micro-diffraction gratings, micro-deformable mirrors) have been studied. Instrumental applications are then derived.

A promising concept has been chosen for a complete experimental demonstration on a bench: a wide-field programmable spectrograph based on a DMD device is under study and a breadboard will be built.

V. ACKNOWLEDGEMNTS

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