

International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas



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Thierry Viard

Christophe Buisset

Xavier Rejeaunier

Frédéric Zamkotsian

et al.



PROGRAMMABLE SPECTROMETER USING MOEMS DEVICES FOR SPACE APPLICATIONS

Thierry VIARD, Christophe BUISSET, Xavier REJEAUNIER ⁽¹⁾

Frédéric ZAMKOTSIAN ⁽²⁾

Luis M. G. VENANCIO ⁽³⁾

(1) *Thales Alenia Space, 100 Boulevard du midi BP 99, 06156 Cannes la Bocca Cedex*

thierry.viard@thalesaleniaspace.com

(2) *Laboratoire d'Astrophysique de Marseille, CNRS, 38 rue Frédéric Joliot Curie 13388 Marseille Cedex 13*

frederic.zamkotsian@oamp.fr

(3) *European Space Agency Keplerlaan1- PO Box 299 – 2200 AG Noordwijk ZH*

ABSTRACT :

A new class of spectrometer can be designed using programmable components such as MOEMS which enable to tune the beam in spectral width and central wavelength. It becomes possible to propose for space applications a spectrometer with programmable resolution and adjustable spectral bandwidth.

The proposed way to tune the output beam is to use the diffraction effect with the so-called PMDG (Programmable Micro Diffraction Gratings) diffractive MEMS. In that case, small moving structures can form programmable gratings, diffracting or not the incoming light.

In the proposed concept, the MOEMS is placed in the focal plane of a first diffracting stage (using a grating for instance). With such implementation, the MOEMS component can be used to select some wavelengths (for instance by reflecting them) and to switch-off the others (for instance by diffracting them). A second diffracting stage is used to recombine the beam composed by all the selected wavelengths. It becomes then possible to change and adjust the filter in λ and $\Delta\lambda$.

This type of implementation is very interesting for space applications (Astronomy, Earth observation, planetary observation). Firstly because it becomes possible to tune the filtering function quasi instantaneously. And secondly because the focal plane dimension can be reduced to a single detector (for application without field of view) or to a linear detector instead of a 2D matrix detector (for application with field of view) thanks to a sequential acquisition of the signal.

1. NEW CONCEPT OF SPECTROMETERS

1.1. PMDG description

Programmable Micro Diffraction Gratings (PMDG) are a new class of MOEMS devices. Most of the MOEMS components are based on mirrors or shutters, in order to shape and/or relocate the incoming wavefront. Another way to tune the output beam is to use the diffraction effect with the so-called diffractive MEMS. In that case, small moving structures can form programmable gratings, diffracting or not the incoming light.

PMDG are built with multiple parallel ribbon structures, with alternating fixed and movable ribbons as the Grating Light Valve (GLV) component developed by Silicon Light Machines (Fig. 1). Actuation of the ribbons is produced by using the electro-static force. The number of parallel ribbons can be very high (up to several thousands) associated with very narrow dimension (width of each ribbon can be around 4 μm), they must be identical from ribbon to ribbon and their surface quality has to be at the level of optical quality.

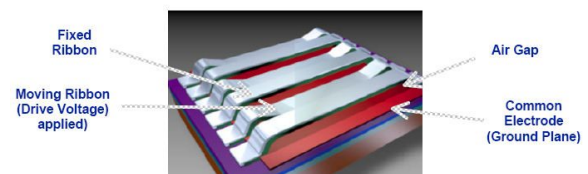


Figure 1: The GLV architecture by Silicon Light Machines [1]

When all ribbons are in the same plane, this device is like a mirror and the light is reflected (Fig. 2). When movable ribbons are pulled down, the shape of the reflecting surface is like a square grating, diffracting the light in the different diffraction orders. If the stroke is equal to $\lambda/4$, the light is completely switched in the diffraction directions.

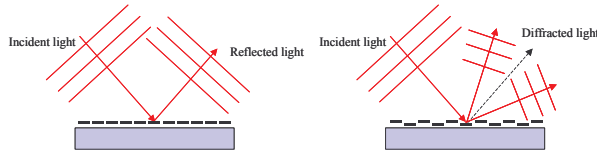


Figure 2: PMDG principle

The original idea was experimentally demonstrated in the early 1990's at Stanford University, becoming then the Grating Light Valve, registered trade mark of Silicon Light Machines [1]. The main application of this component is for imaging display where the PMDG replaces advantageously the conventional LCD or DMD (Texas Instruments) devices [2]. Another PMDG application is spectroscopy (correlation spectroscopy, Hadamard spectroscopy). Correlation spectroscopy allows the fast detection of known species by reconfiguring the device in order to "reproduce" the species spectra and by correlation with the incoming beam spectra, the presence or not of these species could be checked with a single detector. Polychromix has already developed such instrument for on ground applications [3].

1.2. Spectrometer concept

The idea is to have a tuneable spectrometer by using a PMDG component. The principle is to place the MOEMS in the focal plane of a first diffracting stage (using a grating for instance) and to use it as a wavelength selector by reflecting the wanted wavelengths and by switching-off the others (by diffracting them). It becomes then possible to realise a programmable and adjustable filter in λ and $\Delta\lambda$. (Fig 3).

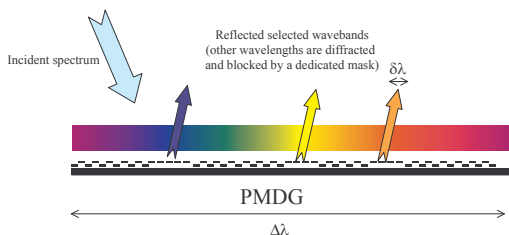


Figure 3: Principle of wavelengths selection by using a PMDG. The wanted wavelengths are reflected while the other one are diffracted and blocked by a specific mask

The spectrometer shall first disperse the light onto the PMDG thanks to a grating associated with a focusing lens for instance and then recombine the beam after wavelengths selection (PMDG level) by exactly the same dispersive component (same grating in our example). This kind of implementation allows to tune the filtering function in spectral bandwidth and in central wavelength quasi instantaneously (Fig 4).

Moreover, a great advantage of such design is the fact that the focal plane dimension can be reduced to a single detector (for application without field of view) or to a linear detector instead of a 2D matrix detector array with an improved 2D PMDG (for application with field of view).

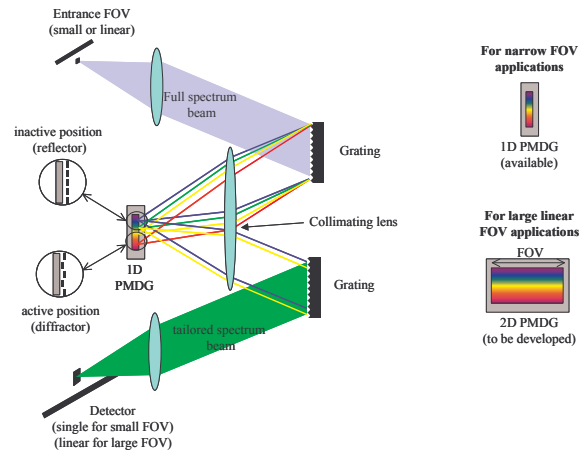


Figure 4 PMDG implementation enabling from a full spectrum input to select any set of λ and $\Delta\lambda$ centred on these lines. The source can be then spectrally analysed with a simple detector in a sequential way.

A consequence of this concept is that the measurements have to be performed sequentially (in wavelength) and not simultaneously as done by the conventional spectrometers. But thanks to the PMDG very fast response time (few microseconds), it is not a problem even for movable targets.

Since the PMDG use allows to adjust wavelength (λ) and waveband ($\Delta\lambda$), its accommodation can replace advantageously conventional solutions based for instance on:

- Dichroic filters
- Filters wheel
- Strip filters

2. POSSIBLE SPECTROMETER DESIGN

2.1. Dimensioning constraints

One constraint of the system is to have several ribbons in the PSF dimension in order to be able to act on the incident beam phase. As a result, if the PSF is inside one ribbon, it will be never possible to diffract the light. The optimum compromise between the efficiency of diffraction and the PMDG dimension is reached with a PSF dimension covering around 6 ribbons [1] (Fig 5).

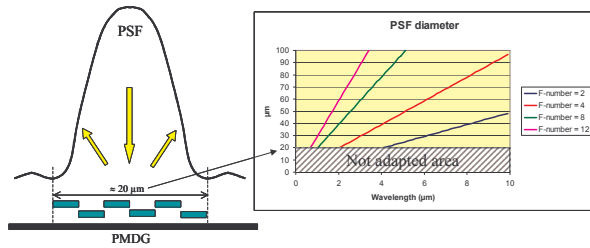


Figure 5 Conditions on F-number (N) and wavelength (λ) for having a correct wavelength diffraction (extinction in specular direction). The PSF dimension is limited here to its first ring (PSF diameter = $2.44\lambda N$)

Such utilisation of PMDG device is very well adapted for IR applications (even for fast aperture) or for visible high resolution imaging instruments (long focal length). For applications with field of view, a 2D PMDG device is required (but not yet developed).

A second constraint is link to the small dimension of PMDG component : 20 mm seems to be a reasonable maximum value for the next decennia. This dimension will have a limiting factor on the achievable number a spectral channels (or resolving power). From the figure 3, if we note W_r as the ribbon width, W as the PMDG dimension and n as the number of ribbons covered by the PSF, the maximum number of channels (N) is given by :

$$N = \frac{\Delta\lambda}{\delta\lambda} = \frac{W}{n \cdot W_r}$$

For a PMDG dimension around 20 mm (considered as challenging), ribbons around $4 \mu\text{m}$ and 6 ribbons in the PSF, the maximal spectral channels is around 1000 which is very promising.

2.2. Spectrometer description

The proposed design for the spectrometer (Fig 6) is based on reflecting elements (mirrors and grating). The reason is to have the most adaptable design as possible with the spectral band (from visible to IR domains).

Two identical gratings are used, first to disperse the wavelengths on the PMDG and then to reform a collimated beam with the selected wavelengths. This output beam is focused on a single detector by an off-axis parabola. The PMDG is placed in the focal plane of a single mirror. The selected wavebands are reflected on the same mirror and are then collimated to the second grating. The none selected wavelengths are diffracted by the PMDG in directions which are blocked by dedicated black painted baffles.

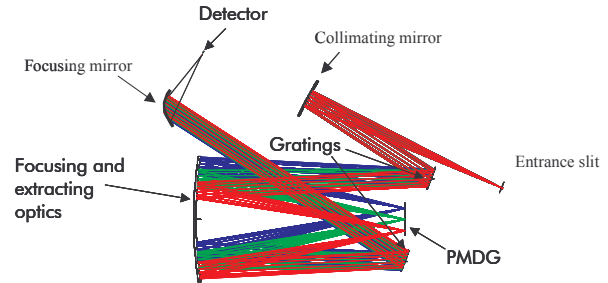


Figure 6 Optical design for a spectrometer using a 20 mm long PMDG component

An athermal mechanical design is preferred for the following reasons :

- Possibility to work at cryogenic temperature,
- Good stability of optics alignment

The mechanical design (Fig 7) shall be also compatible with a fine alignment of the optics during integration. The proposed optical spectro box is made of :

- one integrated Cesium box , this box is fixed on instrument bench by 3 filtering invar blades
- one focusing m1 Cesium mirror
- two grating Cesium mirrors , grating will be performed on the top deposited silicon layer on the Cesium mirror
- the PMDG which is fixed by 3 elastic shim to the Cesium box

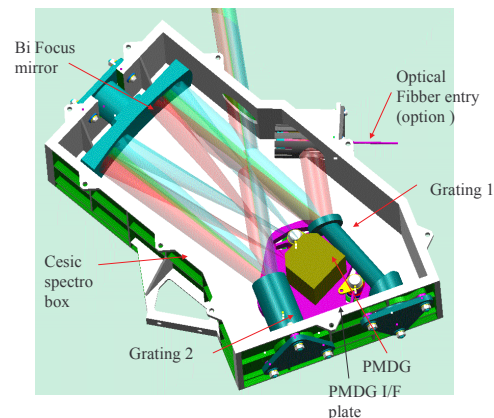


Figure 7 Mechanical design for a spectrometer using a PMDG component. Box dimensions is less than 250 mm x 400 mm.

2.3. Evaluation of performance

The spectral domain is spread over the PMDG dimension (L). The spectral dispersion (provided by the first grating) is linear in function of wavelength. Therefore, the spatial position x_{PMDG} within the PMDG plane experiences a linear evolution with the wavelength. Thus, it can be written that

$$x_{PMDG}(\lambda) = A \cdot \lambda + B$$

Besides assuming that the whole spectral domain, from λ_{min} to λ_{max} , is dispersed on the total width (L) of the PMDG, A and B are derived from

$$A = \frac{L}{\lambda_{max} - \lambda_{min}}$$

$$B = -\frac{L \cdot \lambda_{min}}{\lambda_{max} - \lambda_{min}}$$

The focusing optics on the PMDG is calculated to be diffraction-limited, so that the PSF_{λ} whatever the wavelength is an Airy disk (Bessel function). The next figure (Fig 8) illustrates these assumptions.

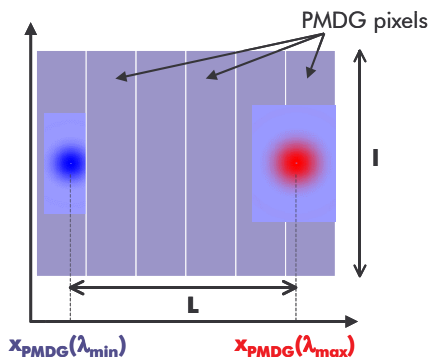


Figure 8 : Scheme illustrating the PSF position in the PMDG plane

A PMDG pattern is created and formed of a combination of ON- and OFF-pixels. A pixel (constituted by 6 ribbons) is ON when it reflects light with a maximum reflectivity (R_{max}) and is OFF when its reflectivity is at the minimum (R_{min}) (when in fact the light is diffracted in other directions).

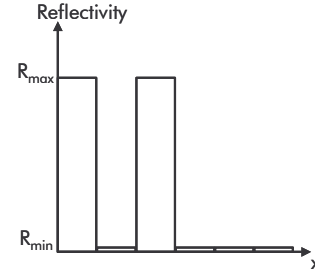


Figure 9 : Example of a PMDG pattern. Here 2 pixels are set ON whereas the others are OFF.

Then for each wavelength, this pattern is multiplied by the PSF_{λ} . The resulting spectral component at λ , $Sp(\lambda)$ is then obtained with integration on the spatial domain of this multiplication.

$$Sp(\lambda) = \iint_{PMDG} PSF_{\lambda} \cdot Pattern \cdot dS$$

Results are presented in the next figure (Fig 10). It shows the spectral transmission of the spectrometer when one pixel every five is ON.

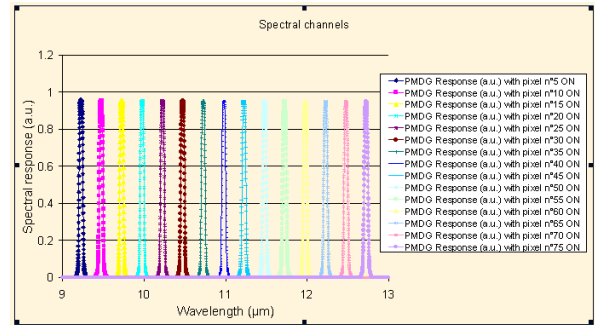


Figure 10 : Example of spectrometer theoretical response when one every 5 pixels are ON

By changing the PMDG pattern, it could be possible to have quasi instantaneous other spectral responses (large or narrow band pass filters, low pass or high pass filters).

3. ADVANTAGES OF USING MOEMS IN SPACE SPECTROMETERS

3.1. Review of possible space missions

Among the future ESA space missions, many could use a spectrometer based on a PMDG component :

- Earth Care missions,
- GMES missions
- Flex missions,
- planetary observation missions
- Exoplanet science theme missions

Exoplanet search missions (DARWIN-like mission) seems particularly well adapted for this technology since :

- they work in IR (PMDG easier to manufacture)
- they have a very small field of view (mature PMDG technology)
- they aim at fixed target observation (compatible with sequential spectral analysis)
- they require hundred of channels (easily achievable by PMDG technology)

We have realised a simulation with DARWIN-like requirements : by implementing a spectrometer as described in chapter 2 using a PMDG component and only one monapixel, all possible spectral figure could be achieved from large band pass filter (6 μm to 20 μm) to narrow band pass filter (around 40 nm) around whatever wavelengths in the DARWIN spectral range (cf Fig 11).

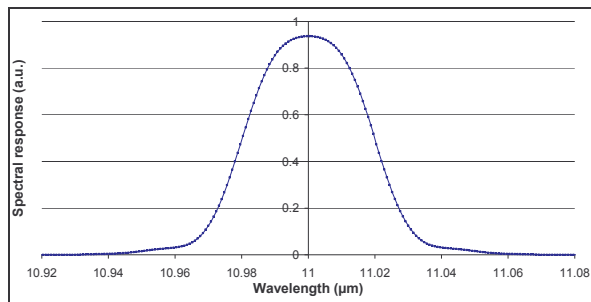


Figure 11: Spectral transmission for one PMDG pixel (at $\lambda=11 \mu\text{m}$ turned ON (narrowest achievable spectral response)

Figure 12 shows the spot diagram of the DARWIN adapted spectrometer in the detector plane thus demonstrating that this optical design is diffraction limited (given by the circle in the figure) and adapted to a $30 \mu\text{m} \times 30 \mu\text{m}$ monapixel detector size.

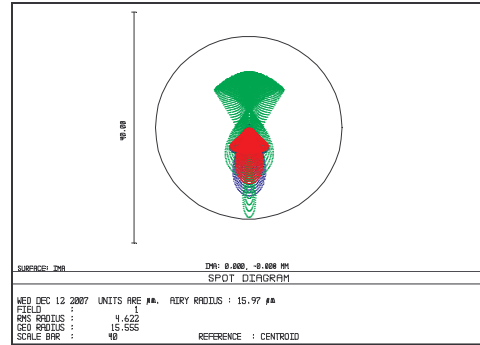


Figure 12 : Spot diagram in the DARWIN detector plane for a waveband 9 μm – 13 μm

3.2. Review of advantages

The following very promising advantages have been identified for DARWIN-like missions trough this first analysis :

At detector level : the use of a PMDG allows to work with a monapixel. A mix of different materials (HgCdTe & SiAs) becomes then possible for a better efficiency adaptation. It becomes also possible to use avalanche gain in order to increase the SNR or to decrease the integration time. The manufacturing efficiency (yield) will be also much better due to a simpler and better selection.

At instrument level : working with a monapixel allows to decrease power dissipation at cryostat level so to decrease the cooler surface and finally the mass and the volume of the instrument.

At system level : working with a fully programmable PMDG allows to increase the spectral analysis capacities by adapting the filtering profile to the observed target [4]. Moreover, by using a monapixel, there is no more pixel to pixel non uniformity. Calibration philosophy can be considerably relaxed. The spectrometer integration requirement can be also relaxed due to the use of a monapixel which can be oversized in order to take into account higher misalignments.

Finally, all these advantages identified in the frame of the Darwin mission can be fully transposed to others missions. A breadboard of spectrometer using a PMDG is presently under test at LAM (Laboratoire d'Astrophysique de Marseille) premises in the framework of an ESA contract [4].

4. CONCLUSION

We have proposed and analysed for the first time in Europe a space spectrometer design based on the use of a MOEMS component. With such a solution, it becomes possible to adapt in real time the spectral response of the instrument depending on the target or images viewing philosophy. The advantages of a spectrometer based on the PMDG technology has been clearly identified. It allows to :

- Save power dissipation (less pixel, less cable...)
- Avoid interpixel calibration.
- Increase detector efficiency (selection of best detector).
- Increase detector manufacturing yield
- Save cooler surface.
- Quickly change spectral resolution.
- Relax FPA alignment (by increasing pixel size).

These advantages have to be balanced with :

- Higher volume (due to gratings implementation and PMDG units)
- Lower optical transmission (due to grating efficiency).

A breadboard of spectrometer using a PMDG is under test and the current results are very promising for future applications.

5. ACKNOWLEDGMENT

The results of studies and analysis presented here above have been achieved in the frame of the ESA contract 20519/06/NL/SFe.

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