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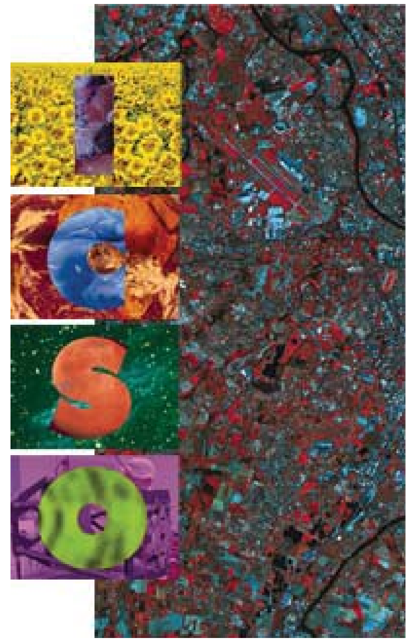

MOEMs, key optical components for future astronomical instrumentation in space

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MOEMS, KEY OPTICAL COMPONENTS 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 and telescopes, especially for space missions. The main advantages of micro-optical components are their compactness, scalability, specific task customization using elementary building blocks, and they allows remote control. As these systems are easily replicable, the price of the components is decreasing dramatically when their number is increasing. The two major applications of MOEMS are Multi-Object Spectroscopy masks and Deformable Mirror systems.*

1 – SCIENCE CONTEXT

Micro-Opto-Electro-Mechanical Systems (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 brings into fashion what astronomy always wanted to do, explaining where we are coming from :

i) How did galaxies form and evolve to reach the universe we observe today?

ii) How did planets form and eventually evolve into Jupiters, Saturns, or, maybe more interestingly, life-carrying Earths?

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. A possible option would be to use Integral-Field Spectrographs, which observe spectroscopically all the pixels within a given field of view. Indeed, the concept is very interesting for specific observations: galaxy clusters, stellar clusters where the density of targets is high.
However, 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.

2. MOEMS

MOEMS 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 allows remote control. The two major applications of MOEMS are Multi-Object Spectroscopy masks and Deformable Mirror systems.

MOEMS technology is closely linked to the micro-electronics fabrication process. Various materials are deposited on the surface of a substrate, and, using masks, their localization on the substrate is precisely defined in order to ensure their specific tasks. In micro-systems, there are two kinds of layers: structural layers and sacrificial layers. The structural layer materials are polysilicon or metal, and the sacrificial layers are silicon oxides or organic materials. The sacrificial layers are chemically dissolved at the end of the fabrication process in order to create air gaps between the remaining structural layers. A great level of sophistication in the micro-electronics technology ensures excellent tolerances on layer thickness and patterning precision.

Micro-mechanical actuation is obtained using electrostatic, magnetic or thermal effects, but the most advanced actuation is achieved by the electrostatic effect. The electrostatic actuator consists of two electrodes of metal or polysilicon heavily doped with phosphorous, isolated from each other by a gap of thickness g filled with dielectric medium, usually air. When a voltage V is applied between the electrodes, an attractive force F is generated, and if one of the electrodes is mobile, it moves toward the other. By neglecting edge effects and bending of the electrodes, i. e. assuming good stiffness of the electrodes, the instantaneous, nonlinear electrostatic force F is defined by the following relationship of key parameters:

$$F = \frac{A\varepsilon V^2}{2g^2}$$

where A is the overlapping electrode area and ε is the dielectric constant in the inter-electrode spacing. Assuming h the inter-electrode initial gap (without voltage), and x the deflection of the upper electrode, the value of g is decreasing from h to $(h - x)$ when the upper electrode is moving. The accessible motion is generally limited to one third of h. At this limit, the nonlinear electrostatic force increases more rapidly than a linear restoring force, applied for example by springs attached to the upper electrode. The electrostatic effect then becomes unstable and the mobile electrode drops toward the fixed electrode and sticks to it.

In the design of MOEMS components, various parameters have to be tuned. These parameters differ according to the functionality of the component. We will consider two different devices, a Micro-Mirror Array (MMA) for Multi-Object Spectroscopy and a Micro-Deformable Mirror (MDM) for wave front correction.

An MMA is an array of electrostatically driven bistable mirrors, with a size of a few tens of micrometers, which can occupy two discrete positions, ON and OFF, with switching times of a few microseconds. The two positions are obtained when the mirror hits physically the substrate, using the electrostatic motion until its unstable portion. Specific parameters for this device are the tilt angle and the actuation voltage. The tilt angle determines the separation between the input beam and the output beam and therefore the possible numerical aperture of the instrument. A large tilt angle reduces also the scattered light of the array entering the output pupil. However, the fabrication process is not compatible with the use of very thick sacrificial layers on top of the substrate, limiting the tilt angle. The two discrete positions are typically rotated ±10° with regard to the substrate plane, i.e. a 40° beam separation. The measurement and the analysis of this scattered light are still to be done. The second parameter is the actuation voltage

MDM are constituted by a reflective surface with an underlying set of actuators driven in the linear portion of the electrostatic motion. For MDM, key aspects are inter-actuator spacing, inter-actuator coupling, actuator bandwidth and low driving voltage. High order wave front correction needs a large number of actuators. The size of conventional Si wafers limits the maximal size of single deformable mirrors, increasing the required density of actuators. Typical inter-actuator spacing could be in the range 200-500 µm. Inter-actuator coupling factor can be defined by the ratio of the motion of an actuator without voltage to the motion of a neighboring actuator in action. If this factor is close to 1, there is too much redundancy, the effective actuator number is drastically reduced and high order deformations cannot be corrected properly. If this factor is zero, sharp slopes are present on the surface, usually on top of the actuator location, resulting in larger residual wave front errors. If this factor is 20-30 %, the surface has a smooth overall shape with low residual errors.

For both devices, MMA and MDM, three additional parameters are of interest: the optical surface quality, the driving electronics and the actuator bandwidth. As these micro-optical components include mirrors, their surface quality must be excellent. We have developed an original method based on Foucault's knife-edge test for the surface characterization of individual MMA micro-mirrors. The driving electronics is also a challenge as the high number of actuators integrated on a semiconductor substrate leaves individual actuator driving impossible. The driving circuit has to be integrated on the wafer or directly bonded to the optically active elements. The driving voltage must then be as low as possible, a few tens of volts will be preferable to the several hundreds of volts often used in present-technology devices. The design of driving circuits requires high attention in order to match the needed bandwidth, and to be compatible with the technology employed to realize the mobile mirrors on top of the electronic driving circuit. Finally, the bandwidth of these components must match the specific requirements.

For space applications, cryogenic-operation is not yet demonstrated for any MOEMS. Specific problems have to be studied in cryogenic conditions: the residual stress in the component layers and the sticking effects.

The bending in the structural layer of the mirrors is due to residual stresses, and technological efforts are to be done to reduce this stress. An additional parameter is the strong dependence of bending with temperature. The pixel bending at low temperature is unknown and its value has to be minimized. For some applications, additional reflective coating is required, but these coatings have residual stress different from the mirror layer stress and new coatings with thermal-expansion characteristics compatible with mirror material must be found. The coating stress is a major issue during cooling, with a high risk of breaking or pealing. Sticking effects in cryogenic conditions have also to be studied with care. In MMA, there is a contact between the two electrodes of micro-mirrors, and sticking is avoided by using a thin insulating layer and a reset electrical pulse. At low temperature, sticking effects are dramatically enhanced and efficient solutions must be found.

3. MICRO-MIRROR ARRAY FOR MULTI-OBJECT SPECTROSCOPY

In order to obtain spectra of hundreds of objects simultaneously, MOS require a reconfigurable multi-slit device. Conventional masks or complex fiber-optics-based mechanisms are impracticable in space. A promising solution is the use of an MMA for generating reflecting slits [Burg 98, Burga 98]. By placing the MMA in the focal plane of the telescope, the light from selected objects is directed toward the spectrograph, while the light from others objects and from the sky background is blocked in a light trap (Fig. 1). MMA allows remote control of the multi-slit configuration in real time.

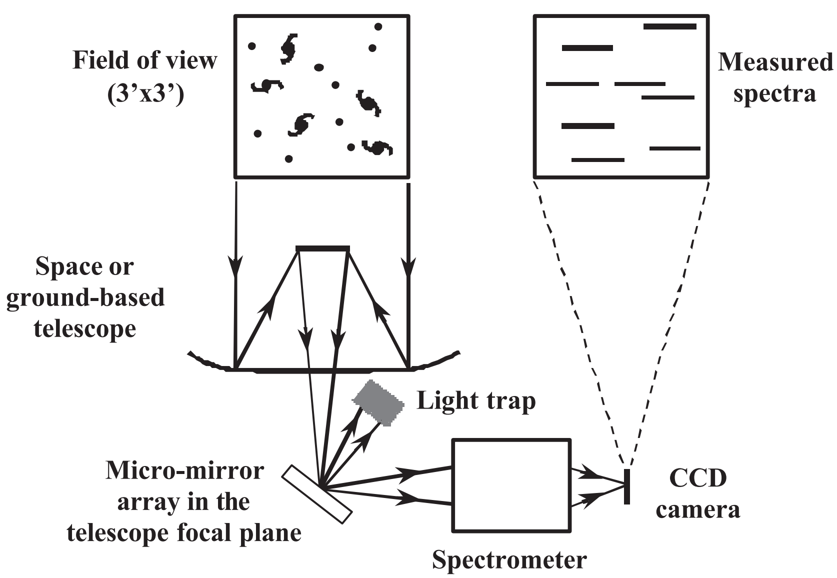


Fig. 1: Principle of Multi-Object Spectrograph with a Multi-Mirror Array for NGST.

We have based our work on a most impressive MOEMS realization, the MMA designed by Texas Instrument for video projection, which is an array of 1K x 1K, 17 µm pitch bistable mirrors [Horn 95]. A picture of the micro-mirrors is shown in Fig. 2. These electrostatically driven mirrors can occupy two discrete positions (ON and OFF), rotated ±10° with regard to the substrate plane. The switching time is a few microseconds. Using this MMA, any required slit configuration might be obtained with the capability to match point sources or extended objects (Fig. 2). In the park position, i.e., without driving voltage applied, the micro-mirrors are undeflected, parallel with the substrate. In action, the micro-mirrors in the ON position direct the light toward the spectrograph and appear bright, while the micro-mirrors in the OFF position are dark.

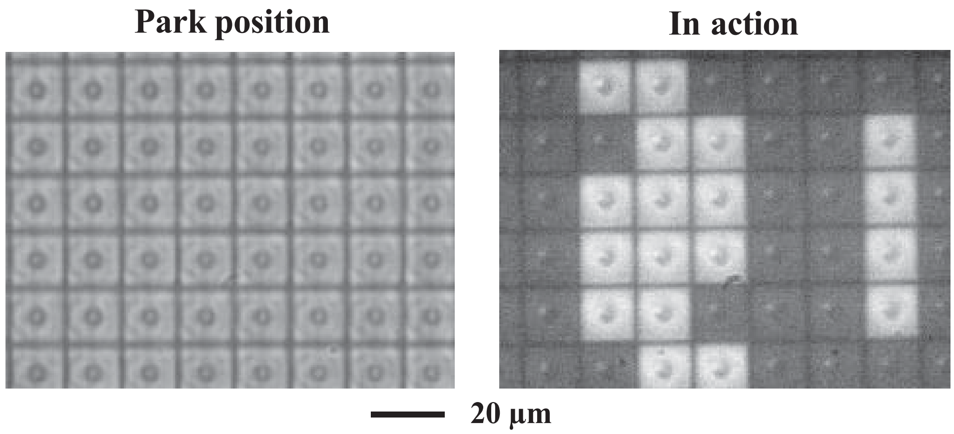


Fig. 2: MMA in park position and in action with various "slit" shapes.

In January 2000, the Ad Hoc Science Working Group (ASWG) made recommendations for three core instruments for the Next Generation Space Telescope (NGST): a camera with NIR and visible filters, sensitive across the 0.6 - 5 microns band, a multi-object dispersive spectrograph (MOS) for 1 - 5 microns with R~1000, and a combined camera/slit spectrograph for 5 - 28 microns with R~1500.
The Laboratoire d'Astrophysique de Marseille (LAM) is the only European laboratory to have participated in the NASA study of a near infra-red MOS equipped with tiltable micro-mirror array (MMA) for NGST (NGST-MOS study, PI John MacKenty). With the aim of including this micro-optical device in a MOS, we have directed our studies along three lines:

- Surface characterization of individual MMA micro-mirrors by an original method based on Foucault's knife-edge test.
- MMA optical modeling by ray tracing.
- Optical design for the MOS including two different concepts.

3.1 Surface characterization of the MMA

For testing micro-optical components, development of accurate surface characterization methods is essential. The most commonly used techniques for surface characterization are based on interferometry, but on a micron-sized regular array with deep discontinuities the results obtained are dramatically affected by diffraction effects. To overcome these effects, we have introduced a novel surface characterization method with an incoherent light source [Zam 99-1, Zam 99-3], based upon Foucault's knife-edge test [Fou 1859]. White light emanating from a slit source is collimated and illuminates the array surface. The reflected beam is refocused into an image slit and an enlarged image of the micro-mirrors is formed on a CCD camera. By moving a knife-edge through the image slit while observing the micro-mirror illumination, we estimate local slopes on the micro-mirror surface. We have used this technique to characterize the MMA designed by Texas Instruments [Horn 95].
In Fig. 3, a slope map for 8x6 micro-mirrors reveals classical knife-edge test figures on each micro-mirror. The slopes are gray-scale coded with values ranging from −0.8 mrad (black) to +0.7 mrad (white). These small slope values and their uniform distribution over the field of view indicate a satisfying flatness of the

surfaces and a good uniformity of the array. This good surface quality is a result of the use of the mature micro-electronics realization process. However, slight mirror-to-mirror shape variations are evident and indicate variable amounts of tilt and astigmatism [Zam 99-3].

We have reconstructed the micro-mirror surface by integration of the local slopes. The example shown in Fig. 4 represents the first mirror along the line indicated by an arrow in Fig. 3. The surface deformations do not exceed one nanometer along the studied profile, and appears to have a double parabolic shape.
Although surface shapes vary from mirror to mirror, deformations in the nanometer range demonstrate the remarkable quality of this device.

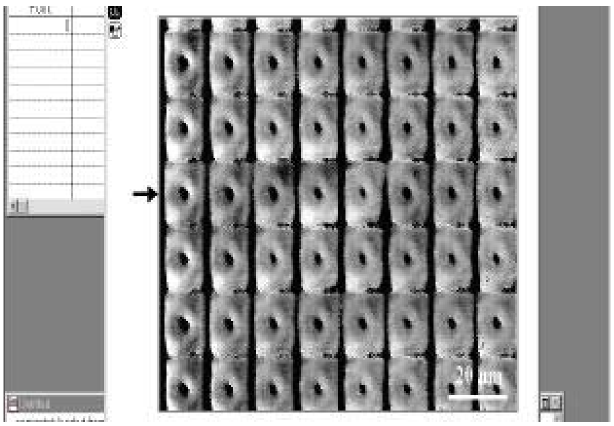


Fig. 3: Local slope map for the whole field of view.

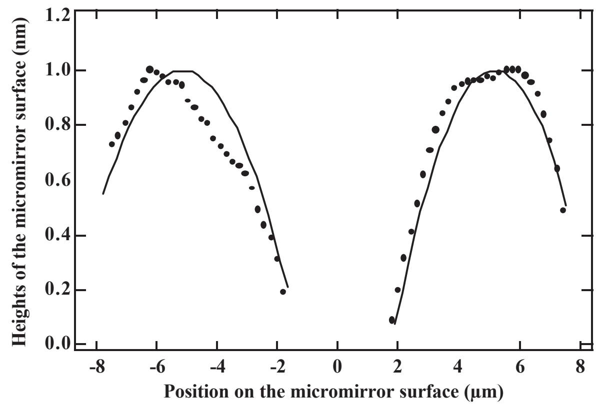


Fig. 4: Reconstruction of the micro-mirror surface along the central line of mirror 1 of the third row of micro-mirrors in Fig. 4, obtained by integration of measured slopes Parabolic approximation is superimposed.

Assuming axi-symmetrical deformation, simulation of the complete micro-mirror surface has been found to have a "palm-tree" shape, with typical maximum deformation less than 2 nm. This shape can be explained by strain relaxation in the thin aluminum layer constituting the mirror surface [Zam 99-3].

3.2 MMA modeling

Optical design of the multi-object spectrograph requires a ray-tracing equivalent of the MMA. Using the non-sequential ray tracing ability of the Synopsys program, we have simulated a block of nine micro-mirrors with individual tilt angles (Fig. 5). In Fig. 5, light focused on the MMA surface is tilted towards the ON position by the central column of mirrors and towards the OFF position by the other mirrors. The simulated micro-mirrors are TI-type mirrors, with rotation about an axis parallel with one of the mirror diagonals, and with ±10° rotation angles.

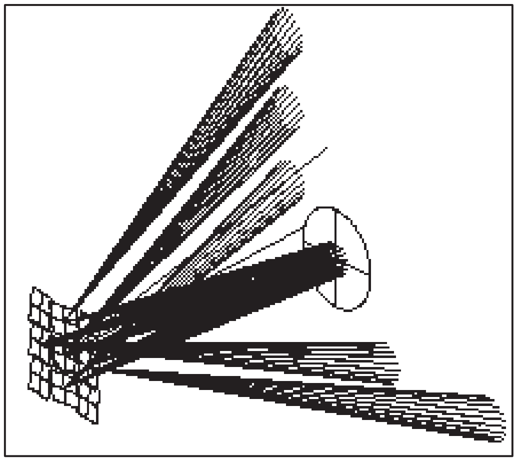


Fig. 5: MMA model for ray tracing.

Simulating an array of 800 x 600 mirrors or more is impossible by this method but, by locating blocks of micro-mirrors in critical field locations, we are able to properly design an MMA-MOS.
Future work focuses on straylight characterization, to evaluate the diffraction effects and simulate the light losses and the parasitic light generated by the mirrors in the OFF position.

3.3 MOS optical design

For our optical design, we have considered an F/24 NGST telescope beam, and, an F/7 output beam. We have studied two different concepts for the MOS: a spectrograph with F/24 to F/7 focal reduction, and an F/7, unit-magnification spectrograph preceded by a focal adaptator [Zam 99-2, Zam 00-2].

The micro-mirror size is determined by the focal ratio. For the unit-magnification spectrograph, we find that the ideal micro-mirror size is the pixel size, in order to optimize the width of the "slit" with respect to the size of the astronomical objects and to optimize the spectral resolution. According to the type of detector, the micro-mirror size is ranging from 15 to 27 µm. For the spectrograph with focal reduction, the micro-mirror size would be in the range 60-90 µm.

The spectrograph with focal reduction is composed of two spherical mirrors for the collimator and the camera and a plane aspheric grating. This optical configuration induces a curved field and tilted spectra. Although the former problem may be resolved by a field lens, the latter remains to be resolved.

Using a preceding focal adaptator, composed of two or three aspheric mirrors, avoids the above problems by allowing the use of the powerful Thevenin-type unit-magnification spectrograph [Mertz 77, Dohl 96]. This design is based on the Offner all-reflecting relay combining two concave spherical mirrors and a convex spherical grating [Off 74]. A compact spectrograph configuration of size 420x250x120 mm^3 and a grating diameter of 30 mm has been designed. This solution provides a perfectly plane image surface, avoiding the problems of the former design.

Our unit-magnification spectrograph configuration is also tolerant to the problem of the tilted focal plane generated by the MMA at the input of the instrument. Excellent aberration correction for the entire FOV is obtained by optimization of all parameters of the system [Zam 00-2].

4. MICRO DEFORMABLE MIRROR

The second major application of MOEMS in future instrumentation is in the field of deformable mirrors. LAM is involved since June 2000 in the European Research Network on the conception of Adaptive Optics systems for Extremely Large Telescopes. The micro-deformable mirrors (MDM) of these systems should be able to reach a large number of actuators (> 100 000) and small inter-actuator spacing (few 100 µm). Due to limitations in conventional technologies, we have based our new deformable mirror concepts on MOEMS technology. We are currently engaged in the definition of required technologies, materials and tests structures. These compact, lightweight and low-consumption deformable mirrors with on-chip electronics will enable the correction of wave front perturbation in highly integrated astronomical instruments for space missions (Fig. 6). 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. The applications of this type of mirror are not limited and MDM is able to tailor within some limits any wave front.

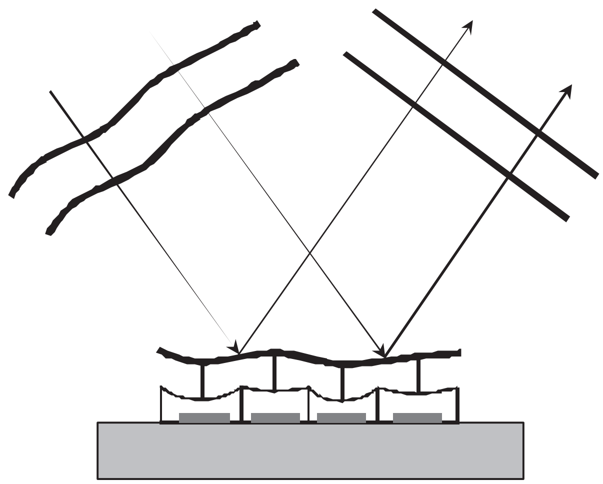
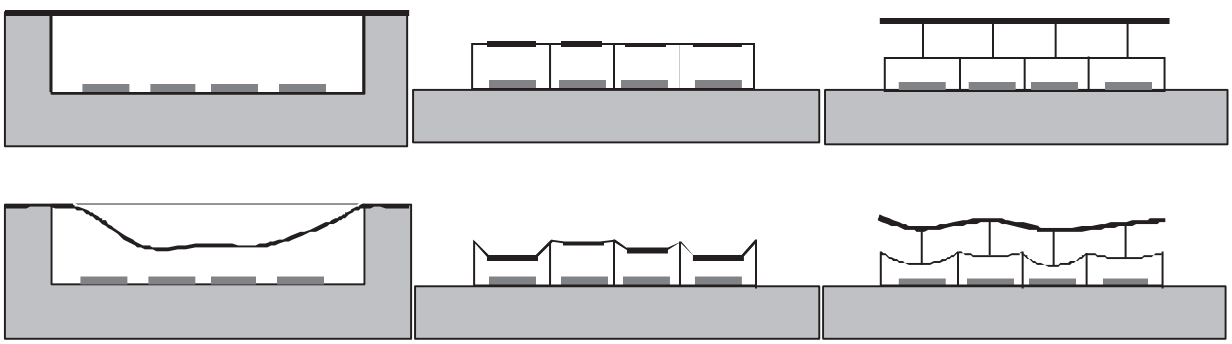


Fig. 6: Principle of wave front correction using a Micro-Deformable Mirror (MDM).

Three main MDM architectures are under study in different laboratories. First, the bulk micro-machined continuous-membrane deformable mirror, studied by Vdovin from Delft University, is a combination of bulk silicon micromachining with standard electronics technology [Vdov 97]. This mirror is formed by a thin flexible conducting membrane, coated with a reflective material, and stretched over an electrostatic electrode structure (Fig. 7 (a)). Local deflections of the membrane are obtained by applying different voltages to the electrodes. This deformable mirror has a continuous flexible mirror with a very good surface quality and a large deflection, but for a low inter-actuator coupling, inter-actuator spacing $l < 1$ mm cannot be reached, reducing therefore the number of possible correction modes. The thin and large suspended flexible mirror is also rather fragile and removing fabrication stresses is very difficult. Finally, increasing the surface of the suspended membrane is not obvious.

Second, the segmented, micro-electro-mechanical deformable mirror realized by Roggeman at University of Michigan and Cowan at Ohio Air Force Research Laboratory consists of a set of segmented piston-only moving surfaces, fabricated in dense array (Fig. 7 (b)) [Rogg 97, Cow 98]. The piston-like motion is obtained by applying a voltage between the active mirror area and an underlying address electrode. Due to the large static background, the segmented deformable mirror has a low optical efficiency (typically 40%) and large interference effects. The driving voltage is remarkably low (15 V), but the actuation efficiency (stroke/driving voltage) is comparable with the previous architecture. This device offers the highest degree of freedom and simplest control algorithms because each segment is completely independent. The segment density can be adapted to the needed aberration correction (low order, high order) and the piston motion can be increased with a larger gap between the electrodes.

Third, the surface micro-machined continuous-membrane deformable mirror made by Bifano at Boston University is based on a single compliant optical membrane supported by multiple attachments to an underlying array of surface-normal electrostatic actuators (Fig. 7 (c)) [Bifa 97]. This type of deformable mirror allows a continuous control of the membrane's local deformation with nanometer precision at the attachment points, and a frequency response exceeding 50 kHz. The number of actuators is not limited and they can be driven with an underlying electronics in the silicon substrate. High optical efficiency and minimal diffraction effects can be achieved. Main disadvantages of this architecture are small-scale print-through deformations of the optical surface due to the fabrication process, weak inter-actuator coupling and rather high driving voltage. The resulting actuation efficiency is lower than the values obtained with the two previous architectures, mainly due to the stiffness of the structure.
Another critical issue is the realization of a mirror layer without any stress, since the deposition of a thin layer on a large surface cannot be achieved without residual stress. The solution adopted by Perreault is a segmented tip-tilt mirror with anchoring posts shared between four square adjacent segments in order to ensure the optical phase continuity of the mirror [Perr 99]. Unfortunately, this solution leads to diffraction effects already discussed in the second type of MDM. This is certainly the most promising architecture, but low actuation efficiency and mirror surface quality need further improvement.



(a) (b) (c)

Fig. 7: Three different architectures of MDM, in the rest position and in action.

These three architectures, bulk micro-machined MDM, surface micro-machined continuous membrane MDM and segmented MDM, are the three main electrostatic MDM architectures. However, their performances do not at present reach the values required for an optimum system. We are therefore studying new MOEMS-based MDM architectures in close collaboration with opto-electronics research laboratories (LAAS, Toulouse, France), and we plan to realize first test devices by the middle of next year. Specific requirements for space applications will be carefully studied.

5. CONCLUSION

Micro-Opto-Electro-Mechanical Systems (MOEMS), designed for a wide range of applications, will be widely integrated in next-generation astronomical instruments and telescopes, especially for space missions. Based on the micro-electronics fabrication process, their main advantages are compactness, scalability, and specific task customization using elementary building blocks. As these systems allow remote control, they are well suited for space applications. The two major applications are Multi-Object Spectroscopy masks and Deformable Mirror systems. Micro-Mirror Arrays are good candidates to direct the light from selected objects toward the spectrograph and generate reconfigurable multi-slit masks in real time. Micro-Deformable Mirrors should enable the correction of wave front perturbation in next generation big space telescopes.

The Laboratoire d'Astrophysique de Marseille is developing since several years an expertise in the design and characterization of micro-optical components, as well as in their integration in astronomical instruments. A strong collaboration between micro-optics and astronomy will certainly lead to reach the best scientific return for the lowest cost in next generation astronomical instrumentation in space.

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