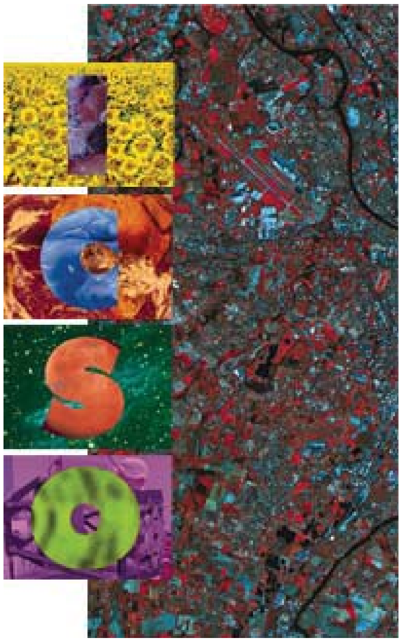
International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



Microoptoelectromechanical systems for space applications

Michel de Labachelerie

International Conference on Space Optics — ICSO 2000, edited by George Otrio, Proc. of SPIE Vol. 10569
1056901 · © 2000 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2307955

MICROOPTOELECTROMECHANICAL SYSTEMS FOR SPACE APPLICATIONS

Michel de LABACHELERIE (labachel@lpmo.edu)

IMFC / CNRS, 32 av. de l'Observatoire, 25044 Besançon Cedex

RESUME **–** Cet article présente une vue d'ensemble sur les développements technologiques dans le domaine des microsystèmes optomécaniques (MOEMS) et discute de leurs potentialités pour les applications spatiales.

ABSTRACT - This paper gives an overview of some new technologies which are currently being developed to manufacture miniature optical systems (MOEMS), and discuss their potential advantages for space applications.

1 - INTRODUCTION

MOEMS technologies are presently being developed very quickly, because these technologies are now considered as key technologies for optical fiber communications – especially in view of high bit rate FTTH (Fiber-to-the-home) optical networks. Therefore, these technologies will probably become available soon on an industrial basis, and could also be used for space applications. For this reason, space optics designers should know about the potential advantages and limitations of Micro-Nanotechnologies to take advantage of their existence. This paper presents an overview of the MicroOptoElectroMechanical Systems (MOEMS) with an emphasis on their advantages for space applications. The characteristic features of these devices are first discussed and then, the basic technologies that are necessary to fabricate MOEMS are presented. Several examples are given in order to describe more precisely what kind of applications are associated to MOEMS. After that, the advantages of MOEMS as well as their technological limitations are detailed. Finally, the potential advantages of these devices for space applications are specifically discussed.

2 - DEFINITION OF MOEMS

MOEMS are often defined by the fact that they are based on the usage of micromechanical elements to perform an optical function. Generally speaking, micromechanical elements can be used for various optical functions :

- Modifying the spatial profile or the direction of an optical beam
- Modifying the optical intensity of a beam
- Modifying the phase or the wavefront shape of an optical beam

In many cases, all these actions can be performed – to some extent - by miniaturised mechanical elements. The mechanical action can either be a physical displacement of some object (rotation of a mirror for instance), or a mechanically induced variation of mechanical stress which has an optical effect (for instance the birefringence produced by a mechanical stress in a waveguide). Devices which rely on thermally induced optical effects (for instance the temperature induced variation of refractive index) are also often considered to belong to the category of MOEMS. Moreover, it is well known by optical designers that the mechanical packaging of optical components – and especially the mechanical structures which are necessary to align optical components – is of crucial importance to make reliable and easy-to-operate optical systems. It will be shown that MOEMS technologies bring new capabilities which allow to design more simple, and probably more robust, optical systems.

Another feature which MOEMS should satisfy is the capability to be batch fabricated using the microelectronics-based fabrication technologies. The main advantage is that their fabrication cost can be drastically decreased, and this is the main reason why they become very popular. One consequence of the batch fabrication capability is that these devices should be small in order to be able to manufacture the largest possible number of devices on the same wafer. However, there is no size limit above which such devices are no more considered as MOEMS. As a matter of fact, these devices are small because one tends to manufacture as many as possible devices on the same limited substrate area to decrease the unit cost.

In conclusion, MOEMS are more precisely defined by their fabrication technologies – which are related to MEMS technologies and based on microelectronics, than by their functional properties.

3 - THE BASIC TECHNOLOGIES OF MOEMS

The basic technologies of MOEMS include first the MEMS fabrication technologies which are used to fabricate microactuators or microsensors. In addition, several optical technologies such as microlens or integrated optics technologies are merged with the MEMS technologies in order to be able to fabricate complex systems MicroOptical Systems.

3.1 - The MEMS technologies

Most of the MEMS technologies rely on a few basic processes :

- Etching of a wafer material with a protection mask defined by photolithography. This technology is mainly used to produce microstructures such as beams, membranes or grooves in crystalline substrates like silicon or quartz.
- 3D material growth by deposition inside a mould which is defined by photolithography (usually it concerns metal electrodeposition inside resist moulds). This technology allows to manufacture any microstructure with high vertical sidewalls (i.e. perpendicular to the wafer).
- Thin layer deposition and subsequent etching to pattern the layer by photolithography
- Sacrificial layer removal to release moving objects : moving objects are deposited above a thin layer which is finally etched away to release the moving part

The first two technologies are classified as “volume micromachining technologies” because they enables to fabricate rather thick (20 to 1000 µm) microstructures, and the last technologies are mainly used for “surface micromachining” since they can be used to machine thin layers of material (say less than 20 µm). For surface micromachined MEMS, all the fabrication technologies of microelectronics were available, however sacrificial layer technologies have been added to fabricate moving objects, and also new specific materials which are not used is microelectronics are needed to perform mechanical actions (piezoelectric or magnetic materials for instance). The basic materials and structures are adapted to the fabrication of specific actuators or sensors.

Actuation of microstructures require a driving force which is easily controlled by an electrical input. Since they only require a metal layer deposition, the easiest to manufacture use :

- A thermal driving force which uses the Joule effect in a conductor deposited above the structure to control its temperature through a current drive.
- An electrostatic driving force which is implemented by depositing conductors on two parts, and applying a voltage difference between them. An electrostatic attractive force tends to decrease the distance between the two parts.

Electrically controlled forces can be generated through other physical effects such as piezoelectric effect, magnetic effect. However, these means are more difficult to implement because they require thin film deposition of specific materials (piezoelectric layers or magnetic layers) which are more difficult to obtain than simple metal layers.

Most of microactuators are based on the following actuation methods :

- Mass-spring type structure : a mass is suspended by an elastic spring and, when submitted to an actuation force (electrostatic, magnetic…), it will move toward another equilibrium position determined by the magnitude of the driving force
- Bimorph structures : a beam is made of two thin layers of different materials, and when heated, the layers are submitted to a differential expansion and will bend perpendicularly to the layers. The thermal drive can be replaced by any force which produces a differential expansion of the layers (piezoelectric force, magnetostriction, …)
- Step-by-step attraction of a moving object by a “sliding” or “rotating” force, which produces the rotation of a rotor like in conventional electromagnetic motors

Many other methods (Shape Memory Alloys, phase changes of a liquid, friction control of a moving object …) have also been experimented.

3.2 - Specific additional technologies for MOEMS

Manufacturing of smooth optical surfaces : although the top surface of a silicon or glass wafer is of good optical quality, after micromachining, the surface smoothness of cavities or sidewalls is often perturbed, and the resulting roughness is too large for optical applications. This is a real manufacturing challenge : it happens that almost all optical quality surfaces that have been demonstrated up to now rely on the initial optical polishing of the wafer surface.

Optical thin film deposition : in order to integrate optical quality mirrors, it is often necessary to deposit optical multilayer coatings that act as mirrors or anti-reflection layers. Depending on the wavelength, various optical materials are known for these multilayers. However, it is necessary to choose optical materials that are fully compatible with the micromachining process, which is not always possible. Moreover, the optical multilayer coatings often produce stress in the microstructure, which can deform considerably the optical surface and lead to a beam distortion.

Integrated optics : planar waveguides and optical fiber technologies are expected to provide a powerful mean to design high performance optical systems. It is thus very useful to implement a waveguide technology which can be monolithically integrated with the micromechanical parts of the system.

Optical sources and detectors : the goal of MOEMS is to integrate on the same wafer a complete optical system, it is thus interesting to be able to bond or to manufacture directly some active devices, such as photodiodes or laser diodes.

4 - EXAMPLES OF MOEMS

4.1 - Beam scanning and switching

One of the most basic action on light beams consists in modifying the direction (or more generally the amplitude distribution) of the beam. The MOEMS that are probably among the first which were demonstrated are scanning micromirrors (1). For instance, thin metal or silicon layers can be patterned to produce small mirrors suspended by torsion beams, and actuated by a electrostatic forces. The applications of such devices are very wide: the simplest is the usage of these micromirrors as scanning elements for bar-code readers, or laser-based vision systems. Using the same technologies, it is easy to manufacture arrays of micromirrors which have been used to demonstrate video displays (2,3). More recently, an optical switching matrix for optical fiber communications has been demonstrated with a matrix of micromirrors (4).

Guided optics micromechanical switches have also been demonstrated. Some of these switches are based on the movement of optical fibers actuated by microelements (5,6) : the input fiber is moved in order to couple light into one or another receiving fiber. Another principle is based on the movement of an integrated optical waveguide located on a moving cantilever beam, which can launch light into one or another receiving waveguide (7). A third principle consists in inserting a mirror oriented at 45 degrees, at the crosspoint of two waveguides or optical fibers, in order to switch the light at 90 degrees from its initial direction (8,9).

4.2 - Amplitude modulation

In this case, we consider the amplitude modulation of a beam without intentional modification of the beam shape. Several light amplitude modulators have been demonstrated. The simplest way is based on the principle of the mechanical chopper : in that case suspended mechanical microstructures which are actuated perpendicularly to the beam are used as variable shutters (10). Another principle, which can be used for coherent beams, is based on Fabry-Perot interferometers (11) : in this case the interferometer is composed of a fixed mirror, and a thin membrane which is parallel and very close to the fixed mirror. The membrane moves toward the fixed mirror under electrostatic actuation, which changes by $\lambda/4$ the optical path inside the micro-interferometer, in order to switch the device from a reflective to a transparent state. A light modulator based on this principle has been designed for optical fiber communication links. This modulator is placed at the receiving end of the fiber, and acts as a variable reflector: when driven by an electrical signal, it modulates the reflection of the incoming beam, and thus produces a return signal without light emitting device at the receiving port (12).

4.3 - Beam shaping

An important application of MOEMS is that they open the possibility to manufacture cheap adaptive optics systems. These systems are based on 2D arrays of micromirrors which can move independently in a direction perpendicular to the substrate, and thus correct locally phase imperfections on the beam wavefront (13). Such active mirrors are already used in astronomy, however their applications could be much wider if they can be manufactured at low cost.

4.4 - Spectral filtering

This is again a very important application of MOEMS. Several tunable microfilters based on the principle of Fabry-Perot micro-interferometers have been demonstrated (14), and also a few grating based microspectrometers have been manufactured (15). A very promising device is the photodiode equipped with an integrated tunable Fabry-Perot filter. Such devices have been demonstrated with III-V compounds micromachining (16,17), and act as a very small microspectrometer for chemical sensing.

4.5 - Laser wavelength control

Micromechanical devices can often be used to control the wavelength of lasers. An external optical system including a mirror, a Fabry-Perot cavity or a diffraction grating with electromechanical actuation can be associated to a laser diode for such a purpose. This kind of device could lead to high performance lasers sources with a wide tuning range (18,19,20), or a better control of the pulse rate (21).

4.6 - Optical alignment and packaging

One of the most fascinating capability of MOEMS for field applications is the numerous possibilities that they offer to simplify the alignment and packaging of optical systems. To illustrate this concept, let us consider the old idea of manufacturing silicon V-grooves for the positioning of optical fibers : these V-grooves can be manufactured within a sub-micron tolerance and they can be employed to align precisely a single mode fiber with another optical system, without additional adjustments. More generally, modern microfabrication methods have the unique capability to enable micron order alignments at the fabrication level, without additional adjustments. This feature is precious because it enables the fabrication of complete optical systems in a very compact way, on a single substrate, and one can get rid of the numerous adjustments which are generally a cause of drift and instability in most of the optical systems. Several microdevices were designed to take advantage of microfabrication capabilities in order to improve optical alignments (22,23). In addition, several authors have shown the concept of micro-optical benches, which include a complete optical system on a single substrate, and for which a very limited number of adjustments are needed (24). Moreover, when the machining technology is not precise enough to obtain a perfect alignment, it is possible to integrate small actuators with the optical element in order to correct the slight residual misalignment of the sensitive device (25)

5 - MOEMS FOR SPACE APPLICATIONS

In this section, we would like to discuss the main potential advantages of MOEMS for space applications.

5.1 - A small weight

One of the most obvious advantage of Microsystems for space applications is their small weight. When the work can be done with the same quality and robustness by a light system, its advantage is immediate in terms of launching cost for space applications. For instance, a small scanning micromirror can be as efficient as a large one (and even better) for a total weight which can be more than one order of magnitude smaller.

5.2 - A volume fabrication for a small additional cost

Another cost advantage of Microsystems comes from the fact that it is possible to fabricate numerous systems for almost the same cost. Therefore, it becomes possible to design systems which are based on arrays of microdevices. For instance, adaptive optics are sophisticated systems that one could not afford except if they are small and inexpensive enough. Moreover, this feature opens the possibility of a rather systematic redundancy which is very useful for space applications. By using MOEMS technology, the additional cost of such a redundancy can be quite easy to support.

5.3 - A small energy consumption

Many optical systems using microactuators will consume less energy if they are small enough, because the energy required to move an object usually increases with its dimensions. Of course, this property will also depend on the energy losses in the actuation system: for instance, electrostatic actuators, which are voltage controlled with almost no current flow, generally exhibit less losses than electromagnetic actuators, because the latter are based on large currents and suffer from Joule effect losses.

5.4 - Robustness

As mentioned before, it is possible to design rather sophisticated microsystems containing only a very limited number of optical adjustments. Since adjustments are generally sources of misalignments, this feature generally leads to more simple and more robust optical devices.

In addition, one should notice that the small size of these micro-optical devices generally leads to other interesting features :

- For interferometer systems, the position of mirrors should be kept within about $\lambda/10$, however, for macro-systems, thermal drifts generally lead to position drifts on the order of one micron. In the case of Microsystems, thermal drifts can become much lower than the optical wavelength, and the penalty associated with these drifts become less important.
- The sensitivity of Microsystems to vibrations is generally lower than for bigger systems. The displacement coming from a parasitic acceleration is proportional to the mass of the object and inversely proportional to its stiffness. Since the maximum tolerable movement is an absolute value (say $\lambda/10$), and since the mass decreases much faster with the dimension than the stiffness, the movement associated to an external vibration is also decreasing quickly with the dimensions of the system.

5.5 - A small response time

The small mass of microdevices is clearly an advantage when quick movements of the device are required. When a step driving force is applied, inertial forces limit the response time for the displacement of the object. In the case of small objects, the position can be modulated at very high speeds. For instance some micro Fabry-Perot modulators can easily work with a frequency bandwidth of 1 MHz (11).

5.6 - Problems associated with radiations

It is worth reporting that some electrostatically driven microdevices can suffer from reliability problems in space because of the presence of radiations. Electrical charges are generated by radiations on the moving parts of electrostatic actuators, which leads to strong attractive forces between the fixed and the moving part. Therefore, the moving part is brought in close contact with the fixed one, and sometimes sticks to it permanently. Some further work should be done to get rid of this problem.

6 - CONCLUSION

The main characteristics of MOEMS have been reviewed and it has been shown that they exhibit several interesting features for space applications. These devices are clearly very attractive for space missions on which the payload should be minimized. Although some specific studies have to be done in order to match their advantages to space applications, a bright future is expected for MOEMS in space applications.

REFERENCES

1. "Silicon torsional scanning mirror", K.E. Petersen, IBM J. Res. Dev. 24 (1980), 631-637
2. "128x128 deformable mirror device", L.J. Hornbeck, IEEE Trans. Electron. Devices, ED-30 (1983), pp. 539-545
3. "A 128x128 Frame-Adressed Deformable Mirror spatial light modulator", R.M. Boysel, Optical Engineering, Vol. 30(1991), p. 1427
4. "Micromirrors relieve communication bottlenecks", D. Bishop, R. Giles, C. Roxlo, Photonics Spectra, March 2000, pp. 167-169
5. "Micromachined 1x2 optical-fiber switch", L.A. Field et al., Sensors & Actuators A 53 (1996), pp. 311-315
6. "Bistable micromechanical fiber-optic switches on silicon with thermal actuators", M. Hoffmann et Al., Sensors & Actuators, Vol. 78 (1999), pp. 28-35
7. "Micro-opto mechanical switch integrated on silicon", E. Ollier et al., Electron Lett. Vol. 31 (23), (1995) pp. 2003-2005
8. "Electrostatically driven micromechanical 2x2 optical switch", K. Hogari et al., Applied Optics 30 (10), (1991), pp. 1253-1257
9. "Vertical Mirrors Fabricated By Deep Reactive Ion Etching For Fiber Optic Switching Applications", C. Marxer, C. Thio, M.-A. Gretillat, O. Anthamatten, R. Baettig, B. Valk, P. Vogel and N. F. de Rooij, IEEE Journ. of MicroElectroMechanical Systems, Vol. 6 (3), Sept. 1997, pp. 277 – 285
10. "Electrostatic Driven Optical Chopper Using SOI Wafer", Osamu Tabata, Ryouji Asahi, Norio Fujitsuka, Masato Kimura and Susumu Sugiyama, Transducers'93, (1993), pp.811-814
11. "Silicon modulator based on mechanically-active anti-reflection layer with 1 Mbit/sec capability for fiber-in-the-loop applications", K.W. Goossen et al., IEEE Photon. Tech. Lett., Vol. 6 (9), (1994), pp. 1119-1121
12. "Packaging of a Reflective Optical Duplexer Based on Silicon Micromechanics", O. Anthamatten, R.K. Battig, B. Valk, and P. Vogel, C. Marxer, M. Gretillat, N.F. de Rooij, LEOS conf. on Optical MEMS and their applications, August 7-9 1996, Keystone, Colorado, USA
13. "Technology, characterisation and applications of adaptive optics mirrors fabricated with IC compatible machining", G. Vdovin, S. Middelhoek, M. Bartek, Proc. SPIE Vol 2534, pp. 116-129, (1995)
14. "Microelectromechanical tunable filter with stable half symmetric cavity", P. Tayebati, P. Wang, Masud Azimi, L. Maflah, D.Vakhshoori, Electron. Lett. Vol. 34 (20), (1998), pp.1967-1968
15. "Microspectrometer for the infrared range", Juergen Mohr,C.Mueller, C.van der Sel, Conf. on Micro-optical Technologies for Measurement, Sensors, and Microsystems, June 1996, Micropolis, Besancon, France, SPIE Proceedings Vol. 2783, pp.277-282

16. “Widely and continuously tunable micromachined resonant-cavity detector with wavelength tracking”, M.S. Wu et al., IEEE Photon. Tech. Lett. 8 (1) , (1996), pp. 98-100
17. “Indium Phosphide Based Micro Optoelectro Mechanics”, K. Hjort, K. Streubel, P. Viktorovitch, IEEE/LEOS Summer topical meeting on Optical MEMS and their applications, August 7-9 1996, Keystone, Colorado, USA
18. “Tunable laser diode using a Nickel micromachined external mirror”, Y. Uenishi et al., Electron. Lett., Vol. 32 (13), (1996), pp. 1207-1208
19. “ Laser diode wavelength locking using a micromachined silicon mirror ”, N. Kaou, C. Chappaz, S. Basrour, M. de Labachelerie, Conf. on Design Test & Microfab. of MEMS & MOEMS, Proc. SPIE Vol. 3680, March 1999, Paris, pp.765-772
20. “Vertical coupled-cavity Microinterferometer on GaAs with deformable-membrane top mirror”, M.C. Larson et Al., IEEE Photon. Tech. Letters, Vol. 7 (4), (1995), pp. 382-384
21. “Repetition-rate tunable micromechanical passively mode-locked semiconductor laser”, Y. Katagiri et al., Electron. Lett., Vol. 32 (25), (1996), pp. 2354-2355
22. “Microconnectors for the passive alignment of optical waveguides and ribbon optical fibers”, N. Kaou, V. Armbruster, J.-C.Jeannot, P. Mollier, H. Porte, N. Devoldere, M. de Labachelerie, Proc. IEEE MEMS 2000, Jan. 23-27 2000, Miyazaki – Japan, pp. 692-697
23. “Passively aligned hybrid integration of 8x1 micromachined Micro-Fresnel lens arrays and 8x1 Vertical-cavity Surface emitting laser arrays for Free-space Optical interconnect”, S.S. Lee et al., IEEE Photon. Tech. Lett. 7 (9), pp. 1031-1033, (1995)
24. “Self-aligned hybrid integration of semiconductor lasers with micromachined micro-optics for optoelectronic packaging”, L.Y. Lin, S.S. Lee, K.S. Pister et al., Appl. Phys. Lett., Vol. 66, (1995), pp. 2946-2949,
25. ”Integration of thin film Optoelectronic devices onto micromachined Movable Platforms”, S.T. Wilkinson et al., IEEE Photon. Tech. Lett. 6 (9) , (1994), pp. 1115-1118